CHAPTER 1

INTRODUCTION TO POWER QUALITY

1.1 INTRODUCTION

This chapter reviews the power quality definition, standards, causes and effects of harmonic distortion in a power system.

1.2 DEFINITION OF ELECTRIC POWER QUALITY

In recent years, there has been an increased emphasis and concern for the quality of power delivered to factories, commercial establishments, and residences. This is due to the increasing usage of harmonic-creating non linear loads such as adjustable-speed drives, switched mode power supplies, arc furnaces, electronic fluorescent lamp ballasts etc.[1]. Power quality loosely defined, as the study of powering and grounding electronic systems so as to maintain the integrity of the power supplied to the system. IEEE Standard 1159 defines power quality as [2]: The concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment. In the IEEE 100 Authoritative Dictionary of IEEE Standard Terms, Power quality is defined as ([1], p. 855): The concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment. Good power quality, however, is not easy to define because what is good power quality to a refrigerator motor may not be good enough for today’s personal computers and other sensitive loads.

1.3 DESCRIPTIONS OF SOME POOR POWER QUALITY EVENTS

The following are some examples and descriptions of poor power quality “events.”

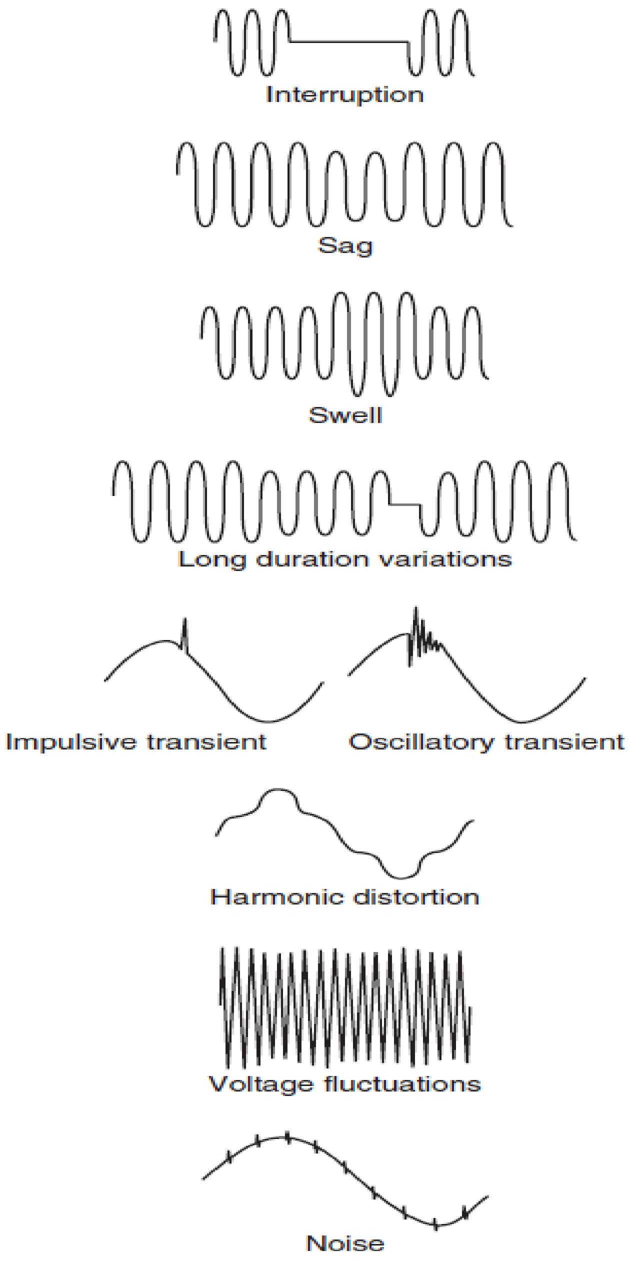


Fig. 1.1 Typical power disturbances [2].

■ A voltage sag/dip is a brief decrease in the r.m.s line-voltage of 10 to 90 percent of the nominal line-voltage. The duration of a sag is 0.5 cycle to 1 minute. Common sources of sags are the starting of large induction motors and utility faults.

- A voltage swell is a brief increase in the r.m.s line-voltage of 110 to 180 percent of the nominal line-voltage for duration of 0.5 cycle to 1 minute. Sources of voltage swells are line faults and incorrect tap settings in tap changers in substations.
- An impulsive transient is a brief, unidirectional variation in voltage, current, or both on a power line. The most common causes of impulsive transients are lightning strikes, switching of inductive loads, or switching in the power distribution system. These transients can result in equipment shutdown or damage, if the disturbance level is high enough. The effects of transients can be mitigated by the use of transient voltage suppressors such as Zener diodes and MOVs (metal-oxide varistors).
- An oscillatory transient is a brief, bidirectional variation in voltage, current, or both on a power line. These can occur due to the switching of power factor correction capacitors, or transformer ferroresonance.
- An interruption is defined as a reduction in line-voltage or current to less than 10 percent of the nominal, not exceeding 60 seconds in length. Another common power-quality event is “notching,” which can be created by rectifiers that have finite line inductance.
- Voltage fluctuations are relatively small (less than 5 percent) variations in the r.m.s line-voltage. These variations can be caused by cycloconverters, arc furnaces, and other systems that draw current not in synchronization with the line frequency. Such fluctuations can result in variations in the lighting intensity due to an effect known as “flicker” which is visible to the end user.
- A voltage “imbalance” is a variation in the amplitudes of three-phase voltages,

relative to one another.

1.4 HARMONICS AS POWER QUALITY PROBLEM

Harmonic disturbances come generally from equipment with a non-linear voltage/current characteristic. Nowadays a large part of industrial, commercial and domestic loads is non-linear, making the distortion level on the low-voltage supply network a serious concern. As time goes on, more and more equipment is being used that creates harmonics in power systems. Conversely, more and more equipment is being used that is susceptible to malfunction due to harmonics. Computers, communication equipment, and other power systems are all susceptible to malfunction or loss of efficiency due to the effects of harmonics. For instance, in electric motors, harmonic current causes AC losses in the core and copper windings. This can result in core heating, winding heating, torque pulsations, and loss of efficiency in these motors. Harmonics can also result in an increase in audible noise from motors and transformers and can excite mechanical resonances in electric motors and their loads.

Harmonic voltages and currents can also cause false tripping of ground fault circuit interrupters (GFCIs). These devices are used extensively in residences for local protection near appliances. False triggering of GFCIs is a nuisance to the end user. Instrument and relay transformer accuracy can be affected by harmonics, which can also cause nuisance tripping of circuit breakers. Harmonics can affect metering as well, and may prompt both negative and positive errors. High-frequency switching circuits such as switching power supplies, power factor correction circuits, and adjustable-speed drives create high-frequency components that are not at multiples of line frequency. Harmonic distortion can be considered as a sort of pollution of the electric system which can cause problems if the sum of the harmonic currents exceeds certain limits.

1.5 HARMONICS AND THEIR CLASSIFICATION

A harmonic is defined as a component with a frequency that is an integer multiple of the fundamental frequency. The harmonic number or harmonic order indicates the harmonic frequency. The ratio of harmonic frequency to fundamental frequency is harmonic order.

Triplen harmonics are the harmonics whose orders are multiples of three. Zero-sequence harmonics are also called homopolar harmonics. In a three-phase system homopolar currents are a sum in the neutral conductor. Interharmonics are voltages or currents with a frequency that is a non-integer multiple of the fundamental frequency. Another term is used namely, subharmonic, which does not have any official definition. It is a particular case of an inter harmonic with a frequency less than the fundamental frequency.

1.6 QUANTITIES DESCRIBING VOLTAGE AND CURRENT DISTORTION

Voltage/current distortion can be characterized in either the time or the frequency domain. Description in the time domain consists of finding the differences between the actual distorted waveform values and the reference sinusoidal waveform values. The difficulty in determining these differences by means of measurement causes this method of description is seldom used. The distortion description in the frequency domain is commonly accepted.

- ### Individual Harmonic Distortion (IHD)

It is the ratio between RMS value of individual harmonic and the rms value of the fundamental component of a wave form.

$$\mathrm{IHD_n} = \frac{\mathrm{I_n}}{\mathrm{I_1}} \text{ x } 100 \qquad (1.1)$$

where I_n is the amplitude of current harmonic ‘n’ and I_1 is the amplitude of fundamental current .

Total Harmonic Distortion(THD)

The ratio of r.m.s. value of the sum of all the harmonic components up to a specified order to the r.m.s. value of the fundamental component is called total harmonic distortion and can be represented as

$$THD = 100\sqrt{\sum_{n=2}^{\infty}\frac{I_n^2}{I_1^2}} \tag{1.2}$$

I_1, I_2, I_3, I_4,….. I_n, are r.m.s. values of harmonics 1,2,3,4,….n. Normally ‘n’ is limited to 50. If risk of resonance is less at higher orders then ‘n’ is limited to 25.This parameter is used in low-voltage, medium-voltage or high-voltage systems. Conventionally, current distortion parameters are suffixed with ‘I’, e.g. 35 % THD_I, and voltage distortion figures with ‘V’, e.g. 4 % THD_V .

Peak Factor

Peak factor is the ratio of the peak value and r.m.s value of a periodic waveform, which for a sinusoidal wave is 1.41. The logical consequence of this is that any other value means a waveform distortion.

Crest Factor

Crest factor is the ratio of r.m.s value to average value of a wave form.

1.7 POWER QUALITY STANDARDS RELATED TO HARMONIC DISTORTION

IEEE standard 519(IEEE Std. 519-1992) was introduced in 1981and updated in 1992. It offers recommended practices for controlling harmonics in electrical systems [1]. The IEEE has also released IEEE Standard 1159 (IEEE Std. 1159-1995), which covers recommended methods for measuring and monitoring power quality Standards, define recommended limits for events that degrade power quality.

➢ IEEE Standards 519 and 1159

IEEE Standard 519-1992 is titled "IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems." The abstract of this standard are being used today in industrial and commercial facilities for harmonics and reactive power control. The standard covers limits to the various disturbances recommended to the power distribution system. The 1992 standard is a revision of an earlier IEEE work published in 1981 covering harmonic control. The basic themes of IEEE Standard 519 are two-fold. First, the utility has the responsibility to produce good quality voltage sine waves. Secondly, end-use customers have the responsibility to limit the harmonic currents their circuits draw from the line. The Table 1.1 shows the limits of individual current harmonics for a generation distribution system and the Table 1.2 shows the limits of Voltage distortion at different voltage levels.

Table 1.1 Current distortion limits for general distribution systems[1] (120V through 69000V)

Maximum Harmonic Current Distortion(In percent of I_L)						
Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD

<20[*]	4.0	2.0	1.5	0.6	0.3	5.0
20<50	7.0	3.5	2.5	1.0	0.5	8.0
50<100	10.0	4.5	4.0	1.5	0.7	12.0
100<1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

*All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L

Where I_{SC} = maximum short-circuit current at PCC.

I_L = maximum demand load-current (fundamental frequency component) at PCC.

h = Individual harmonic order.

TDD=Total Harmonic distortion based on maximum demand load current (or) The total root-sum-square harmonic current distortion expressed in percent of maximum demand load current.

Table 1.2 Voltage distortion limits [1]

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0

69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

1.8 SOURCES OF CURRENT HARMONICS

The sources of harmonic currents and voltages in power systems can be distinguished in to three groups of equipment.

1. Magnetic core equipment, like transformers, electric motors, generators, etc.
2. Conventional equipment, like Arc furnaces, arc welders, high-pressure discharge lamps, etc.
3. Electronic and power electronic equipment.

1.8.1 Magnetic Core Equipment

► *Transformers*

The magnetization curve of transformer is strongly non-linear and hence its location within the saturation region causes distortion of the magnetizing current as shown in Fig. 1.2.These are not a significant source of harmonics under normal operating conditions. But when the voltage is increased by even a small value and reaches saturation the magnetizing current increases causing significant rise in harmonic content. The effects of switching transients which propagate in the system can cause transformer saturation, sometimes over a large area.

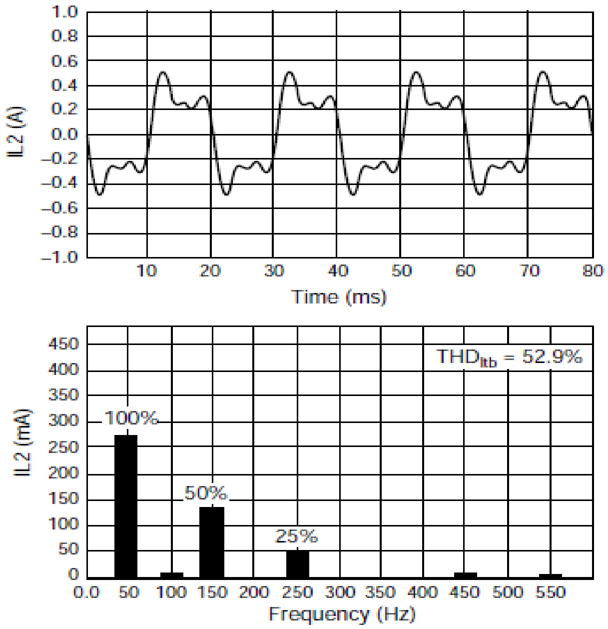


Fig. 1.2 Transformer distorted magnetizing current and its harmonic spectrum.

► *Motors and Generators*

Similar to transformers, motors will also generate harmonic currents in order to produce a magnetic field. Their contribution, however, is very small as the motor magnetizing characteristic, due to the presence of an air gap, is much more linear compared to the transformer magnetization characteristic. The pitch of motor winding can also be a cause of harmonic currents. Typical motor windings have 5–7 slots per pole, which results in the generation of the fifth or seventh harmonic. In spite of the fact they are incomparably smaller than high harmonics in converter equipment, their presence is noticeable in the case of very large motors. Harmonics also occur in generator voltage, since for both practical and economic reasons a spatial distribution of the stator windings which could guarantee a purely sinusoidal voltage waveform is neither advisable nor possible. The induced voltages are therefore slightly distorted, and usually the third harmonic is the dominant one. It causes the third-harmonic current flow under generator load conditions.

1.8.2 Conventional Equipment

This category includes arc furnaces, arc welders, high-pressure discharge lamps etc.

- ***Arc Furnaces***

Distortion of arc furnace currents, and in consequence also of voltages, is an important issue because of their common usage. Moreover, for technological reasons, arc furnaces are presently operated at a lower power factor than in the past. One of the consequences of this is the increasing rated power of the compensating capacitors. This results in lowering the resonant frequency. As the amplitudes of high harmonics are of significant value in this range of the spectrum, a magnification of the supply voltage harmonics may occur. Conditions of arc discharge changes in subsequent phases of the heating process. The highest level of current distortion occurs during the melting phase, whereas it is much lower in the other phases (air refining and refining). With the occurrence of a liquid metal surface a short arc occurs, the current fluctuations are smaller and the current waveform is closer to the sinusoidal one. A typical amplitude spectrum of the current – during melting is shown in Fig. 1.3 and the harmonic spectrum of arc furnace current during melting and refining phases are shown in Fig. 1.4. This spectrum exhibits the dominant harmonics with the largest amplitudes and of orders being both even and odd multiples of the fundamental frequency: 2, 3,….. It is regular for these amplitudes to decrease quickly with the increase in the harmonic frequency. With increasing furnace power the voltage distortion increases, while the current distortion decreases.

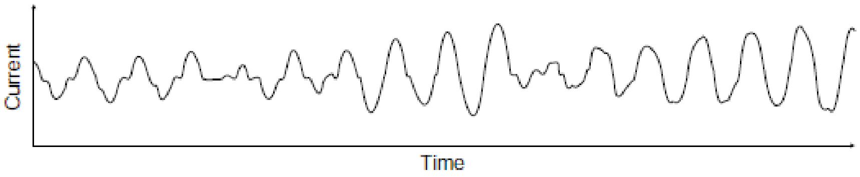


Fig. 1.3 Time graph of a furnace current during the starting phase of melting [2].

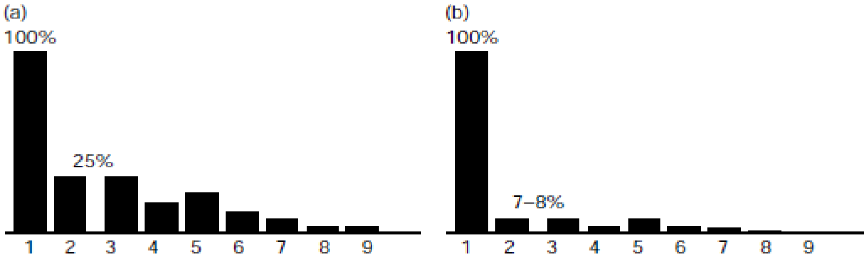


Fig. 1.4 Harmonic spectrum of an arc furnace current (a) During melting (b) During refining[2].

► *Fluorescent Lighting*

Electronic lighting ballasts have become popular recently because of their improved efficiency compared to magnetic ballasts. These devices have unfortunately a great disadvantage because of the harmonics they generate in the supply current. Today power factor corrected types are available in order to reduce the harmonic problems, but at a cost. In any case, smaller units are usually uncorrected. Compact fluorescent lamps (CFLs) are now sold as replacements for tungsten filament bulbs. In these lamps, a small electronic ballast, installed in the connector casing, controls a folded 8 mm diameter fluorescent tube. A typical harmonic current spectrum for these devices is shown in Fig. 1.5. These types of lamps are widely used today leading to serious harmonic problems.

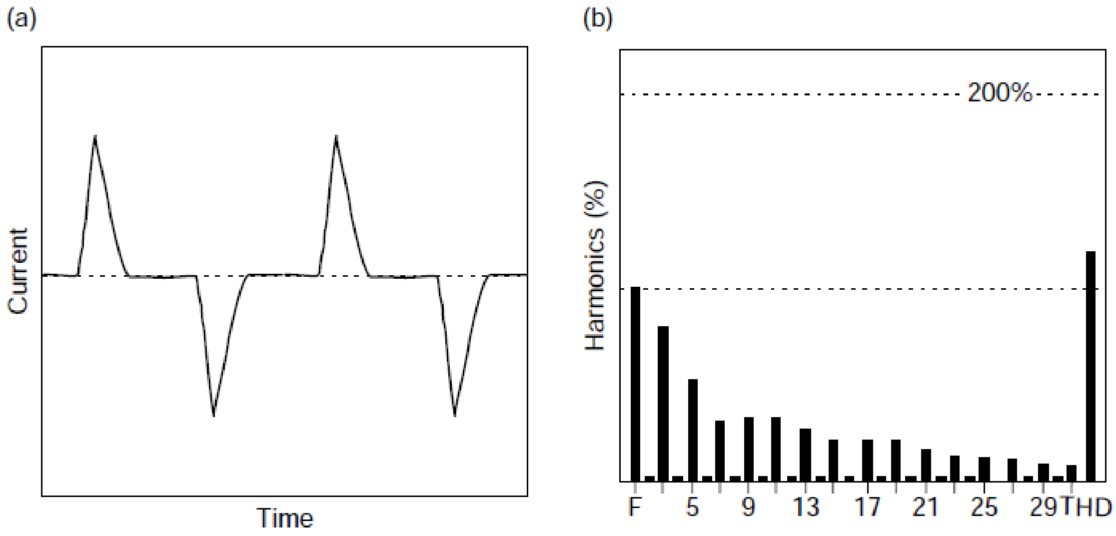


Fig. 1.5 The current wave form of a compact fluorescent lamp and its Harmonic spectrum [2].

1.8.3 Electronic and Power Electronic Equipment

This category includes Switched mode power supplies, Rectifiers, Static var compensators etc.

- ***Switched Mode Power Supplies (SMPS)***

The major part of modern electronic devices is fed by switched mode power supplies (SMPS) with single-phase rectifiers with direct controlled rectification of the supply to charge a reservoir capacitor from which the direct current for the load is derived in order to obtain the output voltage and current required. With this approach, the main advantage is that the size, cost and weight have been reduced and the power unit can be made with practically any form factor. The disadvantage introduced is that now, instead of drawing continuous current from the supply, the unit draws pulses of current which contain large amounts of third- and higher-order harmonic components. Fig. 1.6 shows the waveform and spectrum of a typical current for most of presently used electrical and electronic equipment (the current of a single- phase rectifier with a capacitive filter at the DC side). It can be clearly seen that the 3rd,5th and 7th harmonic values are comparable to the fundamental component value.

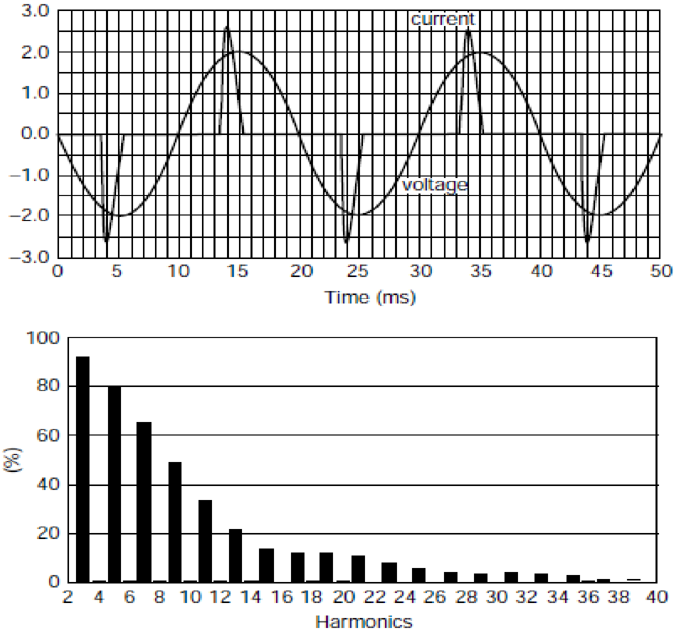


Fig. 1.6 Voltage waveform and harmonic spectrum of the current in a diode bridge with DC side capacitive filter (THD_i=130%)[2].

► *Three Phase Rectifier*

All equipment containing static converters, UPS units and a.c./d.c. converters in general, are based on a three-phase bridge, also known as a six-pulse bridge because there are six voltage pulses per cycle (one per half cycle per phase) on the d.c. output. This bridge produces current harmonics of order 6n±1 in supply networks. In theory, the magnitude of each harmonic should be equal to the reciprocal of the harmonic number, so there would be 20% of the 5th harmonic and 9% of the 11th harmonic, etc. Fig. 1.7 shows an example waveform of a thyristor bridge current against the phase voltage. Commutation notches are clearly visible in the voltage waveform.

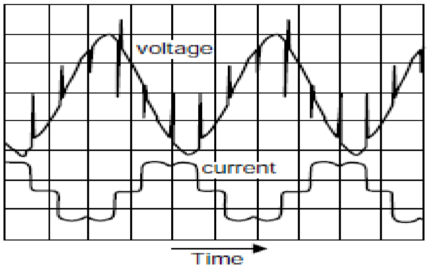
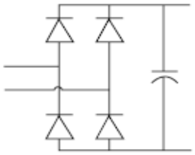
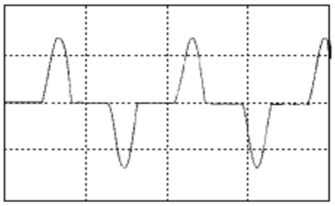
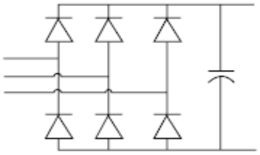
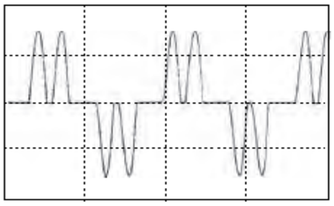
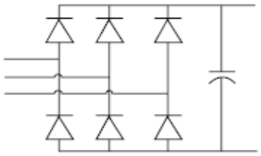
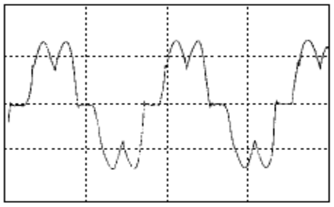
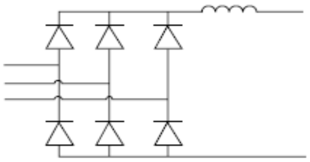
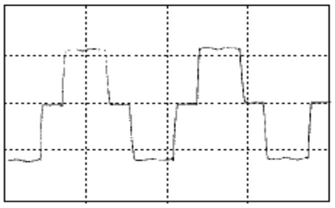
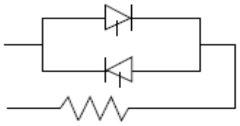
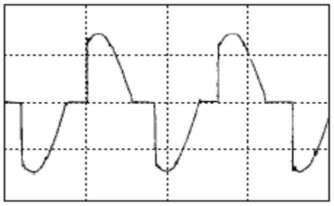


Fig. 1.7 Waveform of the supply voltage and current of a six-pulse thyristor bridge with DC side reactor[2].

Table 1.3 Current waveforms and their THD for various types of converters [2].

Converter type	Current waveform	Comments
		Single-phase rectifier $THD_I \approx 80\,\%$ dominant third harmonic
		6-pulse rectifier with capacitor on the DC side $THD_I \approx 80\,\%$
		6-pulse rectifier with capacitor on the DC side and AC input reactors $> 3\,\%$, or a DC drive $THD_I \approx 40\,\%$
		6-pulse rectifier with DC side reactor $THD_I \approx 28\,\%$
		AC power controller (resistive load) THD_I variable with control angle

► *Static VAR Compensator*

For thyristor's control angle $\alpha = \pi/2$ (with respect to the positive zero crossing of the supply voltage) the phase reactor current is sinusoidal. Increasing the control angle ($\alpha > \pi/2$) not only reduces the current value but also causes the current discontinuity. Harmonics of odd order occur when control angles are identical for both thyristors in the switch T. The current waveforms and their THD for various types of converters are shown in Table 1.3.

1.9 EFFECTS OF HARMONICS

The voltage/current distortion effect is determined by the sensitivity of loads and power sources which are influenced by the distorted quantities. The least sensitive are heating equipment of any kind. The most sensitive equipment are those electronic devices which have been designed assuming an ideal sinusoidal fundamental frequency voltage or current waveforms.

1.9.1 Overheating of Phase and Neutral Conductors

The presence of harmonics in the current can lead to overloading problems both on phase conductors and on the possible neutral conductor. Under the conditions of current deformation, heat deformation inside the cable due to the Joule effect is evidently greater and the line capacity is reduced. The neutral conductors can be overloaded without the neutral current exceeding the nominal phase current. This issue is particularly important in low-voltage systems where harmonic pollution by single-phase loads is an increasingly serious problem. Triplen harmonic currents add arithmetically in the neutral conductor rather than summing to zero as do balanced fundamental and other harmonic currents. Therefore neutral currents will be significantly higher than the phase currents leading to overloading. In a star-connected three-phase system, if the loads are not balanced, a current flows in the neutral conductor as a result of the vector sum of the three-phase currents. Also in a three-phase power system feeding linear single-phase loads, the current in the neutral conductor is rarely zero because the load on each phase is different.

1.9.2 Skin Effect

The skin effect above 350 Hz becomes significant, causing additional loss and heating.

The a.c. resistance to d.c. resistance ratio is dependent on conductor radius and is dependent on the current penetration thickness (δ), which can be expressed as

$$\delta = \sqrt{\frac{2\rho}{\omega \mu}} \qquad (1.4)$$

where μ is the magnetic permeability(H/m), ω the frequency(rad/sec); and ρ the resistivity(Ωm/m^2)[2].

It is evident that δ is dependent on the frequency; in particular it decreases as frequency increases. For this reason in harmonic rich environment the skin effect should be accounted and cables should be properly derated. A possible solution is also provided by multiple cable cores or laminated busbars which can be used as an alternative way to overcome this problem. It is also important to pay attention to the fact that the mounting systems of busbars must be designed in order to avoid mechanical resonance at harmonic frequencies.

1.9.3 Motors and Generators

Harmonics in the current causes increase in the r.m.s. value and increase in the effective resistance of the windings due to the skin effect causing rise in stator and rotor winding losses as a result rise in operating temperature. In electric motors even a small harmonic voltage distortion give rise to additional magnetic flux and hence additional currents in the rotor winding and core causing additional active power loss, temperature rise and increases in machine failure rate.

In a synchronous machine additional losses associated with high harmonics occur mainly in the stator windings and damping cage. Most significant are the harmonics which form a negative-sequence system, i.e. the 5th, 11th, 17th, 23rd…… the rise of stator and rotor winding losses results from both the increase in the r.m.s current value, due to distortion, and the increase in the effective resistance of the windings, due to the skin effect. Flux produced by rotor harmonic currents of an induction motor interacts with air gap flux and causes additional harmonic torques. Positive-sequence harmonics produce a forward rotating field that adds to the torque and supports the machine rotation, whereas the other harmonics (5th, 11th, 17th, 23rd,) have the converse effect. Harmonic torque influence the instantaneous value of the resultant torque and results in its fluctuation.

Mechanical oscillations of electric machines, supplied with distorted voltage, attain their maximum values when the frequency of the motor torque variations is equal or close to the mechanical resonance frequency of the motor and driven machine set. This phenomenon can also occur in a turbine–generator set. The presence of harmonic currents in motor windings increases the acoustic noise emission compared to that for sinusoidal waveforms. By affecting the air gap flux distribution, harmonics can hamper the soft start of a motor or increase its slip.

1.9.4 Transformers

The effects of harmonics on transformers manifest in three ways:

► Eddy current loss increases with the square of the harmonic order in a transformer. These additional losses may result in a much higher operating temperature and a shorter life.

► ***Additional Load Losses***

For transformers feeding non-linear loads, additional losses depend on frequency of load current. Additional losses have no univocal dependence from frequency. In the presence of distorted currents, additional losses may be remarkably different from the case of sinusoidal currents. If the harmonic contents are known, additional losses can be calculated in an analytic way using the method of superposition to calculate the contribution of the various harmonics.

► *Additional No Load Losses*

Non-sinusoidal waveforms lead to additional no-load losses, mainly localized in the magnetic circuit. A d.c. component may occur mainly in LV networks of transformer, due to the extensive use of electronic equipment in households and industry. However, its level is normally low but it may be sufficient to drive transformer cores into saturation which can lead to transformer failure or the generation of extra harmonics. It can also give rise to corrosion processes and have a detrimental effect on protective systems or other loads sensitive to current magnitude and distortion.

1.9.5 Capacitors

The increase in peak voltage value due to high harmonics results in additional dielectric stress in capacitors. It may cause a partial discharge in the insulation, a foil short circuit and result in permanent damage to the capacitor. Voltage harmonics produce additional currents flowing through the capacitor which increase with the harmonic order as a result of the reduction in capacitor equivalent impedance $Z_C \approx (n\omega C)^{-1}$). This may result in capacitor current overload. An excessive current through the capacitor bank results in additional losses and, consequently, adverse effects such as fuses blowing, physicochemical processes in the dielectric resulting in accelerated ageing of the insulation and reduced service life, permanent damage, etc. All these effects can be dramatically magnified by the series or parallel resonance.

1.9.6 Light Sources

The increase in the supply voltage peak value may shorten the service life of incandescent lamps. The discharge light sources, both fluorescent and high-pressure mercury lamps, have a series current-limiting reactor which in connection with a commonly used input parallel capacitor forms a resonant circuit. A close-to-resonance state is the source of additional losses.

1.9.7 Nuisance Tripping of Circuit Breakers

Harmonic current distortion affects the switching capability of breakers only when breaking small currents, and has no effect on interrupting short-circuit currents. High harmonics may increase the current derivative di/dt value at zero crossing (compared to that of a sine wave), which hampers the current interruption process. Residual current circuit-breakers (RCCBs) operate by summing the current in the phase and neutral conductors and then disconnecting the power from the load when the result is not within the defined limit. In harmonic-rich environments, the main issue that can occur is nuisance tripping, for two reasons.

-First of all, the RCCB, which is an electromechanical device, may not sum the higher-frequency components correctly and therefore may trip erroneously.

-The second reason is that the harmonic generating loads usually electronic equipment, also generates switching noise that must be filtered at the equipment's power connection. The filters which are normally used for this purpose have a capacitor installed between line and neutral and ground, leaking a small current to earth. This current value is limited by standards to less than 3.5 mA, but when equipment is connected to one circuit the total leakage current can reach a value sufficient to trip the RCCB. This situation can be easily avoided by providing more circuits, each supplying fewer loads.

In the case of miniature circuit-breakers (MCBs) nuisance tripping is usually caused by the current flowing in the circuit being higher than that expected from calculation or simple measurement due to the presence of harmonic currents.

1.9.8 Increase in Earth Fault Currents

In power supply systems, with an isolated or resonant-earthed neutral point, earth-fault currents may attain intolerably high values due to distorted voltage. This phenomenon is not observed in solidly earthed or impedance-earthed systems, because the short-circuit impedance has a resistive–inductive character and harmonic values are limited with frequency in a natural way. In isolated or compensated power systems the short-circuit impedance within the usual range of voltage harmonic frequencies has a resistive–capacitive character and it decreases with frequency. Short-circuit currents, from the capacitance to earth, due to the voltage harmonics and interharmonics, attain the values which do not ensure self-extinction of earth-fault arcs.

1.9.9 Converters and Electronic Equipment

Converter systems as well as most electronic equipment are sensitive to various disturbances, including harmonics. The resulting irregularities in operation are associated with the following:

1. Zero-crossing noise -When harmonics or transients are present on the supply waveforms, the rate of change of voltage at the zero crossing may become faster and then more difficult to identify, leading to improper operation of zero crossing detectors, because there may be several zero crossings per half cycle.
2. In line-commutated converter control systems, synchronized with the supply voltage zero crossing, the voltage distortion around zero may result in the inequality of the control angles of semiconductor devices. As a consequence, the converter generates non-characteristic harmonics, including even and triplen harmonics, interharmonics and, in particular cases, a d.c. component. Synchronization errors may also occur in the case of comparison of two waveforms. Improper switching of semiconductor devices into the on-

state is particularly hazardous in the inverter mode of operation.

3. Component failures will occur if the maximum value of supply voltage is increased due to harmonic distortion.
4. Disturbed operation of diagnostic and protective devices.
5. Adverse impact on capacitors in power electronics systems, in other electronic equipment, in overvoltage protection circuits, EMC filters, etc. IT equipment, as well as programmable logic controllers, requires the THD factor and relative value of each harmonic present in the supply network not to exceed specified limit values. Higher distortion levels cause incorrect operation, errors or data loss, characteristic ‘humming’ of disk drives, etc. This may lead to dangerous consequences, in particular for health services, banking, air transport, etc.

1.9.10 Measuring Instruments

Measuring instruments are most often calibrated for sinusoidal quantities, and their use under distorted conditions can be a source of errors. The error values depend on numerous factors, such as type of measurement, type of instrument involved, order, magnitude and phase of given harmonic, etc. The following remarks concern several, selected instruments used in measurements.

► *Increase in True R.M.S.Value*

Due to harmonic pollution the true r.m.s value of measured current will be higher than the expected one leading to a wrong estimation of current values. Average reading meters will then provide an under-measurement of up to 40 %, which can result in potentially dangerous conditions: for example, circuit-breakers will be underrated with the consequent risk of failure and nuisance tripping. In addition, since cable ratings are given for particular installation conditions such as heat dissipation capability and maximum working temperature, since harmonic-polluted currents have higher r.m.s values than that measured by an averaging meter, cables may be underrated and consequently reach hotter temperatures than expected, resulting in degradation of the insulation, premature failure and risk of fire.

- ***Errors in Energy Measurements***

Voltage and current harmonics in an electromechanical energy meter will produce additional harmonic torques acting upon the disk. These torques may act in the same, or in the opposite direction as the main torque resulting in measurement errors.

1.9.11 Relay and Contactor Protective Systems

Contactor/relay operation may differ significantly in the presence of harmonic interference. The response not only depends on the device type and manufacturer, but also varies with each piece of equipment tested, as well as with changes in the characteristic features of the spectrum [8]. Contactor/relay sensitivity to current or voltage harmonics decreases with the increase of harmonic order.

1.9.12 Telecommunications Interference

There are three main factors causing interference to telecommunication lines located in the vicinity of power system.

1. Location of harmonic sources with respect to the telecommunications circuits, and amplitudes and frequencies of disturbing components.

2. The type and level of coupling in telecommunication circuits. The mechanism of the influence of extraneous disturbing factors on telecommunication circuits can be that due to electromagnetic or electrostatic induction, or conduction.
3. Sensitivity of telecommunications circuits to external disturbances.

The interference occurs as a result of the coincidence of these three factors. Although this type of interference is still present, it now poses a lesser problem.

1.10 CONCLUSION

Power-quality standards address limits to harmonics and power-quality events at the point of common coupling in power systems. Emphasis is given to causes and effects of current harmonics on different power system components.

UNIT-2

2.1 Introduction:

Voltage sags and interruptions are related power quality problems. Both are usually the result of faults in the power system and switching actions to isolate the faulted sections. They are characterized by rms voltage variations outside the normal operating range of voltages. A *voltage sag* is a short-duration (typically 0.5 to 30 cycles) reduction in rms voltage caused by faults on the power system and the starting of large loads, such as motors. Momentary interruptions (typically no more than 2 to 5 s) cause a complete loss of voltage and are a common result of the actions taken by utilities to clear transient faults on their systems. Sustained interruptions of longer than 1 min are generally due to permanent faults. Utilities have been faced with rising numbers of complaints about the quality of power due to sags and interruptions. There are a number of reasons for this, with the most important being that customers in all sectors (residential, commercial, and industrial) have more sensitive loads. The influx of digital computers and other types of electronic controls is at the heart of the problem. Computer controls tend to lose their memory, and the processes that are being controlled also tend to be more complex and, therefore, take much more time to restart. Industries are relying more on automated equipment to achieve maximum productivity to remain competitive. Thus, an interruption has considerable economic impact.

Hence both are due to,
Result of faults in the power system (short circuit)
Switching actions to isolate the faulted sections.

S.No	Disturbance	Duration	Cause
1	Voltage Sag	Typically 0.5 to 30 cycles	Faults on power system Starting of large loads (Motors)
2	Momentary interruptions	Typically 2 to 5 s	Leads to complete loss of voltage as a result of action taken by utilities to clear transient faults on their systems. Sustained interruptions of longer than 1 min are due to permanent faults.

2.2 Sources of Sags and Interruptions

Voltage sags and interruptions are generally caused by faults (short circuits) on the utility system.

- Fault on the same feeder
- Fault on the parallel feeder
- Fault on transmission system

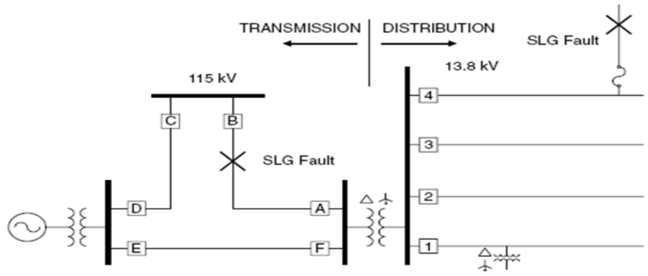


Fig.2.1 SLG Fault Locations on the utility power system

In either of these cases, the customer will experience voltage sag during the period that the fault is actually on the system. As soon as breakers open to clear the fault, normal voltage will be restored at the customer. Any of these fault locations can cause equipment misoperation in customer facilities.

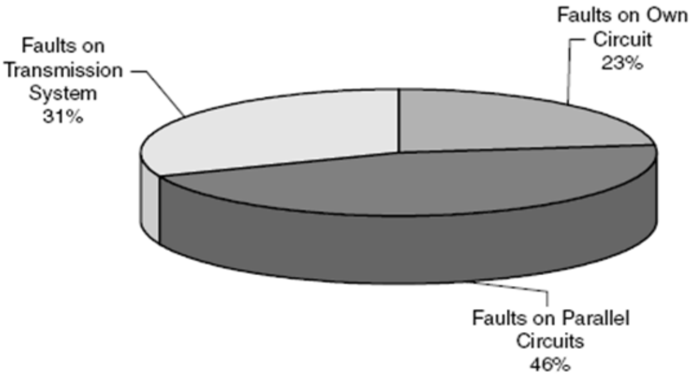


Fig.2.2 Example of fault location that caused mis-operation of sensitive production equipment at industry facility (the example system had multiple overhead distribution feeders and an extensive overhead transmission system supplying the substation

Figure shows the characteristic measured at a customer location on faulted part of the feeder

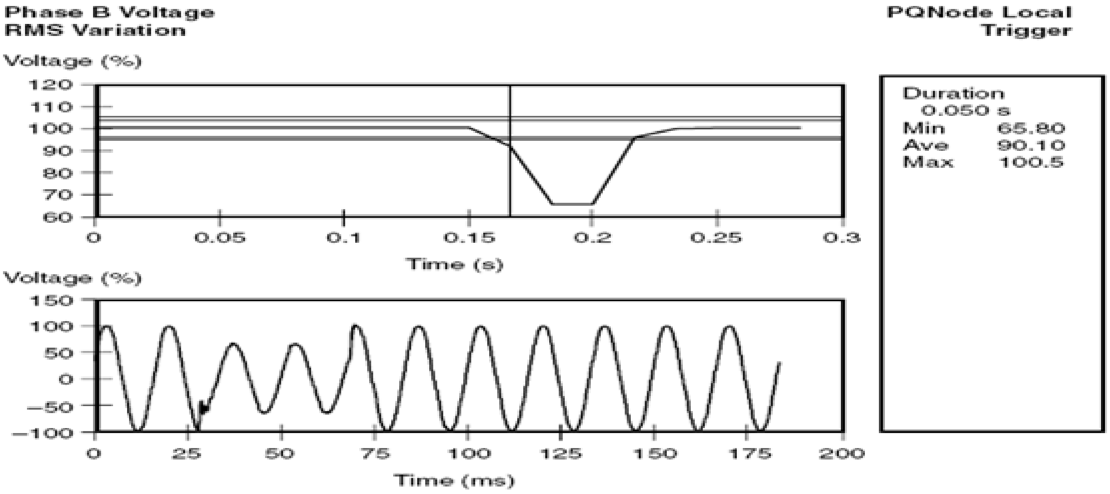


Fig.2.3 Voltage sag due to a short-circuit fault on a parallel utility feeder.

Figure clearly shows the voltage sag prior to fault clearing and the subsequent two fast recloser operations.

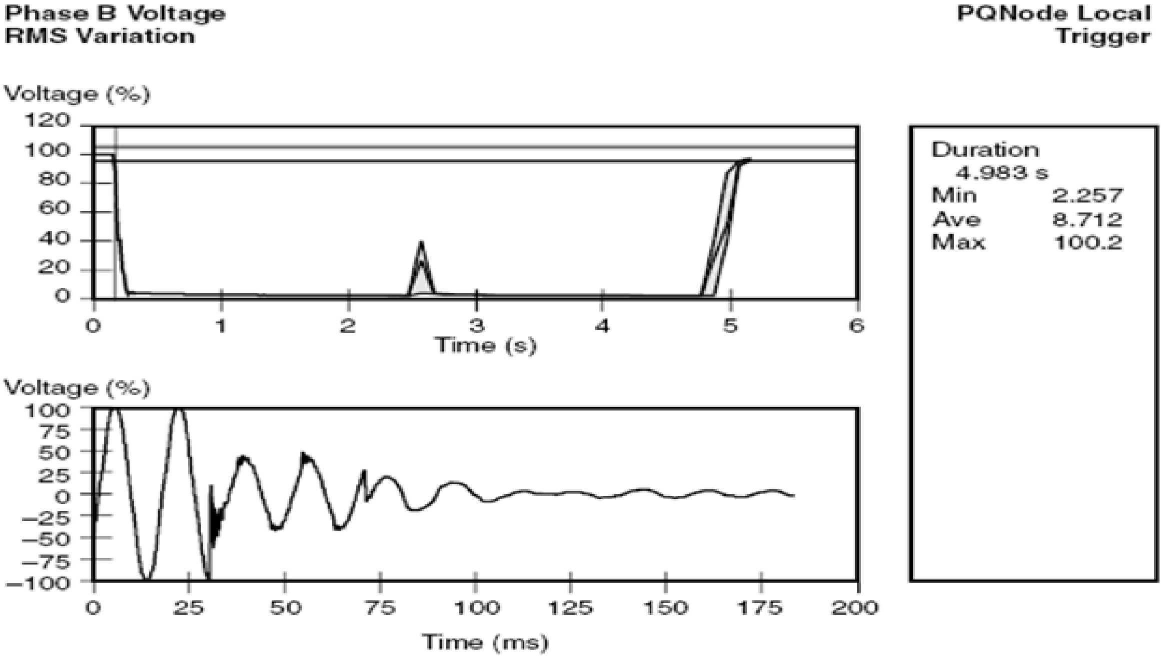


Fig.2.4 Utility short circuit fault event with two fast trip operation of utility line recloser

2.3 Estimating Voltage Sag Performance

It is important to understand the expected voltage sag performance of the supply system to assure the optimum operation of production facilities.

Facilities can be designed
Equipment specifications developed

Procedure for working with Industrial Customers to Assure Compatibility between the Supply System Characteristics and the Facility Operation:

1. Determine the number and characteristics of voltage sags that result from *Transmission System Faults*

2. Determine the number and characteristics of voltage sags that result from *Distribution System Faults* (for facilities that are supplied from distribution systems)

3. Determine the equipment sensitivity to voltage sags. This will determine the actual performance of the production process based on voltage sag performance calculated in steps 1 and 2.

4. Evaluate the economics of different solutions that could improve the performance, either on the supply system (fewer voltage sags) or within the customer facility (better immunity).

2.3.1 Area of Vulnerability (Weakness, Exposure)

The area of vulnerability describes all the fault locations that can cause equipment to misoperate. It is determined by the Total Circuit Miles of Exposure (contact) to faults that can cause voltage magnitudes at an end-user facility to drop below the equipment minimum voltage sag ride-through capability. The concept of an area of vulnerability developed to help evaluate the likelihood (possibility) of sensitive equipment being subjected to voltage lower than its minimum voltage sag ride-through capability.

2.3.2 Minimum Voltage Sag Ride-Through Capability (Voltage Sag Immunity or Susceptibility Limit)

It is defined as the minimum voltage magnitude equipment can withstand or tolerate without misoperation or failure. Figure 2.5 shows an example of an area of vulnerability diagram for MOTOR CONTACTOR AND ADJUSTABLE-SPEED-DRIVE LOADS at an end-user facility served from the distribution system.

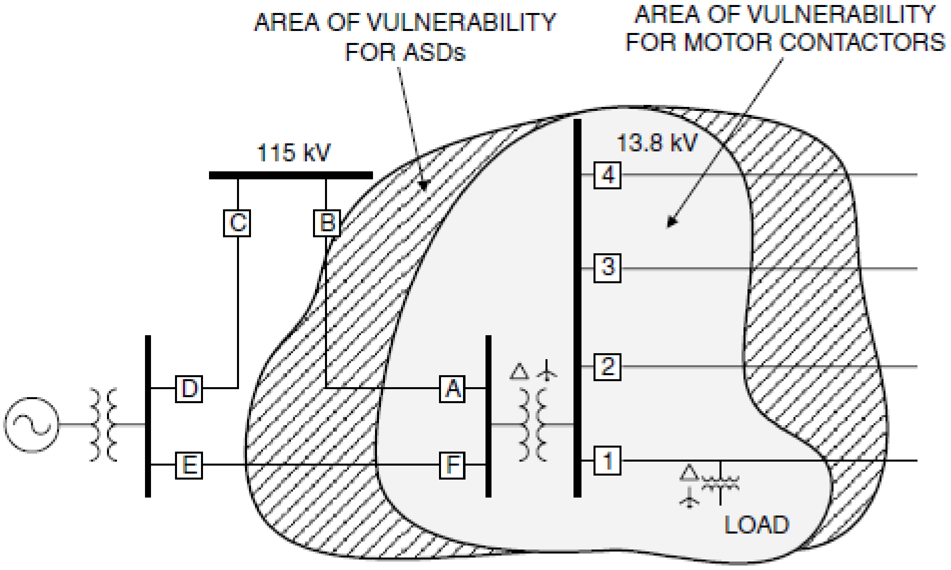


Fig. 2.5 Illustration of an area of vulnerability.

The loads will be subject to faults on both the transmission system and the distribution system. Number of voltage sags that a facility can expect is determined by combining the area of vulnerability with the expected fault performance for this portion of the power system.

Equipment Sensitivity to Voltage Sags. Equipment within an end-user facility may have different sensitivity to voltage sags. Equipment sensitivity to voltage sags is very dependent on,

- Specific load type
- Control settings
- Applications

Characteristics of voltage sag that causes equipment to misoperate are,

- Duration of sag
- Magnitude of the sag
- Phase shift and unbalance
  Missing voltage
  Three-phase voltage unbalance during the sag event

  Point-in-the-wave at which the sag initiates and terminates

2.3.3 Types of Equipment Sensitivity to Voltage Sags

Equipment sensitive to, only the magnitude of voltage sag. Both the magnitude and duration of voltage sag. Characteristics other than magnitude and duration.

Only the Magnitude of Voltage Sag

Devices in this group are sensitive to the minimum voltage magnitude experienced during sag.
Duration of the disturbance is usually of secondary importance for these devices.
Under voltage relays
Process controls
Motor drive controls
Automated machines (e.g., semiconductor manufacturing equipment)

Equipment sensitive to both the magnitude and duration of voltage sag.

- Duration that the rms voltage is below a specified threshold at which the equipment trips
- Equipments that use electronic power supplies-Equipment misoperates or fails when the power supply output voltage drops below specified values.

Equipment sensitive to characteristics other than magnitude and duration

- Phase unbalance during the sag event
- Point-in-the wave at which the sag is initiated
- Any transient oscillations occurring during the disturbance

For end users with sensitive processes, the voltage sag ride-through capability is usually the most important characteristics.

Magnitude-duration plot is a common method to quantify equipment susceptibility (vulnerability/weakness) to voltage sags

Magnitude-duration plot shows the voltage sag magnitude that will cause equipment to misoperate as a function of the sag duration

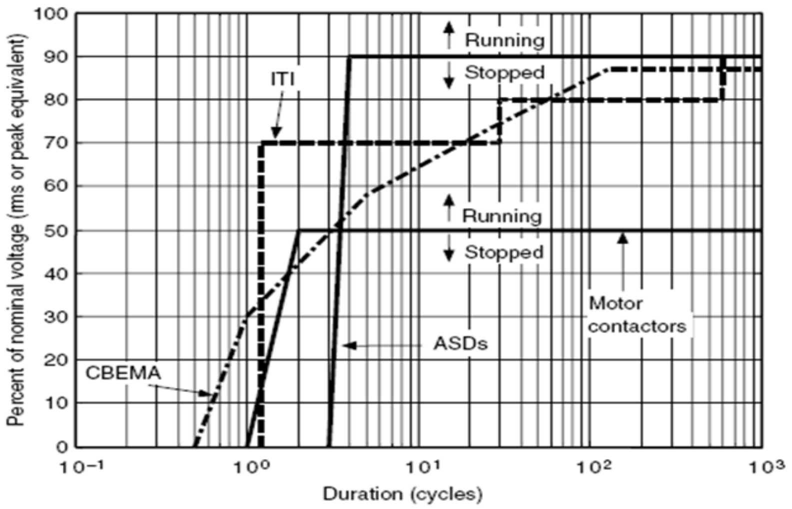


Fig. 2.5 Typical equipment voltage sag ride-through capability curves

- Typical loads will likely trip off when the voltage is below the CBEMA, or ITI curve

- The less sensitive the equipment, the smaller the area of vulnerability

2.4 Voltage sag analysis and calculation of various faulted condition

This section discusses procedures to estimate the transmission system contribution to the overall voltage sag performance at a facility.

- The voltage sag performance for a given customer facility (location) will depend on whether the customer is supplied from

  1. Transmission System
  2. Distribution System

- Customer supplied from the transmission system, the voltage sag performance will depend on

  1. Transmission system fault performance

- Customer supplied from the distribution system, the voltage sag performance will depend on the fault performance on both

  1. Transmission System
  2. Distribution System

2.4.1 Why should we estimate the voltage sag at end user location?

- Transmission line faults and the subsequent opening of the protective devices rarely cause an interruption for any customer because of the interconnected nature of most modern-day transmission networks. These faults do, however, causing voltage sags.

- Depending on the equipment sensitivity, the unit may trip off, resulting in substantial monetary losses.

- The ability to estimate the expected voltage sags at an end-user location is therefore very important.
- Most utilities have detailed short-circuit models of the interconnected transmission system available for programs such as ASPEN* (*Advanced Systems for Power Engineering,) One Liner (www.aspeninc.com)

- Programs can calculate the voltage throughout the system resulting from faults around the system

- Single-line-to-ground faults will not result in the same voltage sag at the customer equipment as a three-phase fault

- Characteristics at the end-use equipment also depend on
  1. How the voltages are changed by transformer connections
  2. How the equipment is connected, i.e., phase-to-ground or phase-to-phase

- Table summarizes voltages at the customer transformer secondary for a single-line-to-ground fault at the primary

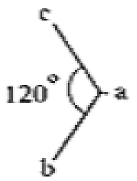
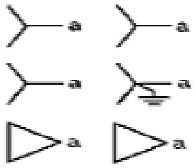
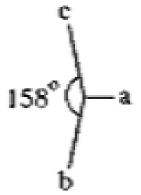
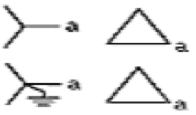
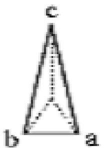
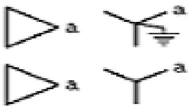
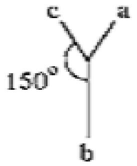
Transformer connection (primary/secondary)	Phase-to-phase			Phase-to-neutral			Phasor diagram
	V_{ab}	V_{bc}	V_{ca}	V_{an}	V_{bn}	V_{cn}	
	0.58	1.00	0.58	0.00	1.00	1.00	
	0.58	1.00	0.58	0.33	0.88	0.88	
	0.33	0.88	0.88	—	—	—	
	0.88	0.88	0.33	0.58	1.00	0.58	

Table 2.1 Transformer secondary Voltages with a Single Line to Ground fault on the primary

Single-line to-ground fault on the primary of a delta-wye grounded transformer does not result in zero voltage on any of the phase-to-ground or phase-to-phase voltages on the secondary of the transformer.
Magnitude of the lowest secondary voltage depends on how the equipment is connected

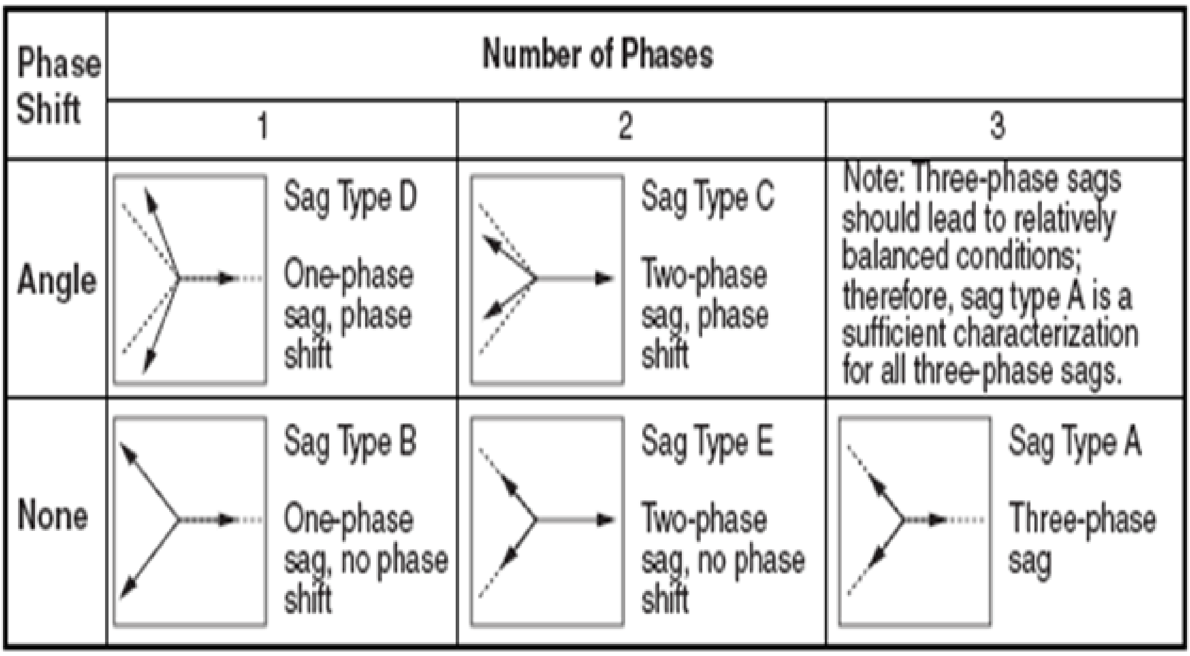
1. Equipment connected line-to-line would experience a minimum voltage of 33 percent

2. Equipment connected line-to-neutral would experience a minimum voltage of 58 percent

It shows the importance of both transformer connections and the equipment connections in determining the actual voltage that equipment will experience during a fault on the supply system.

Math Bollen developed the concept of voltage sag “types” to describe the different voltage sag characteristics that can be experienced at the end-user level for different fault conditions and system configurations

Fault types can be used to summarize the expected performance at a customer location for different types of faults on the supply system.



Phase Shift	Number of Phases		
	1	2	3
Angle	Sag Type D One-phase sag, phase shift	Sag Type C Two-phase sag, phase shift	Note: Three-phase sags should lead to relatively balanced conditions; therefore, sag type A is a sufficient characterization for all three-phase sags.
None	Sag Type B One-phase sag, no phase shift	Sag Type E Two-phase sag, no phase shift	Sag Type A Three-phase sag

Table 2.2. Voltage sag types at end use equipment that result from different types of faults and transformer connections.

Actual expected performance is then determined by combining the area of vulnerability with the expected number of faults within this area of vulnerability.

Fault performance is usually described in terms of faults per 100 miles/year (mi/yr).

Utilities maintain statistics of fault performance at all the different transmission voltages.

System wide statistics can be used along with the area of vulnerability to estimate the actual expected voltage sag performance.

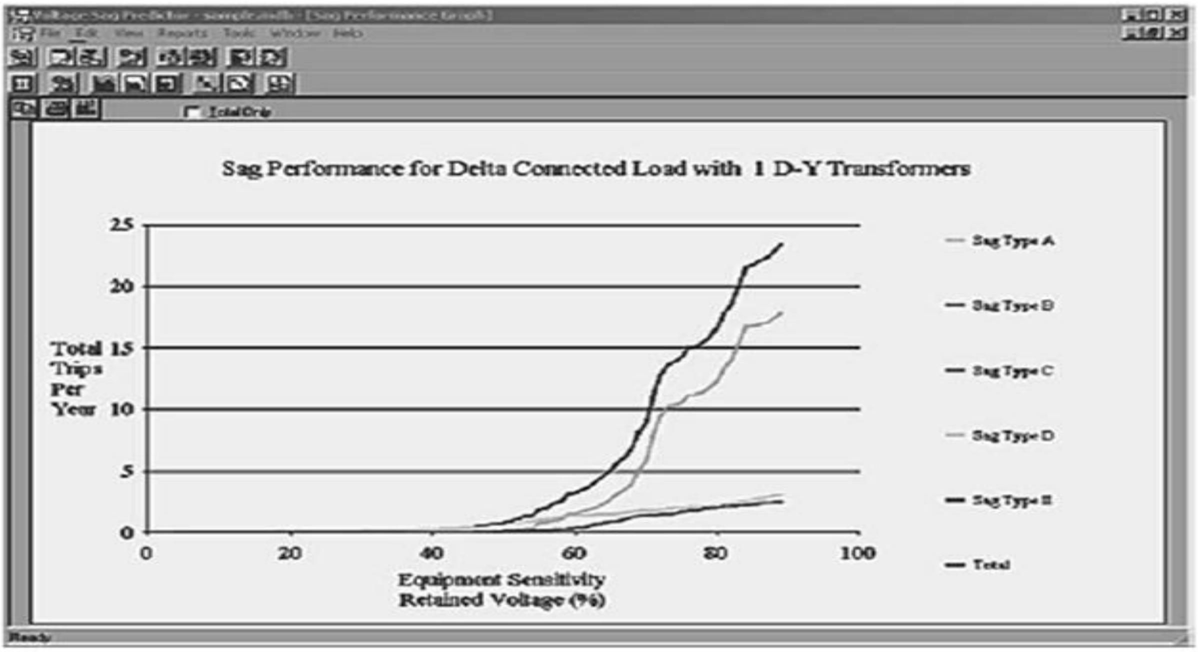


Fig.2.5 Estimated voltage sag performance at customer equipment due to transmission system faults.

Utility distribution system sag performance evaluation. Customers that are supplied at distribution voltage levels are impacted by faults on both the transmission system and the distribution system.

Analysis at the distribution level must include momentary interruptions caused by the operation of protective devices to clear the faults. These interruptions will most likely trip out sensitive equipment.

Overall voltage sag performance at an end-user facility is the total of the expected voltage sag performance from the transmission and distribution systems

- Utility protection scheme plays an important role in the voltage sag and momentary interruption performance

- Critical information needed to compute voltage sag performance are,

1. No of feeders supplied from the substation
2. Average feeder length
3. Average feeder reactance
4. Short-circuit equivalent reactance at the substation
5. Feeder reactors, if any
6. Average feeder fault performance which includes three-phase-line to-ground (3LG) faults and SLG faults in faults per mile per month.

Two possible locations for faults on the distribution systems,

- On the same feeder
- On parallel feeders

Total circuit miles of fault exposures that can cause voltage sags below equipment sag ride-through capability at a specific customer needs to be defined

2.4.2 Faults on Parallel Feeders

Voltage at the end-user facility following a fault on parallel feeders can be estimated by calculating the expected voltage magnitude at the substation.

Voltage magnitude at the substation is impacted by

1. Fault impedance and location
2. Configuration of the power system
3. System protection scheme

Figure shows the effect of the distance between the substation and the fault locations for 3LG and SLG faults on a radial distribution system.

SLG fault curve shows the A-B phase bus voltage on the secondary of a delta-wye–grounded step-down transformer, with an A phase-to-ground fault on the primary.

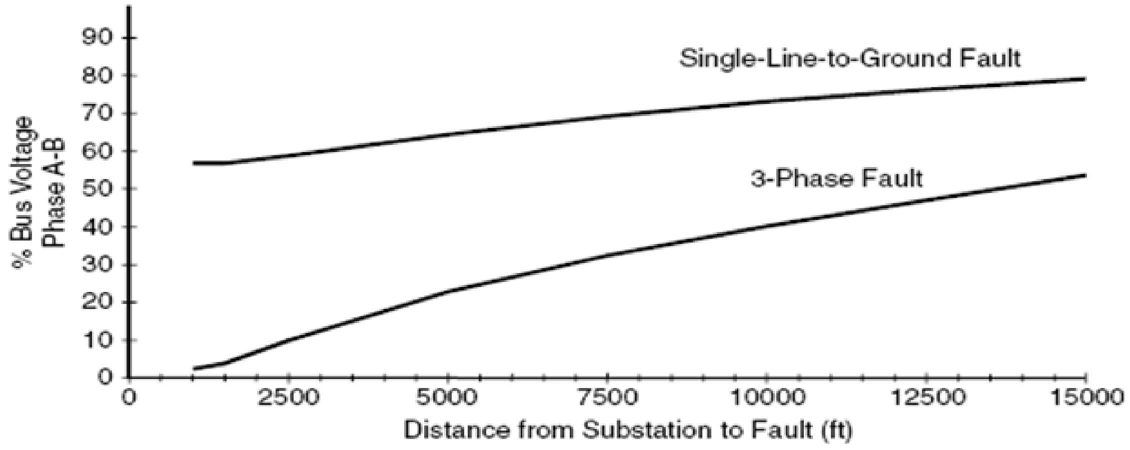


Fig. 2.7 Example of voltage sag magnitude at an end-user location as a function of the fault location along a parallel feeder circuit.

Actual voltage at the end user location can be computed by converting the substation voltage using Table 2.1

Voltage sag performance for specific sensitive equipment having the minimum ride-through voltage of Vs can be computed

$$E_{parallel}(V_s) = N1 * Ep1 + N3 * Ep3$$

N1 & N3 - Fault performance data for SLG and 3LG faults in faults per miles per month

Ep1 & Ep3 - Total circuit miles of exposure to SLG and 3LG faults on parallel feeders that result in voltage sags below the minimum ride-through voltage Vs at the end user location.

2.4.3 Faults on the Same Feeder

- Expected voltage sag magnitude at the end-user location is computed as a function of fault location on the same feeder
- Computation is performed only for fault locations that will result in a sag but will not result in a momentary interruption, which will be computed separately.
- Examples of fault locations include faults beyond a downline recloser or a branched fuse that is coordinated to clear before the substation recloser.
- Voltage sag performance for specific sensitive equipment with ride-through voltage (Vs)

$$E\text{same}(Vs) = N_1 * Es_1 + N_3 * Es_3$$

- Es_1 & Es_3 - Total circuit miles of exposure to SLG and 3LG on the same feeders that result in voltage sags below (Vs) at the end-user location.
- Total expected voltage sag performance for the minimum ride through voltage (Vs) is given by,

$$E\text{parallel}(\text{Vs}) + E\text{same}(Vs)$$

- Expected interruption performance at the specified location can be determined by the length of exposure that will cause a breaker or other protective device in series with the customer facility to operate.
- If the protection is designed to operate the substation breaker for any fault on the feeder, then this length is the total exposure length.
- Expected number of interruptions can be computed as follows,

$$E\text{int} = L\text{int} + (N_1 * N_3)$$

- Lint -Total circuit miles of exposure to SLG and 3LG that results in interruptions at an end-user facility

2.4.4 Fundamental Principles of Protection

- Several things can be done by the utility, end user, and equipment manufacturer to reduce,
    - Number and severity of voltage sags
    - Sensitivity of equipment to voltage sags

Figure 2.8 illustrates voltage sag solution alternatives and their relative costs

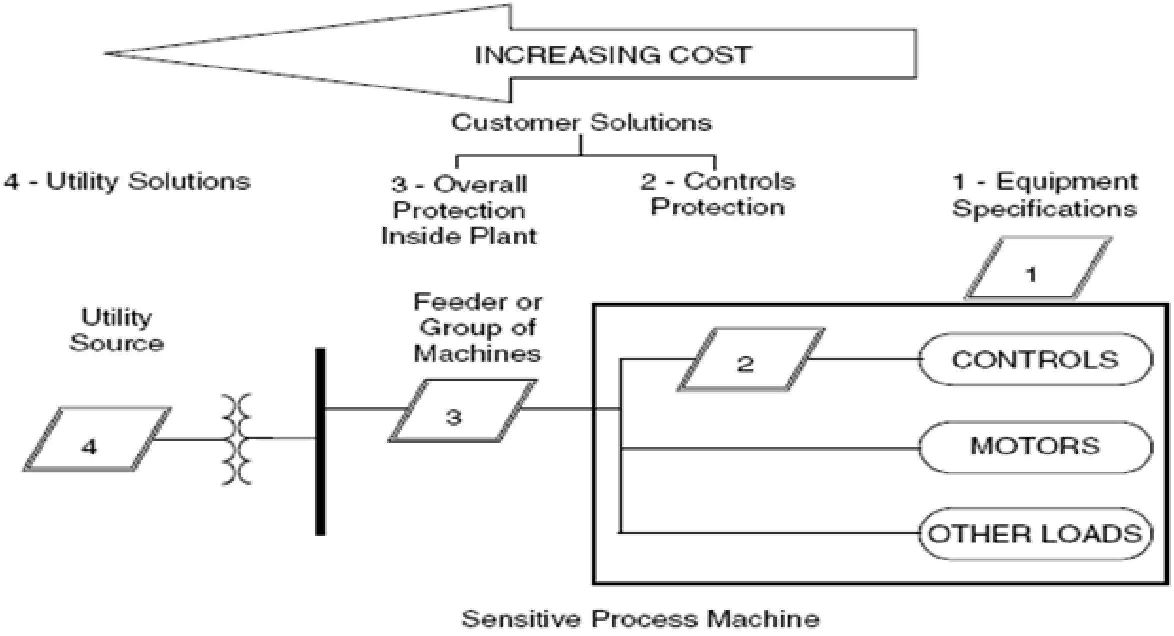


Fig.2.8 Approaches for voltage sag ride-through.

2.5 Solutions for Problems Associated with Voltage Sags:

1. Equipment manufacturers should have voltage sag ride-through capability curves available to their customers so that an initial evaluation of the equipment can be performed.

    - Customers should begin to demand that these types of curves be made available so that they can properly evaluate equipment.

2. The company procuring new equipment should establish a procedure that rates the importance of the equipment

    - If the equipment is critical in nature, the company must make sure that adequate ride-through capability is included when the equipment is purchased.

    - If the equipment is not important or does not cause major disruptions in manufacturing or jeopardize (endanger) plant and personnel safety, voltage sag protection may not be justified.

3. Equipment should at least be able to ride through voltage sags with a minimum voltage of 70 percent (ITI curve). A more ideal ride-through capability for short-duration voltage sags would be 50 percent, as specified by the semiconductor industry in Standard SEMI F-47

If the required ride-through cannot be obtained at the specification stage (lower level), it may be possible to apply an uninterruptible power supply (UPS) system or some other type of power conditioning to the machine control. This is applicable when the machines themselves can withstand the sag or interruption, but the controls would automatically shut them down.

Level 3 needs some sort of backup power supply with the capability to support the load for a brief period is required.

Level 4 represents alterations made to the utility power system to reduce the number of sags and interruptions.

2.5.1 Solutions at the End-User Level

Solutions to improve the reliability and performance of a process or facility can be applied at many different levels.

Different technologies available should be evaluated based on the specific requirements of the process to find optimum solution for improving the overall voltage sag performance.

a). Protection for Small Loads [Ex: < 5 kVA]:

This usually involves protection for equipment controls or small individual machines. Many times, these are single-phase loads that need to be protected.

b). Protection for Individual Equipment or Groups of Equipment up to about 300 kVA:

This usually represents applying power conditioning technologies (UPS) within the facility for protection of CRITICAL EQUIPMENT that can be grouped together conveniently.

- Usually not all the loads in a facility (customer location) need protection, this can be a very ECONOMICAL METHOD of dealing with the CRITICAL LOADS

c). Protection for Large Groups of Loads or whole facilities at the Low-Voltage Level :

- Sometimes such a large portion of the facility is critical or needs protection that it is reasonable to consider protecting large groups of loads at a convenient location (USUALLY THE SERVICE ENTRANCE)

d). Protection at the Medium-Voltage Level or on the Supply System :

If the whole facility needs protection or improved power quality, solutions at the medium-voltage level can be considered

e). Major Technologies available and the Levels where they can be applied

- Ferroresonant transformers(CVTs)
- Magnetic synthesizers

- Active series compensators
- On-line UPS
- Standby UPS
- Hybrid UPS
- Motor-generator sets
- Flywheel energy storage systems
- Superconducting magnetic energy storage (SMES) devices
- Static transfer switches and fast transfer switches

f) Ferroresonant Transformers (CVTs)

- A voltage-regulating transformer that uses core saturation and output capacitance to maintain a stable output voltage even when the input voltage fluctuates.

- It provides a constant output voltage when the input voltage increases above or decreases below the nominal voltage

- Ferro resonant transformers are basically 1:1 transformers which are excited high on their saturation curves, thereby providing an output voltage which is not significantly affected by input voltage variations

- It is the end user protection from voltage sags and transients.

- It uses two basic electrical principles that transformer designers usually try to avoid: RESONANCE & CORE SATURATION.

- Resonance occurs when the impedance of the capacitor equals the impedance of the inductor. In this case a capacitor is in series with the induction of the CVT coil. This causes the current to increase to a point where it saturates the steel core of the CVT.

- Transformer saturation means the magnetic core (steel) cannot take any more magnetic fields. Like a waterlogged sponge, it stops absorbing current and produces a constant output voltage.

- CVTs are especially attractive for constant, low-power loads. Not suitable for Variable loads, especially with high inrush currents

- In a transformer, a current in the primary winding produces a magnetic flux that induces a current and voltage in the secondary winding.

- There is a point where increased current in the primary saturates the core with too much magnetic flux. This is the saturation point.

- At this point the transformer no longer transforms the voltage or current according to the ratio of the primary and secondary turns.

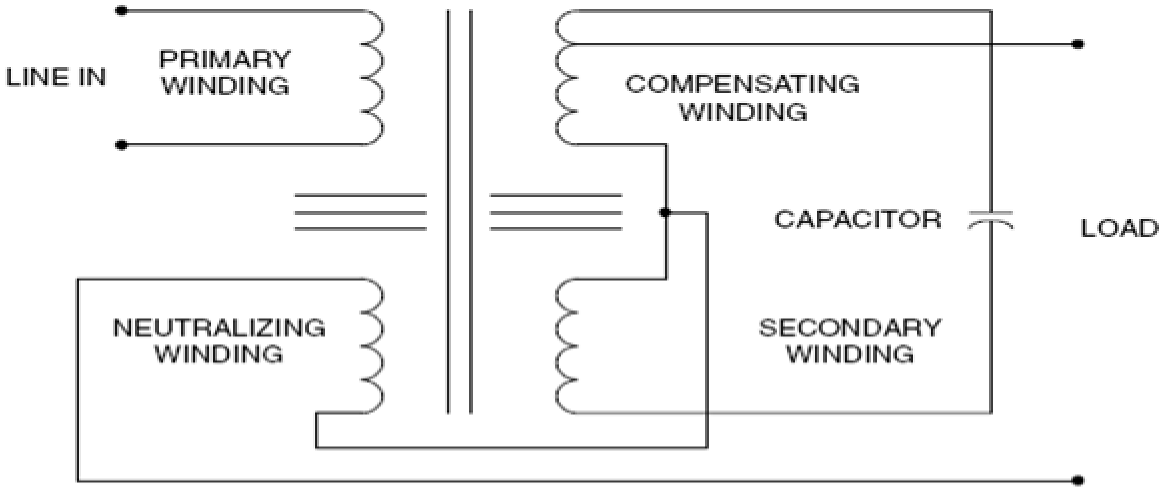


Fig.2.9 Schematic of ferroresonant constant voltage transformer.

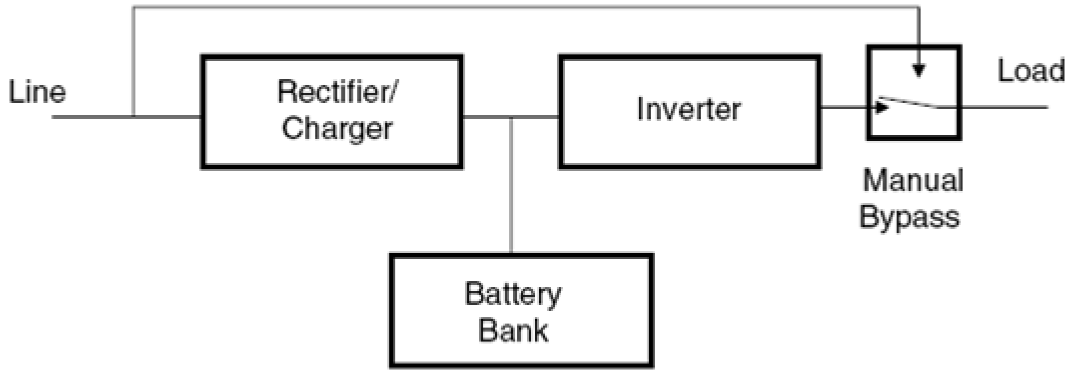


Fig.2.10 On-line UPS

g) Off Line UPS or Standby UPS

Normal line power is used to power the equipment until a disturbance is detected and a switch transfers the load to the battery backed inverter.

The transfer time from the normal source to the battery-backed inverter is important. The CBEMA curve (see Fig.1.17) those 8 ms is the lower limit on interruption through for power-conscious manufacturers.

Therefore a transfer time of 4 ms would ensure continuity of operation for the critical load.

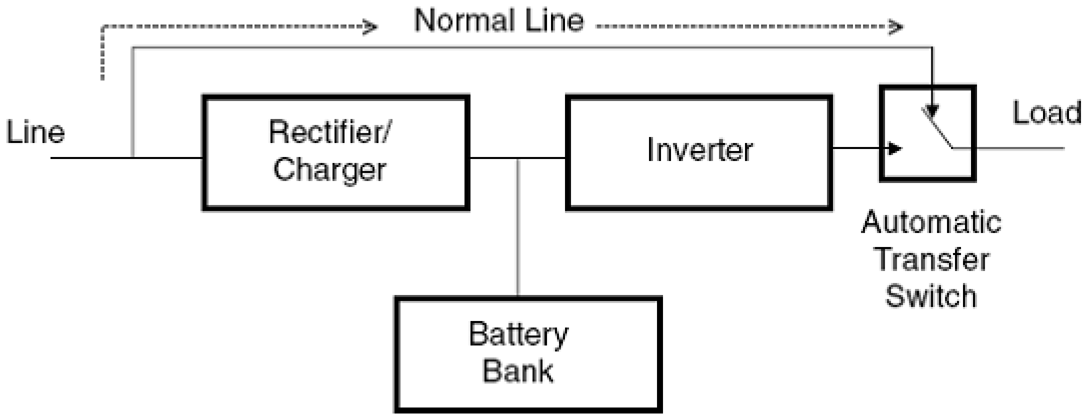


Fig.2.11 Standby UPS

h) Off Line UPS or Standby UPS

A standby power supply does not typically provide any transient protection or voltage regulation as does an on-line UPS.

Common configuration for commodity UPS for protection of small computer loads.

UPS specifications include kilovolt ampere capacity, dynamic and static voltage regulation, harmonic distortion of the input current and output voltage, surge protection, and noise attenuation.

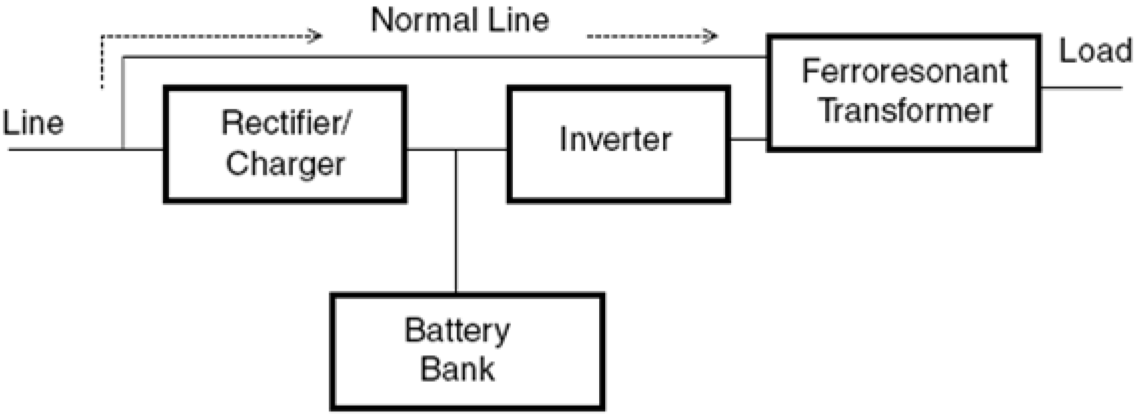


Fig.2.12 Hybrid UPS

Similar in design to the standby UPS, the hybrid UPS utilizes a voltage regulator on the UPS output to provide regulation to load and momentary ride-through when the transfer from normal to UPS supply is made.

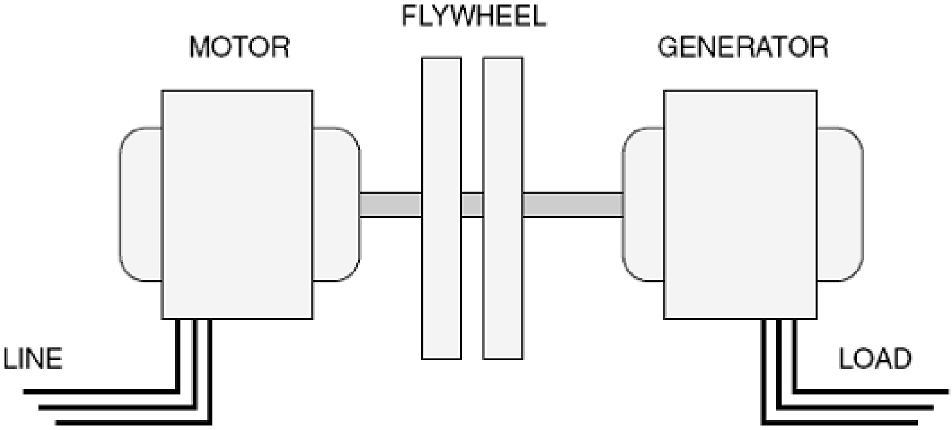


Fig.2.13 Block diagram of typical M-G set with flywheel.

Another type of M-G set uses a special synchronous generator called a written-pole motor that can produce a constant 60-Hz frequency as the machine slows.

It is able to supply a constant output by continually changing the polarity of the rotor’s field poles. Thus, each revolution can have a different number of poles than the last one.

Constant output is maintained as long as the rotor is spinning at speeds between 3150 and 3600 revolutions per minute (rpm).

Flywheel inertia allows the generator rotor to keep rotating at speeds above 3150 rpm once power shuts off.

The rotor weight typically generates enough inertia to keep it spinning fast enough to produce 60 Hz for 15 s under full load.

Another means of compensating for the frequency and voltage drop while energy is being extracted is to rectify the output of the generator and feed it back into an inverter.

This allows more energy to be extracted, but also introduces losses and cost.

Motor-generator sets are only one means to exploit the energy stored in flywheels.

A modern flywheel energy system uses high-speed flywheels and power electronics to achieve sag and interruption ride-through from 10 s to 2 min.

While M-G sets typically operate in the open and are subject to aerodynamic friction losses, these flywheels operate in a vacuum and employ magnetic bearings to substantially reduce standby losses

I) Superconducting magnetic energy storage (SMES) devices

An SMES device can be used to alleviate voltage sags and brief interruptions.

The energy storage in an SMES-based system is provided by the electric energy stored in the current flowing in a superconducting magnet. The superconducting magnet is constructed of a niobium titanium (NbTi) conductor.

Since the coil is lossless, the energy can be released almost instantaneously.

Using voltage regulator and inverter banks, this energy can be injected into the protected electrical system in less than 1 cycle to compensate for the missing voltage during a voltage sag event

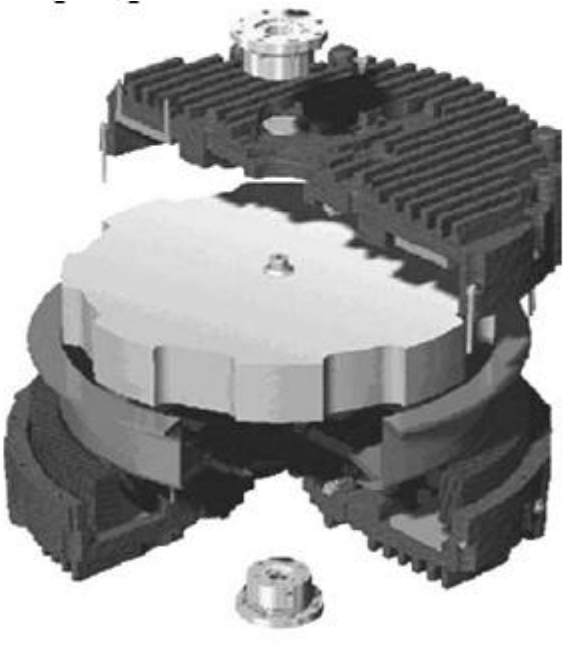


Fig.2.14 Cutaway view of an integrated motor, generator, and flywheel used for energy storage systems. (Courtesy of Active Power, Inc)

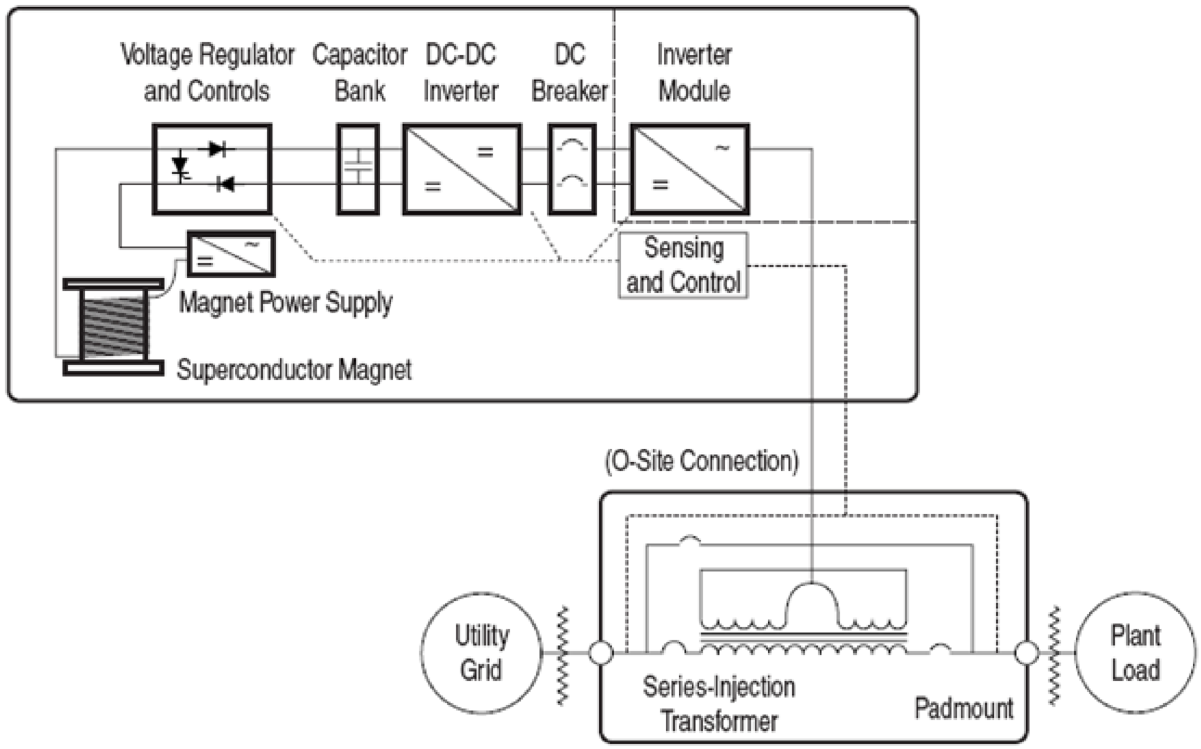


Fig. 2.15 Typical power quality-voltage regulator (PQ-VR) functional block diagram. (*Courtesy of American Superconductor, Inc.*)

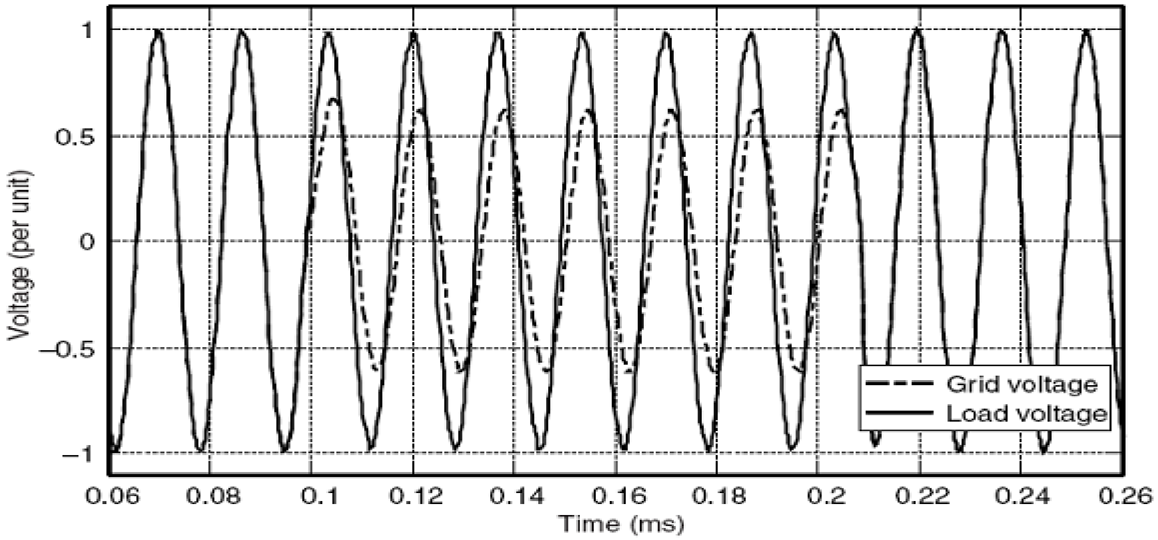


Fig. 2.16 SMES-based system providing ride-through during voltage sag event.

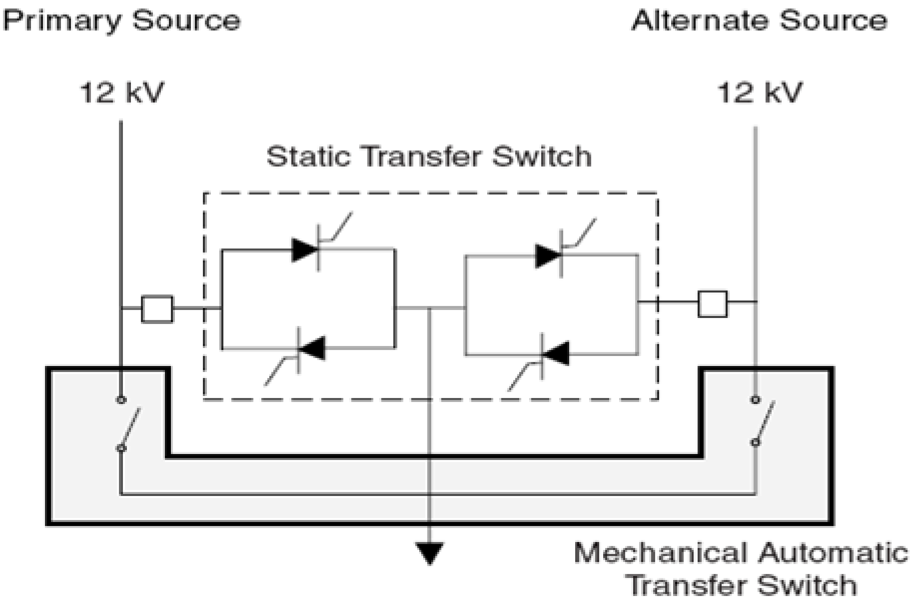


Fig.2.17 Configuration of a static transfer switch used to switch between a primary supply and a backup supply in the event of a disturbance. The controls would switch back to the primary supply after normal power is resorted.

- Conventional transfer switches will switch from the primary supply to a backup supply in seconds.

- Fast transfer switches that use vacuum breaker technology are available that can transfer in about 2 electrical cycles.

- This can be fast enough to protect many sensitive loads.

- Static switches use power electronic switches to accomplish the transfer within about a quarter of an electrical cycle.

2.5.2 Sag performance Evaluation

- Reference to sensitive point
  - Magnitude & duration obtained
- Data required for Estimation
  - **System parameter**
    - System topology
    - Line impedance & component impedance
    - Transformer connection
    - Relay protection (all are fixed parameter)
  - **Fault event related parameter**
    - Fault type, location & fault imp (difficult to analyze)

2.5.3 Voltage sag magnitude determination fault analysis-program

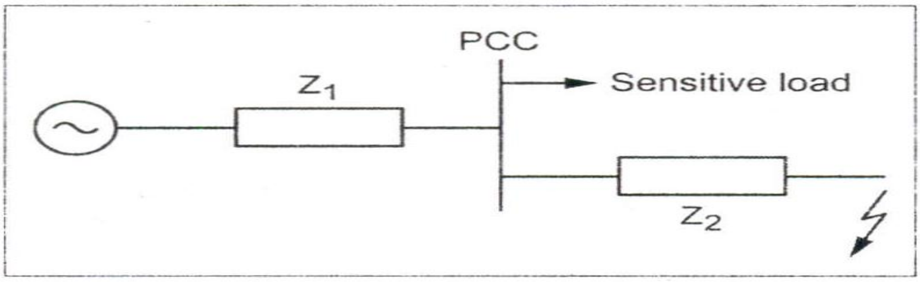


Fig.2.18 Faulted network for voltage sag magnitude determination

2.5.4 Voltage divider model

$$V_{Sag} = \frac{Z_2 + Z_f}{Z_1 + Z_2 + Z_f} \cdot V_0$$

$$V_{Sag} = f(l) = \frac{z \cdot l}{Z_1 + z \cdot l} \cdot V_0$$

Where,

Z_f = Source impedance at the PCC;

Z_2 = Impedance of the feeder between the fault point and the PCC;

Z_f = Fault impedance; V_0 = Prefault voltage at the PCC.

2.5.5 Duration determination

- Sag lasts till fault cleared
  - Type
  - Location
  - Settings of relay

2.5.6 Block diagram of Sag Performance Estimation:

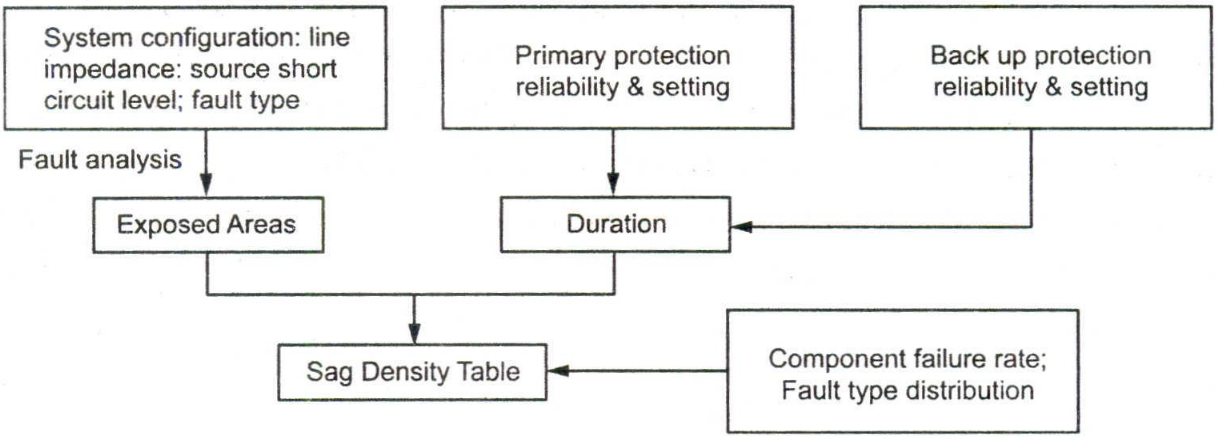


Fig.2.19 Flowchart for Voltage sag estimation process.

2.5.7 Procedure for voltage sag indices

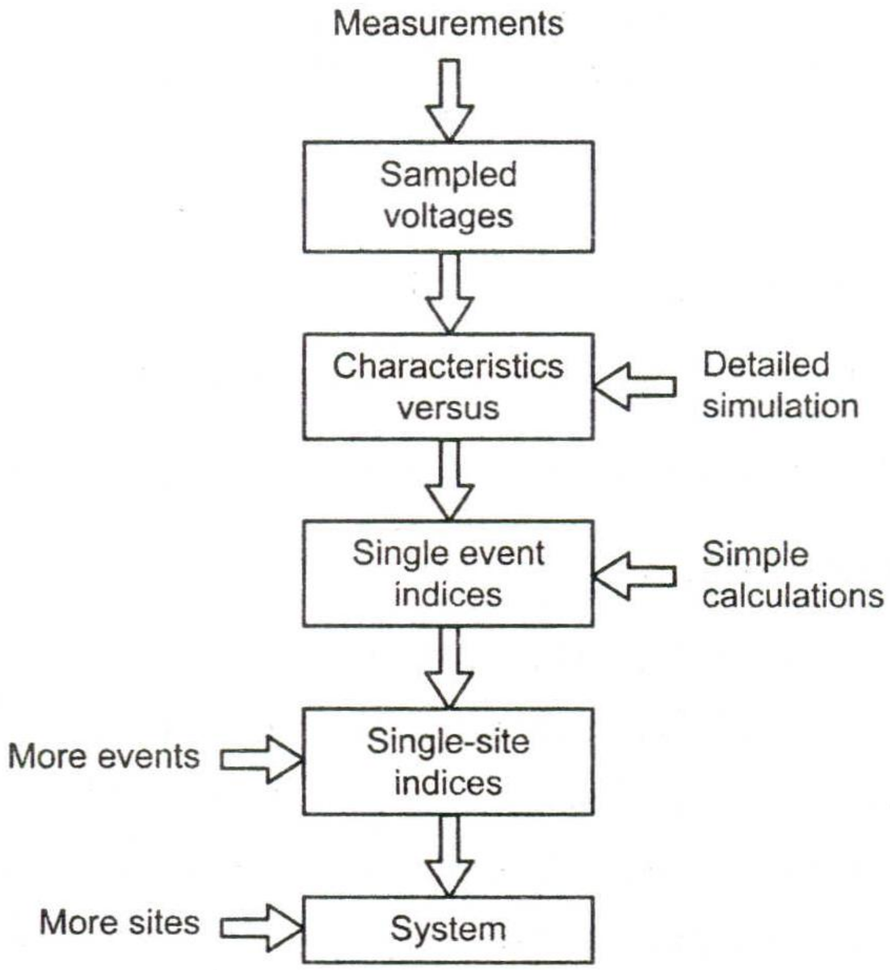
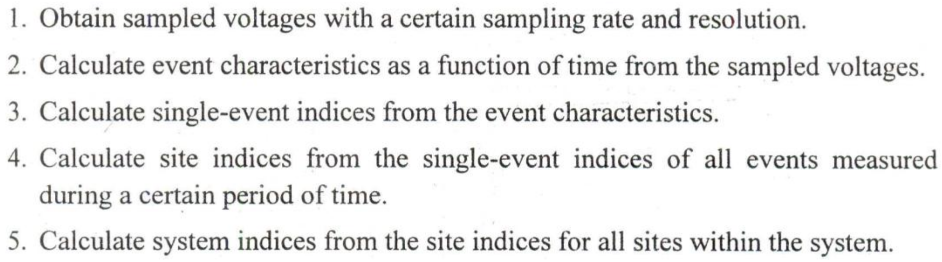


Fig.2.20 Flowchart for Voltage sag indices calculations.

<u>Procedure:</u>



1. Obtain sampled voltages with a certain sampling rate and resolution.
2. Calculate event characteristics as a function of time from the sampled voltages.
3. Calculate single-event indices from the event characteristics.
4. Calculate site indices from the single-event indices of all events measured during a certain period of time.
5. Calculate system indices from the site indices for all sites within the system.

2.6 Voltage Sag due to Induction motor starting:

- Magnitude depends on
  - Characteristics of I.M
  - Strength of the system where motor is connected

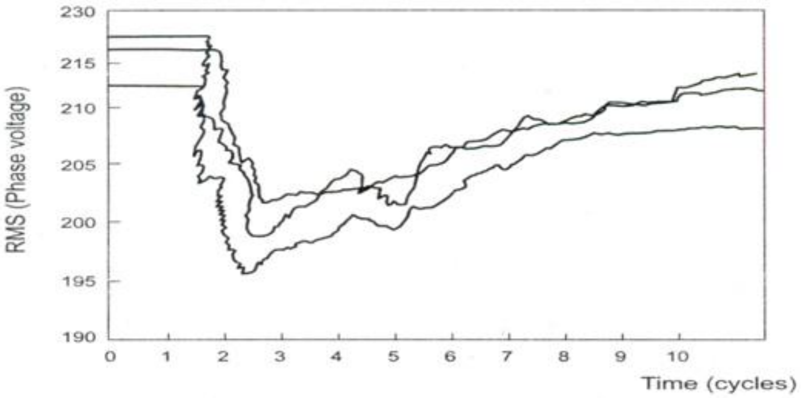


Fig.2.16 Voltage sag due to motor starting

Induction motor starting methods are,

- Autotransformer starters
- Resistance and reactance starters
- Star delta starters

2.6.1 Estimating Sag Severity during full voltage starting

$$Vmin\ (pu)=V(pu)\ .\ KVA_S/(\ kVA_L+kVA_S)$$

Where,

V(pu) = per unit system voltage
kVA_L= motor locked rotor kVA
kVA_S= system short-circuit kVA at motor

2.6.2 Data required for simulation

Transient analysis computer program

- Equivalent circuits parameters such as resistances and reactance.
- Number of motor poles and rated rpm
- Inertia constant values for the motor and load
- Speed versus Torque Characteristics for the motor load

2.7 Voltage Sag due Transformer Energization

The causes for voltage sags due to transformer energizing are :

i) Normal system operation, which includes manual energizing of a transformer.
ii) Reclosing actions

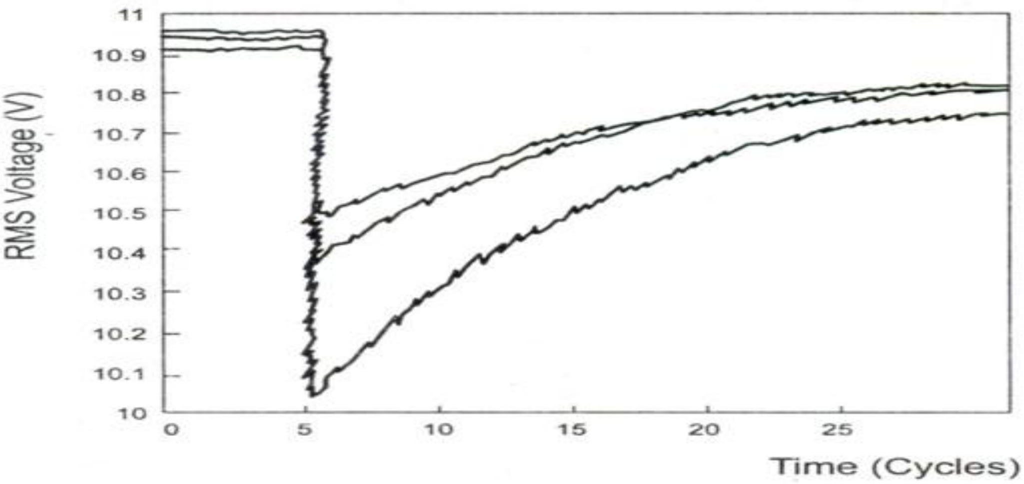


Fig.2.17 Voltage sag due to transformer energizing.

2.8 Voltage sag and Mitigation Technique

- Power system design
  - Faults main cause
    - UG Cables
    - trimming trees
    - surge arrestors
- Equipment Design
  - Manufacturing less sensitive to sags
- Power conditioning Equipment
  - Using PC device at loads

2.8.1 Possible mitigation methods

- Four locations
  - 1,2 cheap not available in market
  - 4 costly
  - 3 widely used

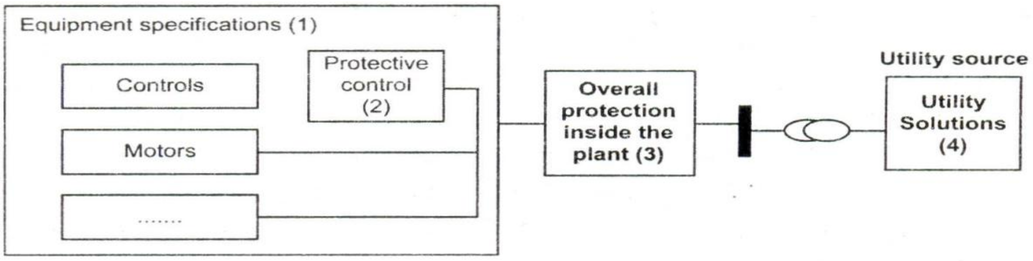


Fig. 2.20 Layout for protection of voltage sag

2.8.2 Dynamic voltage Restorer (DVR) static series compensator with transformer injection

- Series compensation devices
  - Protects against
    - Sags
    - Swells
    - unbalance and
    - Distortion

Generates or absorbs Reactive power

Response time less

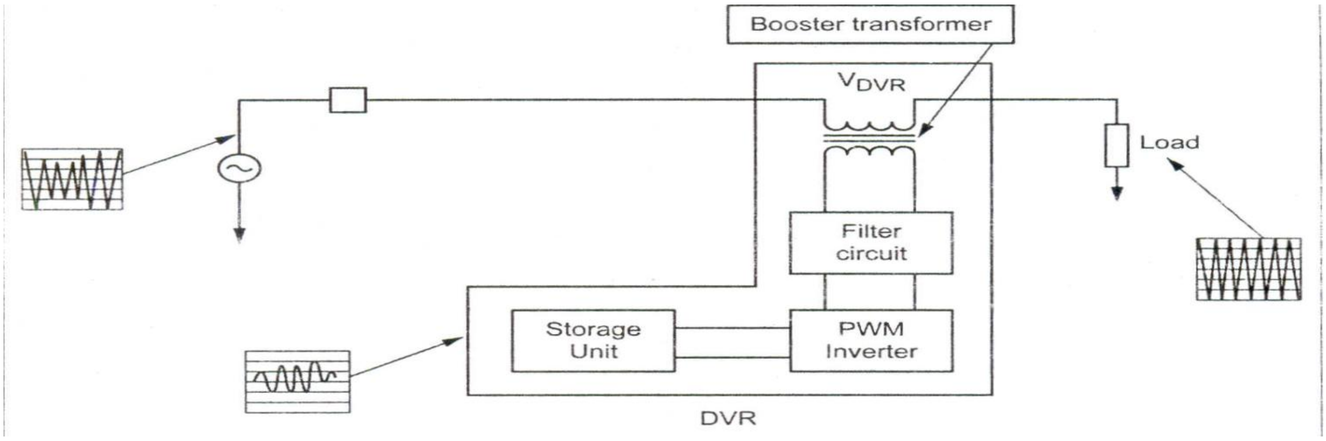


Fig.1.21. DVR used for load compensation

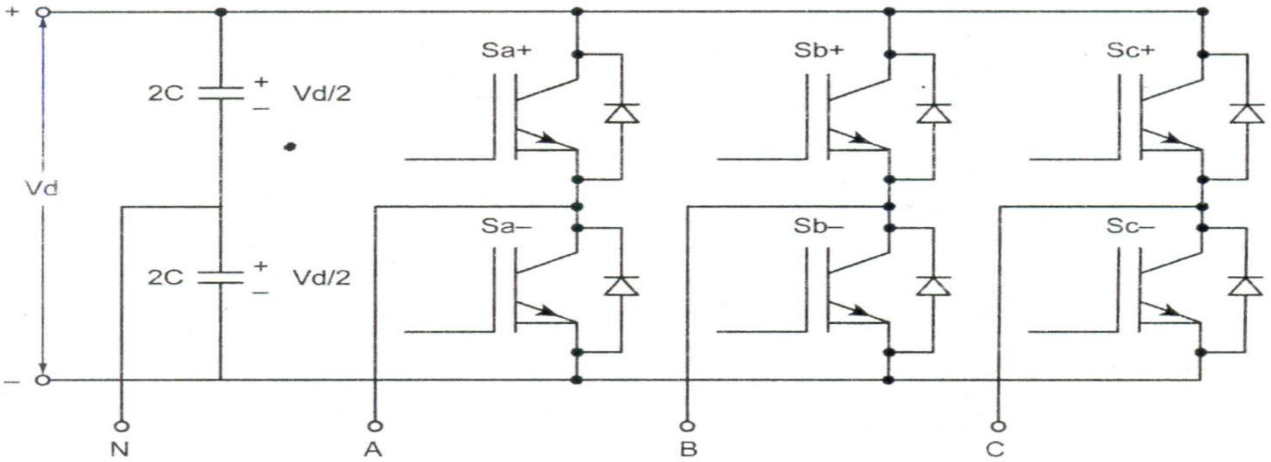


Fig.1.22. DVR detailed switching circuit

2.8.3 Active series compensators (Transformer less series injection)

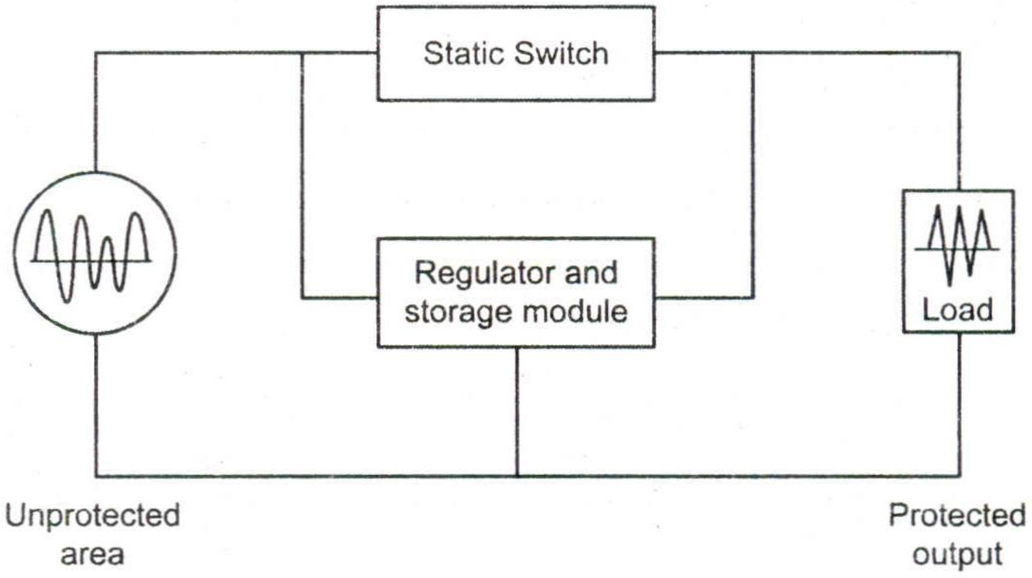


Fig.1.23. Active series filter by static switch

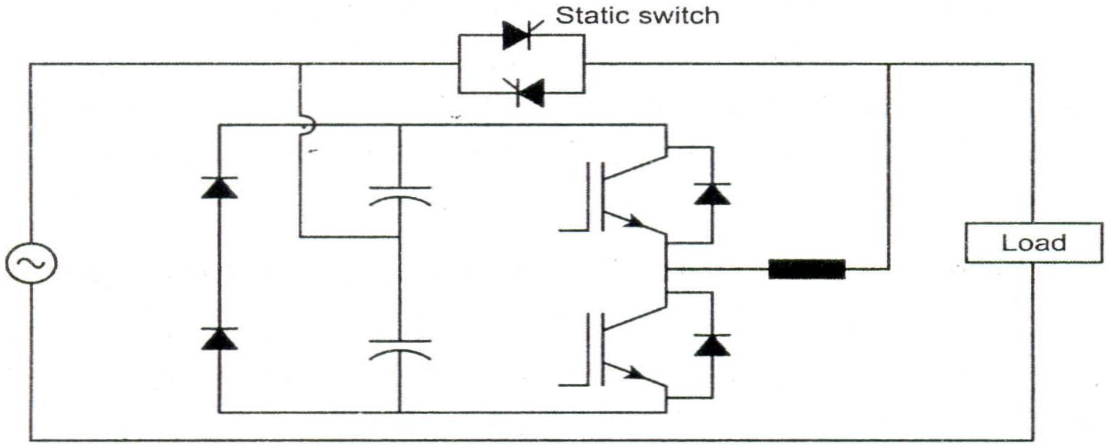


Fig.1.23. Active series filter detailed circuit

2.8.4 DISTRIBUTION STATIC COMPENSATOR (DSTATCOM)

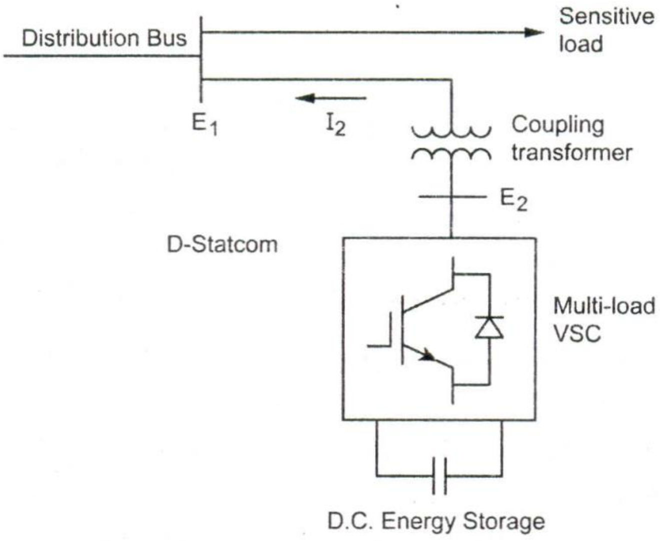


Fig.1.24. DSTATCOM in distribution system

DVR components

- VSC
- DC Energy storage device
- coupling transformer
- Voltage regulation and compensation of Q
- Pf correction
- Elimination of harmonics

Three modes of operation

Vi=Vs ,Vi>Vs , Vi<Vs

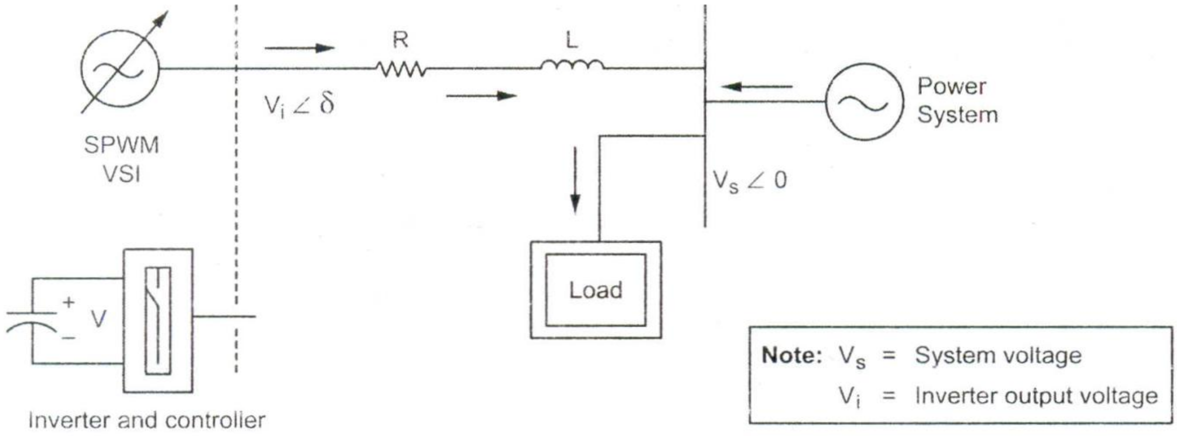
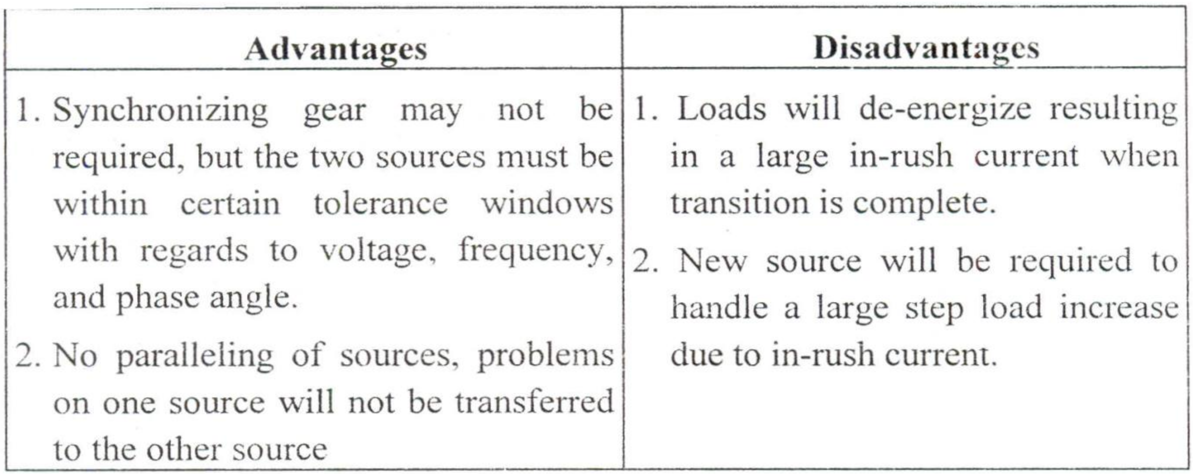


Fig.1.25. DSTATCOM used for load compensation

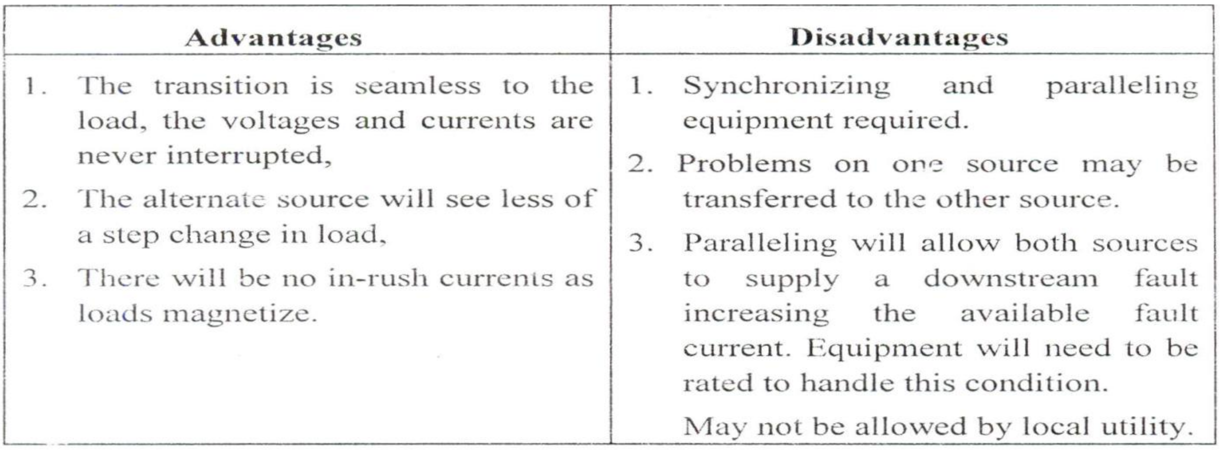
2.8.5 Solid State (Static) Transfer Switch (SSTS)

a) Open Transition



Advantages	Disadvantages
1. Synchronizing gear may not be required, but the two sources must be within certain tolerance windows with regards to voltage, frequency, and phase angle. 2. No paralleling of sources, problems on one source will not be transferred to the other source	1. Loads will de-energize resulting in a large in-rush current when transition is complete. 2. New source will be required to handle a large step load increase due to in-rush current.

b) Closed Transition



Advantages	Disadvantages
1. The transition is seamless to the load, the voltages and currents are never interrupted,	1. Synchronizing and paralleling equipment required.
2. The alternate source will see less of a step change in load,	2. Problems on one source may be transferred to the other source.
3. There will be no in-rush currents as loads magnetize.	3. Paralleling will allow both sources to supply a downstream fault increasing the available fault current. Equipment will need to be rated to handle this condition. May not be allowed by local utility.

2.8.6 Schematic Representation of SSTS as a Custom power Device

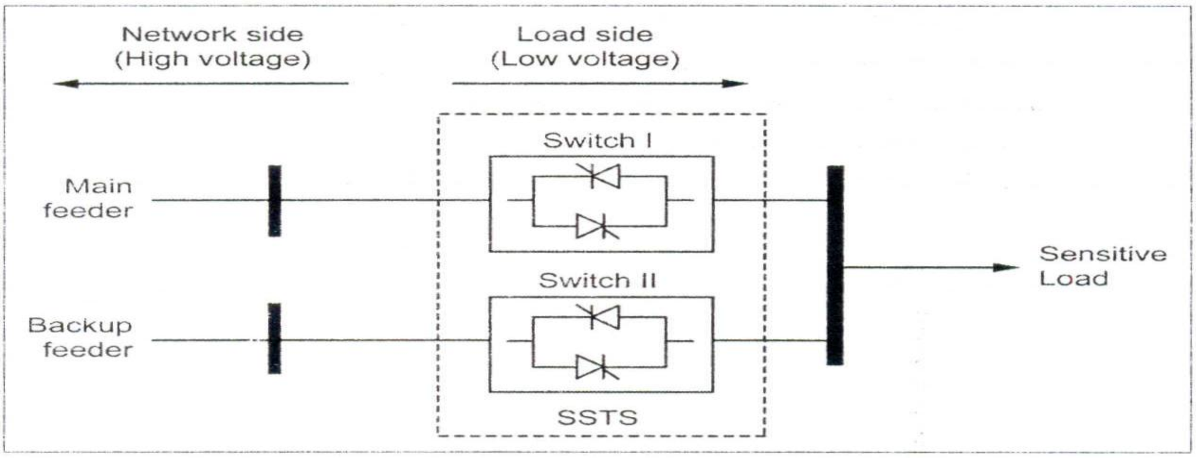


Fig. 1.26 SSTS used as Custom power Device

2.8.7 Thyristor of SSTS conducting Half cycles.

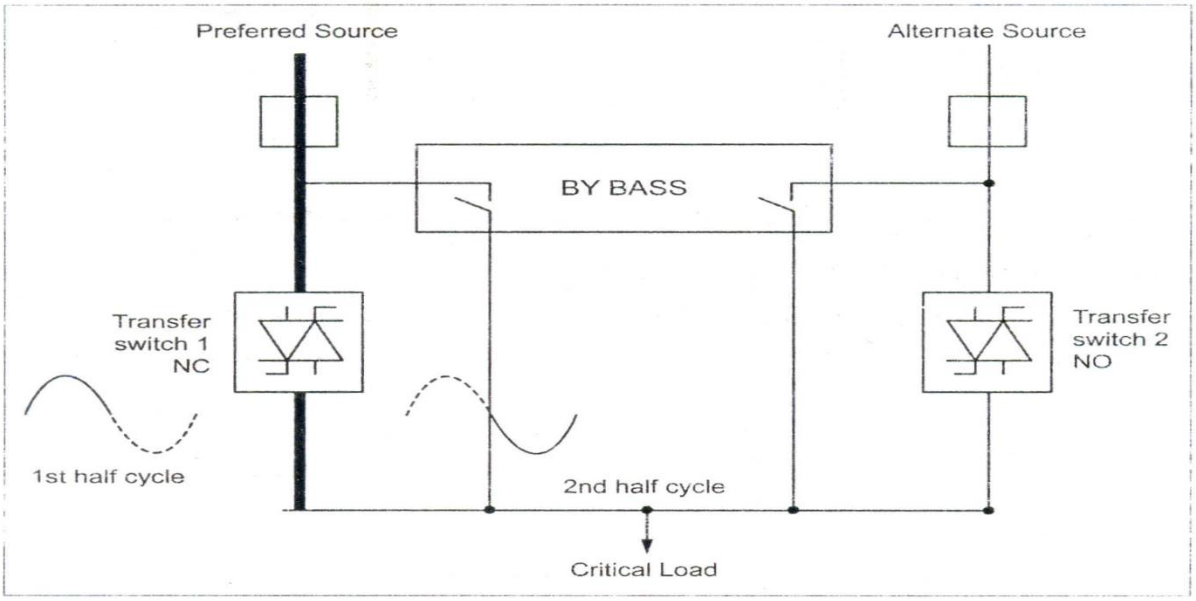


Fig. 1.27 Thyristor based SSTS used as Custom power Device

2.8.8 Static UPS with minimal Energy Storage

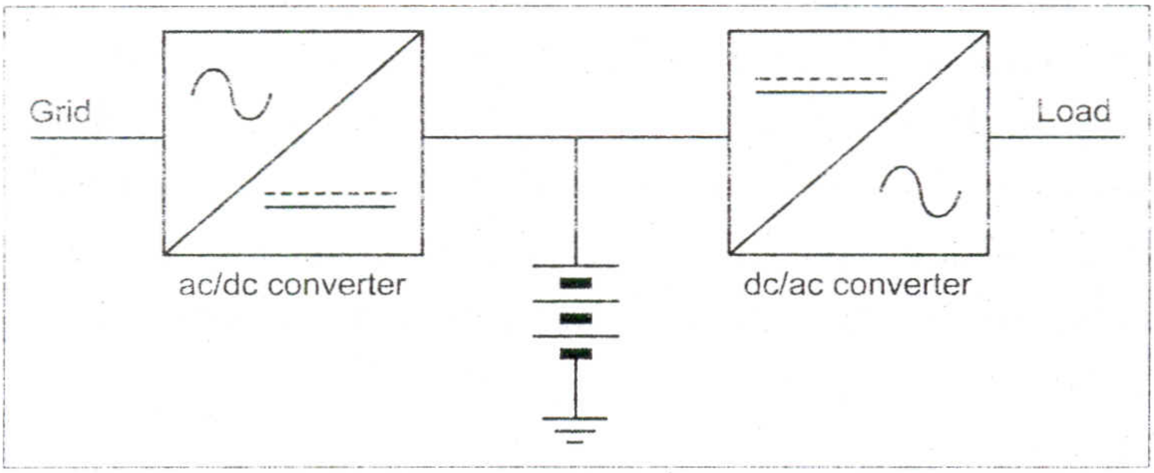


Fig. 1.28 Static UPS with minimal Energy Storage

2.8.9 Backup Storage Energy Supply

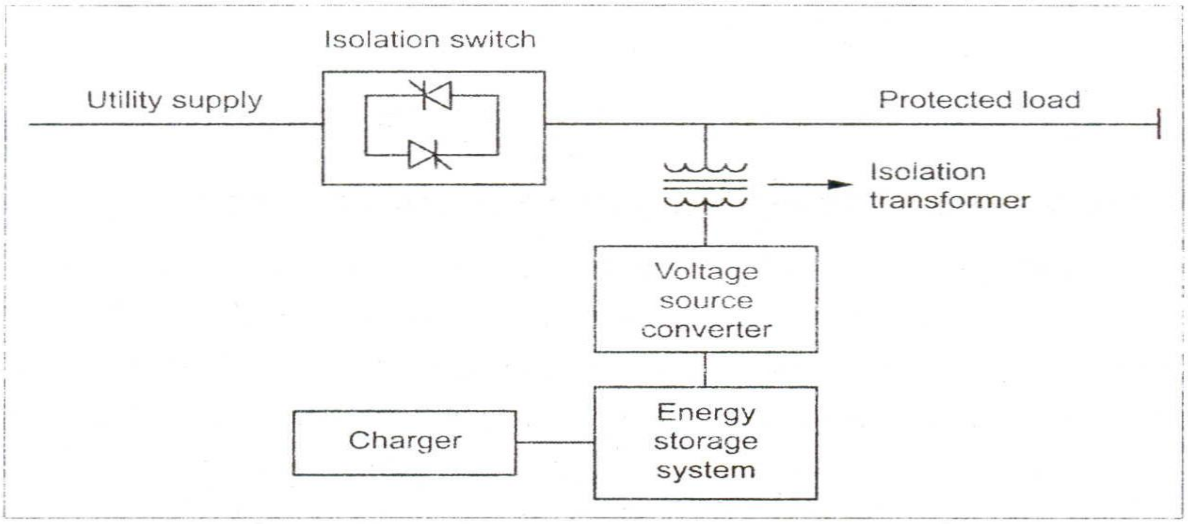


Fig. 1.29 Backup storage Energy Supply

2.8.10 Flywheel with UPS system

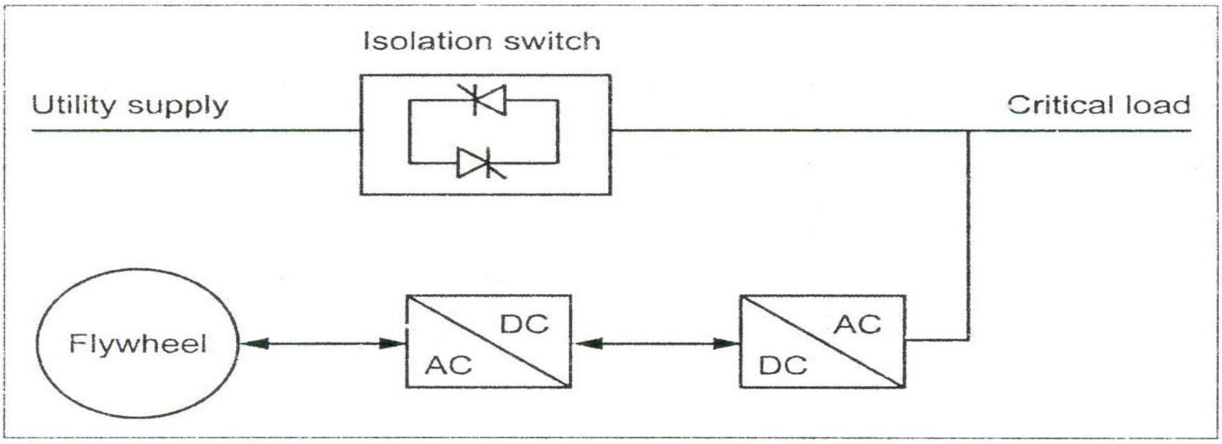


Fig. 1.30 Flywheel with UPS system

2 VOLTAGE SAGS & INTERRUPTION

(SHORT TYPE QUESTIONS AND ANSWERS)

UNIT- 2 WHAT IT IS?

- SAG- it's sources, causes, definition etc.
- INTERRUPTION- causes, definition etc.
- SAG ESTIMATION
- SAG MITIGATING DIVICES
- DIVICES TO PREVENT INTERRUPTION.

1. Explain about sag initiation.

The sudden change in voltage somewhere in the power system or at the equipment terminals, directly attributed to the initiation of a Short circuit fault. The instant of sag initiation can be viewed as the actual start of a voltage sag.

2. Explain interruption

A voltage event in which the voltage is zero during a certain time. The time during which the voltage is zero is referred to as the duration of the interruption. Interruption can be of the following types.

- Interruption momentary (electrical power system)
- Interruption momentary (power quality monitoring)
- Interruption sustained (electrical power system)
- Interruption sustained (power quality)

3. Name the devices used to mitigate voltage sags.

- Ferroresonant transformer
- Magnetic synthesizers
- On-line UPS
- Stand by UPS
- Hybrid UPS
- Motor - Gen sets.
- Supper conducting magnetic storage device.

4. Explain the concept " Area of vulnerability".

The estimation of voltage sag performance is found out from the area of vulnerability .The area of vulnerability is used to evaluate the portion being subjected to voltage sag lower than a critical value.. It depends upon the sensitivity of the equipments. Area of vulnerability describes all the fault locations that can cause equipment to miss operate.

5. What do you meant by voltage sag ride through capability.

voltage sag ride through capability of a device say a motor, how it is capable to work even when there is a sag.

The ultimate idea was to find an industrial solution that allows motors to ride through voltage sags and momentary interruptions safely because our market research didn't find such a device. So, we developed and tested a device that achieved our goal. The device can be installed in the motor starter, where it connects to the starter and other auxiliary components during voltage sag, the device holds the contactors closed until the sag reaches a preset, unsafe limit, then opens the motor starter contactors and treats the event as a momentary interruption.)

6. **Categorize the equipment sensitive to voltage sags.**

Equipment sensitivity to voltage sags can be Categorized as,

- Equipment sensitive to only the magnitude of a voltage sag.
- Equipment sensitive to both the magnitude and duration of a voltage sag.
- Equipment sensitive to characteristics other than magnitude and duration .

7. **Name the various sources of sags and interruption.**

- Faults on the utility system.
- Faults on one of the feeder in the substation or faults somewhere on the transmission system.
- Sags are most often caused by fuse or breaker operation, motor starting, or capacitor switching

8. Explain motor starting sags.

The voltage sag caused by the motor at the time of starting with the intake of heavy load current is called as motor- starting sag.

9. Name the critical information needed to compute voltage sag performance.

Number of feeders supplied from substations.

- Average feeder length
- Average feeder reactance.
- Short- circuit equivalent reactance at the substation.
- Feeder reactors.
- Average feeder fault performance.

10. What is a Ferroresonant transformer?

Ferroresonant transformers are the constant voltage transformers (CVTs) are basically 1:1 transformers which are excited high on their saturation curves thereby providing an output voltage which is not significantly affected by input voltage variation. That is, its iron core is "stuffed full" (packed)of magnetic lines of flux for a large portion of the AC cycle so that variations in supply voltage (primary winding current) have little effect on the core's magnetic flux density, which means the secondary winding outputs a nearly constant voltage despite significant variations in supply (primary winding) voltage.

11. What is a Magnetic synthesizers?

The magnetic synthesizer is another ferroresonants device that consists of inductors and capacitors configured in a parallel resonant circuit with a network of six saturating pulse transformers. The output is synthesized by combining pulses of the saturating transformers into “building blocks” similar to the pseudo sine wave of many electronic inverters . This device is typically used for applications of 50kVA and larger, where voltage regulation, sag mitigation, and/or isolation are needed.

12. What is series compensation?

Series compensation is defined as insertion of reactive power elements into transmission lines. The task of series compensation is to reduce the transmission lines inductivity.

13. What is meant by active series compensation?

Series compensation is defined as insertion of reactive power elements into transmission lines Active series compensators (1kVA to 5kVA, single-phase) which boost voltage by injecting a voltage in series with the remaining voltage during a voltage sag. These devices are also referred to as dynamic voltage restorers (DVRs), dynamic sag correctors (DySCs), or automatic voltage conditioners (AVCs). If active elements are used then it is active series compensation

14. What is a DVR ?

DVR is series connected between a supply and a sensitive load so that it injects the compensating voltage into distribution line in real time. DVR is an effective solution to restore voltage sag by establishing the proper voltage quality level required by customer.

15. What is the difference between a voltage regulator and a Dynamic Voltage Restorer (DVR)

Both are used to mitigate the effects of voltage dip or sag.

A voltage regulator has no energy store. It has a transformer secondary winding in series with the supply. When the input voltage moves outside the tolerance band the primary of that transformer is driven to boost, or in anti-phase to reduce, the voltage appropriately. Because the load voltage is kept constant, the power to the load is constant so, when the input voltage falls, the input current increases.

A DVR has an energy store, so requires no additional input power (in the short term) to boost the voltage during a dip. A DVR can correct a dip to 0 % retained voltage. But the DVR has a limited energy store and so is suitable for short-term effects only - it cannot correct for long term under voltage. Also, the store has to be recharged between events so it is not suitable multiple dips are expected frequently. Typically, DVRs use super capacitors, large secondary batteries or high-speed flywheels as energy stores. Unsurprisingly, DVRs are more expensive than voltage regulators.

16. What is a UPS system?

An Uninterruptible Power Supply (UPS), also known as an Uninterruptible Power Source, Uninterruptible Power System, Continuous Power Supply (CPS) or a battery backup is a device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available.

17. What is an On-line UPS?

In an on-line UPS, the load is always fed through the UPS. The incoming ac power Is rectified into dc power ,which charges a bank of batteries. This DC power is then inverted back in to ac power, to feed the load .If the incoming ac power fails, the inverter is fed from batteries and continues to supply the load.
(The Online UPS takes incoming power, converts it to DC, conditions it, and converts it back to AC)

18. What is a standby or an off-line UPS?

In an off-line UPS the normal line power is used to power the equipments Until a disturbance is detected and a switch transfers the load to the battery backed inverter. In this type of UPS, the primary power source is line power from the utility, and the secondary power source is the battery. It is called a standby UPS because the battery and inverter are normally not supplying power to the equipment. The battery charger is using line power to charge the battery, and the battery and inverter are waiting "on standby" until they are needed. When the AC power goes out, the transfer switch changes to the secondary power source. When line power is restored, the UPS switches back

19. What is a hybrid UPS?

A hybrid UPS is similar in design to the standby UPS but utilizes a voltage regulator on the UPS output to provide regulation to the load and momentary ride through when the transfer from normal to UPS supply is made.

20. What are static transfer switches? Give it’s classification.

The Static Transfer Switch provides break-before-make switching between two independent AC power sources for uninterrupted power to sensitive electronic equipment. When used with redundant AC power sources, the switch permits maintenance without shutting down critical equipment. The switch utilizes solid-state switching devices close to the critical load, thus producing high levels of power availability and power system tolerance

21. what are fast transfer switches?

Fast transfer switches are designed to switch sensitive loads, such as computers or modern entertainment equipment from one AC source to another in case of short voltage dips (4 to 12 ms) or unstable frequency or sudden load variation occurs. The priority source typically is the mains, a generator or shore power. The alternate source typically is an inverter. With its switching time of less than 20 ms sensitive loads will continue to operate without disruption

22. Name the various components of a fast transfer switches.

- single action solenoid
- mechanical assembly

23. Name the various parts of a static transfer switches unit.

- Primary source,
- Alternate source,
- SCRs,
- Mechanical automatic transfer switches.

24. Name the equipments sensitive to only the magnitude of a voltage sags.

The equipment's are under voltage relay process controls, motor drive control. And many types of automated machines.

25. Why there is sag during motor starting ?

During motor starting a sag occurs because, the impedance of the motor initially (when the rotor is stationary) looks much like a short circuit. Once the rotor starts turning, the current decreases and eventually goes to a much lower, steady-state value. However, if a load change causes the motor to come close to stalling or remain in the locked rotor condition, another sag can result for similar reasons.

26. Give the expression for estimating the sag severity during full voltage starting of an induction mot

If full voltage starting is used, the severity of voltage sag during full-voltage starting of a motor is described by the following equation

$$V_{min}(pu) = \frac{V(pu).kVA_{SC}}{kVA_{LR}+kVA_{SC}}$$

Where, V(pu) = actual system voltage, in per unit of nominal
kVA_{LR} = motor locked rotor kVA
kVA_{SC} = system short circuit kVA at the motor terminals

:

2

VOLTAGE SAGS & INTERRUPTION

(LONG TYPE QUESTIONS AND ANSWERS)

1. Discuss the various sources of sags and interruptions.

Most voltage sags originate within your facility. The three most common causes of facility-sourced voltage sags are:

- **Starting a large load**, such as a motor or resistive heater. Electric motors typically draw 150% to 500% of their operating current as they come up to speed. Resistive heaters typically draw 150% of their rated current until they warm up.
- **Loose or defective wiring**, such as insufficiently tightened box screws on power conductors. This effective increases your system impedance, and exaggerates the effect of current increases.
- **Faults or short circuits** elsewhere in your facility. Although the fault will be quickly removed by a fuse or a circuit breaker, they will drag the voltage down until the protective device operates, which can take anywhere from a few cycles to a few seconds.

Voltage sags can also originate on your utility's electric power system. The most common types of utility-sourced voltage sags are:

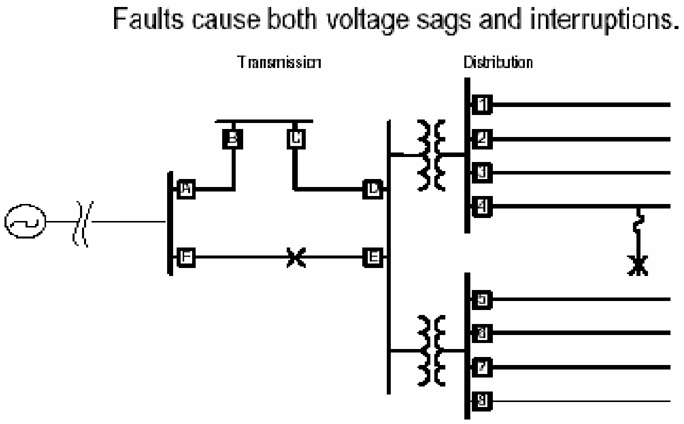


Fig 2.1 Fault location on the utility power systems

- **Faults on distant circuits**, **X** : Single line to ground fault Fig 2.1 fault location on the utility power system

Consider a customer that is supplied from the feeder protected by breaker **4** on the diagram shown in fig 2.1. If there is a fault on this feeder, the customer will experience voltage sag during the fault followed by an interruption when the breaker opens to clear the fault. If the fault is temporary in nature, a reclose operation on the breaker should be successful and the interruption will only be temporary.

A much more common event would be a fault on one of the other feeders (feeder section between breaker **F & E**) From the substation or a fault somewhere on the transmission system. In any of these cases, the customer will experience voltage sag during the period that the fault is actually on the system. As soon as breakers open to clear the fault, normal voltage will be restored to the customer

Typically, these faults are removed by "reclosers", or self-resetting circuit breakers. These reclosers typically delay 1 to 5 seconds before self-resetting. If the fault is still present when the recloser resets, you may see a series of voltage sags, spaced 1 to 5 seconds apart. Faults on utility systems may be phase-to-phase, or phase-to-earth; depending on the transformers between you and the fault, you will see different levels of voltage reduction.

Voltage regulator failures are far less common. Utilities have automated systems to adjust voltage (typically using power factor correction capacitors, or tap switching transformers), and these systems do occasionally fail.

2. Why does equipment fail when there are voltage sags on ac power systems?

i. Equipment fails because there isn't enough voltage.

This is the obvious way -- if there is not enough voltage on the ac power system to provide the energy that the equipment needs, it is going to fail. Actually, the problem is slightly more subtle. In a typical sensitive load, the ac voltage is rectified and converted to pulsed dc. With a bridge rectifier, the pulsing will typically be either twice the power line frequency (for single-phase loads) or six times the power line frequency (for three-phase loads). This pulsing DC is stored in a filter capacitor, which in turn supplies smooth DC as raw material for the rest of the power supply: regulators, etc. If the DC supplied by the filter capacitor drops below some critical level, the regulators will not be able to deliver their designed voltage, and the system will fail. Note that the filter capacitor always stores energy, so there is always an ability to ride through some sags -- after all, the ac power system delivers zero voltage 100 or 120 times each second! But with a deep enough sag that lasts long enough, the filter capacitor voltage will drop below a critical level.

ii. Equipment fails because an undervoltage circuit trips.

Careful system designers may include a circuit that monitors the ac power system for adequate voltage. But "adequate voltage" may not be well defined, or understood. For example, if the sensitive system is running at half load, it may be able to operate at only 70% ac voltage, even though it may be specified to operate with 90% - 110% ac voltage. So the voltage sags to 70%; the equipment can operate without a problem; but the undervoltage monitor may decide to shut the system down.

iii. Equipment fails because an unbalance relay trips.

On three-phase systems, voltage sags are often asymmetrical (they affect one or two phases more than the remaining phases). Three-phase motors and transformers can be damaged by sustained voltage unbalance; it can cause the transformer or motor to overheat. So it makes sense to put in an unbalance relay, which is a device that shuts down the system if the voltage unbalance exceeds some threshold, typically a few percent. But a voltage sag that causes 20-50% unbalance for a second or two is never going to cause a motor or transformer to overheat. It just doesn't last long enough. Still, unbalance relays with inadequate delays can cause the sensitive system to shut down, even for a brief voltage sag.

iv. A quick-acting relay shuts the system down, typically in the EMO circuit.

The EMO (emergency off) circuit in an industrial load typically consists of a normally-closed switch that can disconnect power to a latched relay coil. If the relay operates quickly enough, it may interpret a brief voltage sag as an operator hitting the EMO switch. The whole system will shut down unnecessarily.

v. A reset circuit may incorrectly trip at the end of the voltage sag.

This is the most subtle problem caused by voltage sags. Many electronic reset circuits are designed to operate at "power up" -- when you first turn on the equipment, these circuits will ensure that the microprocessors all start up properly, the latches are all properly initialized, the displays are in their correct mode, etc. These circuits are difficult to design, because they must operate correctly when power is uncertain.

One common design detects a sudden increase in voltage, which always happens when you turn the equipment on. Unfortunately, it also happens at the end of a voltage sag. If the reset circuit misinterprets the end of a voltage sag, the equipment will operate perfectly during the voltage sag, but will abruptly reset itself when the voltage returns to normal. To make this problem even more difficult, it is quite common for different parts of a system to have different reset circuits, so it is possible for one part of the system to be reset even when the rest of the system is not. Without a sag generator with a good data acquisition system, this problem is very difficult to detect and solve.

3. Discuss. Estimating voltage sag performance.

Area of VULNERABILITY (VULNERABLE means that can be hurt, damaged, injured like Ex: Cyclist are more VULNERABLE than motorist . The election defeat puts the party leader in a vulnerable position. The Sag (voltage drop) at different locations in a network are different due to a fault at one point some where in the network)

The concept of an “area of vulnerability” has been developed to help evaluate the like hood of being subjected to voltage sags lower than a critical value. An area of vulnerability is determined by the total circuit miles of exposure to faults that can cause voltage magnitude at an end user facility to drop below the equipment minimum voltage sag ride-through capability Fig 2.2 shows an area of vulnerability diagram for an industrial customer supplied from a transmission system bus.

It is important for customers to understand the sensitivity of their equipment to momentary interruptions and voltage sags. The trip thresholds of sensitive equipment can often be modified, either with available settings in the controls or by manufacturer design changes. Once the sensitivity of equipment is known, an area of vulnerability for faults on adjacent feeders can be identified. This will help in evaluating the likelihood of problems due to utility system faults. The area of vulnerability concept can also be applied to customers supplied from the transmission system. Figure 6-8 shows an area of vulnerability diagram for a customer supplied from a transmission system bus. The figure shows that the area of vulnerability is dependent on the sensitivity of the equipment. Contactors that drop out (means stops) at 50% voltage will have a relatively small area of vulnerability while adjustable-speed drives (ASDs)that drop out at 90% voltage may be sensitive to faults over a wide range of the transmission system.

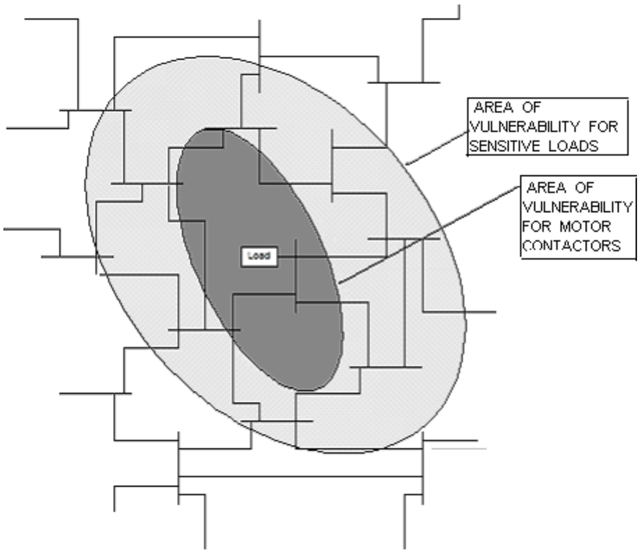


Fig 2.2 Illustration of the area of vulnerability

The expected voltage sag performance is developed by performing short circuit simulations to determine the plant voltage as a function of fault location throughout the power system. Total circuit miles of line exposure that can affect the plant are determined for a particular voltage sag level.

Ride-Through: Measure of the ability of control devices to sustain operation when subjected to partial or total loss of power of a specified duration.

i. Equipment sensitivity to voltage sags:

Equipment within an end-user facility may have different sensitivity to voltage sags.8 Equipment sensitivity to voltage sags is very dependent on the specific load type, control settings, and applications. Consequently, it is often difficult to identify which characteristics of a given voltage sag are most likely to cause equipment to misoperate. The most commonly used characteristics are the duration and magnitude of the sag. Other less commonly used characteristics include phase shift and unbalance, missing voltage, three-phase voltage unbalance during the sag event, and the point-in-the-wave at which the sag initiates and terminates. Generally, equipment sensitivity to voltage sags can be divided into three categories:

- Equipment sensitive to only the magnitude of a voltage sag. This group includes devices such as undervoltage relays, process controls, motor drive controls,6 and many types of automated machines (e.g., semiconductor manufacturing equipment). Devices in this group are sensitive to the minimum (or maximum) voltage magnitude experienced during a sag (or swell). The duration of the disturbance is usually of secondary importance for these devices.

- Equipment sensitive to both the magnitude and duration of a voltage sag. This group includes virtually all equipment that uses electronic power supplies. Such equipment misoperates or fails when the power supply output voltage drops below specified values. Thus, the important characteristic for this type of equipment is the duration that the rms voltage is below a specified threshold at which the equipment trips.

- Equipment sensitive to characteristics other than magnitude and duration. Some devices are affected by other sag characteristics such as the phase unbalance during the sag event, the point-in-the wave at which the sag is initiated, or any transient oscillations occurring during the disturbance. These characteristics are more subtle than magnitude and duration, and their impacts are much more difficult to generalize. As a result, the rms variation performance indices defined here are focused on the more common magnitude and duration characteristics. For end users with sensitive processes, the voltage sag ride-through capability is usually the most important characteristic to consider.

These loads can generally be impacted by very short duration events, and virtually all voltage sag conditions last at least 4 or 5 cycles (unless the fault is cleared by a current-limiting fuse). Thus, one of the most common methods to quantify equipment susceptibility to voltage sag is using a magnitude-duration plot as shown in Fig. 3.6. It shows the voltage sag magnitude that will cause equipment to misoperate as a function of the sag duration. The curve labeled CBEMA represents typical equipment sensitivity characteristics. The curve was developed by the CBEMA and was adopted in IEEE 446 (Orange Book). Since the association reorganized in 1994 and was subsequently renamed the Information Technology Industry Council (ITI), the CBEMA curve was also updated and renamed the ITI curve. Typical loads will likely trip off when the voltage is below the CBEMA, or ITI, curve. The curve labeled ASD represents an example ASD voltage sag ride-through capability for a device that is very sensitive to voltage sags. It trips for sags below 0.9 pu that last for only 4 cycles. The contactor curve represents typical contactor sag ride-through characteristics. It trips for voltage sags below 0.5 pu that last for more than 1 cycle. The area of vulnerability for motor contactors shown in Fig. 3.5 indicates that faults within this area will cause the end-user voltage to drop below 0.5 pu. Motor contactors having a minimum voltage sag ride-through capability of 0.5 pu would have tripped out when a fault causing a voltage sag with duration of more than 1 cycle occurs within the area of vulnerability. However, faults outside this area will not cause the voltage to drop below 0.5 pu. The same discussion applies to the area of vulnerability for ASD loads. The less sensitive the equipment, the smaller the area of vulnerability will be (and the fewer times sags will cause the equipment to misoperate).

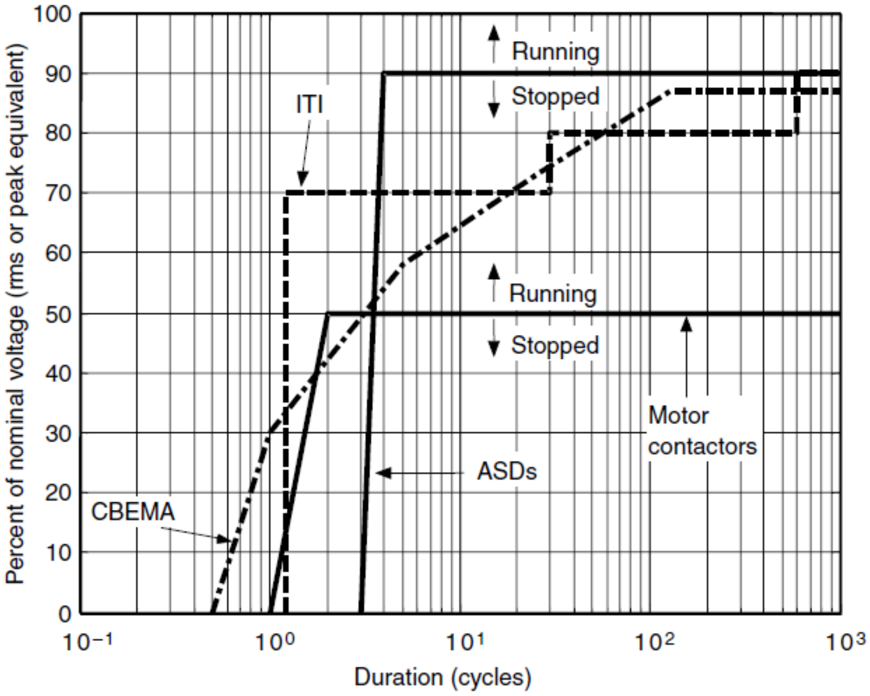
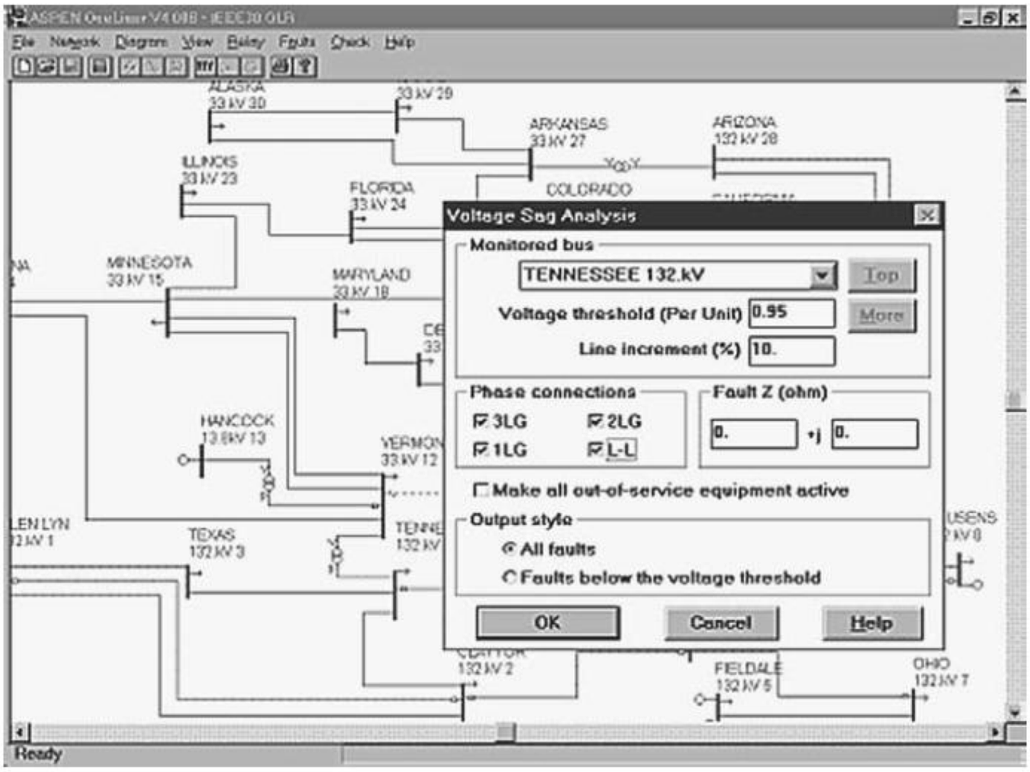


Figure 3.6 Typical equipment voltage sag ride-through capability curves.

- Equipment sensitivity to only the magnitude of a voltage sags.
- Equipment sensitivity to both the magnitude and duration of a voltage Sags.
- Equipment sensitivity to characteristics other than the magnitude and duration.

ii. Transmission System Sag Performance Evaluation

The voltage sag performance for a given customer facility will depend on whether the customer is supplied from the transmission system or from the distribution system. For a customer supplied from the transmission system, the voltage sag performance will depend on only the transmission system fault performance. On the other hand, for a customer supplied from the distribution system, the voltage sag performance will depend on the fault performance on both the transmission and distribution systems. This section discusses procedures to estimate the transmission system contribution to the overall voltage sag performance at a facility. Section 3.2.4 focuses on the distribution system contribution to the overall voltage sag performance. Transmission line faults and the subsequent opening of the protective devices rarely cause an interruption for any customer because of the interconnected nature of most modern-day transmission networks. These faults do, however, cause voltage sags. Depending on the equipment sensitivity, the unit may trip off, resulting in substantial monetary losses. The ability to estimate the expected voltage sags at an end-user location is therefore very important. Most utilities have detailed short-circuit models of the interconnected transmission system available for programs such as ASPEN* One Liner (Fig. 3.7). These programs can calculate the voltage throughout the system resulting from faults around the system. Many of them can also apply faults at locations along the transmission lines to help calculate the area of vulnerability at a specific location. The area of vulnerability describes all the fault locations that can cause equipment to misoperate. The type of fault must also be considered in this analysis. Single-line-to-ground faults will not result in the same voltage sag at the customer equipment as a three-phase fault. The characteristics at the end-use equipment also depend on how the voltages are changed by transformer connections and how the equipment is connected, i.e., phase-to-ground or phase-to-phase. Table 3.1 summarizes voltages at the customer transformer secondary for a single- line-to-ground fault at the primary.


Voltage Sag Analysis

Monitored bus: TENNESSEE 132.kV

Voltage threshold (Per Unit) 0.95

Line increment (%) 10.

Phase connections: ☑ 3LG ☑ 2LG ☑ 1LG ☑ L-L

Fault Z (ohm) 0. +j 0.

☐ Make all out-of-service equipment active

Output style:
● All faults
○ Faults below the voltage threshold

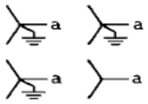
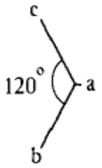
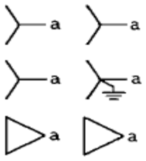
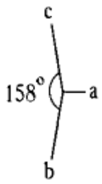
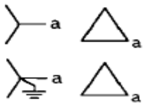
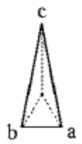
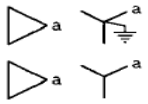
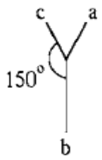
Figure 3.7 Example of modeling the transmission system in a short-circuit program for calculation of the area of vulnerability.

The relationships in Table 3.1 illustrate the fact that a single-line to-ground fault on the primary of a delta-wye grounded transformer does not result in zero voltage on any of the phase-to-ground or phase-to-phase voltages on the secondary of the transformer. The magnitude of the lowest secondary voltage depends on how the equipment is connected:

- Equipment connected line-to-line would experience a minimum voltage of 33 percent.
- Equipment connected line-to-neutral would experience a minimum voltage of 58 percent.

This illustrates the importance of both transformer connections and the equipment connections in determining the actual voltage that equipment will experience during a fault on the supply system. Math Bollen16 developed the concept of voltage sag "types" to describe the different voltage sag characteristics that can be experienced at the end-user level for different fault conditions and system configurations. The five types that can commonly be experienced are illustrated in Fig. These fault types can be used to conveniently summarize the expected performance at a customer location for different types of faults on the supply system.

TABLE 3.1 Transformer Secondary Voltages with a Single-Line-to-Ground Fault on the Primary

Transformer connection (primary/secondary)	Phase-to-phase			Phase-to-neutral			Phasor diagram
	V_{ab}	V_{bc}	V_{ca}	V_{an}	V_{bn}	V_{cn}	
	0.58	1.00	0.58	0.00	1.00	1.00	
	0.58	1.00	0.58	0.33	0.88	0.88	
	0.33	0.88	0.88	—	—	—	
	0.88	0.88	0.33	0.58	1.00	0.58	

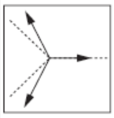
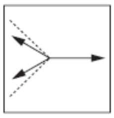
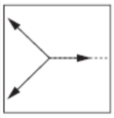
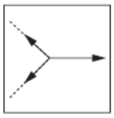
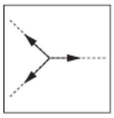
Phase Shift	Number of Phases		
	1	2	3
Angle	 Sag Type D One-phase sag, phase shift	 Sag Type C Two-phase sag, phase shift	Note: Three-phase sags should lead to relatively balanced conditions; therefore, sag type A is a sufficient characterization for all three-phase sags.
None	 Sag Type B One-phase sag, no phase shift	 Sag Type E Two-phase sag, no phase shift	 Sag Type A Three-phase sag

Figure 3.8 Voltage sag types at end-use equipment that result from different types of faults and transformer connections.

Table 3.2 is an example of an area of vulnerability listing giving all the fault locations that can result in voltage sags below 80 percent at the customer equipment (in this case a customer with equipment connected line-to-line and supplied through one delta-wye transformer from the transmission system Tennessee 132-kV bus). The actual expected performance is then determined by combining the area of vulnerability with the expected number of faults within this area of vulnerability. The fault performance is usually described in terms of faults per 100 miles/year (mi/yr). Most utilities maintain statistics of fault performance at all the different transmission voltages. These system wide statistics can be used along with the area of vulnerability to estimate the actual expected voltage sag performance. Figure 3.9 gives an example of this type of analysis. The figure shows the expected number of voltage sags per year at the customer equipment due to transmission system faults. The performance is broken down into the different sag types because the equipment sensitivity may be different for sags that affect all three phases versus sags that only affect one or two phases.

iii. Utility Distribution System Sag Performance Evaluation

Customers that are supplied at distribution voltage levels are impacted by faults on both the transmission system and the distribution system. The analysis at the distribution level must also include momentary interruptions caused by the operation of protective devices to clear the faults.7 These interruptions will most likely trip out sensitive equipment. The example presented in this section illustrates data requirements and computation procedures for evaluating the expected voltage sag and momentary interruption performance. The overall voltage sag performance at an end-user facility is the total of the expected voltage sag performance from the transmission and distribution systems. Figure 3.10 shows a typical distribution system with multiple feeders and fused branches, and protective devices. The utility protection scheme plays an important role in the voltage sag and momentary interruption performance. The critical information needed to compute voltage sag performance can be summarized as follows.

- Number of feeders supplied from the substation.
- Average feeder length.
- Average feeder reactance.
- Short-circuit equivalent reactance at the substation.

TABLE 3.2 Calculating Expected Sag Performance at a Specific Customer Site for a Given Voltage Level

Fault type	Faulted bus	Bus voltage	Voltage at monitored bus (pu)	Sag type
3LG	Tennessee	132	0	A
3LG	Nevada	132	0.23	A
3LG	Texas	132	0.33	A
2LG	Tennessee	132	0.38	C
2LG	Nevada	132	0.41	C
3LG	Claytor	132	0.42	A
1LG	Tennessee	132	0.45	D
2LG	Texas	132	0.48	C
3LG	Glen Lyn	132	0.48	A
3LG	Reusens	132	0.5	A
1LG	Nevada	132	0.5	D
L-L	Tennessee	132	0.5	C
2LG	Claytor	132	0.52	C
L-L	Nevada	132	0.52	C
L-L	Texas	132	0.55	C
2LG	Glen Lyn	132	0.57	C
L-L	Claytor	132	0.59	C
3LG	Arizona	132	0.59	A
2LG	Reusens	132	0.59	C
1LG	Texas	132	0.6	D
L-L	Glen Lyn	132	0.63	C
1LG	Claytor	132	0.63	D
L-L	Reusens	132	0.65	C
3LG	Ohio	132	0.65	A
1LG	Glen Lyn	132	0.67	D
1LG	Reusens	132	0.67	D
2LG	Arizona	132	0.67	C
2LG	Ohio	132	0.7	C
L-L	Arizona	132	0.7	C
3LG	Fieldale	132	0.72	A
L-L	Ohio	132	0.73	C
2LG	Fieldale	132	0.76	C
3LG	New Hampshire	33	0.76	A
1LG	Ohio	132	0.77	D
3LG	Vermont	33	0.77	A
L-L	Fieldale	132	0.78	C
1LG	Arizona	132	0.78	D
2LG	Vermont	33	0.79	C
L-L	Vermont	33	0.79	C
3LG	Minnesota	33	0.8	A

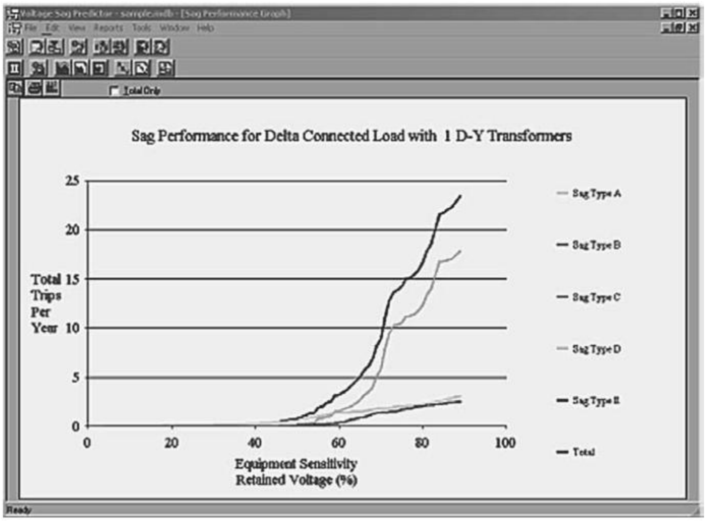


Figure 3.9 Estimated voltage sag performance at customer equipment due to transmission system faults.

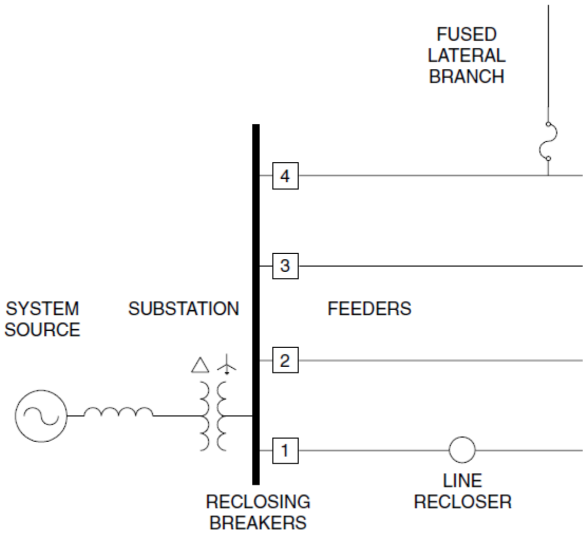


Figure 3.10 Typical distribution system illustrating protection devices.

- Feeder reactors, if any.
- Average feeder fault performance which includes three-phase-lineto- ground (3LG) faults and single-line-to-ground (SLG) faults in faults per mile per month. The feeder performance data may be available from protection logs. However, data for faults that are cleared by downline fuses or downline protective devices may be difficult to obtain and this information may have to be estimated.

There are two possible locations for faults on the distribution systems, i.e., on the same feeder and on parallel feeders. An area of vulnerability defining the total circuit miles of fault exposures that can cause voltage sags below equipment sag ride-through capability at a specific customer needs to be defined. The computation of the expected voltage sag performance can be performed as follows:

Faults on parallel feeders. Voltage experienced at the end-user facility following a fault on parallel feeders can be estimated by calculating the expected voltage magnitude at the substation. The voltage magnitude at the substation is impacted by the fault impedance and location, the configuration of the power system, and the system protection scheme. Figure 3.11 illustrates the effect of the distance between the substation and the fault locations for 3LG and SLG faults on a radial distribution system. The SLG fault curve shows the A-B phase bus voltage on the secondary of a delta-wye–grounded step-down transformer, with an A phase-to-ground fault on the primary. The actual voltage at the enduser location can be computed by converting the substation voltage using Table 3.1. The voltage sag performance for a specific sensitive equipment having the minimum ride-through voltage of Vs can be computed as follows:

$$E_{\text{parallel}}(v_s) = N_1 \times E_{p1} + N_3 \times E_{p3}$$

where N1 and N3 are the fault performance data for SLG and 3LG faults in faults per miles per month, and Ep1 and Ep3 are the total circuit miles of exposure to SLG and 3LG faults on parallel feeders that result in voltage sags below the minimum ride-through voltage vs at the end-user location.

Faults on the same feeder. In this step the expected voltage sag magnitude at the end-user location is computed as a function of fault location on the same feeder. Note that however, the computation is performed only for fault locations that will result in a sag but will not result in a momentary interruption, which will be computed separately. Examples of such fault locations include faults beyond a downline recloser or a branched fuse that is

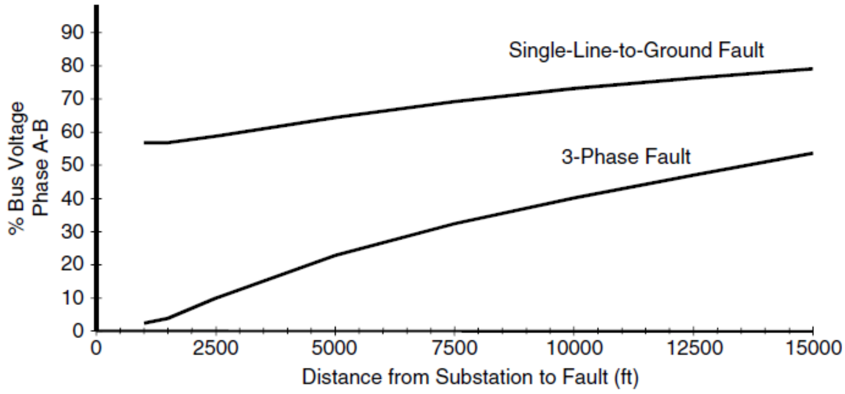


Figure 3.11 Example of voltage sag magnitude at an end-user location as a function of the fault location along a parallel feeder circuit.

coordinated to clear before the substation recloser. The voltage sag performance for specific sensitive equipment with ride-through voltage vs is computed as follows:

$$E_{\text{same}}(v_s) = N_1 \times E_{s1} + N_3 \times E_{s3}$$

where Es1and Es3 are the total circuit miles of exposure to SLG and 3LG on the same feeders that result in voltage sags below vs at the end-user location. The total expected voltage sag performance for the minimum ridethrough voltage vs would be the sum of expected voltage sag performance on the parallel and the same feeders, i.e., $E_{\text{parallel}}(V_s)+E_{\text{same}}(V_s)$. The total expected sag performance can be computed for other voltage thresholds, which then can be plotted to produce a plot similar to ones in Fig. 3.9. The expected interruption performance at the specified location can be determined by the length of exposure that will cause a breaker or other protective device in series with the customer facility to operate. For example, if the protection is designed to operate the substation breaker for any fault on the feeder, then this length is the total exposure length. The expected number of interruptions can be computed as follows:

$$E_{\text{int}} = L_{\text{int}} \times (N_1 + N_3)$$

Where, L_{int} is the total circuit miles of exposure to SLG and 3LG that results in interruptions at an end-user facility.

The critical information needed to compute voltage sag performance. (to be mentioned)

- Number of feeders supplied from substations.
- Average feeder length.
- Average feeder reactance.
- Short- circuit equivalent reactance at the substation.
- Feeder reactors. Average feeder fault performance.

4.Determining Sag Severity During Full-Voltage Starting.

The severity of voltage sag during full-voltage starting of a motor is described by the following equation:

$$\mathbf{V_{MIN}\,(pu) = (\,V(pu) \times kVA_{SC}) \div (\,kVA_{LR} + kVA_{SC})}$$

Where, V(pu) is the actual system voltage in per unit of nominal, kVA_{LR} is the motor locked rotor kVA, and kVA_{SC} is the system short-circuit kVA at the motor terminals.

$$\underset{\text{(Starting Current)}}{\text{Locked Rotor Amps}} = \frac{1000 \text{ x hp x kVA / hp}}{1.73 \text{ x Volts}}$$

If the result is above the minimum allowable steady-state voltage for the affected equipment, then you can use full voltage starting. If the result is below the allowable steady-state voltage, then you must compare the sag magnitude versus duration characteristic to the voltage tolerance envelope of the effected equipment. Note that the required calculations are fairly complicated, so you'll need to use a motor-starting or general transient analysis computer program or have the motor manufacturer use its application engineering capabilities to do the calculations and provide the resulting information.

5.Discuss about motor starting sags.

Motors have the undesirable effect of drawing several times their full load current while starting. By flowing through the system impedances, this large current will cause voltage sag which may dim lights, cause contactors to drop out, and disrupt sensitive equipment. The situation is made worse by an extremely poor starting displacement factor usually in the range of 15 to 30 percent.

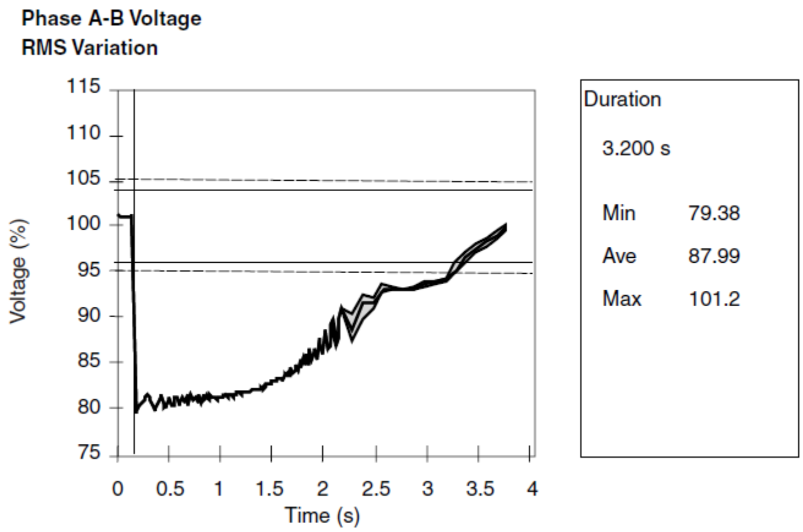
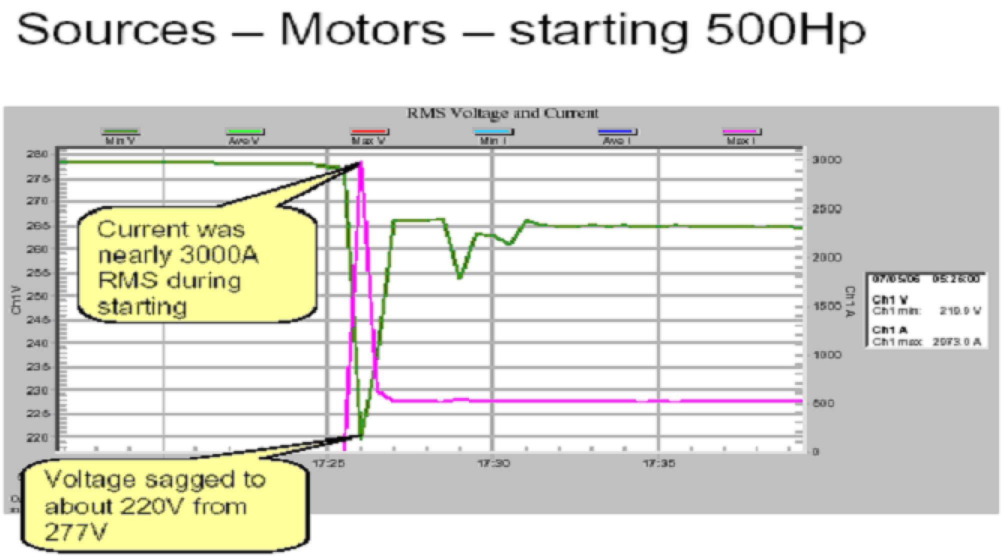


Figure 2.3 Temporary voltage sag caused by motor starting.

The severity of voltage sag during full-voltage starting of a motor is described by the following equation:

$$V_{MIN}\ (pu) = (\ V(pu) \times kVA_{SC}) \div (\ kVA_{LR} + kVA_{SC})$$

Where, V(pu) is the actual system voltage in per unit of nominal, kVA_{LR} is the motor locked rotor kVA, and kVA_{SC} is the system short-circuit kVA at the motor terminals.



Current was nearly 3000A RMS during starting

Voltage sagged to about 220V from 277V

Fig 2.4 Voltage sag during starting of 500Hp Motor

If the motor starting operation results in a voltage sag that causes tripping of equipment within the facility or at other customer facilities, you can use one of the following methods to reduce the voltage sag.

i. **Keep large motors on a separate supply from the sensitive loads**. Following this advice usually prevents problems with other equipment. The PCC will be at the distribution voltage level, where the voltage sag is less severe than at the motor terminals.

ii. **Use resistance and reactance starters**. These initially insert an impedance in series with the motor. After a time delay, the starter bypasses this impedance. Starting resistors may be bypassed in several steps while starting reactors are bypassed in a single step. This approach requires the motor be able to develop sufficient torque with the added impedance.

iii. **Use delta-wye starters**. These connect the stator in wye for starting, then after a time delay, reconnect the windings in delta. The wye connection reduces the starting voltage to 57% of the system line-line voltage, which causes the starting torque to fall to 33% of its full start value. The reduced voltage during the initial stage of the starting reduces the inrush current and the resulting voltage sag.

iv. **Use shunt capacitor starters**. These devices work by switching in, along with the motor, a large shunt capacitor bank that supplies a large portion of the motor VAR requirements during the start process. The capacitor bank then automatically disconnects once the motor is up to speed (usually based on overvoltage relay).

v. **Use series capacitors on distribution circuits supplying large motors**. This will reduce the effective impedance seen by the motor during starting as well as the resulting voltage sag on the motor side of the series capacitor. However, the source side of the series capacitor may still experience a more severe voltage sag.

6.Explain the need for series compentation. Explain active series compensation.

Series compensation is defined as insertion of reactive power elements into transmission lines. The task of series compensation is to reduce the transmission lines inductivity.

A series compensating device can boost the voltage by injecting a voltage in series with the remaining voltage during a voltage sag condition. These are referred as active series compensation device. They are available in size ranges from small single phase devices (1 to 5 kVA) to very large devices. (2mVA)

Series Compensation is a well-established technology that primarily is used to reduce transfer reactances, most notably in bulk transmission corridors. The result is a significant increase in the transmission system transient and voltage stability. Series Compensation is self-regulating in the sense that its reactive power output follows the variations in transmission line current, a fact that makes the series compensation concept extremely straightforward and cost effective.

A single line diagram illustrating the power electronics that are used to Achive the compensation is shown in fig which we call as transformerless series series injection.

Transformerless series injection

In the event of voltage sag, the static switch of this series injection device is opened and the load is supplied by an inverter. The power of the dc bus of the inverter is maintained by charging two capacitors connected in series. For sags down to 50% retained voltage, the rated voltage can be supplied to the load. Optional additional energy storage (e.g. extra capacitors) can mitigate a complete outage for a limited time duration and mitigate deeper asymmetrical sags, such as a complete outage of one phase. Only the basic operation is considered further.

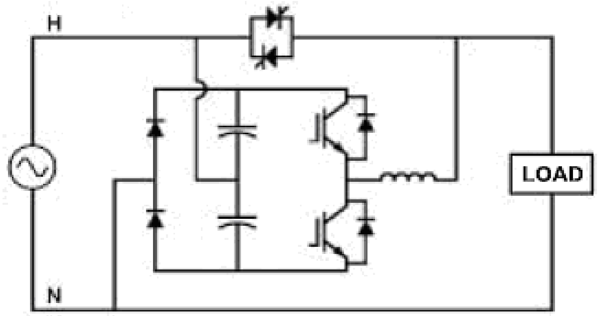


fig 2.5 operation of the active series compensator

Other Type Of Series Compensation

Static Series Compensator (SSC): The static series compensator is a waveform synthesis device based on power electronics that is series connected directly into the utility primary feeder by means of a set of single phase insertion transformers. This device does not protect a load against interruptions and is generally limited its design to providing correction for voltage sags that have a minimum voltage no lower than about 50% of nominal voltage. An example of this device (a dynamic voltage restorer-DVR) is shown in figure 2.6.

The DVR uses a voltage source converter (VSC) connected in series with the protected load (through an insertion transformer for medium voltage applications) to compensate amplitude and phase angle of the voltage applied to the load. The dc capacitor between the charger and the VSC serves as an energy buffer, generating and absorbing power during voltage sags and voltage swells, respectively. This process enables the voltage, as seen by the load, to be of the desired magnitude whenever disturbances occur upstream.

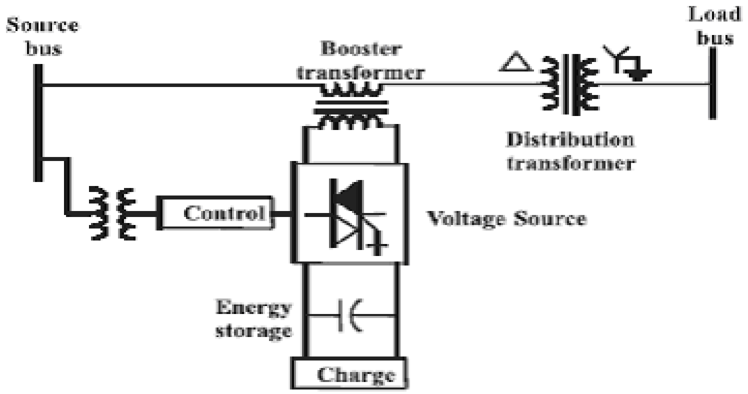


Fig2.6 Basic configuration of DVR

7. Discuss the various devices used for mitigating voltage sags. (or) End User Solutions For Voltage Sag Mitigation.

For this the followings are to be explained.

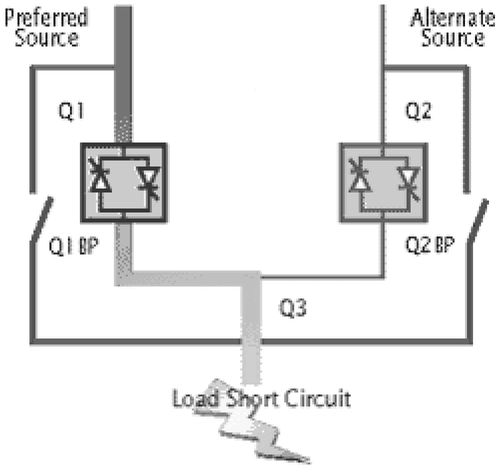
- Ferroresonant transformer.
- Magnetic synthesizer.
- Active series compensator.
- All three types of UPS.
- Motor generator sets.
- Flywheel energy storage systems.
- Superconducting magnetic energy storage devices.

Note: (static switches and fast transfer switches does not come under the above list they only form a part of the device. There are other devices too, but what ever dugan has covered we are restricted to that only. In this text material the above devices have been covered separately except Flywheel energy storage systems .So combine them also brief them discuss all(because various devices asked) at least give diagrams. examiner need diagrams. And some of you know stories better.)

8. Write a note on static and fast transfer switches.

The **Static Transfer Switch** provides break-before-make switching between two independent AC power sources for uniterrupted power to sensitive electronic equipment. When used with redundant AC power sources, the switch permits maintenance without shutting down critical equipment. The switch utilizes solid-state switching devices close to the critical load, thus producing high levels of power availability and power system tolerance. It is available in 100-4,000 A models. The switch is suited for data processing, distributed computing, telecommunications equipment, and high-tech manufacturing applications. Features include:

- 0.25 cycle maximum transfers between AC power sources.
- Manual and automatic transfers.
- Selectable preferred input sources.
- AccuVar TVSS for both AC inputs.
- Clear LCD monitoring panel with on-screen instructions.



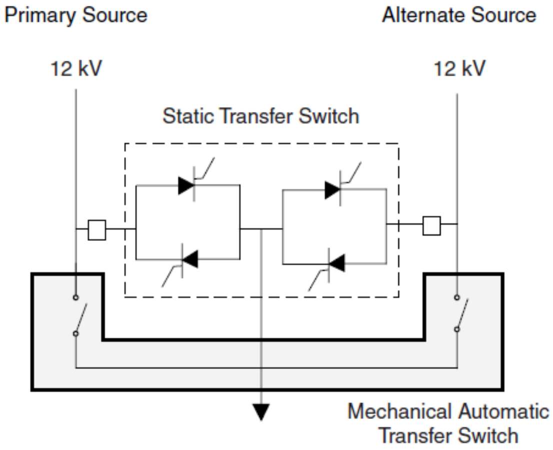


Fig 2.7 Configuration of a static transfer switch

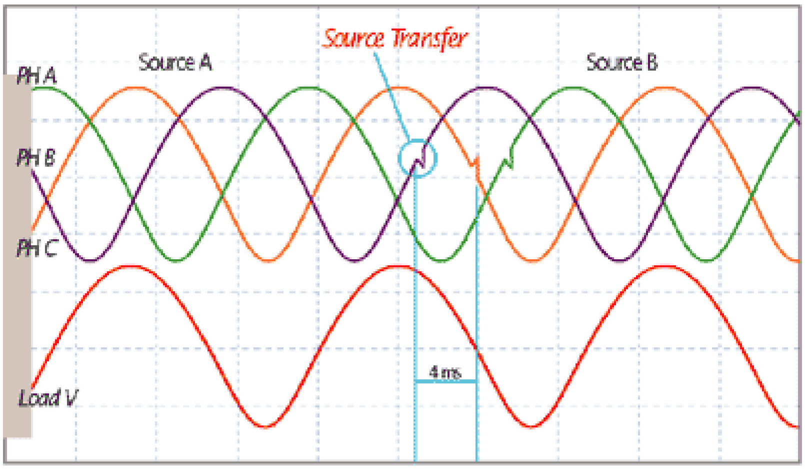


fig 2.8 Atypical wave form showing the status of waveform in a particular phase

Static switches are also used for operation in three-phase networks for currents of a dozen or so to a few hundred amperes. An important feature of static switches is a very high instantaneous overload capacity (e.g. 2000%/20ms).

The control system of static-switch should provide very quick switching of power networks there are switches with switching time below 6ms and return to basic power supply of 0.2ms.

Advantages

This ensures the uninterrupted operation of the loads even those, which are very sensitive to short supply voltage decays. Where the standard contactors are used, disruptions in power supply can last for as long as tens or even hundreds of milliseconds.

Static switches is that they do not generate switching overvoltages like standard contactors. So their application in environments sensitive to overvoltages, like these with inductive loads is recommended.

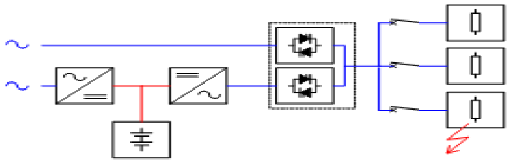


Fig 2.9. Configuration of a static transfer switch with load.

Low Voltage Static Transfer Switches (voltages upto 600v, current ratings from 200 to 4000 amps)

Applications:

- Critical IT operations
- Telecommunication
- Network operations centers
- Fiber optic nerve centre
- Process control
- Data centers
- Airport security system
- Commercial buildings
- Power generation plants
- Utilites

Medium Voltage Static Transfer Switches (voltages from 4.16kv to 34.5kv)

Applications

- Automated manufacturing
- Automotive assembly lines
- Telecommunication centers
- Computer networks
- E-commerce business
- R&D labs
- Commercial buildings
- Power quality and industrial parks
- commercial printing machines
- internet data centers
- semiconductor industry

Fast Transfer Switches

An electrically powered, **fast acting transfer switch** utilizes two electric power switches mounted in spaced relation with the handles confronting and moveable in a common plane, but in opposite directions, so that when simultaneously operated by an electrically powered operator positioned between the two switches, one switch is ON and the other is OFF. A mechanical assembly converts the motion of a single acting solenoid into reciprocal operation of the switch handles.

The mechanical assembly includes an electromagnet drive plate to which the electromagnet of the solenoid is secured and an armature drive plate carrying the solenoid armature. A latch mechanism alternately holds one drive plate and then the other stationary so that the electromagnet and armature alternately move to effect reciprocal movement of the handle of the one electric power switch, and through the rigid strap, the handle of the second electric power switch.

9. With neat diagram explain the various UPS systems.

An Uninterruptible Power Supply (UPS), also known as an Uninterruptible Power Source, Uninterruptible Power System, Continuous Power Supply (CPS) or a battery backup is a device which maintains a continuous supply of electric power to connected equipment by supplying power from a separate source when utility power is not available.

ON-LINE UPS

In an on-line UPS, the load is always fed through the UPS. The incoming ac power Is rectified into dc power ,which charges a bank of batteries. This DC power is then inverted back in to ac power, to feed the load .If the incoming ac power fails, the inverter is fed from batteries and continues to supply the load.

The on-line type of UPS, in addition to providing protection against complete failure of the utility supply, provides protection against all common power problems, and for this reason it is also known as a power conditioner and a line conditioner.

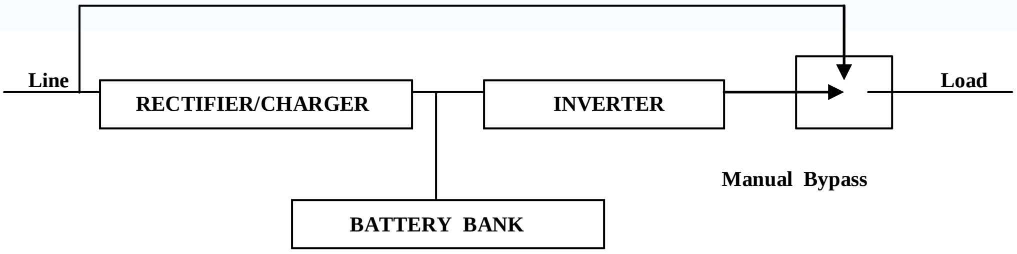


Fig 2.10 On-line UPS

Standby (Or) An Off-Line UPS

In an off-line UPS the normal line power is used to power the equipments Until a disturbance is detected and a switch transfers the load to the battery backed inverter. In this type of UPS, the primary power source is line power from the utility, and the secondary power source is the battery. It is called a standby UPS because the battery and inverter are normally not supplying power to the equipment. The battery charger is using line power to charge the battery, and the battery and inverter are waiting "on standby" until they are needed. When the AC power goes out, the transfer switch changes to the secondary power source. When line power is restored, the UPS switches back.

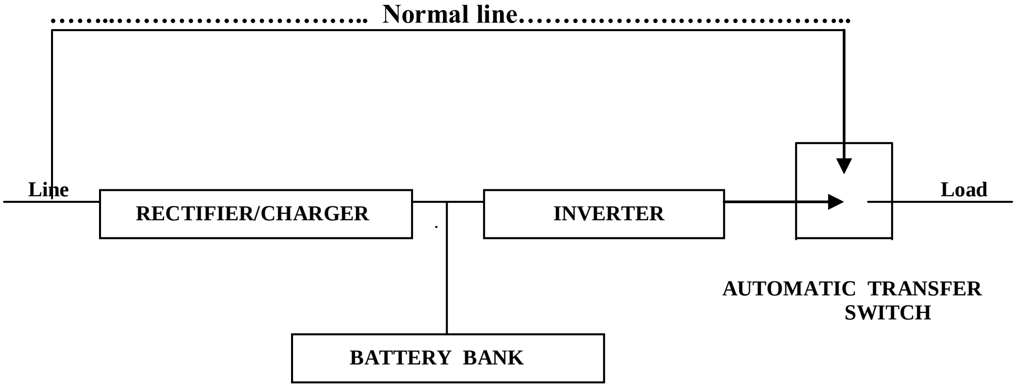


Fig 2.11 Standby UPS.

Hybrid UPS

A hybrid UPS is similar in design to the standby UPS but utilizes a voltage regulator on the UPS output to provide regulation to the load and momentary ride through when the transfer from normal to UPS supply is made.

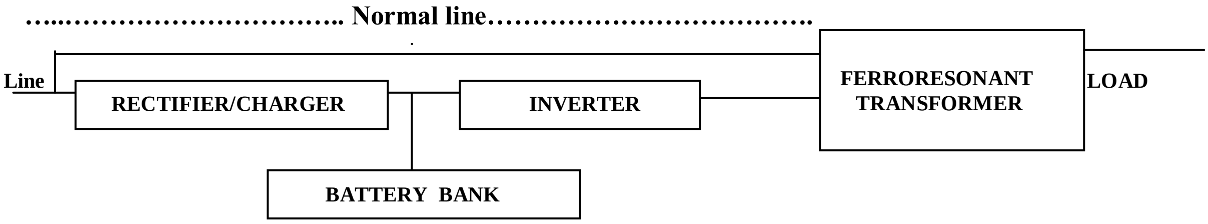


Fig 2.12 Hybrid UPS

10. Discuss about equipment sensitivity to voltage sags.

11.Explain the following sag mitigating devices with neat diagrams.

i) Magnetic synthesizers,
ii) Motor- Generator sets,
iii)Super conducting magnetic energy storage devices.

i. Magnetic Synthesizers

Magnetic synthesizers use a similar operating principle to CVTs except they are three phase devices and make use of the three phase magnetics to provide improved voltage sag support and regulation for three phase load. They don't protect a critical load against a complete power outage, but via a limited stored energy capability using capacitors, they can provide ride-through, typically to one cycle. Battery backup capabilities permit additional operating time.

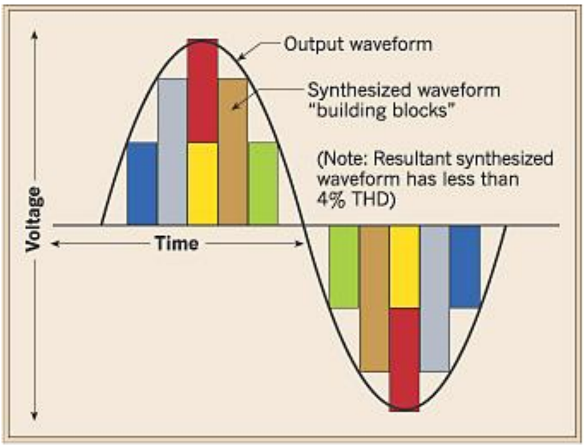


Fig 2.13 A synthesized wave form

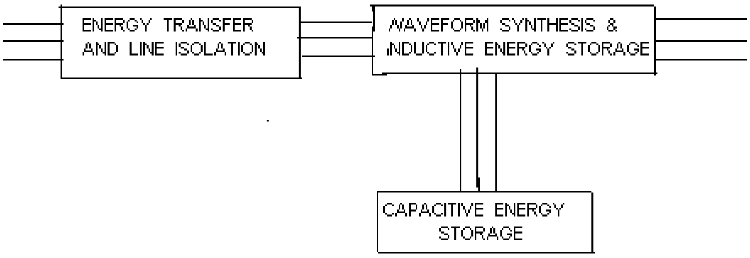


Fig 2.14 block diagram of a magnetic synthesizer

Magnetic synthesizers use building blocks to synthesize a sinusoidal waveform with very low THD. The magnetic synthesizer is another ferroresonant device that consists of inductors and capacitors configured in a parallel resonant circuit with a network of six saturating pulse transformers. Fig 2.13 shows the block diagram of a magnetic synthesizer .The output is synthesized by combining pulses of the saturating transformers into "building blocks" similar to the pseudo sine wave of many electronic inverters (Fig 2. 14). This device is typically used for applications of 50kVA and larger, where voltage regulation, sag mitigation, and/or isolation are needed.

Magnetic synthesizers are good for solving a wide variety of power quality problems, including voltage sags, sustained under voltages, notches, transients, and even waveform distortions. Over a size range of 15 to 200kVA and typically applicable for process loads of larger computer systems where voltage sags or steady- state Voltage variations are important issues.

These devices use ferromagnetic (pulsed transformers and inductors) and capacitors to synthesize a high-quality 3-phase output, using only the input as a source of energy. The output is fully isolated from imperfections in the input power. They can also maintain a reduced capacity of 3-phase power if one input phase is lost, but the angle between output phases won't be 120°.

The only moving parts and semiconductor devices are located in their controls. A typical installation would include a synthesizer combined with a static switch and a reliable, synchronized alternate power supply, such as a second utility line feed. The static transfer switch would transfer to the alternate source in about a quarter cycle, providing uninterrupted power to sensitive electronic equipment. This would eliminate the need for a UPS.

A magnetic synthesizer typically has the following operating characteristics:

- It can operate with an input voltage range as low as ±40% or more of the nominal voltage.
- Output power factor remains in the range of 0.96 or higher from half to full load.
- Because it regenerates an output voltage waveform, output distortion, which is typically less than 4%, is independent of any input voltage distortion, including notching (Figure above).
- Efficiency at full load is typically in the range of 89% to 93%.
- Minimum maintenance is required beyond annual replacement of failed capacitors. Redundant capacitors built into the units allow several capacitors to fail between inspections without any noticeable effect to the device's performance.
- Output voltage varies about 1.2% for every 1% change in supply frequency. For example, a 2-Hz change in generator frequency, which is very large, results in an output voltage change of only 4%, which has little effect for most loads.
- It accepts 100% single-phase switch-mode power supply loading without any requirement for derating, including all neutral components.
- Input current distortion remains less than 8% THD even when supplying nonlinear loads with more than 100% current THD.

ii) Motor- Generator sets. (Rotary Uninterruptible Power Source Unit)

Rotary UPS (RUPS) units utilize rotating members to provide uninterrupted power to loads. In this configuration, an AC induction motor drives an AC generator, which supplies power to critical loads. The motor operates from normal utility power. A diesel engine or other type of prime mover is coupled to the same shaft as the motor and the generator. During normal operation, the diesel engine is decoupled from the common shaft by an electric clutch. If the utility power fails, the prime mover shaft is coupled to the generator shaft and the generator gets its mechanical power from the prime mover. The motor shaft is attached to the flywheel, and the total inertia of the system is sufficient to maintain power to the loads until the prime mover comes up to full speed. Once the normal power returns, the induction motor becomes the primary source of mechanical power and the prime mover is decoupled from the shaft.

A flywheel and motor-generator (M/G) combination can protect critical processes against all voltage sags where the duration is shorter than the hold-up time of the flywheel. When a sag occurs, the motor-generator set feeds the load, the energy being supplied by the gradually slowing flywheel. Different connection topologies of the flywheel to the M/G-set exist, of which figure 2 shows the main components of a connection using power electronics.

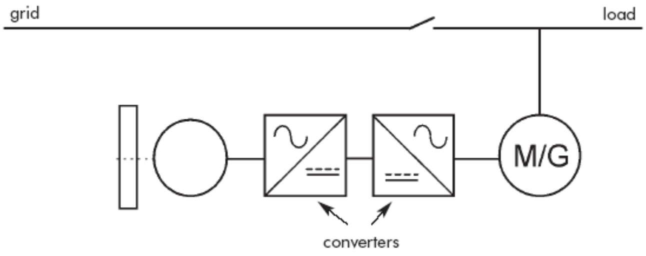


Figure 2- Block diagram of a ride-through using a flywheel.

The disadvantages of motor generator set

- There are losses associated with the machines.
- Noise and maintenance issues.

- The frequency and voltage drop during interruption as the machine slows. This may not work well with some loads.

11. With neat diagram explain the principle and working of ferroresonant transformer.

“Ferroresonance” is a phenomenon associated with the behavior of iron cores while operating near a point of magnetic saturation (where the core is so strongly magnetized that further increases in winding current results in little or no increase in magnetic flux). The ferroresonant transformer is a power transformer engineered to operate in a condition of persistent core saturation. That is, its iron core is “stuffed (made up of or packed) full” of magnetic lines of flux for a large portion of the AC cycle so that variations in supply voltage (primary winding current) have little effect on the core's magnetic flux density, which means the secondary winding outputs a nearly constant voltage despite significant variations in supply (primary winding) voltage. Normally, core saturation in a transformer results in distortion of the sine wave shape, and the ferroresonant transformer is no exception. To combat this side effect, ferroresonant transformers have an auxiliary secondary winding paralleled with one or more capacitors, forming a resonant circuit tuned to the power supply frequency. This “tank circuit” serves as a filter to reject harmonics created by the core saturation, and provides the added benefit of storing energy in the form of AC oscillations, which is available for sustaining output winding voltage for brief periods of input voltage loss (milliseconds' worth of time, but certainly better than nothing). (Figure below)

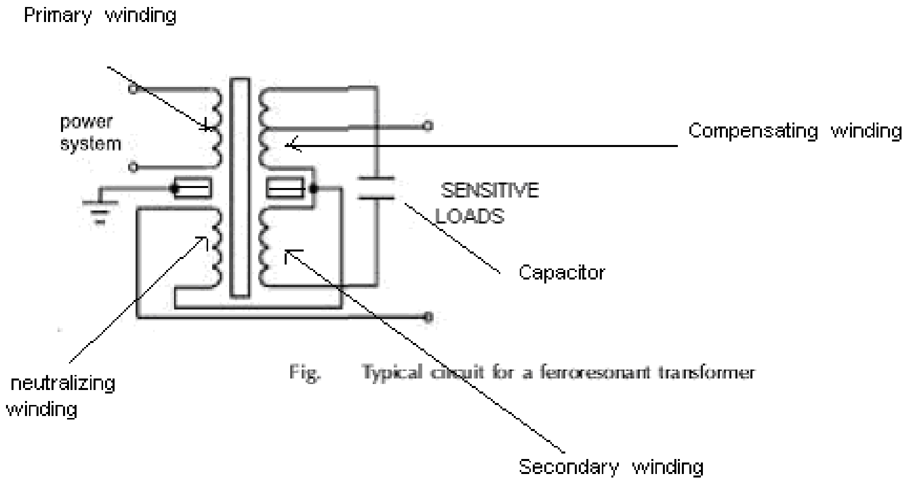
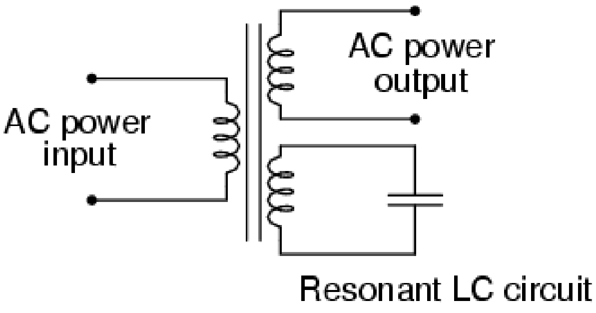


Fig. Typical circuit for a ferroresonant transformer



Ferroresonant transformer provides voltage regulation of the output. In addition to blocking harmonics created by the saturated core, this resonant circuit also “filters out” harmonic frequencies generated by nonlinear (switching) loads in the secondary winding circuit and any harmonics present in the source voltage, providing “clean” power to the load. Ferroresonant transformers offer several features useful in AC power conditioning:

constant output voltage given substantial variations in input voltage, harmonic filtering between the power source and the load, and the ability to “ride through” brief losses in power by keeping a reserve of energy in its resonant tank circuit. These transformers are also highly tolerant of excessive loading and transient (momentary) voltage surges. They are so tolerant, in fact, that some may be briefly paralleled with unsynchronized AC power sources, allowing a load to be switched from one source of power to another in a “make-before-break” fashion with no interruption of power on the secondary side.

Disadvantages: They waste a lot of energy (due to hysteresis losses in the saturated core), generating significant heat in the process, and are intolerant of frequency variations, which means they don't work very well when powered by small engine-driven generators having poor speed regulation. Voltages produced in the resonant winding/capacitor circuit tend to be very high, necessitating expensive capacitors and presenting the service technician with very dangerous working voltages..

12. How to increase voltage sag immunity?

Here are eleven quick, simple fixes that will increase voltage sag immunity. Of course, like every engineering change, there are tradeoffs that you will need to consider as you're selecting a solution.

a. Find and fix the problem. Yes, it's an obvious suggestion. But it's the best place to start. Figure out exactly what is causing the problem with a sag generator equipped with a good data acquisition system. Once you know what the problem is (if you even have a sag problem!), it will be much easier to fix. Tradeoff: Takes time and money; if you're a good at guessing, you might skip this step.

b. Add a power quality relay. These small, simple devices detect voltage sags, and give you a simple relay contact when a sag occurs. The best ones (such as PSL's PQ1 also detect other disturbances, such as high frequency impulses and voltage swells. Your system can then adjust its behavior whenever a voltage sag occurs - for example, by resetting some of its components. Tradeoff: Can require some simple reprogramming of your system.

c. Switch power supply settings. Many power supplies can be set to accommodate different voltage ranges, and these ranges often overlap. Choose a range where your nominal voltage is near the top of the range, and you'll have more room for voltage sags. For example, if your power supply has Range #1, 95V-250V (accommodating Japan and Europe), and Range #2, 110V-270V (accommodating North America and Australia), and you have a 240V nominal voltage, you will have greater sag immunity on Range #1. Tradeoff: Less margin at the top end against voltage swells.

d. Connect your single-phase power supply phase-to-phase. If you can stay within your power supply's acceptable voltage range, and if you have three-phase power available, you can get a quick 70% boost in available voltage by connecting phase-to-phase. For example, if your power supply is rated as 90V-250V, and you are using it on a 120V circuit, you can only tolerate a sag to 75%. But if you connect it phase-to-phase, the nominal voltage will be 208V and you will be able to tolerate a sag to 45%. Tradeoffs: Less margin for voltage swells; sometimes inconvenient; sensitive to sags on two phases, instead of just one.

e. Reduce the load on your power supply. Lightly loaded power supplies always tolerate voltage sags better than heavily loaded power supplies. If you can determine that a particular power supply is causing your equipment to miss-operate during a voltage sag, consider moving some of its loads to another power supply. Tradeoffs: May be inconvenient to install; carefully consider effects of a shut-down on one of the power supplies.

f. Increase the rating of your power supply. If you can't move the loads, use a bigger supply for the same load -- relative to its rating, it will be more lightly loaded. Tradeoffs: cost and size tend to go up; there may not be room for a larger power supply.

g. Use a three-phase power supply instead of a single-phase supply. A properly-designed (and lightly loaded) three-phase power supply will effectively tolerate voltage sags on one or two phases that would shut down a single-phase power supply. Trade-off: Cost and size are larger; requires three-phase circuit breakers, shut-down circuits.

h. Run your power supply from a DC bus. Sometimes you can substitute a DC-operated power supply for an AC-sourced supply. If it does nothing else, this will narrow down your problems to supporting a DC bus, which can often be done with simple capacitors or batteries. (This is the approach that high-reliability telecommunications systems take, using a 48 Vdc supply as their power distribution system.) Trade-offs: protective devices (fuses, circuit breakers, etc.) need to be changed or rated for DC; may not be convenient.

i. Change the trip settings. If you can identify an unbalance relay, an under voltage relay, or an internal reset or protection circuit that is inadvertently tripping during a voltage sag, change its settings. Consider changing the threshold, and consider changing the trip delay; either or both might make sense. Sometimes this can be as simple as twisting a knob; sometimes it may take a component change or firmware adjustment. You can only use this solution when the trip settings were set too conservatively to begin with; trips are useful and important, so you don't want to eliminate them completely. Trade-offs: someone chose those set-points for a reason, so you don't want to change them arbitrarily; changing components and/or firmware can create service and repair problems later on.

j. Slow the relay down. If the equipment is mis operating because a relay in the EMO circuit is operating too quickly, consider slowing it down. You might use a relay with more mechanical mass (such as a contactor), or you might use a relay hold-in accessory. Trade-offs: possibly more complexity on the EMO circuit; you don't want to slow the EMO circuit down so much that it becomes unsafe.

k. Get rid of the voltage sag itself. As a last resort, consider installing a quick-operating voltage regulator on your AC supply. There are a variety of technologies: ferroresonant transformers, solid-state voltage compensation, etc. But make sure that you aren't making the problem worse; if the original cause of the voltage sag is downstream from your voltage sag regulator, the voltage sags will actually get deeper and longer when you install the fix. Tradeoffs: size and cost.

UNIT-3

Over voltages

3.1 Sources of over voltages

There are two main sources of transient overvoltages on utility systems:

1. Capacitor switching
2. Lightning.

The transient overvoltages can be generated at

- high frequency (load switching and lightning)
- medium frequency (capacitor energizing)
- low frequency.

3.1.1 Capacitor switching

Capacitor switching is one of the most common switching events on utility systems. Capacitors are used to provide reactive power (in units of vars) to correct the power factor, which reduces losses and supports the voltage on the system.

(a) Advantages of capacitor switching

1. They are a very economical and generally trouble-free means of accomplishing the above mentioned tasks.
2. The alternative methods such as the use of rotating machines and electronic var compensators are much more costly or have high maintenance costs. Thus, the use of capacitors on power systems is comparatively cheaper and common.

(b) Drawbacks of capacitor switching

1. The use of capacitors yields oscillatory transients when switched.

(c) Capacitor Switching – control techniques / control variables

1. Some capacitors are energized all the time (a fixed bank), while others are switched according to load levels.
2. Various control means, including time, temperature, voltage, current, and reactive power, are used to determine when the capacitors are switched.
3. It is common for controls to combine two or more of these functions, such as temperature with voltage override

(d) Power Quality Problems

The common symptoms of Power Quality problems related to utility capacitor switching overvoltages are that the problems appear at nearly the same time each day. On distribution feeders with industrial loads, capacitors are frequently switched by time clock in anticipation of an increase in load with the beginning of the working day. Common problems are ASDs trips and malfunctions of other electronically controlled load equipment that occur without a noticeable blinking of the lights or impact on other, more conventional loads.

(e) How transients are generated during Capacitor switching?

Figure 3.1 shows the one-line diagram of a typical utility feeder capacitor-switching situation. When the switch is closed, a transient similar to the one in Figure. 3.2 may be observed up line from the capacitor at the monitor location.

1. The capacitor switch contacts are closed at a point near the system voltage peak. This is common to all switching techniques because the insulation across the switch contacts tends to break down when the voltage across the switch is at a maximum value.
2. The voltage across the capacitor at this instant is zero.
3. The capacitor voltage cannot change instantaneously and hence the system voltage at the capacitor location is briefly pulled down to zero and rises as the capacitor begins to charge toward the system voltage.
4. Because the power system source is inductive, the capacitor voltage overshoots and rings at the natural frequency of the system.
5. At the monitoring location shown, the initial change in voltage will not go completely to zero because of the impedance between the observation point and the switched capacitor. However, the initial drop and subsequent ringing transient that is indicative of a capacitor-switching event will be observable to some degree.

(f) Magnitudes of the transients generated

1. The overshoot will generate a transient between 1.0 and 2.0 pu depending on system damping. In this case the transient observed at the monitoring location is about 1.34 pu.
2. Utility capacitor-switching transients are commonly in the 1.3- to 1.4-pu range but have also been observed near the theoretical maximum.

(g) Disturbances due to the transients generated

1. The transient shown in the oscillogram propagates into the local power system and will generally pass through distribution transformers into customer load facilities by nearly the amount related to the turns ratio of the transformer.
2. If there are capacitors on the secondary system, the voltage may actually be magnified on the load side of the transformer if the natural frequencies of the systems are properly aligned.
3. While such brief transients up to 2.0 pu are not generally damaging to the system insulation, they can often cause misoperation of electronic power conversion devices.
4. Controllers may interpret the high voltage as a sign that there is an impending dangerous situation and subsequently disconnect the load to be safe.
5. The transient may also interfere with the gating of thyristors.
6. Switching of grounded-wye transformer banks may also result in unusual transient voltages in the local grounding system due to the current surge that accompanies the energization.
7. Figure 3.3 shows the phase current observed for the capacitor-switching incident described in the preceding text. The transient current flowing in the feeder peaks at nearly 4 times the load current.

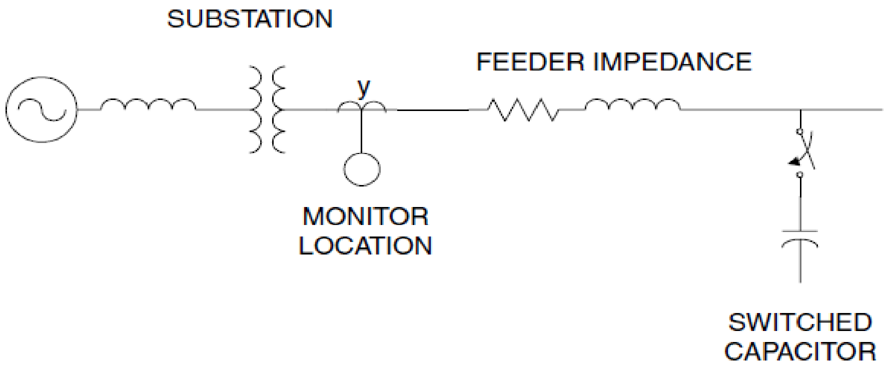


Figure 3.1 One-line diagram of a capacitor-switching operation corresponding to the waveform in Figure. 3.2.

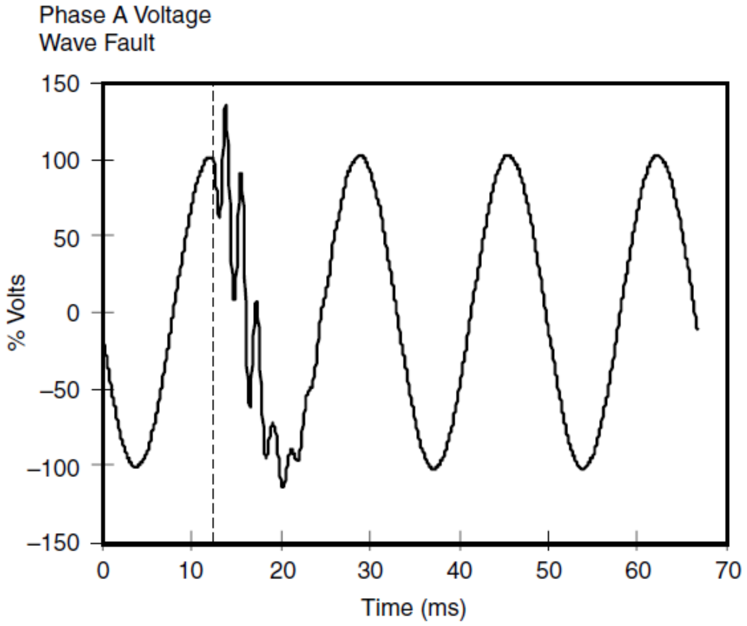


Figure 3.2 Typical utility capacitor-switching transient reaching 134 percent voltage, observed upline from the capacitor.

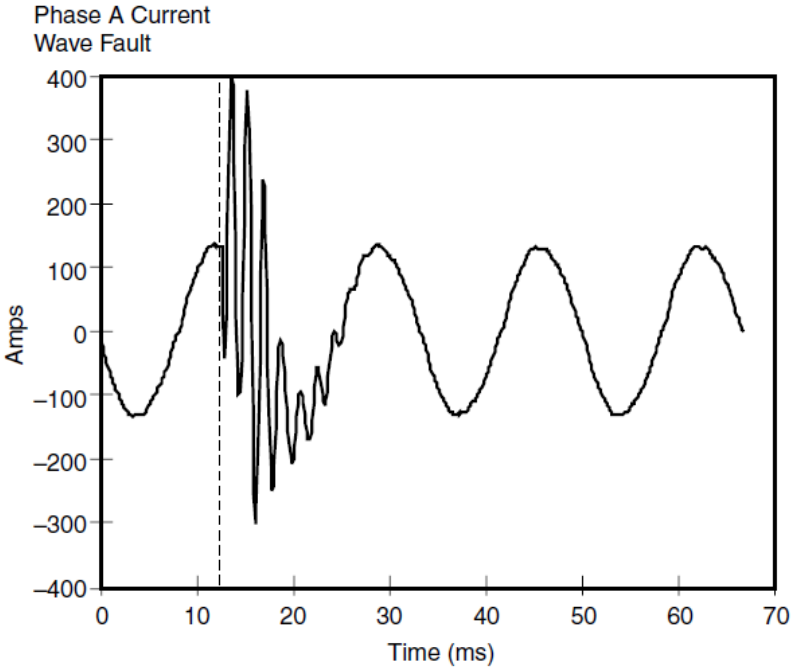
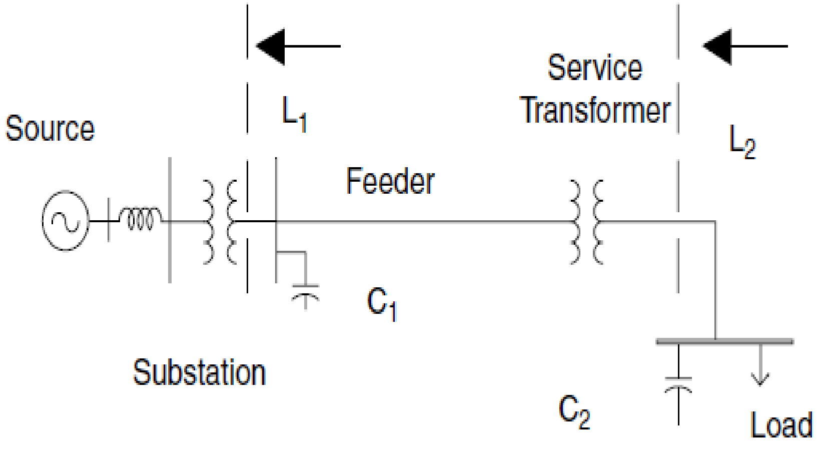


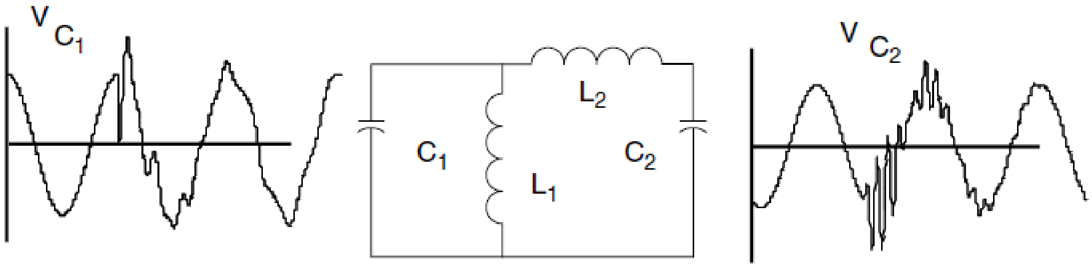
Figure 3.3 Feeder current associated with capacitor-switching event.

3.1.2 Magnification of capacitor-switching transients

A potential side effect of adding power factor correction capacitors at the customer location is that they may increase the impact of utility capacitor-switching transients on end-use equipment. there is always a brief voltage transient of at least 1.3 to 1.4 pu when capacitor banks are switched. The transient is generally no higher than 2.0 pu on the primary distribution system, although ungrounded capacitor banks may yield somewhat higher values. Load side capacitors can magnify this transient overvoltage at the end-user bus for certain low-voltage capacitor and step-down transformer sizes. The circuit of concern for this phenomenon is illustrated in Figure 3.4. Transient overvoltages on the end-user side may reach as high as 3.0 to 4.0 pu on the low-voltage bus under these conditions, with potentially damaging consequences for all types of customer equipment.



(a) Voltage magnification at customer capacitor due to energizing capacitor on utility system



(b) Equivalent Circuit

Switching frequency $f_1 = \dfrac{1}{2\pi\sqrt{L_1C_1}}$

Natural frequency of customer resonant $f_2 = \dfrac{1}{2\pi\sqrt{L_2C_2}}$ circuit

Voltage Magnification ⇔ $f_1 \approx f_2$

Figure 3.4 Voltage magnification of capacitor bank switching.

Resizing the customer's power factor correction capacitors or step-down transformer is therefore usually not a practical solution. One solution is to control the transient overvoltage at the utility capacitor. Some of the control techniques are given below.

1. At the customer location, high-energy surge arresters can be applied to limit the transient voltage magnitude at the customer bus. Energy levels associated with the magnified transient will typically be about 1 kJ.
2. Another means of limiting the voltage magnification transient is to convert the end-user power factor correction banks to harmonic filters.
3. An inductance in series with the power factor correction bank will decrease the transient voltage at the customer bus to acceptable levels. This solution has multiple benefits including providing correction for the displacement power factor, controlling harmonic distortion levels within the facility, and limiting the concern for magnified capacitor switching transients.
4. In many cases, there are only a small number of load devices, such as adjustable-speed motor drives, that are adversely affected by the transient. It is frequently more economical to place line reactors in series with the drives to block the high-frequency magnification transient.
5. A 3 percent reactor is generally effective. While offering only a small impedance to power frequency current, it offers considerably larger impedance to the transient. Many types of drives have this protection inherently, either through an isolation transformer or a dc bus reactance.

3.1.3 Lightning

Lightning is a potent source of impulsive transients. Figure 3.5 illustrates some of the places where lightning can strike that result in lightning currents being conducted from the power system into loads.

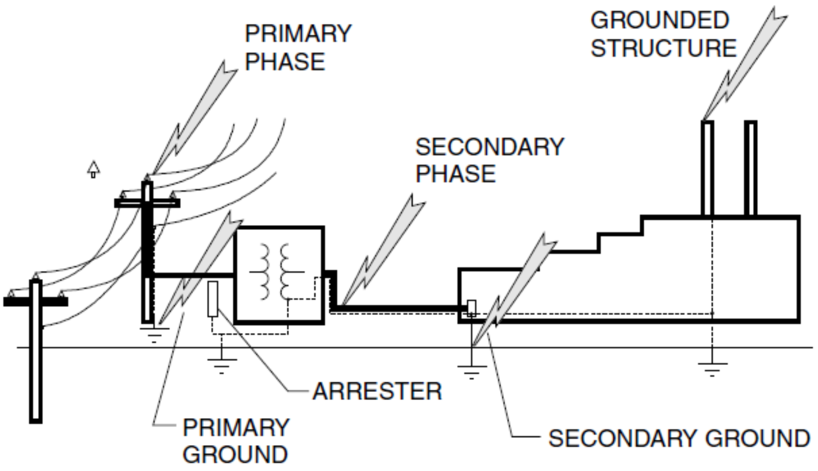


Figure 3.5 Lightning strike locations where lightning impulses will be conducted into load facilities.

The most obvious conduction path occurs during a direct strike to a phase wire, either on the primary or the secondary side of the transformer. This can generate very high overvoltages. Very similar transient overvoltages can be generated by lightning currents flowing along ground conductor paths. Note that there can be numerous paths for lightning currents to enter the grounding system. Common ones, indicated by the dotted lines in Fig. 3.5, include the primary ground, the secondary ground, and the structure of the load facilities.

A direct strike to a phase conductor generally causes line flashover near the strike point. Not only does this generate an impulsive transient, but it causes a fault with the accompanying voltage sags and interruptions. The lightning surge can be conducted a considerable distance along utility lines and cause multiple flashovers at pole and tower structures as it passes.

Lightning does not have to actually strike a conductor to inject impulses into the power system. Lightning may simply strike near the line and induce an impulse by the collapse of the electric field. Lightning may also simply strike the ground near a facility causing the local ground reference to rise considerably. This may force currents along grounded conductors into a remote ground, possibly passing near sensitive load apparatus.

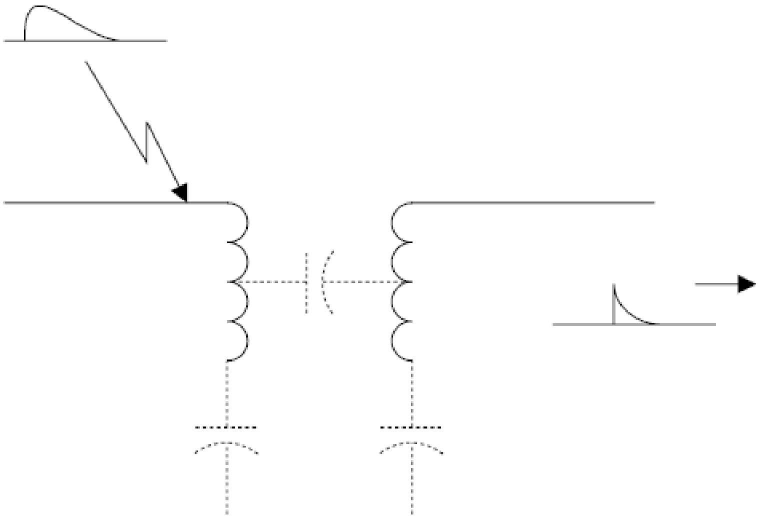


Figure 3.6 Coupling of impulses through the interwinding capacitance of transformers.

Many investigators in this field postulate that lightning surges enter loads from the utility system through the interwinding capacitance of the service transformer as shown in Fig. 3.6. The concept is that the lightning impulse is so fast that the inductance of the transformer windings blocks the first part of the wave from passing through by the turns ratio. However, the interwinding capacitance may offer a ready path for the high-frequency surge. This can permit the existence of a voltage on the secondary terminals that is much higher than what the turns ratio of the windings would suggest.

The degree to which capacitive coupling occurs is greatly dependent on the design of the transformer. Not all transformers have a straightforward high-to-low capacitance because of the way the windings are constructed. The winding-to-ground capacitance may be greater than the winding-to-winding capacitance, and more of the impulse may actually be coupled to ground than to the secondary winding. In any case, the resulting transient is a very short single impulse, or train of impulses, because the interwinding capacitance charges quickly. Arresters on the secondary winding should have no difficulty dissipating the energy in such a surge, but the rates of rise can be high. Thus, lead length becomes very important to the success of an arrester in keeping this impulse out of load equipment.

Many times, a longer impulse, which is sometimes oscillatory, is observed on the secondary when there is a strike to a utility's primary distribution system. This is likely due not to capacitive coupling through the service transformer but to conduction around the transformer through the grounding systems as shown in Fig. 3.7. This is a particular problem if the load system offers a better ground and much of the surge current flows through conductors in the load facility on its way to ground.

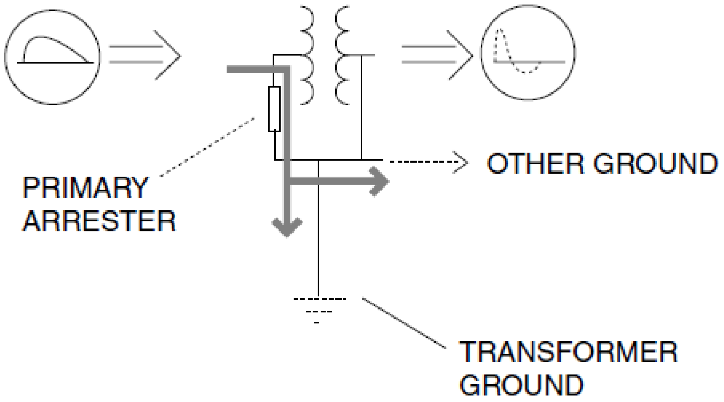


Figure 3.7 Lightning impulses bypassing the service transformer through ground connections.

The chief power quality problems with lightning stroke currents entering the ground system are,

1. They raise the potential of the local ground above other grounds in the vicinity by several kilovolts. Sensitive electronic equipment that is connected between two ground references, such as a computer connected to the telephone system through a modem, can fail when subjected to the lightning surge voltages.
2. They induce high voltages in phase conductors as they pass through cables on the way to a better ground.

3.1.4 Ferroresonance

Ferroresonance or nonlinear resonance is a complex electrical phenomenon. It can cause overvoltages and overcurrents in an electrical power system and can pose a risk to transmission and distribution equipment and to operational personnel. The term *ferroresonance* refers to a special kind of resonance that involves capacitance and iron-core inductance. It occurs when a circuit containing a nonlinear inductance is fed from a source that has series capacitance. The most common condition in which it causes disturbances is when the magnetizing impedance of a transformer is placed in series with a system capacitor. The circuit series capacitance can be due to a number of elements, such as the circuit-to-circuit capacitance of parallel lines, conductor to earth capacitance, circuit breaker grading capacitance, busbarcapacitance, or bushing capacitance, etc.

Ferroresonance should not be confused with linear resonance that occurs when inductive and capacitive reactances of a circuit are equal. In linear resonance the current and voltage are linearly related in a manner which is frequency dependent. In the case of ferroresonance it is characterized by a sudden jump of voltage or current from one stable operating state to another one. The relationship between voltage and current is dependent not only on frequency but also on a number of other factors such as the system voltage magnitude, initial magnetic flux condition of transformer iron core, the total loss in the ferroresonant circuit and the point on wave of initial switching. Under controlled conditions, ferroresonance can be exploited for useful purpose such as in a constant-voltage transformer.

The concept of ferroresonance can be explained in terms of linear-system resonance as follows. Consider a simple series *RLC* circuit as shown in Figure 3.8. Neglecting the resistance *R* for the moment, the current flowing in the circuit can be expressed as follows:

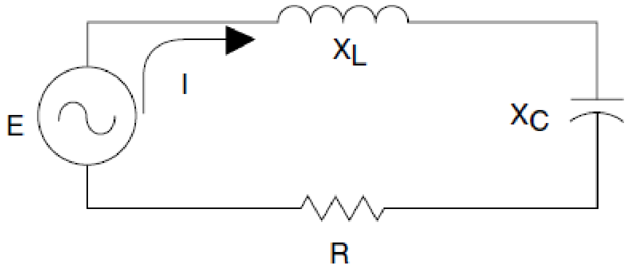


Figure 3.8 Simple series *RLC* circuit.

$$I = \frac{E}{j\,(X_L - |X_C|)}$$

where E = driving voltage
X_L = reactance of L
X_C = reactance of C

When $X_L = |X_C|$, a series-resonant circuit is formed, and the equation yields an infinitely large current that in reality would be limited by R. An alternate solution to the series RLC circuit can be obtained by writing two equations defining the voltage across the inductor, i.e.,

$$v = jX_L I$$

$$v = E + j|X_C|I$$

Where v is the voltage variable.

Figure 3.9 shows the graphical solution of these two equations for two different reactances, X_L and X_L'. X_L' represents the series-resonant condition. The intersection point between the capacitive and inductive lines gives the voltage across inductor E_L . The voltage across capacitor E_C is determined as shown in Figure 3.9. At resonance, the two lines will intersect at infinitely large voltage and current since the $|X_C|$ line is parallel to the X_L' line.

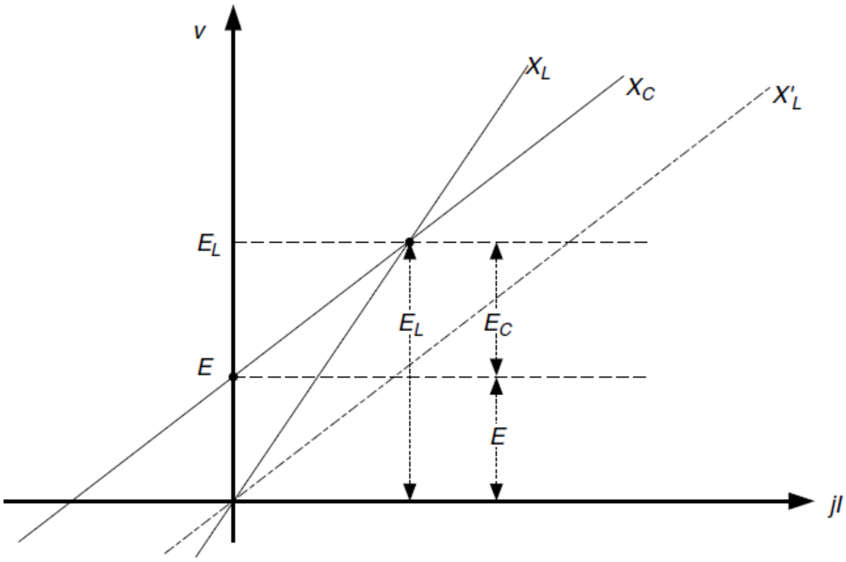


Figure 3.9 Graphical solution to the linear *LC* circuit.

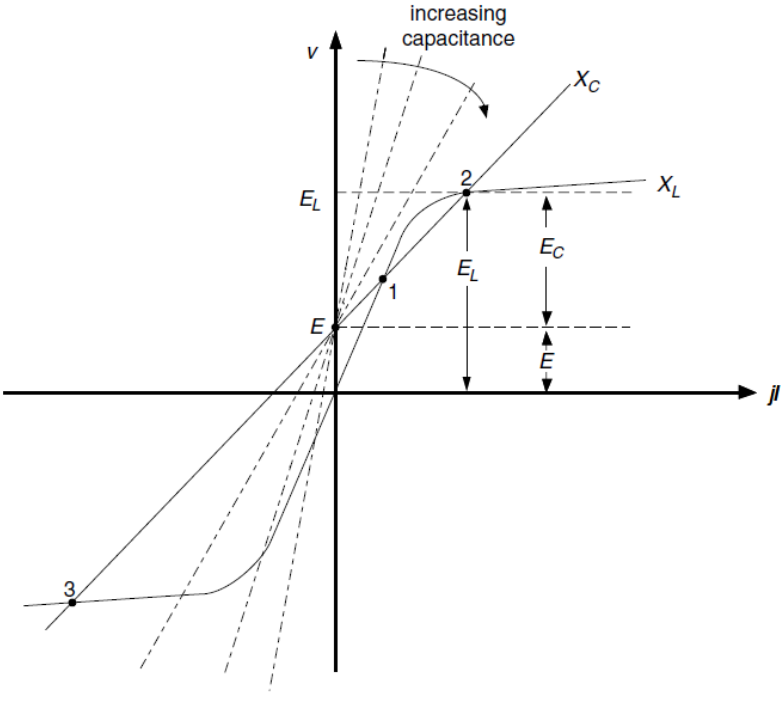


Figure 3.10 Graphical solution to the nonlinear *LC* circuit.

Now, let us assume that the inductive element in the circuit has a nonlinear reactance characteristic like that found in transformer magnetizing reactance. Figure 3.10 illustrates the graphical solution of the equations following the methodology for linear circuits.

While the analogy cannot be made perfectly, the diagram is useful to help understand ferroresonance phenomena. It is obvious that there may be as many as three intersections between the capacitive reactance line and the inductive reactance curve. Intersection 2 is an unstable solution, and this operating point gives rise to some of the chaotic behavior of ferroresonance. Intersections 1 and 3 are stable and will exist in the steady state. Intersection 3 results in high voltages and high currents.

Figures 3.11 and 3.12 show examples of ferroresonant voltages that can result from this simple series circuit. The same inductive characteristic was assumed for each case. The capacitance was varied to achieve a different operating point after an initial transient that pushes the system into resonance. The unstable case yields voltages in excess of 4.0 pu, while the stable case settles in at voltages slightly over 2.0 pu. Either condition can impose excessive duty on power system elements and load equipment. For a small capacitance, the $|X_C|$ line is very steep, resulting in an intersection point on the third quadrant only. This can yield a range of voltages from less than 1.0 pu to voltages like those shown in Figure 3.12.

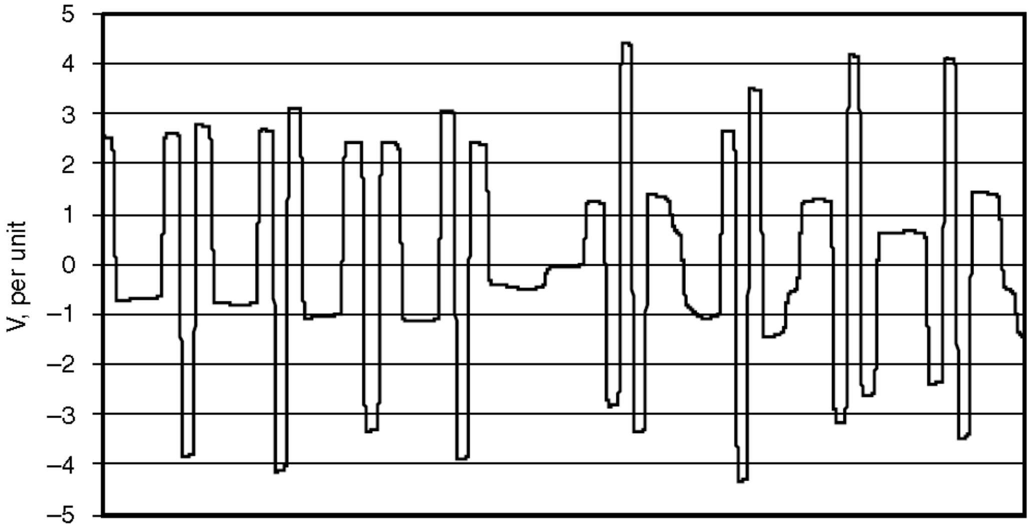


Figure 3.11 Example of unstable, chaotic ferroresonance voltages.

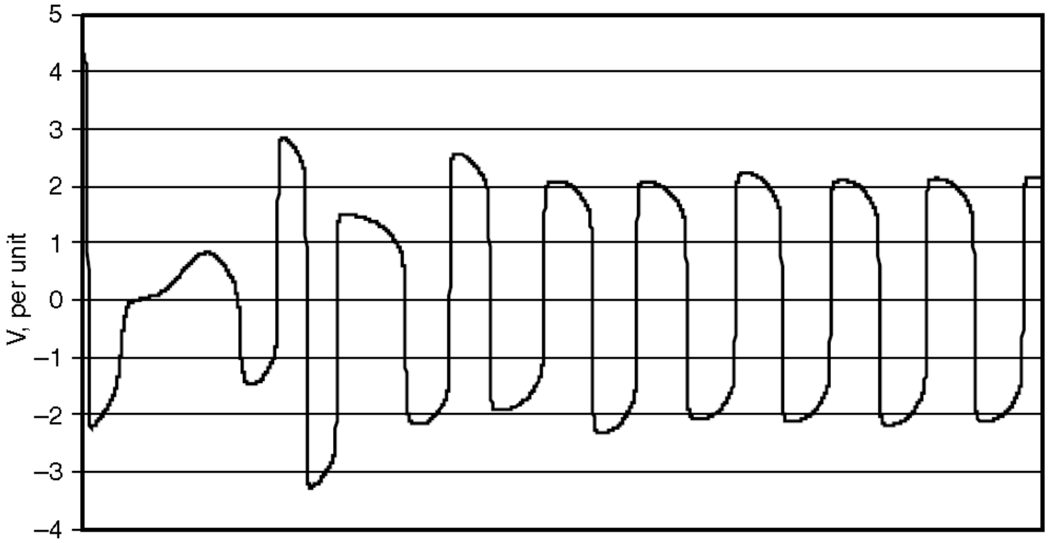


Figure 3.12 Example of ferroresonance voltages settling into a stable operating point (intersection 3) after an initial transient.

It is obvious that there may be as many as three intersections between the capacitive reactance line and the inductive reactance curve. Intersection 2 is an unstable solution, and this operating point gives rise to some of the chaotic behavior of ferroresonance. Intersections 1 and 3 are stable and will exist in the steady state. Intersection 3 results in high voltages and high currents.

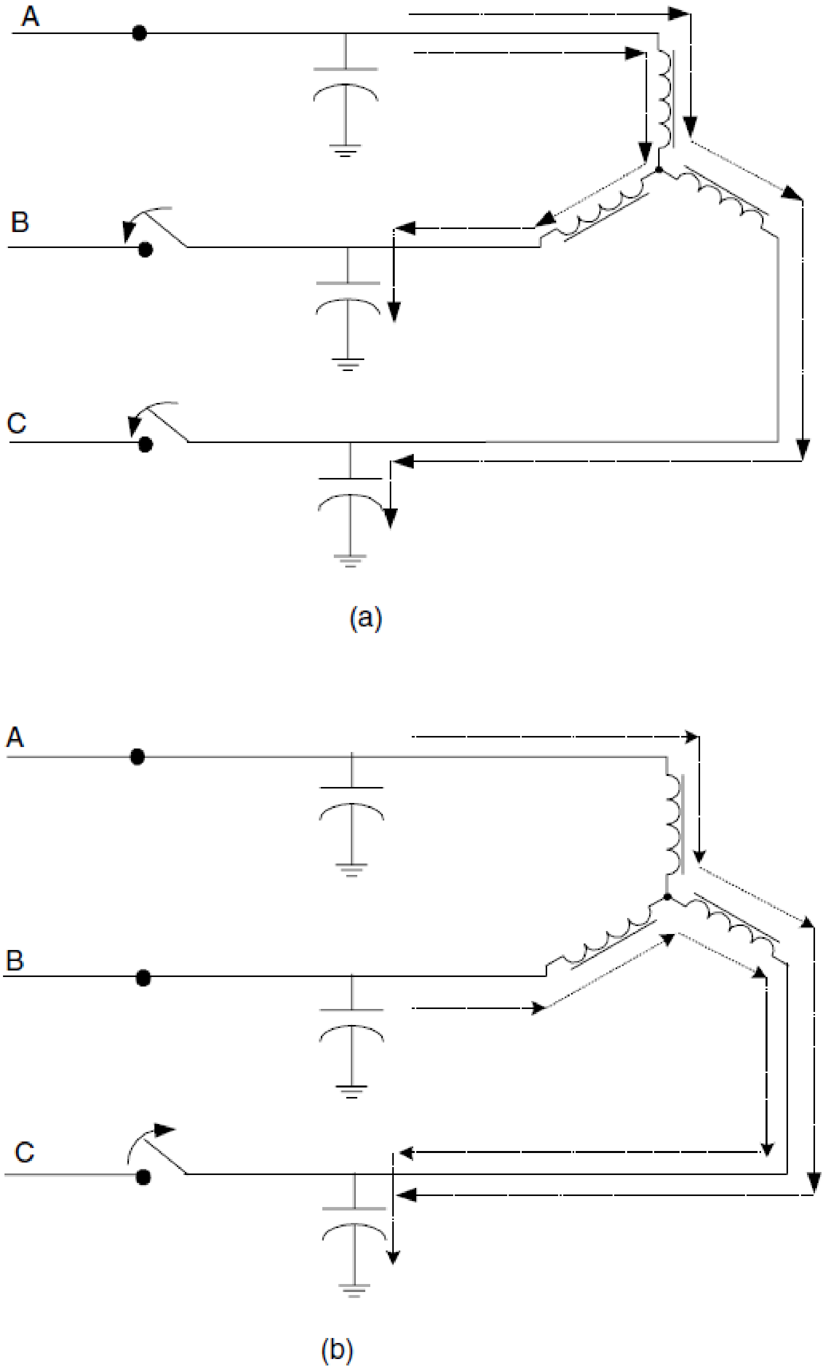


Figure 3.13 Common system conditions where ferroresonance may occur: (*a*) one phase closed, (*b*) one phase open.

The most common events leading to ferroresonance are

1. Manual switching of an unloaded, cable-fed, three-phase transformer where only one phase is closed (Figure 3.13a). Ferroresonance may be noted when the first phase is closed upon energization or before the last phase is opened on deenergization.
2. Manual switching of an unloaded, cable-fed, three-phase transformer where one of the phases is open (Figure 3.13b). Again, this may happen during energization or deenergization.
3. One or two riser-pole fuses may blow leaving a transformer with one or two phases open. Single-phase reclosers may also cause this condition.

It should be noted that these events do not always yield noticeable ferroresonance. System conditions that help increase the likelihood of ferroresonance include

- Higher distribution voltage levels, most notably 25- and 35-kV-class systems
- Switching of lightly loaded and unloaded transformers
- Ungrounded transformer primary connections
- Very lengthy underground cable circuits
- Cable damage and manual switching during construction of underground cable systems
- Weak systems, i.e., low short-circuit currents
- Low-loss transformers
- Three-phase systems with single-phase switching devices

While it is easier to cause ferroresonance at the higher voltage levels, its occurrence is possible at all distribution voltage levels. The proportion of losses, magnetizing reactance, and capacitance at lower levels may limit the effects of ferroresonance, but it can still occur. There are several modes of ferroresonance with varying physical and electrical manifestations. Some have very high voltages and currents, while others have voltages close to normal. There may or may not be failures or other evidence of ferroresonance in the electrical components. Therefore, it may be difficult to tell if ferroresonance has occurred in many cases, unless there are witnesses or power quality measurement instruments.

Common indicators of ferroresonance are as follows.

- Audible
- Overheating
- High overvoltages and surge arrester failure
- Flicker

Audible noise - During ferroresonance, there may be an audible noise, often likened to that of a large bucket of bolts being shook, whining, a buzzer, or an anvil chorus pounding on the transformer enclosure from within. The noise is caused by the magnetostriction of the steel core being driven into saturation. While difficult to describe in words, this noise is distinctively different and louder than the normal hum of a transformer. Most electrical system operating personnel are able to recognize it immediately upon first hearing it.

Overheating - Transformer overheating often, although not always, accompanies ferroresonance. This is especially true when the iron core is driven deep into saturation. Since the core is saturated repeatedly, the magnetic flux will find its way into parts of the transformer where the flux is not expected such as the tank wall and other metallic parts. The stray flux heating is often evidenced from the charring or bubbling of the paint on the top of the tank. This is not necessarily an indication that the unit is damaged, but damage can occur in this situation if ferroresonance has persisted sufficiently long to cause overheating of some of the larger internal connections. This may in turn damage solid insulation structures beyond repair. It should be noted that some transformers exhibiting signs of ferroresonance such as loud, chaotic noises do not show signs of appreciable heating. The design of the transformer and the ferroresonance mode determine how the transformer will respond.

High overvoltages and surge arrester failure. - When overvoltages accompany ferroresonance, there could be electrical damage to both the primary and secondary circuits. Surge arresters are common casualties of the event. They are designed to intercept brief overvoltages and clamp them to an acceptable level. While they may be able to withstand several overvoltage events, there is a definite limit to their energy absorption capabilities. Low-voltage arresters in end-user facilities are more susceptible than utility arresters, and their failure is sometimes the only indication that ferroresonance has occurred.

Flicker. During ferroresonance the voltage magnitude may fluctuate wildly. End users at the secondary circuit may actually see their light bulbs flicker. Some electronic appliances may be very susceptible to such voltage excursions. Prolonged exposure can shorten the expected life of the equipment or may cause immediate failure. In facilities that transfer over to the UPS system in the event of utility-side disturbances, repeated and persistent sounding of the alarms on the UPS may occur as the voltage fluctuates.

3.2 Mitigation of Voltage Swells

A voltage swell is an increase in the RMS voltage in the range of 1.1 to 1.8 p.u. for duration greater than half a main cycle and less than 1 minute. It is caused by system faults, load switching and capacitor switching. This is one of the most common power quality problems due to the increased use of a large numbers of sophisticated electronic equipment in industrial distribution system. High quality in the power supply is needed, since failures due to such disturbances usually have a high impact on production cost. There are many different solutions to compensate voltage disturbances. Some of the common techniques followed are

- DVR ,(Dynamic voltage restorer)
- Power Conditioners,
- Constant Voltage Transformers (CVT)

3.2.1 Dynamic Voltage Restorer

Dynamic Voltage Restorer (DVR), is one of the most efficient and effective modern custom power device used in power distribution networks. DVR is a recently proposed series connected solid state device that injects voltage into the system in order to regulate the load side voltage. It is normally installed in a distribution system between the supply and the critical load feeder at the point of common coupling (PCC). Other than voltage sags and swells compensation, DVR can also added other features like: line voltage harmonics compensation, reduction of transients in voltage and fault current limitations. The Figure 3.14 shows the location of a DVR in a distribution system.

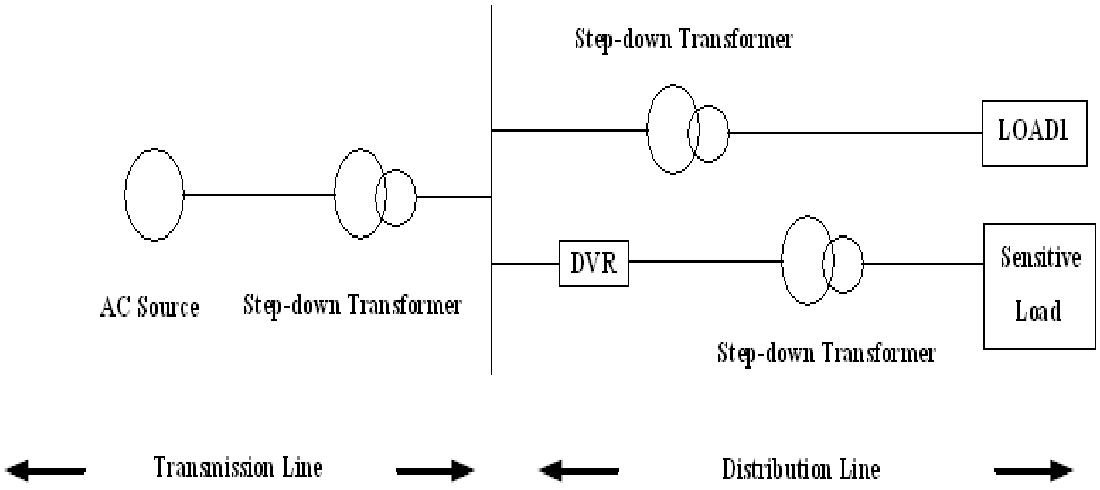


Figure 3.14 Location of DVR

(a) Basic Configuration of DVR:

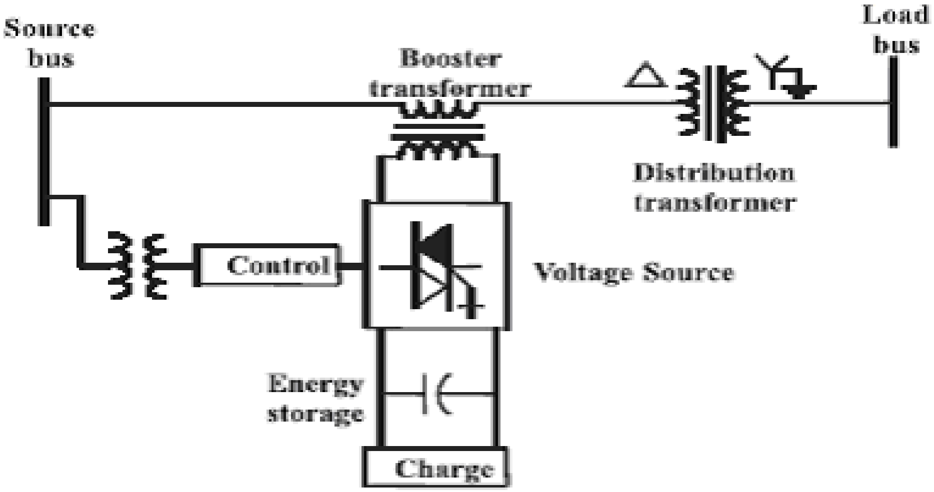


Figure 3.15 Basic configuration of DVR

The general configuration of the DVR (Figure 3.15) consists of:

i. An Injection/ Booster transformer
ii. A Harmonic filter
iii. Storage Devices
iv. A Voltage Source Converter (VSC)
v. DC charging circuit
vi. A Control and Protection system

Injection/ Booster transformer - The Injection / Booster transformer is a specially designed transformer that attempts to limit the coupling of noise and transient energy from the primary side to the secondary side. Its main tasks are:

- It connects the DVR to the distribution network via the HV-windings and transforms and couples the injected compensating voltages generated by the voltage source converters to the incoming supply voltage.
- In addition, the Injection / Booster transformer serves the purpose of isolating the load from the system (VSC and control mechanism).

Harmonic Filter - The main task of harmonic filter is to keep the harmonic voltage content generated by the VSC to the permissible level.

Voltage Source Converter - A VSC is a power electronic system consists of a storage device and switching devices, which can generate a sinusoidal voltage at any required frequency, magnitude, and phase angle. In the DVR application, the VSC is used to temporarily replace the supply voltage or to generate the part of the supply voltage which is missing. There are four main types of switching devices: Metal Oxide Semiconductor Field Effect Transistors (MOSFET), Gate Turn-Off thyristors (GTO), Insulated Gate Bipolar Transistors (IGBT), and Integrated Gate Commutated Thyristors (IGCT). Each type has its own benefits and drawbacks. The IGCT is a recent compact device with enhanced performance and reliability that allows building VSC with very large power ratings. Because of the highly sophisticated converter design with IGCTs, the DVR can compensate dips which are beyond the capability of the past DVRs using conventional devices. The purpose of storage devices is to supply the necessary energy to the VSC via a dc link for the generation of injected voltages. The different kinds of energy storage devices are Superconductive magnetic energy storage (SMES), batteries and capacitance.

DC Charging Circuit - The dc charging circuit has two main tasks.

- The first task is to charge the energy source after a sag compensation event.
- The second task is to maintain dc link voltage at the nominal dc link voltage.

Control and protection - The control mechanism of the general configuration typically consists of hardware with programmable logic. All protective functions of the DVR should be implemented in the software. Differential current protection of the transformer, or short circuit current on the customer load side are only two examples of many protection functions possibility.

Thus the installation of a DVR enables the voltage, as seen by the load, to be of the desired magnitude whenever disturbances occur upstream.

3.2.2 Power Conditioners

A power conditioner (also known as a line conditioner or power line conditioner) is a device intended to improve the quality of the power that is delivered to electrical load equipment. A power conditioner, acts in one or more ways to deliver a voltage of the proper level and characteristics to enable load equipment to function properly. An AC power conditioner is the typical power conditioner that provides clean AC power to sensitive electrical equipment. Power line conditioners take in power and modify it based on the requirements of the machinery to which they are connected. A good quality power conditioner is designed with internal filter banks to isolate the individual power outlets or receptacles on the power conditioner.

Power conditioners can vary greatly in specific functionality and size, with both parameters generally determined by the application. Some power conditioners provide only minimal voltage or more power quality problems. Units may be small enough to mount on a printed circuit board or large enough to protect an entire factory. Small power conditioners are rated in volt-amperes (V·A) while larger units are rated in kilovolt-amperes (kVA).

The issue of impedance vs. frequency becomes important when selecting a power conditioning interface that must function as both a low impedance “source” for AC power and as a high impedance “barrier” to unwanted power disturbances. Just as a stereo system will perform badly if amplifier and speaker impedance is mismatched, so a computer system will perform poorly if it’s attached to a power conditioner with the wrong impedance. Switch mode power supplies (SMPS) are used in most of today’s computer systems. This technology is more efficient and less costly than the older linear style power supplies that were in wide use in earlier generations of technology. Switch mode supplies utilize current from the AC power line in a completely different manner than their predecessors. Without a power conditioner supply utilizes current from the power line in a discontinuous manner.

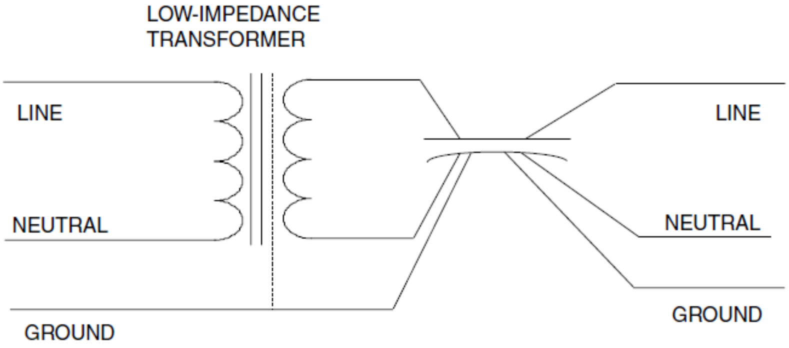


Figure 3.16 Low impedance power conditioner

Systems with switch mode power supplies, however, want a power conditioner that places no limitations on their peak current demands. By definition, they require a low impedance source. It’s here where the difference in transformer technology becomes apparent. Several types of high impedance transformers are found in the marketplace today. Perhaps the most popular is the ferroresonant transformer. The high impedance nature of a ferroresonant transformer is an inherent part of its voltage regulating capability and cannot be avoided or dismissed. Any high impedance source alters the operation of the switch mode power supply, and it begins to function in a different manner. Almost all the negative aspects of high impedance sources can be mitigated by employing two tactics. First, the use of multiple devices will prevent the noises. Second, many of the current limitation issues (poor crest factor, limited inrush, etc.) associated with high impedance devices can be mitigated by selecting a larger conditioner than is required for the operating amperage of the load. Both actions have negative economic consequences.

Switch mode power supplies in modern computer systems use current from the power line in large, brief “gulps”. They want little or no opposition to their demands for current. By definition, this makes switch mode power supplies a “low impedance load.” Like an audio system, low impedance computer loads need to be matched with a source that is low impedance at power line frequencies but offers high impedance to noise and unwanted power disturbances. These modern power supplies should never be mismatched with a high impedance power conditioner. The appropriate solution for today’s modern systems is a power conditioner that uses a low impedance isolation transformer. This will permit the switch mode supply to work as it was designed and will eliminate any negative interaction between the power conditioner and the computer. At the same time, the rules of electricity dictate that the same transformer will offer increasingly higher impedance as the frequency of the current increases into the range of damaging or disruptive power disturbances. Figure 3.16 shows Low-impedance power conditioner (LIPC).

Low-impedance power conditioners have much lower impedance and have a filter as part of their design. The filter is on the output side and protects against high-frequency, source-side, common-mode, and normal-mode disturbances (i.e., noise and impulses). Note the new neutral-to-ground connection that can be made on the load side because of the existence of an isolation transformer. However, low- to medium-frequency transients (capacitor switching) can cause problems for LIPCs: The transient can be magnified by the output filter capacitor. Finally, the application of low impedance power conditioners is more economical.

3.2.3 Constant Voltage Transformers (CVT)

Constant Voltage Transformers (CVTs) (same as Ferroresonant transformers) are basically 1:1 transformers that can handle most voltage swell (sag also) conditions. Unlike conventional transformers, the CVT or ferroresonant transformer allows the core to become saturated with magnetic flux, which maintains a relatively constant output voltage during input voltage variations such as undervoltages, overvoltages, and harmonic distortion. However, apart from maintaining the voltage, it also provides a high degree of filtration & isolation. It also rides over brown outs & blackouts of a few milliseconds. If properly sized, a CVT can regulate its output voltage during a voltage disturbances to sixty percent of nominal voltage for virtually any duration. However, they are not effective during momentary voltage interruptions or extremely deep voltage sags (generally below fifty percent of nominal). CVTs are often favored over other sag-mitigation devices because they are relatively maintenance-free, with no batteries to replace or moving parts to maintain .

The Constant Voltage Transformer (CVT) functions very much like an ordinary transformer except that a portion of the core is driven far into magnetic flux saturation. The basic structure is shown in Figure 3.17 where it is seen that there is a primary winding, a secondary winding (usually tapped and a choke winding, which forms part of the filter circuit). Another feature of the transformer is the magnetic shunts that provide primary and secondary leakage flux paths.

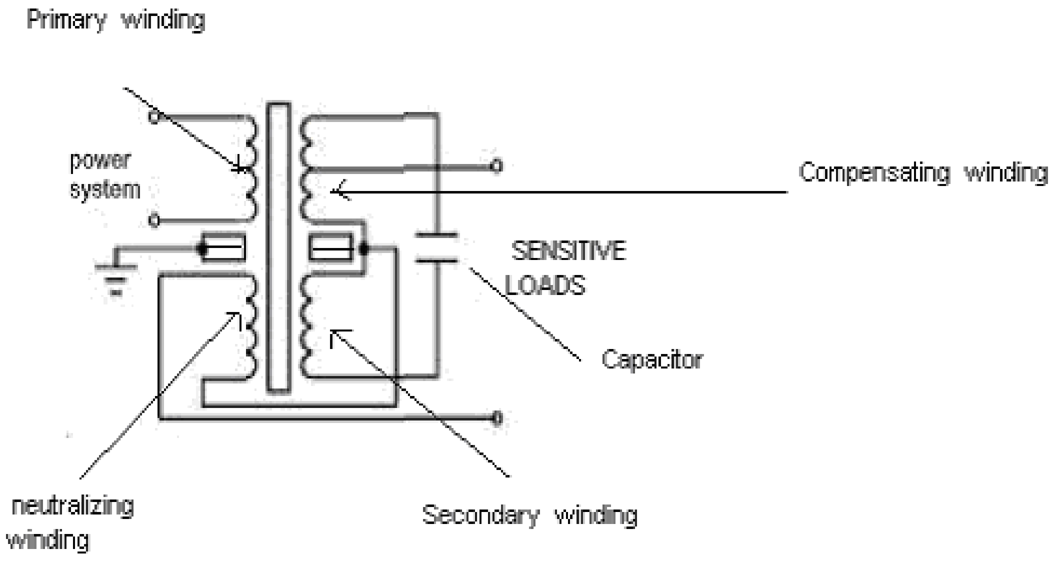


Figure 3.17 Basic structure of CVT

The primary winding is connected to the supply and when current flows in this winding the magnetic flux is established in the core. This flux is divided into two components, the main flux, which links with the secondary and the primary leakage flux, which passes through the shunts and only links the primary winding. The main flux is responsible for transferring electrical energy to the secondary and output windings.

In order to achieve voltage stability, the portion of the magnetic core carrying the main flux and the secondary leakage flux is heavily saturated. This means that the magnetising current in the primary (the current required to set up the main flux in the core) will be large, as it must develop sufficient magneto-motiveforce (mmf) to drive the flux through the saturated section of the core. This magnetising current is far larger than the rated full-load current of the transformer and therefore the device would be useless, as is. However by connecting the capacitor into the secondary circuit, as shown, an additional component of current is forced to flow in the primary winding that is in anti-phase to the large magnetising current, thereby cancelling it out. The net effect is to achieve a saturated core without having excessive current in the primary winding.

Voltage stability is achieved as follows: When the input voltage is reduced the main flux is also reduced, giving a reduction in the output voltage. Since the main flux is reduced, the magnetising current decreases as does the voltage drop across the primary winding leakage reactance (which results from the primary winding leakage flux passing through the shunts). This means that the resultant voltage induced into the secondary winding remains essentially constant. If the degree of core saturation, the amount of leakage flux and the capacitor are all chosen correctly, then a large swing in the input voltage can be compensated for, giving very little variation in the output voltage.

The saturation of the core leads to there being harmonic fluxes present. These cause distortion of the output voltage waveform. Therefore to restore the quality of the voltage waveform the filter circuit is incorporated. Filtering is achieved by connecting the choke winding in series with the capacitor circuit.

The primary and secondary windings are physically separated from one another. This means that the capacitive coupling between primary and secondary windings is kept to a minimum. This capacitive coupling is largely responsible for transferring fast rise-time surges from the input to the output of the CVT. Therefore a fair degree of surge protection is offered by the CVT and typically common mode and transverse mode surge attenuation of between 40 and 60 dB is achieved.

3.3 Surge Arrestors

The most common devices for preventing power quality problems from damaging equipment are surge suppressors. Surge suppressors protect sensitive equipment from being zapped by voltage surges or lightning strokes on the power system. They are the shock absorbers or safety valves of electrical power systems. If they are located on the utility side of the meter, they are called surge or lightning arresters. If they are located on the end-user side of the meter, they are called transient voltage surge suppressors (TVSSs). They divert to ground or limit the transient voltage caused by lightning or switching surges to a level that will not harm the equipment they are protecting. They are connected so that the transient “sees” the surge suppressor before it reaches the protected equipment.

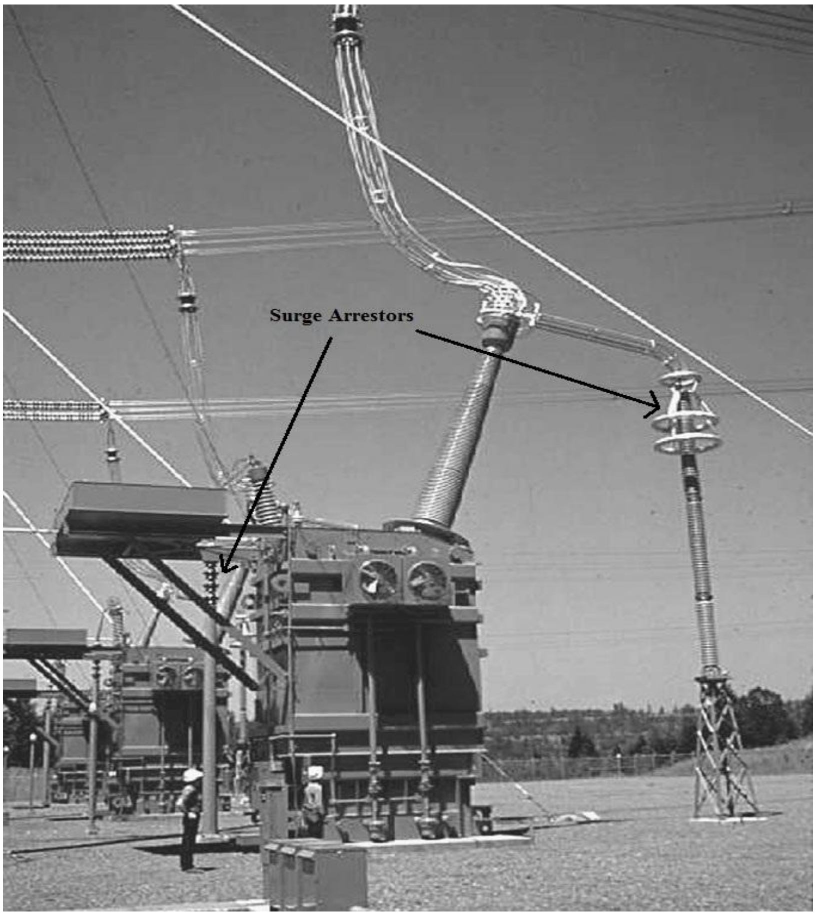
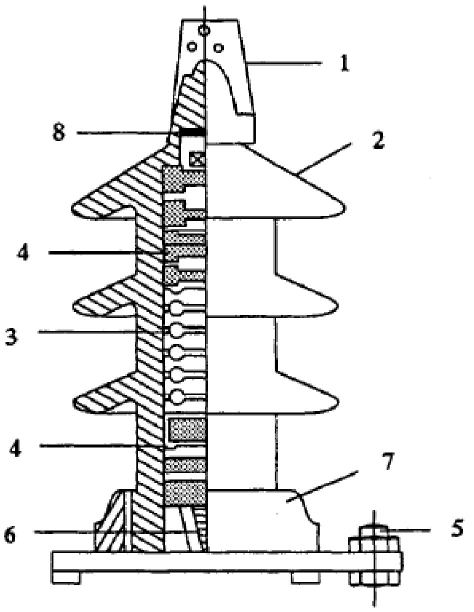


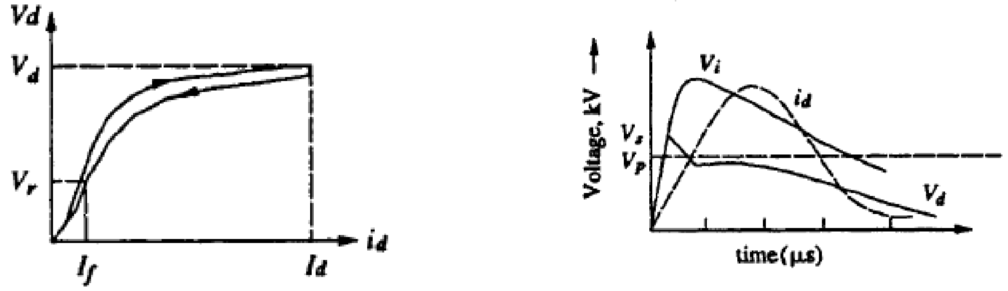
Figure 3.18 Transformer surge arresters. (*Courtesy of Bonneville Power Administration.*)

Utilities specify and locate arresters near equipment they wish to protect, like transformers, distribution lines, and substation equipment. They install arresters on the high-voltage side of distribution transformers. As shown in Figure 3.18, they use surge suppressors on the high-voltage and low-voltage side of substation transformers.



1. Line end connector
2. Porcelain housing
3. Series gaps
4. Non-linear resistance element blocks
5. Ground connection
6. Spring
7. Base
8. Water tight sealing

Figure 3.19 Non-linear element surge arrester



(a) Volt-ampere characteristic of a non-linear resistor block

(b) Surge arrester operation

I_f— Power frequency follow-on current at system voltage Vr
V_d— Max. voltage across the diverter during discharge of surge current with peak value I_d

Vs — Sparkover voltage
V_p — Protective level
V_i — Surge voltage
i_d — Discharge current
V_d —Voltage across the diverter when discharging the current i_d

Figure 3.20 Characteristics of a surge arrester

An ideal arrester should: (i) conduct electric current at a certain voltage above the rated voltage; (ii) hold the voltage with little change for the duration of overvoltage; and (iii) substantially cease conduction at very nearly the same voltage at which conduction started.

Surge arrestors are non-linear resistors in series with spark gaps which act as fast switches. A typical surge arrester is shown in Fig. 3.19 and its characteristics are given in Fig. 3.20.

A number of non-linear resistor elements made of silicon carbide are stacked one over the other into two or three sections. They are usually separated by spark gaps (see Fig. 3.13). the entire assembly is housed in a porcelain water-tight housing. The volt-ampere characteristic of a resistance element is of the form,

$$I = kV^a$$

where, I = discharge current,
V = applied voltage across the element, and
k and a are constants depending on the material and dimensions of the element. The value for a varies from 4 - 6 for a SiC arrester.

The dynamic characteristic is shown in Fig. 3.14(a).

When a surge voltage (V_i of Fig. 3.14b) is applied to the surge diverter, it breaks down giving the discharge current i_d and maintains a voltage V_d across it Thus, it provides a protection to the apparatus to be protected above the protective level Vp (seeFig.3.14b).

The lighter designs operate for smaller duration of currents, while the heavy *duty* surge arresters with assisted or active gaps are designed for high currents and long duration surges. The lighter design arresters can interrupt 100 to 300 A of power frequency follow-on current and about 5000 A of surge currents.

Even though a number of arresters installed which are gapped arresters made of Silicon Carbide (SiC) is still in use, the arresters installed today are all Metal-oxide (MO) arresters without gaps. The distinctive feature of a MO-arrester is its extremely nonlinear voltage-current characteristic, rendering unnecessary the disconnection of the arrester from the line through serial spark-gaps, as is found in the former gapped arresters with SiC-resistors.

3.3.1 MOA – metal oxide arresters

The development of MOA (metal oxide arresters) represented a breakthrough in overvoltage protection devices. It became possible to design arresters without using gaps which were indispensable in the conventional lightning arresters, which utilized non-linear resistors made of silicon Carbide (SiC) and spark gaps. Figure 3.21 shows a block diagram of the valve arrangements in the two types of arrester. In Fig.3.21(a) the elements and the spark gaps are connected in series. In Fig 3.21 (b) the elements are stacked on top of each other without the need for spark gaps.

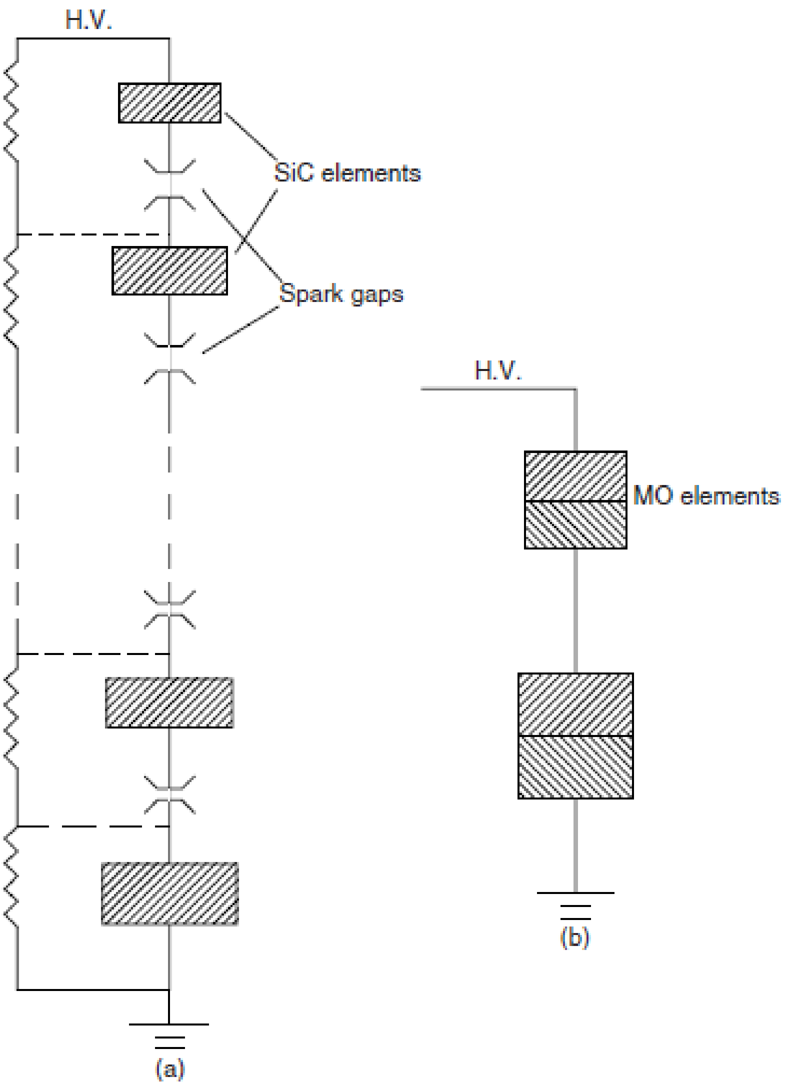


Figure 3.21 Block diagram of valve arrangements in (a) SiC, (b) MOA

The value for *a* in the V-I characteristics for a ZnO arrester varies from 25 - 30 for a SiC arrester. A comparison of the V-I characteristic of the ZnO and SiC arresters are shown in the Figure 3.22.

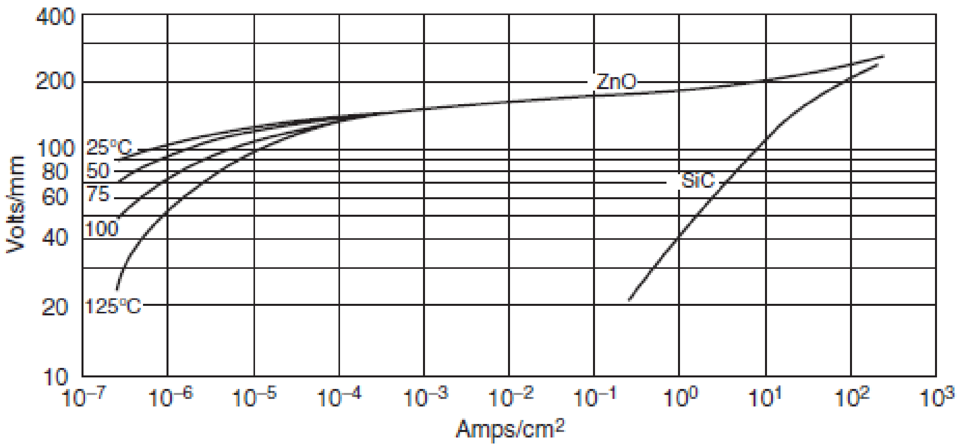
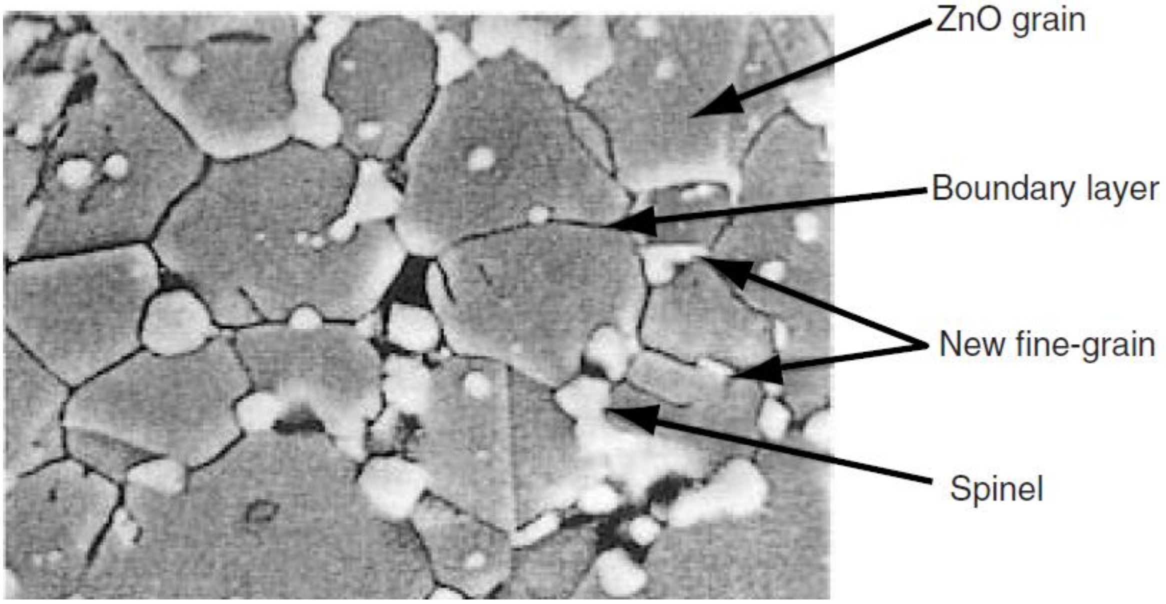
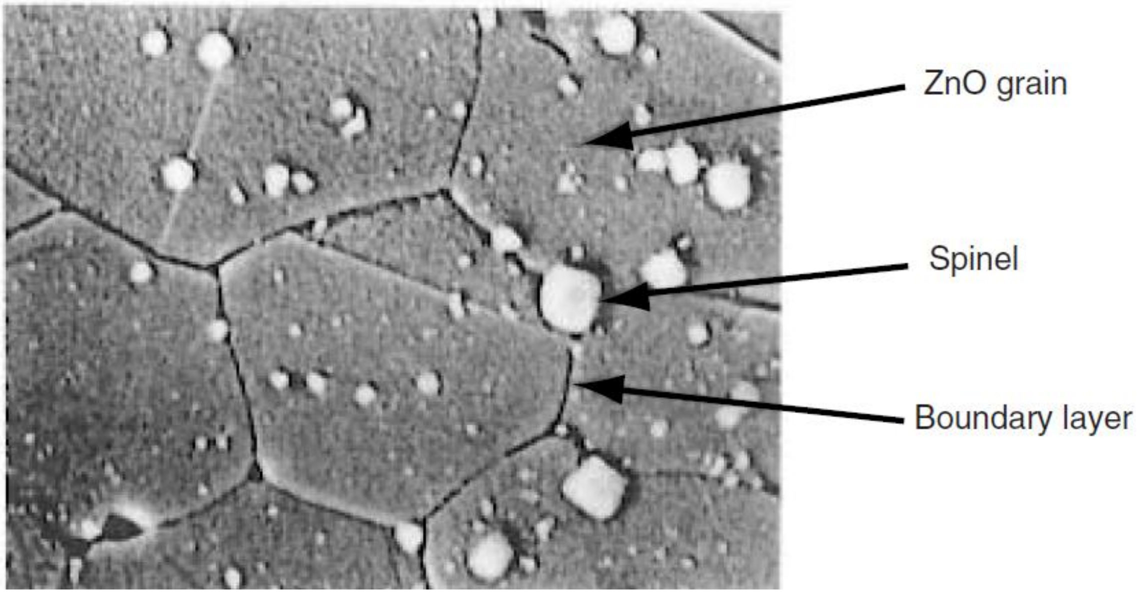


Figure 3.22 Normalized volt–ampere characteristic of zinc oxide and silicon carbide valve elements

The metal oxide varistors, consist of compacted and sintered granules of zinc oxide with a small amount of other carefully selected metal oxide additives (Bi2O3, MnO, Cr2O3, Sb2O3) to improve the V–I non-linearity,. The ZnO grains have a low resistivity, while the additives (oxides) which form the boundaries between the grains provide high resistance. The two are strongly bonded when sintered at high temperature. Figure 3.23 shows the microstructure of a metal oxide varistor.



(a) Microstructure of new element



(b) Microstructure of conventional element

Figure 3.23 Cross-section, showing the microstructure of ZnO elements.(a) Latest type (advanced). (b) Older conventional type

From Fig.3.22 it can be seen that for a change in current from 10^{-3} to 10^{2} A/cm2, the voltage increase for ZnO is only 56 percent_ With such a high degree of non-linearity it is entirely feasible to use these elements without series gaps in an arrester with a current of only tens of μA at operating voltage. The elements are manufactured in the form of discs of several sizes. The disc voltage rating has been increasing with the improvement in the manufacturing technology and the microstructure composition.

3.4 Low pass filter

The frequency components of a transient are several orders of magnitude above the power frequency of an AC circuit and, of course, a DC circuit. Therefore, an obvious solution is to install a low-pass filter between the source of transients and the sensitive load. The simplest form of filter is a capacitor placed across the line. The impedance of the capacitor forms a voltage divider with the source impedance, resulting in attenuation of the transient at high frequencies. This simple approach may have undesirable side effects, such as

a) unwanted resonances with inductive components located elsewhere in the circuit leading to high peak voltages
b) high inrush currents during switching
c) excessive reactive load on the power system voltage.

These undesirable effects can be reduced by adding a series resistor hence, the very popular use of RC snubbers and suppression networks. However, the price of the added resistance is less effective clamping. Beyond the simple RC network, conventional filters comprising inductances and capacitors are widely used for interference protection.

A low-pass filter is a filter that passes low-frequency signals but attenuates (reduces the amplitude of signals with frequencies higher than the cutoff frequency. Low pass filters are composed of series inductors and parallel capacitors this L-C combination provides a low impedance path to ground for selected resonant frequencies.

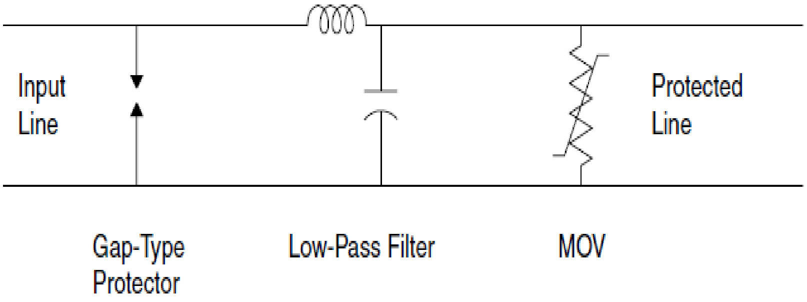


Figure 3.24 A hybrid transient protector with low pass filter.

The low pass filter limits transfer of high frequency transients. The inductor helps in blocking high - frequency transients and forces them in to the first supressor. The capacitor limits the rate of riseof the voltage magnitude . Figure 3.24 shows a hybrid transient protector where voltage clamping devices are added in parallel to the capacitors.

There is a fundamental limitation in the use of capacitors and filters for transient protection when the source of transients in unknown. The capacitor response is indeed nonlinear with frequency, but it is still a linear function of current. To design a protection scheme against random transients, it is often necessary to make an assumption about the characteristics of the impinging transient. If an error in the source impedance or in the open-circuit voltage is made in that assumption, the consequences may be severe.

3.5 Utility System Lightning Protection

Many power quality problems stem from lightning. Not only can the high-voltage impulses damage load equipment, but the temporary fault that follows a lightning strike to the line causes voltage sags and interruptions. Here are some strategies for utilities to use to decrease the impact of lightning.

3.5.1 Shielding

One of the strategies open to utilities for lines that are particularly susceptible to lightning strikes is to shield the line by installing a grounded neutral wire over the phase wires. This will intercept most lightning strokes before they strike the phase wires. This can help, but will not necessarily prevent line flashovers because of the possibility of back flashovers. Shielding overhead utility lines is common at transmission voltage levels and in substations, but is not common on distribution lines because of the added cost of taller poles and the lower benefit due to lower flashover levels of the lines. On distribution circuits, the grounded neutral wire is typically installed underneath the phase conductors to facilitate the connection of line-to-neutral connected equipment such as transformers and capacitors.

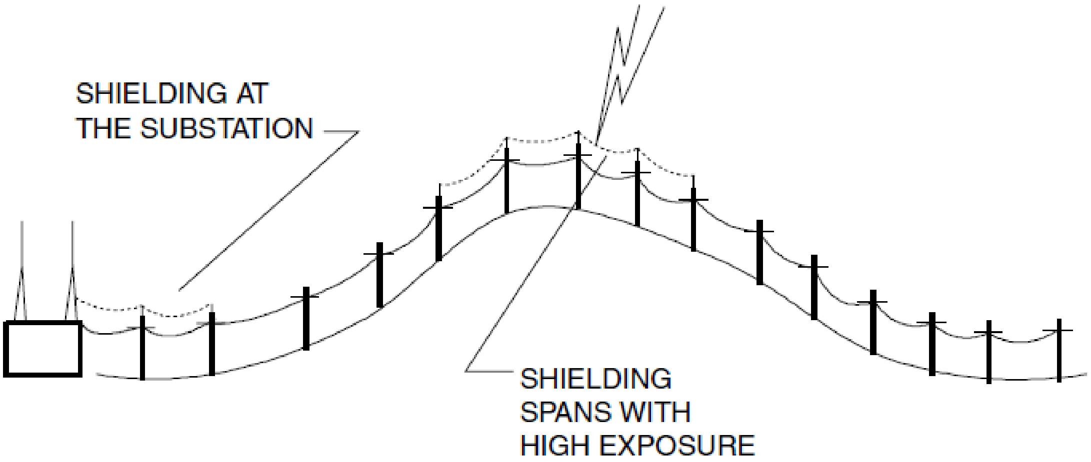


Figure 3.25 Shielding a portion of a distribution feeder to reduce the incidence of temporary lightning-induced faults.

Shielding is not quite as simple as adding a wire and grounding it every few poles. When lightning strikes the shield wire, the voltages at the top of the pole will still be extremely high and could cause back flashovers to the line. This will result in a temporary fault. To minimize this possibility, the path of the ground lead down the pole must be carefully chosen to maintain adequate clearance with the phase conductors. Also, the grounding resistance plays an important role in the magnitude of the voltage and must be maintained as low as possible.

However, when it becomes obvious that a particular section of feeder is being struck frequently, it may be justifiable to retrofit that section with a shield wire to reduce the number of transient faults and to maintain a higher level of power quality. Figure 3.25 illustrates this concept.

It is not uncommon for a few spans near the substation to be shielded. The substation is generally shielded anyway, and this helps prevent high-current faults close to the substation that can damage the substation transformer and breakers. It is also common near substations for distribution lines to be underbuilt on transmission or subtransmission structures. Since the transmission is shielded, this provides shielding for the distribution as well, provided adequate clearance can be maintained for the ground lead. This is not always an easy task. Another section of the feeder may crest a ridge giving it unusual exposure to lightning. Shielding in that area may be an effective way of reducing lightning-induced faults. Poles in the affected section may have to be extended to accommodate the shield wire and considerable effort put into improving the grounds. This increases the cost of this solution. It is possible that line arresters would be a more economical and effective option for many applications.

3.5.2 Line arresters

Another strategy for lines that are struck frequently is to apply arresters periodically along the phase wires. Normally, lines flash over first at the pole insulators. Therefore, preventing insulator flashover will reduce the interruption and sag rate significantly. This is more economical than shielding and results in fewer line flashovers. Neither shielding nor line arresters will prevent all flashovers from lightning. The aim is to significantly reduce flashovers in particular trouble spots.

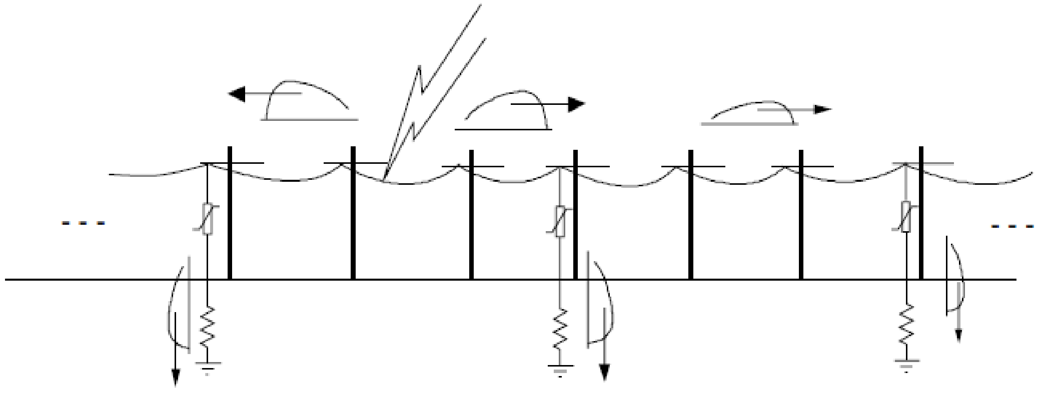


Figure 3.26 Periodically spaced line arresters help prevent flashovers.

As shown in Fig. 3.26, the arresters bleed off some of the stroke current as it passes along the line. The amount that an individual arrester bleeds off will depend on the grounding resistance. The idea is to space the arresters sufficiently close to prevent the voltage at unprotected poles in the middle from exceeding the basic impulse level (BIL) of the line insulators. This usually requires an arrester at every second or third pole. In the case of a feeder supplying a highly critical load, or a feeder with high ground resistance, it may be necessary to place arresters at every pole. A transients study of different configurations will show what is required. Some utilities place line arresters only on the top phase when one phase is mounted higher than the others. In other geometries, it will be necessary to put arresters on all three phases to achieve a consistent reduction in flashovers.

Figure 3.27 Typical polymer-housed utility distribution arrester for overhead line applications. (*Courtesy of Cooper Power Systems.*)

Figure 3.27 shows a typical utility arrester that is used for overhead line protection applications. This model consists of MOV blocks encapsulated in a polymer housing that is resistant to sunlight and other natural elements. Older-technology models used porcelain housings like that shown on the primary side of the transformer in Fig. 3.22. There are already sufficient arresters on many lines in densely populated areas in North America to achieve sufficient line protection. These arresters are on the distribution transformers, which are installed close together and in sufficient numbers in these areas to help protect the lines from flashover.

3.5.3 Low-side surges

Some utility and end-user problems with lightning impulses are closely related. One of the most significant ones is called the “low-side surge” problem by many utility engineers. The name was coined by distribution transformer designers because it appears from the transformer’s perspective that a current surge is suddenly injected into the low-voltage side terminals. Utilities have not applied secondary arresters at low-voltage levels in great numbers.

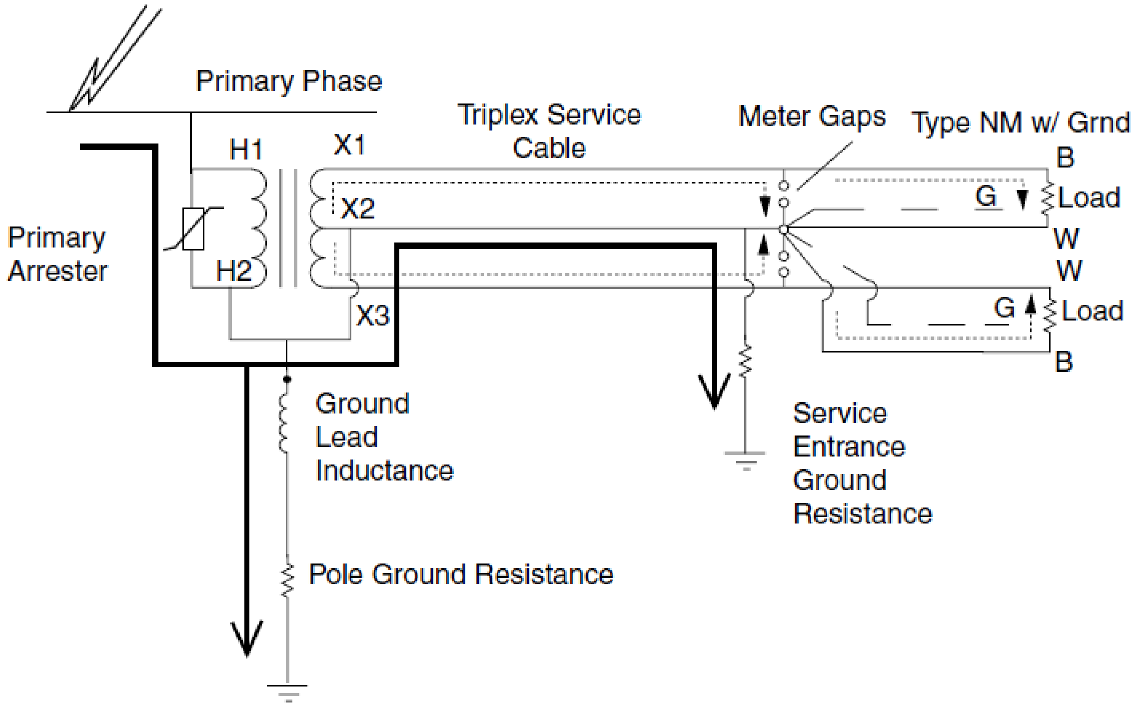


Figure 3.28 Primary arrester discharge current divides between pole and load ground.

From the customer’s point of view it appears to be an impulse coming from the utility and is likely to be termed a *secondary surge.*

Both problems are actually different side effects of the same surge phenomenon—lightning current flowing from either the utility side or the customer side along the service cable neutral. Figure 3.28 shows one possible scenario. Lightning strikes the primary line, and the current is discharged through the primary arrester to the pole ground lead. This lead is also connected to the *X*2 bushing of the transformer at the top of the pole. Thus, some of the current will flow toward the load ground. The amount of current into the load ground is primarily dependent on the size of the pole ground resistance relative to the load ground. Inductive elements may play a significant role in the current division for the front of the surge, but the ground resistances basically dictate the division of the bulk of the stroke current.

The current that flows through the secondary cables causes a voltage drop in the neutral conductor that is only partially compensated by mutual inductive effects with the phase conductors. Thus, there is a net voltage across the cable, forcing current through the transformer secondary windings and into the load as shown by the dashed lines in Fig.3.23. If there is a complete path, substantial surge current will flow. As it flows through the transformer secondary, a surge voltage is induced in the primary, sometimes causing a layer-to-layer insulation failure near the grounded end. If there is not a complete path, the voltage will build up across the load and may flash over somewhere on the secondary. It is common for the meter gaps to flash over, but not always before there is damage on the secondary because the meter gaps are usually 6 to 8 kV, or higher.

The amount of voltage induced in the cable is dependent on the rate of rise of the current, which is dependent on other circuit parameters as well as the lightning stroke. The chief power quality problems this causes are

1. The impulse entering the load can cause failure or misoperation of load equipment.
2. The utility transformer will fail causing an extended power outage.
3. The failing transformer may subject the load to sustained steady state overvoltages because part of the primary winding is shorted, decreasing the transformer turns ratio. Failure usually occurs in seconds but has been known to take hours.

The key to this problem is the amount of surge current traveling through the secondary service cable. Keep in mind that the same effect occurs regardless of the direction of the current. All that is required is for the current to get into the ground circuits and for a substantial portion to flow through the cable on its way to another ground. Thus, lightning strikes to either the utility system or the end-user facilities have the same effects. Transformer protection is more of an issue in residential services, but the secondary transients will appear in industrial systems as well.

Protecting the transformer: There are two common ways for the utility to protect the transformer:

1. Use transformers with interlaced secondary windings.
2. Apply surge arresters at the *X* terminals.

Figure 3.29 Example of a distribution transformer protected against lightning with tank-mounted primary and secondary arresters. (*Courtesy of Cooper Power Systems.*)

Of course, the former is a design characteristic of the transformer and cannot be changed once the transformer has been made. If the transformer is a noninterlaced design, the only option is to apply arresters to the low-voltage side.

Note that arresters at the load service entrance will not protect the transformer. In fact, they will virtually guarantee that there will be a surge current path and thereby cause additional stress on the transformer.

While interlaced transformers have a lower failure rate in lightning prone areas than noninterlaced transformers, recent evidence suggests that low-voltage arresters have better success in preventing failures.

Figure 3.29 shows an example of a well-protected utility pole-top distribution transformer. The primary arrester is mounted directly on the tank with very short lead lengths. With the evidence mounting that lightning surges have steeper wavefronts than previously believed, this is an ever increasing requirement for good protection practice. It requires a special fuse in the cutout to prevent fuse damage on lightning current discharge. The transformer protection is completed by using a robust secondary arrester. This shows a heavy-duty, secondary arrester adapted for external mounting on transformers. Internally mounted arresters are also available. An arrester rating of 40-kA discharge current is recommended. The voltage discharge is not extremely critical in this application but is typically 3 to 5 kV. Transformer secondaries are generally assumed to have a BIL of 20 to 30 kV. Gap-type arresters also work in this application but cause voltage sags, which the MOV-type arresters avoid.

3.5.4 Cable protection

One increasingly significant source of extended power outages on underground distribution (UD) systems is cable failures. The earliest utility distribution cables installed in the United States are now reaching the end of their useful life. As a cable ages, the insulation becomes progressively weaker and a moderate transient overvoltage causes breakdown and failure.

Many utilities are exploring ways of extending the cable life by arrester protection. Cable replacement is so costly that it is often worthwhile to retrofit the system with arresters even if the gain in life is only a few years. Depending on voltage class, the cable may have been installed with only one arrester at the riser pole or both a riserpole arrester and an open-point arrester (see Fig. 3.30).

To provide additional protection, utilities may choose from a number of options:

1. Add an open-point arrester, if one does not exist.
2. Add a third arrester on the next-to-last transformer.
3. Add arresters at every transformer.
4. Add special low-discharge voltage arresters.
5. Inject an insulation-restoring fluid into the cable.
6. Employ a scout arrester scheme on the primary.

The cable life is an exponential function of the number of impulses of a certain magnitude that it receives, according to Hopkinson.The damage to the cable is related by

$$D = NV^c$$

where D _ constant, representing damage to the cable
N _ number of impulses
V _ magnitude of impulses
c _ empirical constant ranging from 10 to 15
Therefore, anything that will decrease the magnitude of the impulses only slightly has the potential to extend cable life a great deal.

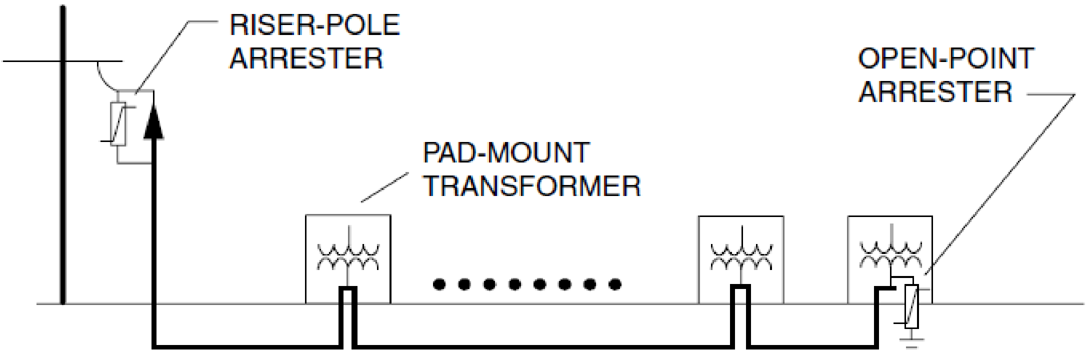


Figure 3.30 Typical UD cable arrester application.

Open-point arrester - Voltage waves double in magnitude when they strike an open point. Thus, the peak voltage appearing on the cable is about twice the discharge voltage of the riser-pole arrester. There is sufficient margin with new cables to get by without open-point arresters at some voltage classes. While open-point arresters are common at 35 kV, they are not used universally at lower voltage classes. When the number of cable failures associated with storms begins to increase noticeably, the first option should be to add an arrester at the open point if there is not already one present.

Next-to-last transformer - Open-point arresters do not completely eliminate cable failures during lightning storms. With an open-point arrester, the greatest overvoltage stress is generally found at the next-to-last transformer. Thus, we often see cable and transformer failures at this location. The problem is readily solved by an additional arrester at the nextto-last transformer. In fact, this second arrester practically obliterates the impulse, providing effective protection for the rest of the cable system as well. Thus, some consider the most optimal UD cable protection configuration to be three arresters: a riser-pole arrester, an open-point arrester, and an arrester at the transformer next closest to the open point. This choice protects as well as having arresters at all transformers and is less costly, particularly in retrofitting.

Under-oil arresters - Transformer manufacturers can supply padmounted transformers for UD cable systems with the primaryarresters inside the transformer compartment, under oil. If applied consistently, this achieves very good protection of the UD cable system by having arresters distributed along the cable. Of course, this protection comes at an incremental cost that must be evaluated to determine if it is economical for a utility to consider.

Elbow arresters - The introduction of elbow arresters for transformer connections in UD cable systems has opened up protection options not previously economical. Previously, arrester installations on UD cable systems were adaptations of overhead arrester technology and were costly to implement. That is one reason why open-point arresters have not been used universally. The other alternative was under-oil arresters and it is also very costly to change out a pad-mount transformer just to get an open-point arrester. Now, the arrester is an integral part of the UD system hardware and installation at nearly any point on the system is practical. This is a particularly good option for many retrofit programs.

Lower-discharge arresters - The gapped MOV arrester technology described earlier in this chapter was developed specifically to improve the surge protection for UD cables and prolong their life. The arresters are able to achieve a substantially lower discharge voltage under lightning surge conditions while still providing the capability to withstand normal system conditions. By combining the gaps from the old SiC technology with fewer MOV blocks, a 20 to 30 percent gain could be made in the lightning protective margin. The gaps share the voltage with the MOV blocks during steady-state operation and prevent thermal runaway. Following the logic of the Hopkinson formula, presented at the beginning of this section, converting to this kind of arrester in the UD cable system can be expected to yield a substantial increase in cable life.

Fluid injection - This is a relatively new technology in which a restorative fluid is injected into a run of cable. The fluid fills the voids that have been created in the insulation by aging and gives the cable many more years of life. A vacuum is pulled on the receiving end and pressure is applied at the injection end. If there are no splices to block the flow, the fluid slowly penetrates the cable.

3.6 Computer Tools for Transients Analysis

The most widely used computer programs for transients analysis of power systems are the Electromagnetic Transients Program, commonly known as EMTP, and its derivatives such as the Alternate Transients Program (ATP). EMTP was originally developed by Hermann W. Dommel at the Bonneville Power Administration (BPA) in the late 1960s15 and has been continuously upgraded since. One of the reasons this program is popular is its low cost due to some versions being in the public domain. Some of the simulations presented here have been performed with a commercial analysis tool known as PSCAD/EMTDC, a program developed by the Manitoba HVDC Research Center. This program features a very sophisticated graphical user interface that enables the user to be very productive in this difficult analysis. Some power system analysts use computer programs developed more for the analysis of electronic circuits, such as the well known SPICE program and its derivatives.

Although the programs just discussed continue to be used extensively, there are now many other capable programs available. We will not attempt to list each one because there are so many and, also, at the present rate of software development, any such list would soon be outdated. The reader is referred to the Internet since all vendors of this type of software maintain websites.

Nearly all the tools for power systems solve the problem in the time domain, re-creating the waveform point by point. A few programs solve in the frequency domain and use the Fourier transform to convert to the time domain. Unfortunately, this essentially restricts the addressable problems to linear circuits. Time-domain solution is required to model nonlinear elements such as surge arresters and transformer magnetizing characteristics. The penalty for this extra capability is longer solution times, which with modern computers becomes less of a problem each day.

It takes considerably more modeling expertise to perform electromagnetic transients studies than to perform more common power system analyses such as of the power flow or of a short circuit. Therefore, this task is usually relegated to a few specialists within the utility organization or to consultants.

While transients programs for electronic circuit analysis may formulate the problem in any number of ways, power systems analysts almost uniformly favor some type of nodal admittance formulation. For one thing, the system admittance matrix is sparse allowing the use of very fast and efficient sparsity techniques for solving large problems. Also, the nodal admittance formulation reflects how most power engineers view the power system, with series and shunt elements connected to buses where the voltage is measured with respect to a single reference.

To obtain conductance for elements described by differential equations, transients programs discretize the equations with an appropriate numerical integration formula. The simple trapezoidal rule method appears to be the most commonly used, but there are also a variety of Runge-Kutta and other formulations used. Nonlinearities are handled by iterative solution methods. Some programs include the nonlinearities in the general formulation, while others, such as those that follow the EMTP methodology, separate the linear and nonlinear portions of the circuit to achieve faster solutions. This impairs the ability of the program to solve some classes of nonlinear problems but is not usually a significant constraint for most power system problems.

3

OVERVOLTAGES

(SHORT TYPE QUESTIONS AND ANSWERS)

WHAT IS IN UNIT -3

- Sources of over voltages: Capacitor switching, lightning, ferroresonance.
- How to mitigation of voltage swells: Surge arresters, low pass filters, power conditioners
- Lightning protection, shielding, line arresters,
- protection of transformers and cables,
- Computer analysis tools for transients, PSCAD and EMTP.

1. What is the phenomena of Overvoltage

An overvoltage is an increase in the rms ac voltage greater than 110% at the power frequency for a duration longer than 1 minute.

Overvoltages are usually the result of load switching (e.g., switching off a large load), or energizing a capacitor bank). The overvoltages result because the system is either too weak for the desired voltage regulation or voltage controls are inadequate. Incorrect tap settings on transformers can also result in system overvoltages.

2. Name the various sources of over voltages?

The various sources of overvoltages are ,

- capacitor switching
- Lightning
- Ferro resonance.

3. What is capacitance switching?

When a long unloaded line or a capacitor bank is switched off the capacitive current produces high voltage transients across the breaker contacts. This interrupting or chopping of capacitive current is called capacitive current chopping / braking.

4. What is lightning phenomena?

Lightning is a huge spark, which is due to the electrical discharges taking place between the separate charge centers in the same cloud or between cloud and earth.

Or

Lighting phenomenon is a peak discharge in which charge accumulated in the clouds discharges in to a neighboring cloud or to the ground

5. Define Ferro resonance? Give some practical instances under which Ferro resonance may occur?

The phenomenon of Ferroresonance refers to a special kind of resonance that involves capacitance and iron core inductance .The most common condition in which it causes distrubances is when the magnetising impedances of a transformer is places in series with a system capacitor.

6. Give the Conditions/ practical instances for Ferroresonance.

Ferroresonance occurs when an unloaded 3-phase system consisting of an inductive and a capacitive component is interrupted by single phase means. In practice this is typical of a high voltage electrical distribution network of transformers (inductive component) and power cables (capacitive component). If such a network has no load and the applied voltage is then interrupted on a single phase, a ferroresonance may be observed. If the remaining phases are not interrupted and the phenomenon continues, overvoltage can lead to the breakdown of insulation in connected components resulting in failure

7. What is the difference between a ferro resonant circuit and a linear resonant circuit

The main differences between a ferro resonant circuit and a linear resonant circuit are for a given ω

- its resonance possibility in a wide range of values of C.
- the frequency of the voltage and current waves which may be different from that of the sinusoidal voltage source,
- the existence of several stable steady state responses for a given configuration and values

8.Mention the common indication of ferroresonance

Following are the common indications of ferroresonance

- Audible noise
- Overheating
- High voltages and surge arrester failures
- Flicker

9. Mention the various system conditions that help increase the probability of ferroresonance

- Switching of lightly loaded and un loaded transformer
- Ungrounded transformer primary connection
- Very lengthy underground cable circuit.
- Three phase systems with single phase switching devices.
- Cable damage and manual switching during construction of under ground cables.

10. Mention the most common events leading to ferroresonance

- Manual switching of an unloaded, cable-fed three phase transformer where only one phase is closed.

- Manual switching of an unloaded, cable-fed three phase transformer where only one phases is open
- One or two riser - pole fuse may blow leaving a transformer with one or two phases open

11. How to prevent ferrroresonance?

- Use grounded-wye/grounded-wye systems.
- Keep primary cable runs short.
- Place switch/ protection directly upstream of the transformer.
- Have some load on the transformer when switching.
- Surge arrestors may be used to help suppress overvoltages.
- Use three-phase switchgear instead of fuses. This is not economical in many cases.
- Open or close all three cutouts as simultaneously as possible.
- Eliminate fuses. Relay on feeder breaker for fault interruption.
- Various measures to prevent inadvertent fuse operation.

12. Name the various methods of mitigating voltage swell?

- DVR (Dynamic voltage restorer),
- Power Conditioners,
- Constant Voltage Transformers (CVT).

13. Name the various devices for over voltage protection?

- Surge arrester
- Transient voltage surge suppressor(TVSS)

- Isolation transformer
- Low pass filters
- Low impedance power conditioner
- Utility surge arrester.

14. What is a utility surge arrester?

Surge arrester is a protective device for limiting surge voltages by discharging or bypassing surge current, and it also prevents continued flow of follow current while remaining capable of repeating these functions

15.What does a surge arrester do?

A surge arrester, or surge diverter, acts like a trapdoor to excess electrical energy. Sometimes called over-voltages, or transients, or surges, unwanted bursts of electricity are lured(attracted) to the trapdoor by what is called a low-impedance path to ground. The trapdoor is a metal oxide varistor, or MOV, which opens or "clamps" when the overvoltage exceeds a certain level, and safely diverts most of the excess energy to the ground rod.

When the over-voltage or transient is over, the MOV automatically resets and is ready for the next one. It is important to note that with lightning or other fast acting impulses, the leading edge of the impulse will pass the first MOV, even as the majority of the surge is racing to, and through, the trapdoor, hence the need for a second stage "point of use" plug-in type surge arrester inside the home or business.

16. What is a low pass filter?

A low-pass filter is a filter that passes low-frequency signals but attenuates (reduces the amplitude of signals with frequencies higher than the cutoff frequency. Low pass filters are composed of series inductors and parallel capacitors this L-.C combination provides a low impedance path to ground for selected resonant frequencies.

17.What is a low impedance power conditioner?

These line conditioners provide the best all-round power conditioning and surge protection for sensitive electronic equipment. The integral low-impedance isolation transformer provides 100% isolation from the input ac line. The secondary neutral-to-ground bond eliminates all surge voltages between neutral and ground. Surge protection and noise filtering are superior to conventional surge protection and filtering devices.

18.Name the different methods Utility System Lightning protection?

- Shielding
- Line arrester

19.What is shielding?

Shielding is nothing but installing a ground conductor above the phase conductor.

- Common in transmission and substations.
- Not common in distribution.
- Goal is to prevent lightning from striking the phase conductor.
- Ground lead must be kept well away from phase conductors and be as straight as possible.
- Ground resistance needs to be as low as possible.

20. What is a line arrester?

These are mainly used for overhead line protection. Made up of MOV blocks encapsulated in a polymer housing. The arresters bleed off some of the stroke current as it passes along the line. And can be located at every second or third pole.

21.What is PSCAD ? What are it's application?

PSCAD is a general-purpose time domain simulation tool for studying transient behavior of electrical networks. The program includes a comprehensive library of models including all aspects of AC and DC power systems and controls. To augment(to increase) the component library, the program provides the ability to create user models and libraries with the built-in graphical component workshop.

22.What is EMTP? What are it’s application?

The Electromagnetic Transients Program (EMTP) is a computer program for simulating electromagnetic, electromechanical, and control system transients on multi-phase electric power systems. Studies involving use of the EMTP fall in two general categories.

Applications

- One is design, which includes insulation coordination, equipment ratings, protective device specification, control systems design, etc.

- Other is solving operational problems such as unexplained outages or equipment failures.

23. What is an isolation transformer?

An isolation transformer is a transformer, often with symmetrical windings, which is used to decouple two circuits. An isolation transformer allows an AC signal or power to be taken from one device and fed into another without electrically connecting the two circuits. Isolation transformers block transmission of DC signals from one circuit to the other, but allow AC signals to pass. They also block interference caused by ground loops. Isolation transformers with electrostatic shields are used for power supplies for sensitive equipment such as computers or laboratory instruments

24. What is the difference between a Surge arrester and TVSS?

A TVSS is an abbreviation for "transient voltage surge suppressor." A TVSS is a device that attenuates (reduces in magnitude) random, high energy, short duration electrical power anomalies (disturbances)caused by utilities, atmospheric phenomena, or inductive loads.

A surge diverter is a device that is connected between line and earth, ie., in parallel with the equipment under protection at the substation. It limits the duration and amplitude of the follow current by transferring the high voltage surges on power system to ground.

25. What is a TVSS?

Transient voltage surge suppressors is a protective device for limiting transient voltages by diverting or limiting surge current, it also prevents continued flow of follow current while remaining capable of repeating these functions.

26. Give the circuit diagram of a hybrid transient protector.

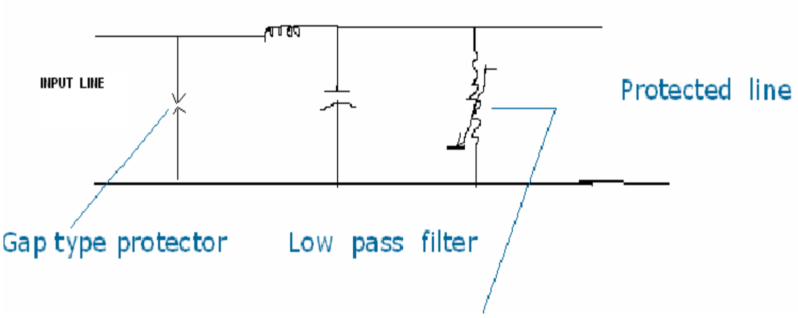


Fig 3.2 Hybrid transient protector.

27. Differentiate between crow bar devices and clamping devices

Crowbar devices: Normally open devices, that conduct current during over voltage transients. These devices are usually manufactured with a gap filled with air or a special gas. The gap arcs over when a sufficiently high overvoltage transient appears.
In case of Crowbar devices the power frequency drops to zero or to a very low value.

Clamping devices: For ac circuits are commonly nonlinear resistors (varistors) that conducts very low amounts of current until an over voltage occurs. Then they starts to conduct heavily, and their impedance drops rapidly with increasing voltage. In case of clamping devices the voltage is not reduced below the conduction level. When they begin to conducts. Ex. MOV (Metal oxide varistors)

28. What are the clamping devices for ac circuits?

Clamping devices for ac circuits are commonly nonlinear resistors (varistors) that conducts very low amounts of current until an over voltage occurs. Then they starts to conduct heavily, and their impedance drops rapidly with increasing voltage Ex: MOV (Metal oxide varistors i.e the chief ingredient is zinc oxide)

A metal oxide varistor (MOV) is a device commonly used in surge protectors. There are two characteristics MOV’s that make them desirable for surge protection. First, the resistance of an MOV decreases with an increase in voltage. In addition, MOV’s are fast acting and can respond to a surge in just a few nanoseconds. This results in suppressing a surge before it has a chance to damage electronic equipment.

29. What is clamping voltage?

A Clamping voltage-also referred to as peak let through or suppressed voltage rating-is the amount of voltage a surge suppressor permits to pass through it to the attached load during a transient event. Clamping voltage is a performance measurement of a surge suppressor's ability to attenuate a transient. This performance value is confirmed by Underwriters Laboratories during tests conducted while evaluating a surge suppressor for listing.

30. Where are surge suppressors installed?

An AC surge suppressors are typically installed in these three areas:

- At a utility service entrance for protection of an entire facility.
- In distribution panel boards and switchboards for protection of sensitive downstream loads.
- Connected to a wall outlet for individual protection of a specific piece of equipment, such as a computer or solid-state controller.

31. Why the gapless MOV (Zno) arrester is preferred over gapped MOV & Gapped Silicon carbide arrester?

The gapless MOV provides a somewhat better discharge characteristics without high spark over transient and useful where there is a need for increased protective margin.

3 OVERVOLTAGES

(LONG TYPE QUESTIONS AND ANSWERS)

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1. Discuss the various sources of Transient over voltages on utility systems.

There are two main sources of transient over voltages on utility systems.

i. Capacitor switching (de-energization of transmission lines cables capacitor banks).
ii. Lightning.
iii. Ferroresonance.

The making and breaking of circuits due to frequent switching operation in a power system may give rise to over voltage transient in the system owing to large inductances and capacitances the major of which is Ferroresonance.

i. Capacitor switching (de-energization of transmission lines cables capacitor banks)

one of the more common causes of electrical transients is switching of capacitor banks in power systems. Electrical utilities switch capacitor banks during peak load hours to offset the lagging kVAR demand of the load. The leading kVARs drawn by the capacitor banks offset the lagging kVAR demand of the load, reducing the net kVA load on the circuit.

Capacitor switching is one of the most common switching events on utility systems .During capacitance switching operations that result in excessive overvoltages, the stored energy in the electric field of capacitance is released in the system. Dropping of A long open-circuited line or an underground cable or disconnection of capacitor banks may present hazardous overvoltages. Fig 3.3 shows the single diagram of a typical utility feeder capacitor switching situation . Fig 3.4 shows the equivalent circuit for capacitance switching where L is the inductance up to the circuit breaker point and c is the Capacitance of the capacitor bank which is being isolated by the breaker the system voltage, current in fig.3.5b). Till instant ‘A’ (the current zero) The potential across the breaker contact is zero. After this, the potential across the contacts starts increasing to attain $2V_m$.(or1.3 to 1.4 per unit).

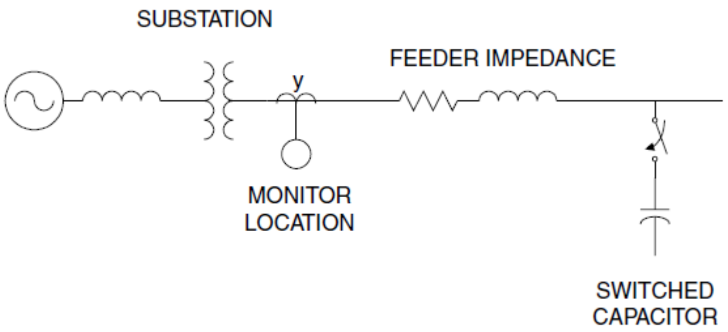


Fig 3.3 one line diagram of a capacitor switching operation.

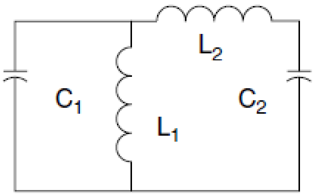


Fig 3.4 Equivalent circuit for capacitance switching

Magnification of capacitor- switching transient:

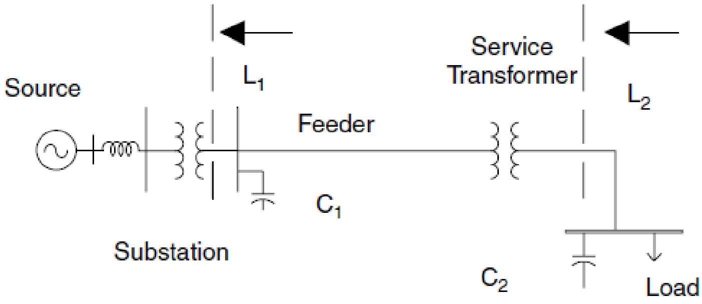


fig 3.5(a) voltage magnification at customer capacitor due to energizing capacitor on utility system

The problem of adding power factor correction capacitors at the customer location is that they may increase the impact of utility capacitor switching transients on end user equipments.

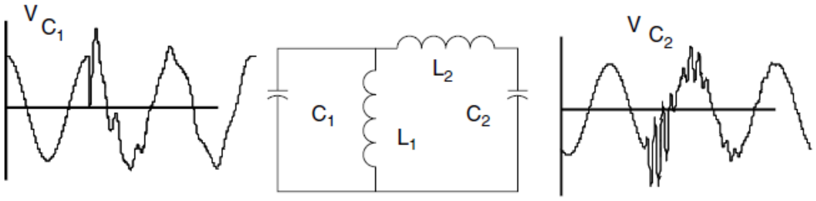


Fig 3.5(b) Voltage Magnification of capacitor bank switching

ii) Lightning

Lightning is a potent source of impulsive transient the common places where lightning may strike is primary phase, secondary phase , and point where secondary is grounded, of a transformer and on grounded structure.

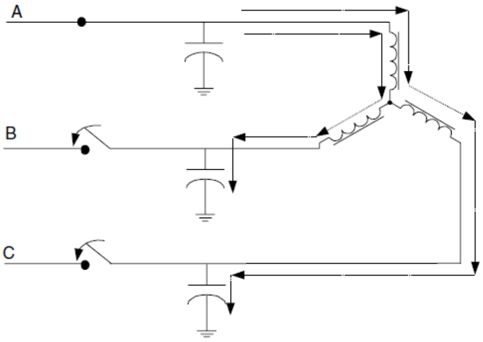
iii) Ferroresonance

The phenomenon of Ferroresonance refers to a special kind of resonance that involves capacitance and iron core inductance. The most common condition in which it causes distrubances is when the magnetising impedances of a transformer is places in series with a system capacitor.

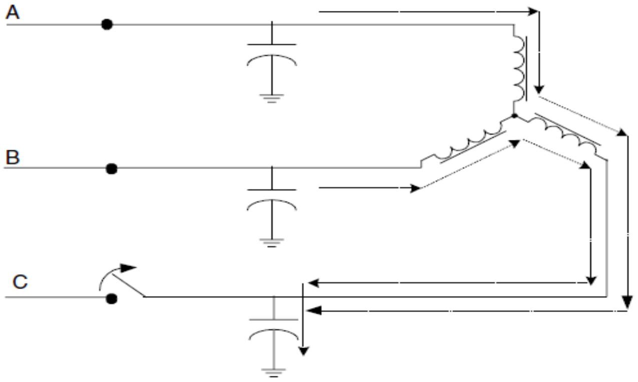
Conditions (or) practical instances for Ferroresonance:

Ferroresonance occurs when an unloaded 3-phase system consisting of an inductive and a capacitive component is interrupted by single phase means. In practice this is typical of a high voltage electrical distribution network of transformers (inductive component) and power cables (capacitive component). If such a network has no load and the applied voltage is then interrupted on a single phase, a ferroresonance may be observed. If the remaining phases are not interrupted and the phenomenon continues, overvoltage can lead to the breakdown of insulation in connected components resulting in failure. The phenomenon of Ferroresonance is the occurrence of an unstable high voltage, typically on 3 phase electrical systems which only occurs under specific conditions. The nature of the overvoltage can cause the failure of equipment.

Conditions for Ferroresonance occurs when an unloaded 3-phase system consisting of an inductive and a capacitive component is interrupted by single phase means.



(a)



(b)

Figure 4.14 Common system conditions where ferroresonance may occur: (a) one phase closed, (b) one phase open.

In practice this is typical of a high voltage electrical distribution network of transformers (inductive component) and power cables (capacitive component). If such a network has no load and the applied voltage is then interrupted on a single phase, a ferroresonance may be observed. If the remaining phases are not interrupted and the phenomenon continues, overvoltage can lead to the breakdown of insulation in connected components resulting in failure.

How to prevent ferroresonance? (Or) Strategies for dealing with ferroresonance.

- Use three-phase switchgear instead of fuses. This is not economical in many cases.
- Open or close all three cutouts as simultaneously as possible.
- Eliminate fuses. Relay on feeder breaker for fault interruption.
- Various measures to prevent inadvertent fuse operation.

2. Explain the ferroresonance phenomena in detail with neat circuit diagram.

The term ferroresonance refers to a special kind of resonance that involves capacitance and iron-core inductance. The most common condition in which it causes disturbances is when the magnetizing impedance of a transformer is placed in series with a system capacitor. This happens when there is an open-phase conductor. Under controlled conditions, ferroresonance can be exploited for useful purpose such as in a constant-voltage transformer.

Ferroresonance is different than resonance in linear system elements. In linear systems, resonance results in high sinusoidal voltages and currents of the resonant frequency. Linear-system resonance is the phenomenon behind the magnification of harmonics in power systems.

Ferroresonance can also result in high voltages and currents, but the resulting waveforms are usually irregular and chaotic in shape. The concept of ferroresonance can be explained in terms of linear-system resonance as follows. Consider a simple series RLC circuit as shown in Fig. 4.9. Neglecting the resistance R for the moment, the current flowing in the circuit can be expressed as follows:

$$I = \frac{E}{j\,(X_L - |X_C|)}$$

Where, E = driving voltage

X_L =reactance of L

X_C =reactance of C

When $X_L = |X_C|$, a series-resonant circuit is formed, and the equation yields an infinitely large current that in reality would be limited by R. An alternate solution to the series RLC circuit can be obtained by writing two equations defining the voltage across the inductor, i.e.,

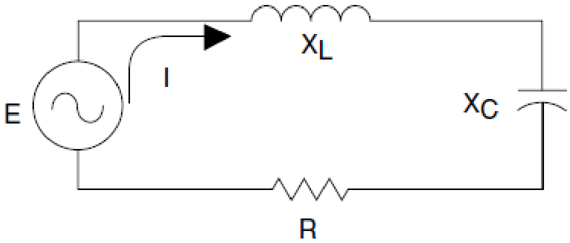


Figure 4.9 Simple series RLC circuit.

$$v = jX_L I$$

$$v = E + j|X_C|I$$

Where, v is a voltage variable. Figure 4.10 shows the graphical solution of these two equations for two different reactances, X_L and X_L'. X_L' represents the series-resonant condition. The intersection point between the capacitive and inductive lines gives the voltage across inductor EL. The voltage across capacitor E_C is determined as shown in Fig. 4.10. At resonance, the two lines will intersect at infinitely large voltage and current since the $|X_C|$ line is parallel to the X_L' line. Now, let us assume that the inductive element in the circuit has a nonlinear reactance characteristic like that found in transformer magnetizing reactance. Figure 4.11 illustrates the graphical solution of the equations following the methodology just presented for linear circuits.

While the analogy cannot be made perfectly, the diagram is useful to help understand ferroresonance phenomena. It is obvious that there may be as many as three intersections between the capacitive reactance line and the inductive reactance curve. Intersection 2 is an unstable solution, and this operating point gives rise to some of the chaotic behavior of ferroresonance. Intersections 1 and 3 are stable and will exist in the steady state. Intersection 3 results in high voltages and high currents. Figures 4.12 and 4.13 show examples of ferroresonant voltages that can result from this simple series circuit. The same inductive characteristic was assumed for each case. The capacitance was varied to achieve a different operating point after an initial transient that pushes the system into resonance. The unstable case yields voltages in excess of 4.0 pu, while the stable case settles in at voltages slightly over 2.0 pu. Either condition can impose excessive duty on power system elements and load equipment. For a small capacitance, the |XC| line is very steep, resulting in an intersection point on the third quadrant only. This can yield a range of voltages from less than 1.0 pu to voltages like those shown in Fig. 4.13.

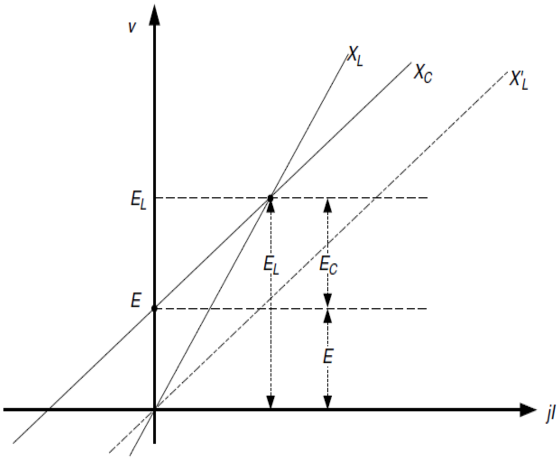


Figure 4.10 Graphical solution to the linear LC circuit.

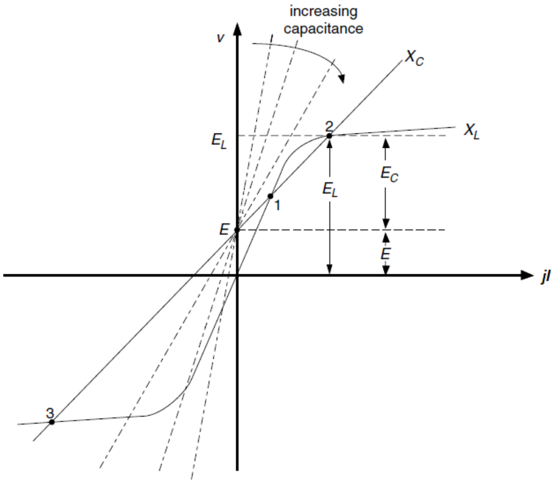


Figure 4.11 Graphical solution to the nonlinear LC circuit.

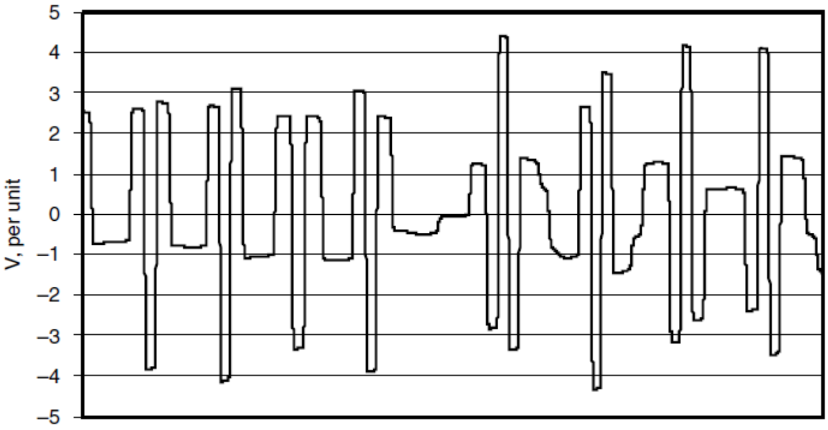


Figure 4.12 Example of unstable, chaotic ferroresonance voltages.

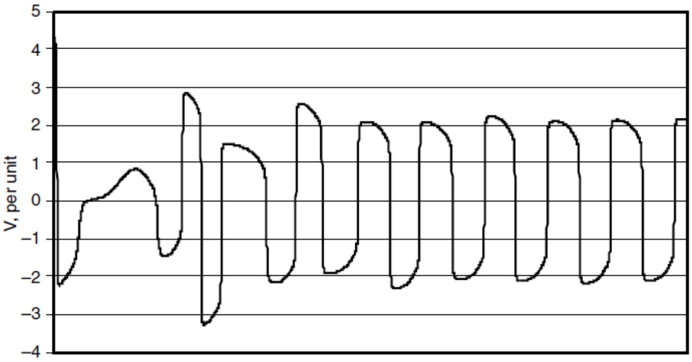


Figure 4.13 Example of ferroresonance voltages settling into a stable operating point (intersection 3) after an initial transient.

When C is very large, the capacitive reactance line will intersect only at points 1 and 3. One operating state is of low voltage and lagging current (intersection 1), and the other is of high voltage and leading current (intersection 3). The operating points during ferroresonance can oscillate between intersection points 1 and 3 depending on the applied voltage. Often, the resistance in the circuit prevents operation at point 3 and no high voltages will occur. In practice, ferroresonance most commonly occurs when unloaded transformers become isolated on underground cables of a certain range of lengths. The capacitance of overhead distribution lines is generally insufficient to yield the appropriate conditions. The minimum length of cable required to cause ferroresonance varies with the system voltage level. The capacitance of cables is nearly the same for all distribution voltage levels, varying from 40 to 100 nF per 1000 feet (ft), depending on conductor size. However, the magnetizing reactance of a 35-kV-class distribution transformer is several times higher (the curve is steeper) than a comparably sized 15-kV-class transformer. Therefore, damaging ferroresonance has been more common at the higher voltages. For delta-connected transformers, ferroresonance can occur for less than 100 ft of cable. For this reason, many utilities avoid this connection on cable-fed transformers.

The grounded wye-wye transformer has become the most commonly used connection in underground systems in North American. It is more resistant, but not immune, to ferroresonance because most units use a three-legged or five-legged core design that couples the phases magnetically. It may require a minimum of several hundred feet of cable to provide enough capacitance to create a ferroresonant condition for this connection. The most common events leading to ferroresonance are,

- Manual switching of an unloaded, cable-fed, three-phase transformer where only one phase is closed (Fig. 4.14a). Ferroresonance may be noted when the first phase is closed upon energization or before the last phase is opened on deenergization.
- Manual switching of an unloaded, cable-fed, three-phase transformer where one of the phases is open (Fig. 4.14b). Again, this may happen during energization or deenergization.
- One or two riser-pole fuses may blow leaving a transformer with one or two phases open. Single-phase reclosers may also cause this condition. Today, many modern commercial loads have controls that transfer the load to backup systems when they sense this condition.

Unfortunately, this leaves the transformer without any load to damp out the resonance. It should be noted that these events do not always yield noticeable ferroresonance. Some utility personnel claim to have worked with underground cable systems for decades without seeing ferroresonance. System conditions that help increase the likelihood of ferroresonance include

- Higher distribution voltage levels, most notably 25- and 35-kV-class systems.
- Switching of lightly loaded and unloaded transformers.
- Ungrounded transformer primary connections.

The most common events leading to ferroresonance

- Manual switching of an unloaded, cable-fed three phase transformer where only one phase is closed.
- Manual switching of an unloaded, cable-fed three phase transformer where only one phases is open
- One or two riser - pole fuse may blow leaving a transformer with one or two phases open

2. Explain the principle of over voltage protection of a load equipment.

The fundamental principles of overvoltage protection of load equipment are,

- Limit the voltage across sensitive insulation.
- Divert the surge current away from the load.

- Block the surge current from entering the load.
- Bond grounds together at the equipment.
- Reduce, or prevent, surge current from flowing between grounds.
- Create a low-pass filter using limiting and blocking principles.

Figure 4.16 illustrates these principles, which are applied to protect from a lightning strike. The main function of surge arresters and transient voltage surge suppressors (TVSSs) is to limit the voltage that can appear between two points in the circuit. This is an important concept to understand. One of the common misconceptions about varistors, and similar devices, is that they somehow are able to absorb the surge or divert it to ground independently of the rest of the system. That may be a beneficial side effect of the arrester application if there is a suitable path for the surge current to flow into, but the foremost concern in arrester application is to place the arresters directly across the sensitive insulation that is to be protected so that the voltage seen by the insulation is limited to a safe value. Surge currents, just like power currents, must obey Kirchoff's laws. They must flow in a complete circuit, and they cause a voltage drop in every conductor through which they flow. One of the points to which arresters, or surge suppressors, are connected is frequently the local ground, but this need not be the case.

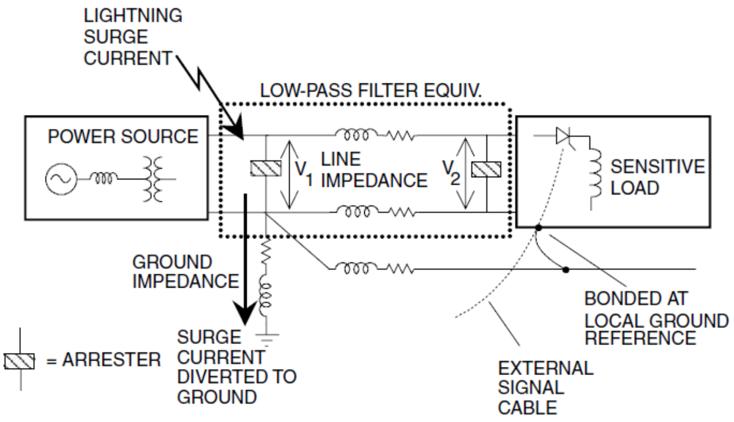


Figure 4.16 Demonstrating the principles of overvoltage protection.

Keep in mind that the local ground may not remain at zero potential during transient impulse events. Surge suppression devices should be located as closely as possible to the critical insulation with a minimum of lead length on all terminals. While it is common to find arresters located at the main panels and subpanels, arresters applied at the point where the power line enters the load equipment are generally the most effective in protecting that particular load. In some cases, the best location is actually inside the load device. For example, many electronic controls made for service in the power system environment have protectors [metal-oxide varistor (MOV) arresters, gaps, zener diodes, or surge capacitors] on every line that leaves the cabinet.

In Fig. 4.16 the first arrester is connected from the line to the neutral- ground bond at the service entrance. It limits the line voltage V1 from rising too high relative to the neutral and ground voltage at the panel. When it performs its voltage-limiting action, it provides a low impedance path for the surge current to travel onto the ground lead. Note that the ground lead and the ground connection itself have significant impedance. Therefore, the potential of the whole power system is raised with respect to that of the remote ground by the voltage drop across the ground impedance. For common values of surge currents and ground impedances, this can be several kilovolts.

One hopes, in this situation, that most of the surge energy will be discharged through the first arrester directly into ground. In that sense, the arrester becomes a surge "diverter." This is another important function related to surge arrester application. In fact, some prefer to call a surge arrester a surge diverter because its voltage-limiting action offers a low-impedance path around the load being protected. However, it can only be a diverter if there is a suitable path into which the current can be diverted. That is not always easy to achieve, and the surge current is sometimes diverted toward another critical load where it is not wanted. In this figure, there is another possible path for the surge current the signal cable indicated by the dotted line and bonded to the safety ground. If this is connected to another device that is referenced to ground elsewhere, there will be some amount of surge current flowing down the safety ground conductor.

Damaging voltages can be impressed across the load as a result. The first arrester at the service entrance is electrically too remote to provide adequate load protection. Therefore, a second arrester is applied at the load—again, directly across the insulation to be protected. It is connected "line to neutral" so that it only protects against normal mode transients. This illustrates the principles without complicating the diagram but should be considered as the minimum protection one would apply to protect the load. Frequently, surge suppressors will have suppression on all lines to ground, all lines to neutral, and neutral to ground. While lightning surge currents are seeking a remote ground reference, many transient overvoltages generated by switching will be those of a normal mode and will not seek ground. In cases where surge currents are diverted into other load circuits, arresters must be applied at each load along the path to ensure protection.

Note that the signal cable is bonded to the local ground reference at the load just before the cable enters the cabinet. It might seem that this creates an unwanted ground loop. However, it is essential to achieving protection of the load and the low-voltage signal circuits. Otherwise, the power components can rise in potential with respect to the signal circuit reference by several kilovolts. Many loads have multiple power and signal cables connected to them. Also, a load may be in an environment where it is close to another load and operators or sensitive equipment are routinely in contact with both loads. This raises the possibility that a lightning strike may raise the potential of one ground much higher than the others. This can cause a flashover across the insulation that is between the two ground references or cause physical harm to operators. Thus, all ground reference conductors (safety grounds, cable shields, cabinets, etc.) should be bonded together at the load equipment.

The principle is not to prevent the local ground reference from rising in potential with the surge; with lightning, that is impossible. Rather, the principle is to tie the references together so that all power and signal cable references in the vicinity rise together. This phenomenon is a common reason for failure of electronic devices. The situation occurs in TV receivers connected to cables, computers connected to modems, computers with widespread peripherals powered from various sources, and in manufacturing facilities with networked machines.

Since a few feet of conductor make a significant difference at lightning surge frequencies, it is sometimes necessary to create a special low-inductance, ground reference plane for sensitive electronic equipment such as mainframe computers that occupy large spaces.4 Efforts to block the surge current are most effective for high-frequency surge currents such as those originating with lightning strokes and capacitor-switching events. Since power frequency currents must pass through the surge suppressor with minimal additional impedance, it is difficult and expensive to build filters that are capable of discriminating between low-frequency surges and power frequency currents.

Blocking can be done relatively easily for high-frequency transients by placing an inductor, or choke, in series with the load. The high surge voltage will drop across the inductor. One must carefully consider that high voltage could damage the insulation of both the inductor and the loads. However, a line choke alone is frequently an effective means to block such high-frequency transients as line-notching transients from adjustable-speed drives.

The blocking function is frequently combined with the voltage-limiting function to form a low-pass filter in which there is a shunt-connected voltage-limiting device on either side of the series choke. Figure 4.16 illustrates how such a circuit naturally occurs when there are arresters on both ends of the line feeding the load. The line provides the blocking function in proportion to its length. Such a circuit has very beneficial overvoltage protection characteristics. The inductance forces the bulk of fast-rising surges into the first arrester. The second arrester then simply has to accommodate what little surge energy gets through. Such circuits are commonly built into outlet strips for computer protection.

Many surge-protection problems occur because the surge current travels between two, or more, separate connections to ground. This is a particular problem with lightning protection because lightning currents are seeking ground and basically divide according to the ratios of the impedances of the ground paths. The surge current does not even have to enter the power, or phase, conductors to cause problems. There will be a significant voltage drop along the ground conductors that will frequently appear across critical insulation.

The grounds involved may be entirely within the load facility, or some of the grounds may be on the utility system. Ideally, there would be only one ground path for lightning within a facility, but many facilities have multiple paths. For example, there may be a driven ground at the service entrance or substation transformer and a second ground at a water well that actually creates a better ground. Thus, when lightning strikes, the bulk of the surge current will tend to flow toward the well. This can impress an excessively high voltage across the pump insulation, even if the electrical system is not intentionally bonded to a second ground. When lightning strikes, the potentials can become so great that the power system insulation will flash over somewhere.

The amount of current flowing between the grounds may be reduced by improving all the intentional grounds at the service entrance and nearby on the utility system. This will normally reduce, but not eliminate entirely, the incidence of equipment failure within the facility due to lightning. However, some structures also have significant lightning exposure, and the damaging surge currents can flow back into the utility grounds. It doesn't matter which direction the currents flow; they cause the same problems. Again, the same principle applies, which is to improve the grounds for the structure to minimize the amount of current that might seek another path to ground.

When it is impractical to keep the currents from flowing between two grounds, both ends of any power or signal cables running between the two grounds must be protected with voltage-limiting devices to ensure adequate protection. This is common practice for both utility and enduser systems where a control cabinet is located quite some distance from the switch, or other device, being controlled.

3. Discuss the voltage Swell mitigation techniques?

3 DVR ,(Dynamic voltage restorer)
4 Power Conditioners,
5 Constant Voltage Transformers (CVT)

i. DVR,(Dynamic voltage restorer)

The DVR uses a voltage source converter (VSC) connected in series with the protected load (through an insertion transformer for medium voltage applications) to compensate amplitude and phase angle of the voltage applied to the load. The dc capacitor between the charger and the VSC serves as an energy buffer, generating and absorbing power during voltage sags and voltage swells, respectively. This process enables the voltage, as seen by the load, to be of the desired magnitude whenever disturbances occur upstream.

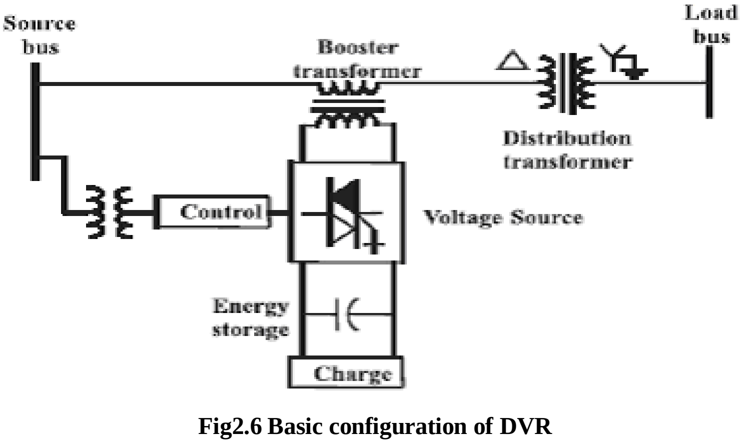


Fig2.6 Basic configuration of DVR

ii. Power Conditioners (**we prefer low impedance power conditioner**)

A power conditioner (also known as a line conditioner or power line conditioner) is a device intended

- To improve the "quality" of the power that is delivered to electrical load equipment.
- To deliver a voltage of the proper level and characteristics to enable load equipment to function properly. In some usages, "power conditioner" refers to a voltage regulator with at least one other function to improve power quality (e.g. noise suppression, transient impulse protection, etc.).
- Power or line conditioners regulate, filter, and suppress noise in AC power for sensitive computer and other solid state equipment.
- They provide electrical isolation and noise and spike attenuation to ensure the quality and consistency of power to sensitive medical, laboratory, computer, and other high technology equipment.

Construction

Power conditioners typically consist of voltage regulators in combination with output isolation transformers and transient voltage suppression circuitry.

Important Specification

Important specifications to consider when searching for power conditioners include power rating, input voltage, output voltage, voltage regulation accuracy, phase, and frequency

iii. Constant Voltage Transformers (CVT)

Constant Voltage Transformers (CVTs) (same as Ferroresonant transformers) Basically 1:1 transformers that can handle most voltage swell (sag also) conditions. secondary winding outputs a nearly constant voltage despite significant variations in supply (primary winding) voltage (nothing more to explain because there is no chance that it will be asked as an individual question if asked that will be under Unit-2.

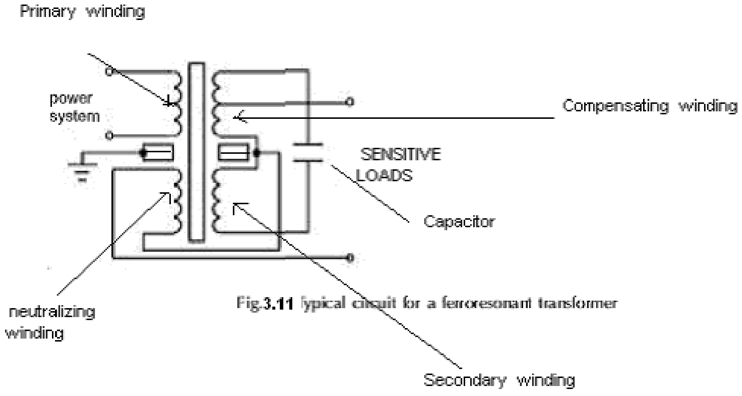


Fig.3.11 Typical circuit for a ferroresonant transformer

4. Discuss the various devices for Overvoltage Protection

The various Devices for over voltage protection are

i. Surge arrester & transient voltage surge suppressor
ii. Isolation transformer
iii. Low-pass filters
iv. Low impedance power conditioner
v. Utility surge arrester

3 Surge arrester & transient voltage surge suppressor

A surge diverter is a device that is connected between line and earth, ie., in parallel with the equipment under protection at the substation. It limits the duration and amplitude of the follow current by transferring the high voltage surges on power system to ground. Transient voltage surge suppressor is a protective device for limiting transient voltages by diverting or limiting surge current. It also prevents continued flow of follow current while remaining capable of repeating these functions.

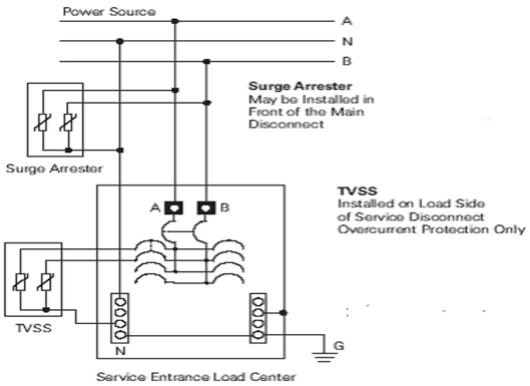


Fig 3.12 Location comparison of TVSS and surge arrester.

A surge arrester, or surge diverter, acts like a trapdoor to excess electrical energy. Sometimes called over-voltages, or transients, or surges, unwanted bursts of electricity are lured(attracted) to the trapdoor by what is called a low-impedance path to ground. The trapdoor is a metal oxide varistor, or MOV, which opens or "clamps" when the overvoltage exceeds a certain level, and safely diverts most of the excess energy to the ground rod.

When the over-voltage or transient is over, the MOV automatically resets and is ready for the next one. It is important to note that with lightning or other fast acting impulses, the leading edge of the impulse will pass the first MOV, even as the majority of the surge is racing to, and through, the trapdoor, hence the need for a second stage "point of use" plug-in type surge arrester inside the home or business.

4 ISOLATION TRANSFRMER

If an isolation transformer (a transformer with the same number of “turns” in the primary and secondary coils) is connected between an AC source and an AC load, we will measure the same voltage and the same current at both source and load terminals.

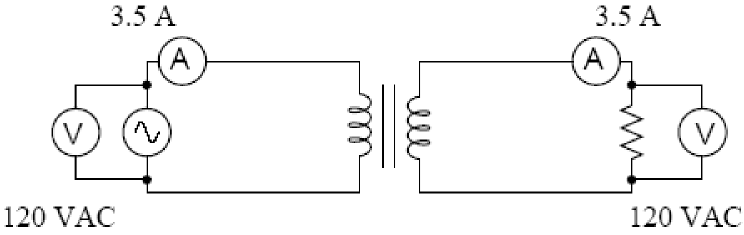


Fig 3.13 conceptual diagram of an isolation transformer.

An isolation transformer is a transformer, often with symmetrical windings, which is used to decouple two circuits. An isolation transformer allows an AC signal or power to be taken from one device and fed into another without electrically connecting the two circuits. Isolation transformers block transmission of DC signals from one circuit to the other, but allow AC signals to pass.

[In an electrical system, ground loop refers to a current, generally unwanted, in a conductor connecting two points that are supposed to be at the same potential, often ground, but are actually at different potentials. Ground loops can be detrimental to the intended operation of the electrical system.]

Isolation transformers with electrostatic shields are used for power supplies for sensitive equipment such as computers or laboratory instruments. as shown in fig3.14 below.

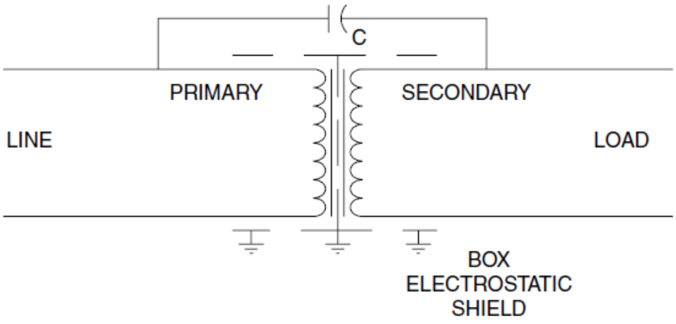


Fig.3.14 Isolation transformer with electrostatic shields

Advantages

- They also block interference caused by ground loops.
- They also attenuate high frequency noise and transients from one side to other.
- Voltage notching due to power electronic switching can be eliminated to the load side
- Capacitor switching and lightning transients coming from the utility system can be attenuated

- And moreover they allow the user to define a new ground reference

5 Low pass filter

A low-pass filter is a filter that passes low-frequency signals but attenuates (reduces the amplitude of signals with frequencies higher than the cutoff frequency. Low pass filters are composed of series inductors and parallel capacitors this L-C combination provides a low impedance path to ground for selected resonant frequencies.

The low pass filter limits transfer of high frequency transients. The inductor helps in blocking high - frequency transients and forces them in to the first supressor. The capacitor limits the rate of riseof the voltage magnitude Fig 3.15 shows a hybrid transient protector where voltage clamping devices are added in parallel to the capacitors.

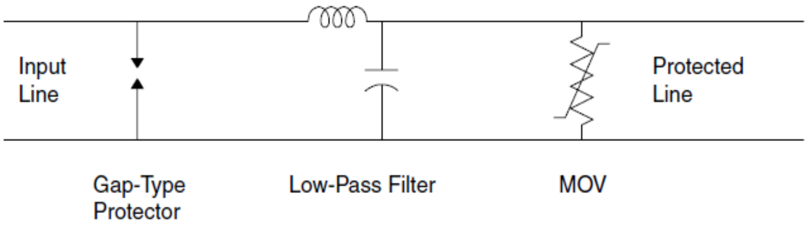


Fig 3.14 A hybrid transient protector with low pass filter.

6 Low impedance power conditioner.

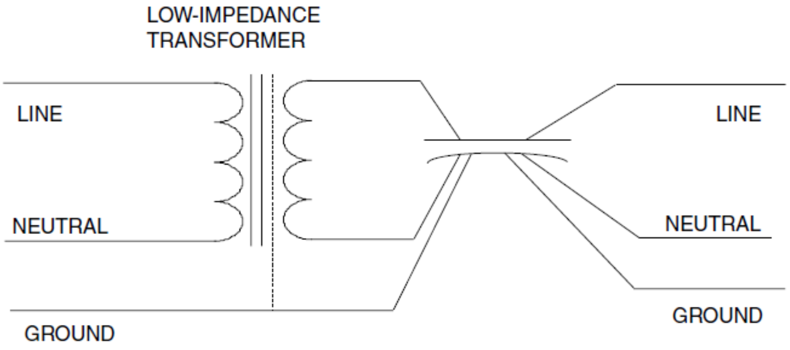


Fig3.15 Low impedance power conditioner

Switch mode power supplies in modern computer systems use current from the power line in large, brief "gulps". They want little or no opposition to their demands for current. By definition, this makes switch mode power supplies a "low impedance load".

Like an audio system, low impedance loads need to be matched with their power source. In this case of a system with a switch mode power supply, this source must be low impedance at power line frequencies but offer high impedance to noise and unwanted power disturbances. These modern power supplies should never be mismatched with a high impedance.

These line conditioners provide the best all-round power conditioning and surge protection for sensitive electronic equipment. . The integral isolation transformer provide complete isolation between the primary and secondary, and permits bonding its output neutral to ground, which completely eliminates all disturbances between neutral and ground, regardless of source. The series inductance of the isolation transformer in combination with capacitive elements and MOVs, provide superb noise filtering, as well as coordinated multi-stage surge protection.

Applications include:

- Sensitive telecommunications,
- Radio base stations (RBS)/base transmitter stations (BTS),
- Industrial and medical equipment,
- Other sensitive, specialized microprocessor-based equipment.

7 Utility surge arrestor

The three most common surge arrester technologies employed by utilities are,

I) Gapped silicon Carbide
II) Gapped MOV
III) Gapless MOV. Most arrester manufactured today use a MOV as the main voltage limiting elements. The Chief ingredient of a MOV is Zinc Oxide. (ZnO).

I) Gapped silicon Carbide

The older technology arrester use silicon carbide as the(SiC) energy dissipating non linear resistive element. As (SiC) is not ideal it is not non-linear enough and thus imposes certain design restriction. It allows the spark gap to clear and reseal without causing a fault and reduced the sparkover transient to 50% of the total sparkover voltage.

Gaps are necessary with the SiC because an economical SiC element giving the required discharge voltage is unable to withstand continues system operating voltage.

II) Gapped MOV

The gapped MOV tech. was introduced commercially in the early 90’s and accepted in some applications where there is need for increased protective margins. This technology combines resistance graded gaps and MOV blocks. It has a lower lightning discharge voltage but has a higher transient over voltage withstand characteristics.

III) Gapless MOV

The recently developed ideal surge arrester. It is a revolutionary advanced surge protective device for power systems. It is constructed by a series connection of zinc oxide (ZnO) elements having a highly non linear resistance. The excellent non-linear characteristic of zinc oxide elements has enabled to make surge arresters without series connected spark gaps. i.e. fully solid state arresters suitable for system protection up to the highest voltages. It is dimensioned so that the peak value of the phase to ground voltage in Normal operation never exceeds the sum of the rated voltages of the series connected disc. Fig 3.16 shows the comparative lightning wave discharge voltage characteristic for an 8X20µs(front time 8 µs and tail time 20 µs)

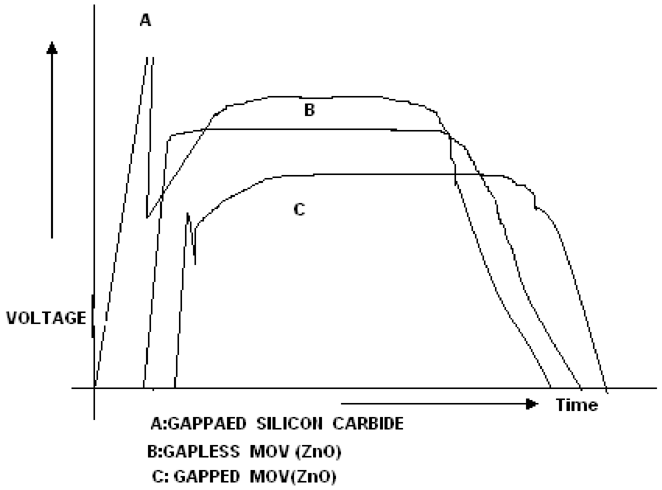


Fig 3.16

5. Discuss the common utility surge arresters with comparative wave discharge characteristics.

[ref previous question less chance for such a question because it come under HVE and PROTECTION.]

6. Name the different methods Utility System Lightning protection?

The different methods of Utility System Lightning protection are,

i. shielding
ii. line arrester

i. shielding

One of the strategies open to utilities for lines that are particularly susceptible to lightning strikes is to shield the line by installing a grounded neutral wire over the phase wires. This will intercept most lightning strokes before they strike the phase wires. This can help, but will not necessarily prevent line flashovers because of the possibility of back flashovers.

Shielding overhead utility lines is common at transmission voltage levels and in substations, but is not common on distribution lines because of the added cost of taller poles and the lower benefit due to lower flashover levels of the lines. On distribution circuits, the grounded neutral wire is typically installed underneath the phase conductors to facilitate the connection of line-to-neutral connected equipment such as transformers and capacitors. Shielding is not quite as simple as adding a wire and grounding it every few poles. When lightning strikes the shield wire, the voltages at the top of the pole will still be extremely high and could cause back flashovers to the line. This will result in a temporary fault. To minimize this possibility, the path of the ground lead down the pole must be carefully chosen to maintain adequate clearance with the phase conductors. Also, the grounding resistance plays an important role in the magnitude of the voltage and must be maintained as low as possible. However, when it becomes obvious that a particular section of feeder is being struck frequently, it may be justifiable to retrofit that section with a shield wire to reduce the number of transient faults and to maintain a higher level of power quality. Figure 4.29 illustrates this concept. It is not uncommon for a few spans near the substation to be shielded.

The substation is generally shielded anyway, and this helps prevent high-current faults close to the substation that can damage the substation transformer and breakers. It is also common near substations for distribution lines to be underbuilt on transmission or sub transmission structures. Since the transmission is shielded, this provides shielding for the distribution as well, provided adequate clearance can be maintained for the ground lead. This is not always an easy task. Another section of the feeder may crest a ridge giving it unusual exposure to lightning. Shielding in that area may be an effective way of Ref page 145 Dugan very clearly given. Draw the fig given in page 146.

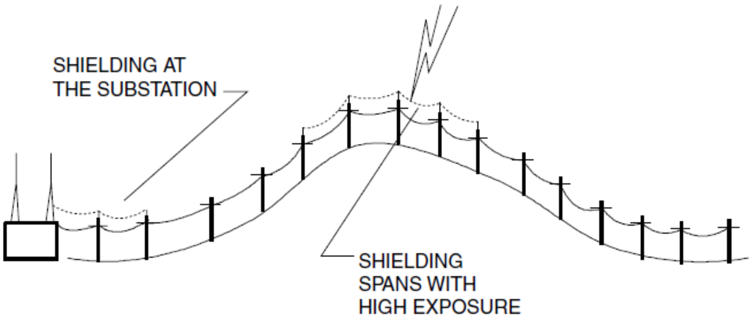


Figure 4.29 Shielding a portion of a distribution feeder to reduce the incidence of temporary lightning-induced faults.

reducing lightning-induced faults. Poles in the affected section may have to be extended to accommodate the shield wire and considerable effort put into improving the grounds. This increases the cost of this solution. It is possible that line arresters would be a more economical
and effective option for many applications.

ii. Line arrester

Another strategy for lines that are struck frequently is to apply arresters periodically along the phase wires. Normally, lines flash over first at the pole insulators. Therefore, preventing insulator flashover will reduce the interruption and sag rate significantly. Stansberry6 argues that this is more economical than shielding and results in fewer line flashovers. Neither shielding nor line arresters will prevent all flashovers from lightning. The aim is to significantly reduce flashovers in particular trouble spots.

As shown in Fig. 4.30, the arresters bleed off some of the stroke current as it passes along the line. The amount that an individual arrester bleeds off will depend on the grounding resistance. The idea is to space the arresters sufficiently close to prevent the voltage at unprotected poles in the middle from exceeding the basic impulse level (BIL) of the line insulators. This usually requires an arrester at every second or third pole. In the case of a feeder supplying a highly critical load, or a feeder with high ground resistance, it may be necessary to place arresters at every pole.

A transients study of different configurations will show what is required. Some utilities place line arresters only on the top phase when one phase is mounted higher than the others. In other geometries, it will be necessary to put arresters on all three phases to achieve a consistent reduction in flashovers.

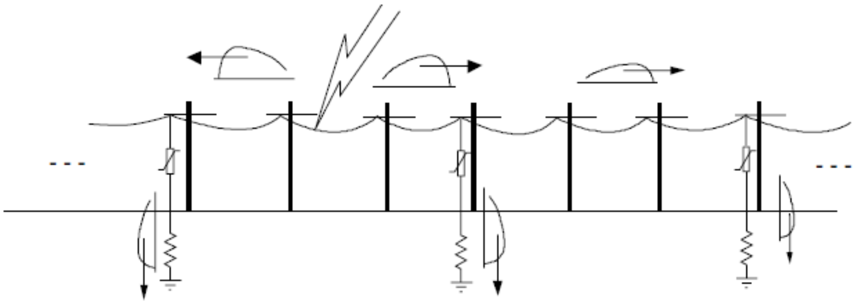


Figure 4.30 Periodically spaced line arresters help prevent flashovers.

Figure 4.31 Typical polymer-housed utility distribution arrester for overhead line applications. (Courtesy of Cooper Power Systems.)

Figure 4.31 shows a typical utility arrester that is used for overhead line protection applications. This model consists of MOV blocks encapsulated in a polymer housing that is resistant to sunlight and other natural elements. Older-technology models used porcelain housings like that shown on the primary side of the transformer in Fig. 4.33. There are already sufficient arresters on many lines in densely populated areas in North America to achieve sufficient line protection.

These arresters are on the distribution transformers, which are installed close together and in sufficient numbers in these areas to help protect the lines from flashover.

7. Write a note on PSAD

PSCAD stands for **Power Systems Computer Aided Design,** and represents a family of power system simulation products. Presently, it is used as a Graphical User Interface for the EMTDC™ transients' instantaneous solution engine.

PSCAD becomes an indispensable tool for a variety of power system designs and studies. It is a multi-purpose tool. It is equally capable in the areas of power electronic design and simulation, power quality analysis, and electrical utility system planning studies.

As electrical power and power electronic systems become more prevalent in electric vehicles, ships, trains, and distributed generation systems, the need for easy-to-use and accurate simulation and modeling tools becomes ever more important. It is easier and much less expensive to design and optimize electrical devices and systems prior to prototyping or manufacturing. Thus, PSCAD is becoming a true Power System Computer-Aided Design tool for a variety of industry application.

PSCAD users include engineers and technologists from energy utilities, electrical equipment manufacturers, engineering consulting firms, and research and academic institutions. PSCAD is used in the planning, design, and operational phases of power systems. It is also very prevalent in power system research around the world.

Some typical examples of how PSCAD™ can be applied to better understand electrical power systems are:

- **To find over-voltages** in a power system due to a fault condition (incorporates transformer non-linearities; provides multiple-run capability to determine best/worst-case scenarios in terms of location of fault, point-on-wave of the fault, and type of fault).

- **To find over-voltages** in a power system due to an event such as a lightning strike (accommodates a nano-second time step).

- **To find the harmonics** generated by virtually any power electronic device or system, including STATCOM's, HVDC transmission links, SVC's, and machine drives (provides accurate models of the power electronic switching devices such as thyristors, GTO's, IGBT's, diodes, etc.; includes detailed analog and digital control system models).

- **To investigate and mitigate** the pulsing effects of diesel generators and wind turbines, as well as other devices on the overall electric power grid.

- **To find** the maximum energy in a surge arrester for a given electrical disturbance.

- **To design** and fine tune control systems to optimize performance.

- **To investigate** the sub-synchronous response (SSR) impact when a machine and multi-mass turbine interact with power electronic equipment or series compensated transmission lines.
- **To model** voltage source converters (VSC) or STATCOMs along with their detailed control systems models.
- **To investigate** power system instabilities created by harmonic resonance or control system interactions.
- **To perform insulation co-ordination studies**.

- **To design** and simulate variable speed drives of many types including cyclo-converters and electric vehicle and ship propulsion system drives.

- **To design** industrial systems, such as compensation controllers, power electronic drives, electric furnaces, and filters.

- **To study** the transient and harmonic impact of distributed generation systems such as wind and micro-turbine systems on the power grid.

- **To study** and mitigate capacitor switching transients.

- **To study** the system impact of transmission line imbalances during contingency periods.

PSCAD is a multi-purpose power system simulator and can thus be used for any scenario where a detailed understanding of the full time domain of analysis is beneficial. This includes the design and modeling of virtually any electrical power system.

8. Write a note on EMTP.

The Electromagnetic Transients Program (EMTP) is a computer program for simulating electromagnetic, electromechanical, and control system transients on multi-phase electric power systems and it's derivatives Alternative Transients Program (ATP).

Studies involving use of the EMTP fall in two general categories.

- One is design, which includes insulation coordination, equipment ratings, protective device specification, control systems design, etc.

- The other is solving operational problems such as unexplained outages or equipment failures.

COMPONENTS

- Uncoupled and coupled linear, lumped R,L,C elements.

- Transmission lines and cables with distributed and frequency-dependent parameters.

- Nonlinear resistances and inductances, hysteretic inductor, time-varying resistance, TACS/MODELS controlled resistance.

- Components with nonlinearities: transformers including saturation and hysteresis, surge arresters (gapless and with gap), arcs.

- Ordinary switches, time-dependent and voltage-dependent switches, statistical switching (Monte-Carlo studies).

- Valves (diodes, thyristors, triacs), TACS/MODELS controlled switches.

- Analytical sources: step, ramp, sinusoidal, exponential surge functions, TACS/MODELS defined sources.

- Rotating machines: 3-phase synchronous machine, universal machine model.

- User-defined electrical components that include MODELS interaction

Typical Applications

EMTP is used world-wide for switching and lightning surge analysis, insulation coordination and shaft torsional oscillation studies, protective relay modeling, harmonic and power quality studies, HVDC and FACTS modeling. Typical EMTP studies are:

- Lightning overvoltage studies
- Switching transients and faults
- Statistical and systematic overvoltage studies
- Very fast transients in GIS and groundings
- Machine modeling
- Transient stability, motor startup
- Shaft torsional oscillations
- Transformer and shunt reactor/capacitor switching
- Ferroresonance
- Power electronic applications
- Circuit breaker duty (electric arc), current chopping
- FACTS devices: STATCOM, SVC, UPFC, TCSC modeling
- Harmonic analysis, network resonances
- Protective device testing

Some Additional Information

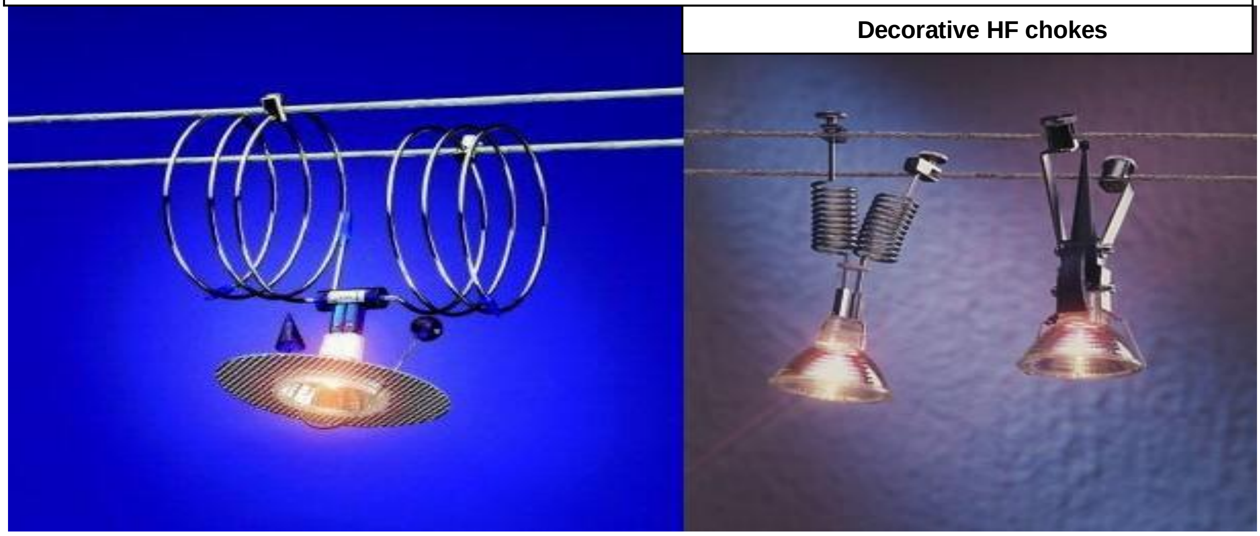
Noise- Electrical noise, or noise, is unwanted electrical signals that produce undesirable effects in the circuits in which they occur.

Common Mode Noise- Common Mode Noise present equally and in phase in each current carrying wire with respect to a ground plane or a circuit. Common mode noise can be caused by radiated emission from a source of EMI. Common mode noise can also couple from one circuit to another by inductive or capacitive means. Lightning discharges may also produce common mode noise in power wiring.

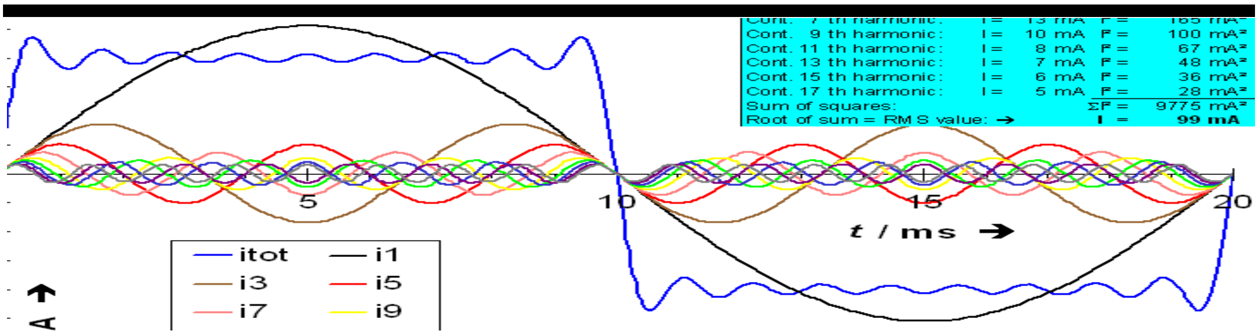
Ground loop- Potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

UNIT-4

HARMONICS



Decorative HF chokes



Cont. 7 th harmonic:	I =	13 mA	I^2 =	165 mA²
Cont. 9 th harmonic:	I =	10 mA	I^2 =	100 mA²
Cont. 11 th harmonic:	I =	8 mA	I^2 =	67 mA²
Cont. 13 th harmonic:	I =	7 mA	I^2 =	48 mA²
Cont. 15 th harmonic:	I =	6 mA	I^2 =	36 mA²
Cont. 17 th harmonic:	I =	5 mA	I^2 =	28 mA²
Sum of squares:			ΣI^2 =	9775 mA²
Root of sum = RMS value: →			**I =**	**99 mA**

Syllabus:

Harmonic sources from commercial and industrial loads, locating harmonic sources. Power system response characteristics - Harmonics Vs transients. Effect of harmonics - harmonic distortion - voltage and current distortion - harmonic indices - inter harmonics – resonance. Harmonic distortion evaluation - devices for controlling harmonic distortion - passive and active filters. IEEE and IEC standards

4.1 Introduction

Ideally, an electricity supply should invariably show a perfectly sinusoidal voltage signal at every customer location. However, for a number of reasons, utilities often find it hard to preserve such desirable conditions. The deviation of the voltage and current waveforms from sinusoidal is described in terms of the waveform distortion, often expressed as harmonic distortion.

Harmonic distortion is not new and it constitutes at present one of the main concerns for engineers in the several stages of energy utilization within the power industry. In the first electric power systems, harmonic distortion was mainly caused by saturation of transformers, industrial arc furnaces, and other arc devices like large electric welders. The major concern was the effect that harmonic distortion could have on electric machines, telephone interference, and increased risk of faults from overvoltage conditions developed on power factor correction capacitors.

The increasing use of nonlinear loads in industry is keeping harmonic distortion in distribution networks on the rise. The most used nonlinear device is perhaps the static power converter so widely used in industrial applications in the steel, paper, and textile industries. Other applications include multipurpose motor speed control, electrical transportation systems, and electrodomestic appliances.

No doubt harmonic studies from the planning to the design stages of power utility and industrial installations will prove to be an effective way to keep networks and equipment under acceptable operating conditions and to anticipate potential problems with the installation or addition of nonlinear loads.

Book name: HARMONICS AND POWER SYSTEMS
The ELECTRIC POWER ENGINEERING Series
Series Editor Leo L. Grigsby

4.2 Harmonic sources from commercial loads

Commercial facilities such as office complexes, department stores, hospitals, Internet data centers and IT industries are dominated with high-efficiency fluorescent lighting with electronic ballasts, adjustable-speed drives for the heating, ventilation, and air conditioning (HVAC) loads, elevator drives, and sensitive electronic equipment supplied by single-phase switch-mode power supplies. Commercial loads are characterized by a large number of small harmonic-producing loads. Depending on the diversity of the different load types, these small harmonic currents may add in phase or cancel each other. The voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion. Since power factor correction capacitors are not typically used in commercial facilities, the circuit impedance is dominated by the service entrance transformers and conductor impedances. Therefore, the voltage distortion can be estimated simply by multiplying the current by the impedance adjusted for frequency. Characteristics of typical nonlinear commercial loads are given below and it is detailed in the following sections.

- Single phase power supplies.
- Fluorescent lighting
- Adjustable speed drives for HVAC and elevators

a) Single-phase power supplies

Electronic power converter loads with their capacity for producing harmonic currents now constitute the most important class of nonlinear loads in the power system. A major concern in commercial buildings is that power supplies for single-phase electronic equipment will produce too much harmonic current. DC power for modern electronic and Microprocessor-based office equipment is commonly derived from single-phase full-wave diode bridge rectifiers. The percentage of load that contains electronic power supplies is increasing at a dramatic pace, with the increased utilization of personal computers in every commercial sector.

There are two common types of single-phase power supplies.

i) Older technologies use ac-side voltage control methods, such as transformers, to reduce voltages to the level required for the dc bus. The inductance of the transformer provides a beneficial side effect by smoothing the input current waveform, reducing harmonic content.

ii) Recent-technology (see Figure 4.1) switch-mode power supplies use dc-to-dc conversion techniques to achieve a smooth dc output with small, lightweight components.

The recent switch-mode power supply system has input diode bridge. It is directly connected to the ac line, eliminating the transformer. This results in a coarsely regulated dc voltage on the capacitor. This direct current is then converted back to alternating current at a very high frequency by the inverter and subsequently rectified again. Personal computers, printers, copiers, and most other single-phase electronic equipment now almost universally employ switch-mode power supplies. The key advantages are the light weight, compact size, efficient operation, and lack of need for a transformer.

Switch-mode power supplies can usually tolerate large variations in input voltage. Because there is no large ac-side inductance, the input current to the power supply comes in very short pulses as the capacitor C1 regains its charge on each half cycle. Figure 4.2 illustrates the current waveform and spectrum for an entire circuit supplying a variety of electronic equipment with switch-mode power supplies. A distinctive characteristic of switch-mode power supplies is a very high third-harmonic content in the current. Since third-harmonic current components are additive in the neutral of a three-phase system, the increasing application of switch-mode power supplies causes concern for overloading of neutral conductors, especially in older buildings where an undersized neutral may have been installed. There is also a concern for transformer overheating due to a combination of harmonic content of the current, stray flux, and high neutral currents.

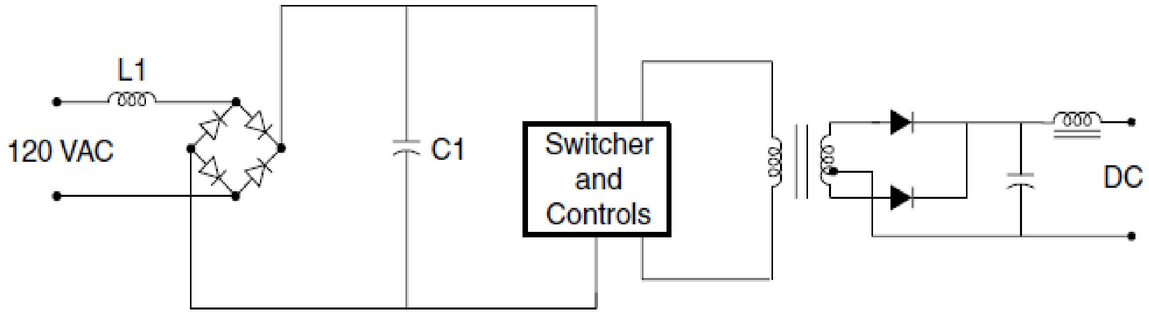
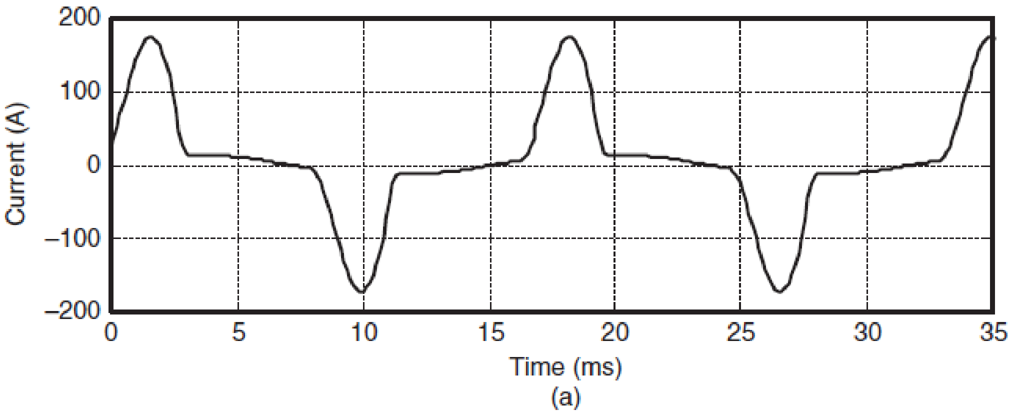


Figure 4.1. Switched mode power supply



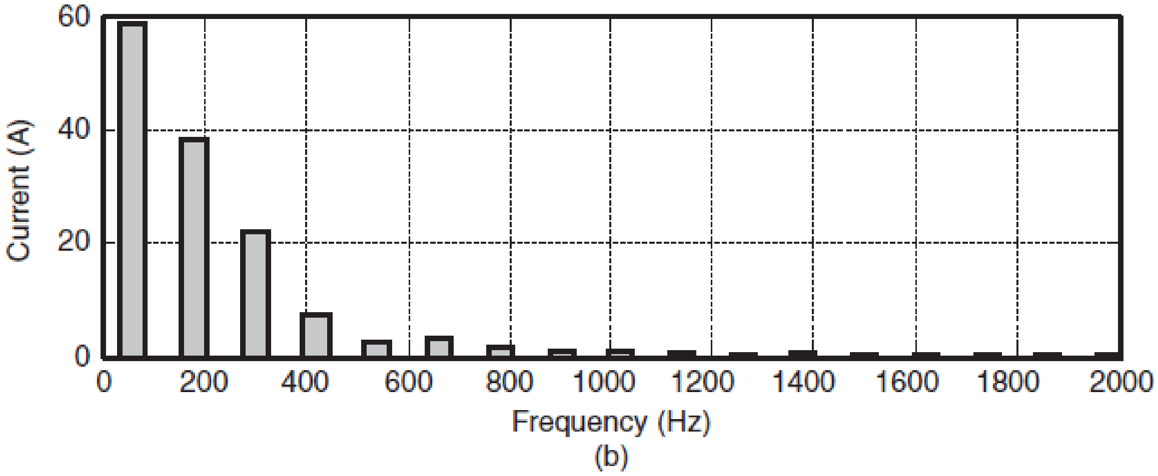


Figure 4.2 SMPS current and harmonic spectrum.

b) Fluorescent lighting

Fluorescent lights are discharge lamps; thus they require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge is established, the voltage decreases as the arc current increases. It is essentially a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, ballast is also a current-limiting device in lighting applications.

There are two types of ballasts
i). Magnetic Ballast
ii). Electronic Ballast

i) Magnetic Ballast

A standard magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. A single magnetic ballast can drive one or two fluorescent lamps, and it operates at the line fundamental frequency, i.e., 50 or 60 Hz. The iron-core magnetic ballast contributes additional heat losses, which makes it inefficient compared to an electronic ballast.

ii). Electronic Ballast

An electronic ballast employs a switch-mode–type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. This high frequency has two advantages. First, a small inductor is sufficient to limit. the arc current. Second, the high frequency eliminates or greatly reduces the 100- or 120-Hz flicker associated with an iron-core magnetic ballast. A single electronic ballast typically can drive up to four fluorescent lamps.

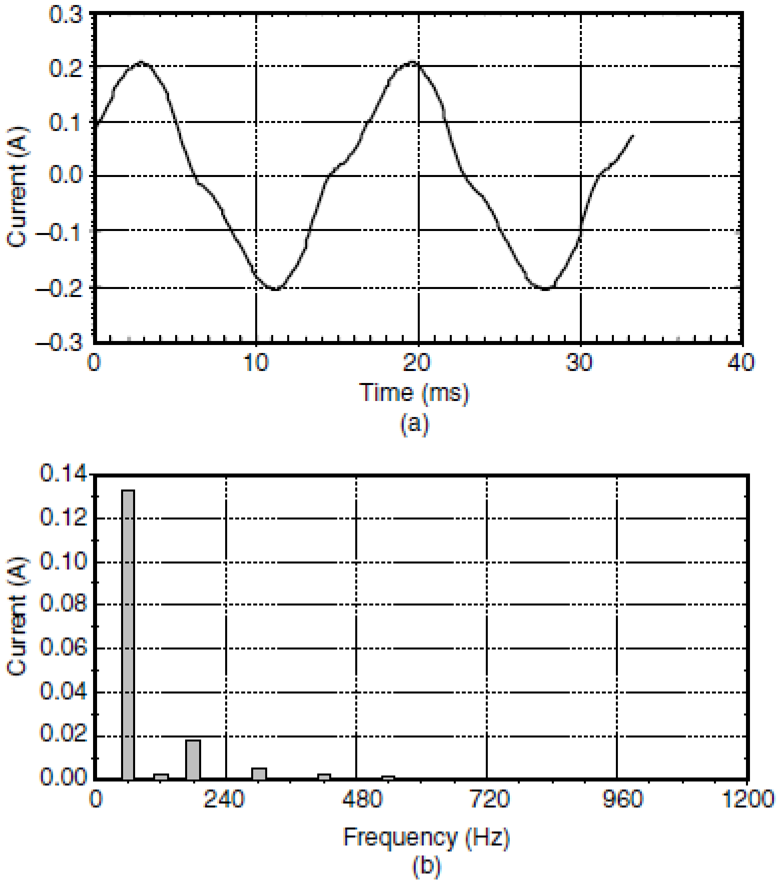


Figure 4.3 Fluorescent lamp with (a) magnetic ballast current waveform and (b) its harmonic spectrum.

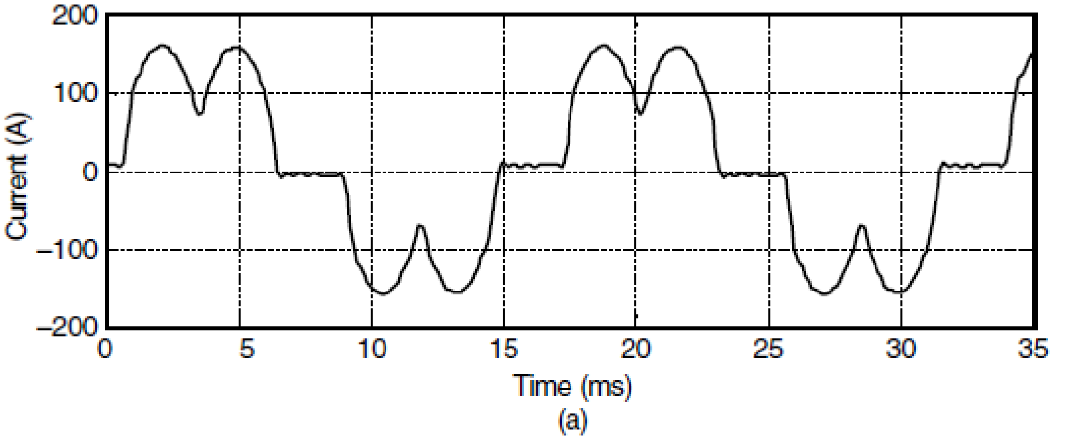
Standard magnetic ballasts are usually rather benign sources of additional harmonics themselves since the main harmonic distortion comes from the behavior of the arc. Figure 4.2 shows a measured fluorescent lamp current and harmonic spectrum. The current THD is a moderate 15 percent. As a comparison, electronic ballasts, which employ switch-mode power supplies, can produce double or triple the standard magnetic ballast harmonic output. Figure 5.13 shows a fluorescent lamp with an electronic ballast that has a current THD of 144. Other electronic ballasts have been specifically designed to minimize harmonics and may actually produce less harmonic distortion than the normal magnetic ballast-lamp combination. Electronic ballasts typically produce current THDs in the range of between 10 and 32 percent.
A current THD greater than 32 percent is considered excessive according to ANSI C82.11-1993, High-Frequency Fluorescent Lamp Ballasts. Most electronic ballasts are equipped with passive filtering to reduce the input current harmonic distortion to less than 20 percent.

4.3 Harmonic sources from industrial loads

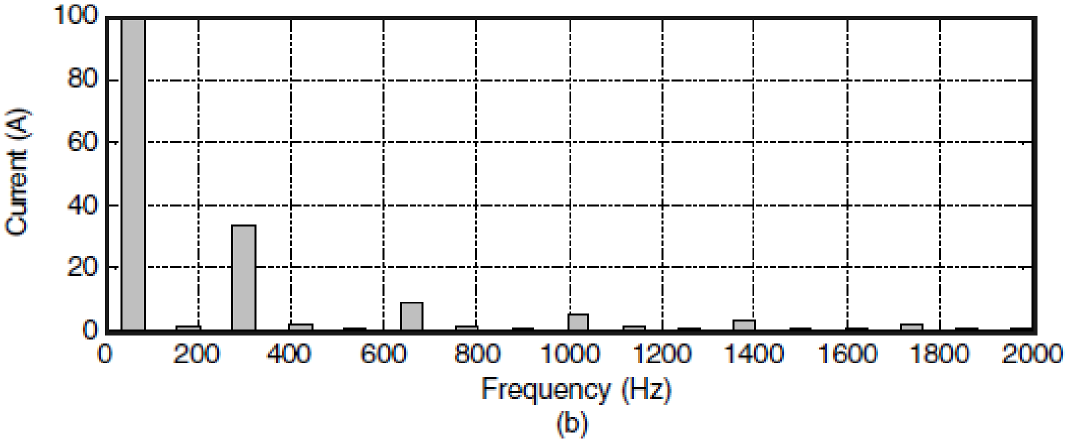
- Three phase power converters
- D.C drives
- AC drives
- Rotating machines
- Arcing devices (Furnace arc welders, discharge -type lightning like fluorescent, sodium vapor mercury vapor)
- Saturable devices(transformers and other electromagnetic devices with a steel core)

4.3.1 Three-phase power converters:

Three-phase electronic power converters differ from single-phase converters mainly because they do not generate third-harmonic currents. This is a great advantage because the third-harmonic current is the largest component of harmonics. However, they can still be significant sources of harmonics at their characteristic frequencies, as shown in figure. This is a typical current source type of adjustable-speed drive. The harmonic spectrum given in Fig. 4.4 would also be typical of a dc motor drive input current. Voltage source inverter drives (such as PWM-type drives) can have much higher distortion levels as shown



(a)



(b)

Figure 4.4: Current and harmonic spectrum for CSI-type ASD.

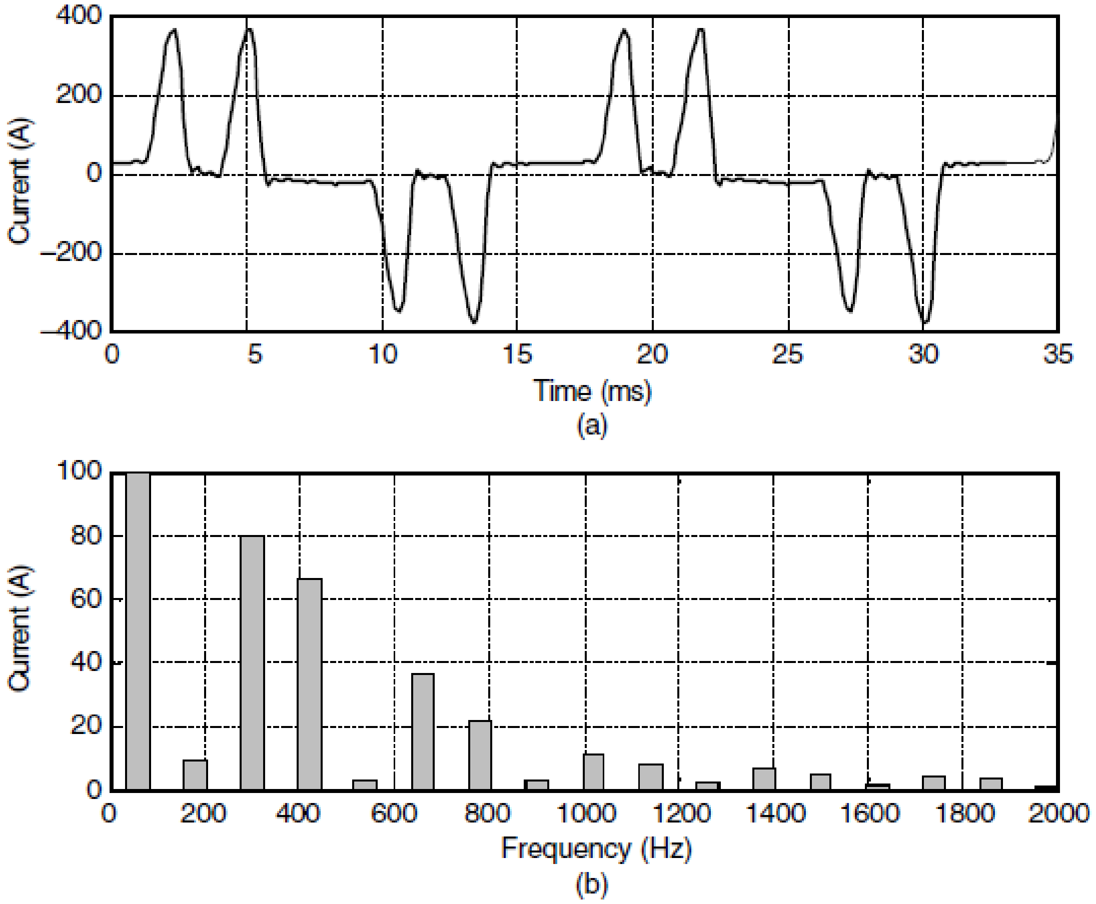


Figure 4.5: Current and harmonic spectrum for PWM-type ASD.

The input to the PWM drive is generally designed like a three-phase version of the switch-mode power supply in computers. The rectifier feeds directly from the ac bus to a large capacitor on the dc bus. With little intentional inductance, the capacitor is charged in very short pulses, creating the distinctive "rabbit ear" ac-side current waveform with very high distortion. Whereas the switch-mode power supplies are generally for very small loads, PWM drives are now being applied for loads up to 500 horsepower (hp). This is a justifiable cause for concern from power engineers.

DC drives. Rectification is the only step required for dc drives. Therefore, they have the advantage of relatively simple control systems. Compared with ac drive systems, the dc drive offers a wider speed range and higher starting torque. However, purchase and maintenance costs for dc motors are high, while the cost of power electronic devices has been dropping year after year. Thus, economic considerations limit use of the dc drive to applications that require the speed and torque characteristics of the dc motor. Most dc drives use the six-pulse rectifier shown in Fig. 4.5. Large drives may employ a 12-pulse rectifier. This reduces thyristor current duties and reduces some of the larger ac current harmonics. The two largest harmonic currents for the six-pulse drive are the fifth and seventh. They are also the most troublesome in terms of system response. A 12-pulse rectifier in this application can be expected to eliminate about 90 percent of the fifth and seventh harmonics, depending on system imbalances. The disadvantages of the 12-pulse drive are that there is more cost in electronics and another transformer is generally required.

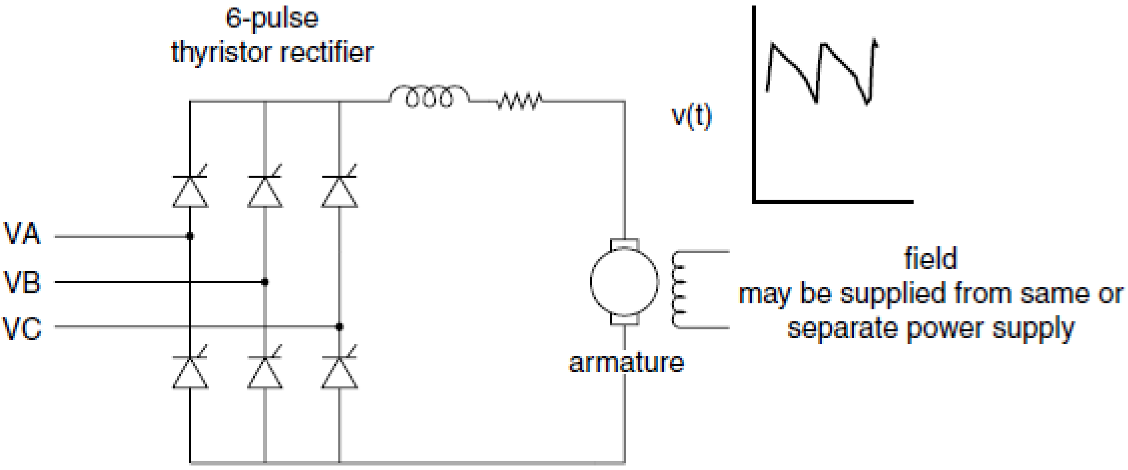


Figure 4.6: Six-pulse AC/DC rectifier using an Adjustable Speed Drive.

AC drives. In ac drives, the rectifier output is inverted to produce a variable-frequency ac voltage for the motor. Inverters are classified as voltage source inverters (VSIs) or current source inverters (CSIs). A VSI requires a constant dc (i.e., low-ripple) voltage input to the inverter stage. This is achieved with a capacitor or *LC* filter in the dc link. The CSI requires a constant current input; hence, a series inductor is placed in the dc link. AC drives generally use standard squirrel cage induction motors. These motors are rugged, relatively low in cost, and require little maintenance. Synchronous motors are used where precise speed control is critical. A popular ac drive configuration uses a VSI employing PWM techniques to synthesize an ac waveform as a train of variable-width dc pulses (see Fig. 4.6). The inverter uses either SCRs, gate turnoff (GTO) thyristors, or power transistors for this purpose. Currently, the VSI PWM drive offers the best energy efficiency for applications over a wide speed range for drives up through at least 500 hp. Another advantage of PWM drives is that, unlike other types of drives, it is not necessary to vary rectifier output voltage to control motor speed. This allows the rectifier thyristors to be replaced with diodes, and the thyristor control circuitry to be eliminated. Very high power drives employ SCRs and inverters. These may be 6-pulse, as shown in Fig. 4.7, or like large dc drives, 12-pulse. VSI drives (Fig. 4.8) are limited to applications that do not require rapid changes in speed. CSI drives (Fig. 4.9) have good acceleration/deceleration characteristics but require a motor with a leading power factor (synchronous or induction with capacitors) or added control circuitry to commutate the inverter thyristors. In either case, the CSI drive must be designed for use with a specific motor. Thyristors in current source inverters must be protected against inductive voltage spikes, which increases the cost of this type of drive.

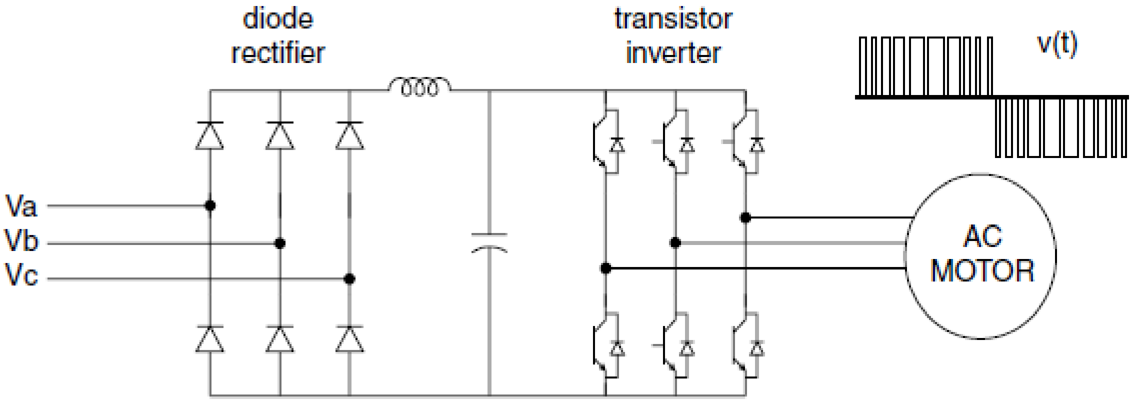
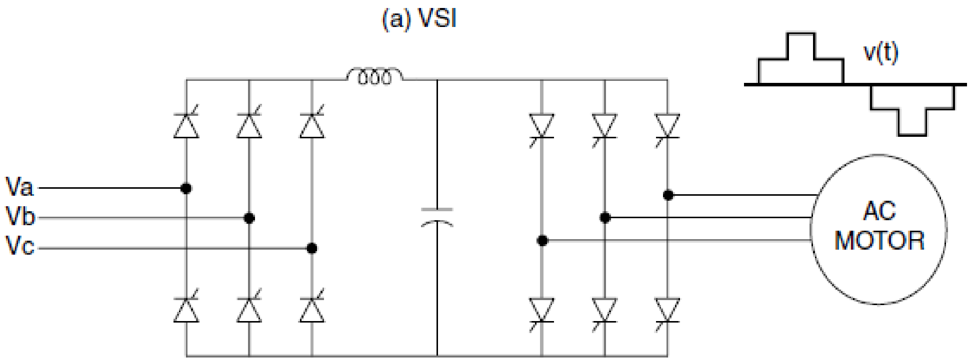


Figure 4.7: PWM based Adjustable Speed Drive.



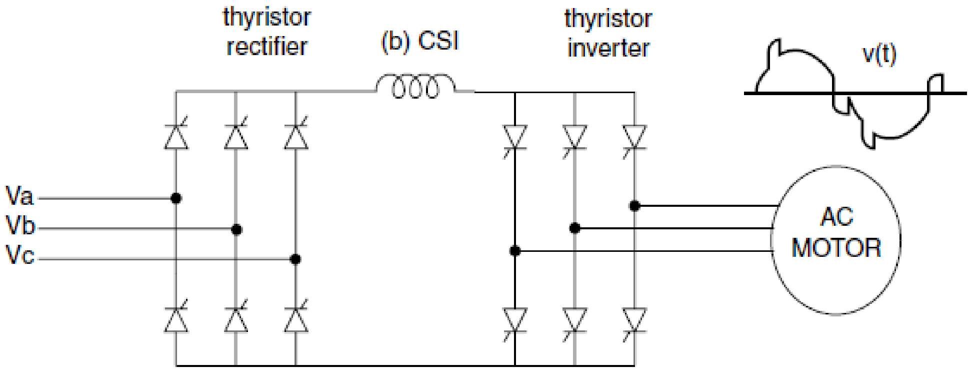


Figure 4.8. Large AC Adjustable Speed Drives.

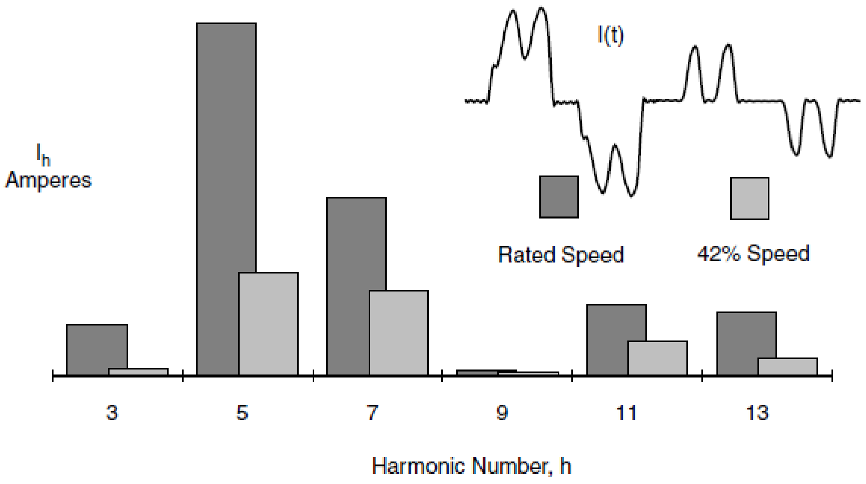


Figure 4.9. Effect of PWM ASD speed on ac current harmonics.

Impact of operating condition. The harmonic current distortion in adjustable-speed drives is not constant. The waveform changes significantly for different speed and torque values. Figure 10 shows two operating conditions for a PWM adjustable speed drive. While the waveform at 42 percent speed is much more distorted proportionately, the drive injects considerably higher magnitude harmonic currents at rated speed. The bar chart shows the amount of current injected. This will be the limiting design factor, not the highest THD. Engineers should be careful to understand the basis of data and measurements concerning these drives before making design decisions.

4.3.2 Arcing devices

This category includes arc furnaces, arc welders, and discharge-type lighting (fluorescent, sodium vapor, mercury vapor) with magnetic (rather than electronic) ballasts. As shown in Fig.4.10, the arc is basically a voltage clamp in series with a reactance that limits current to a reasonable value.

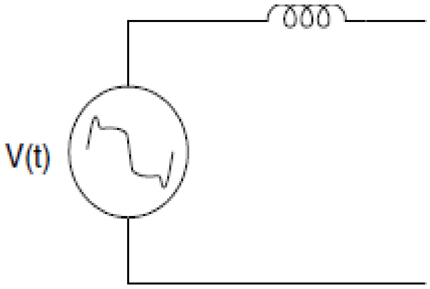


Figure 4.10. Equivalent circuit for an arcing device.

The voltage-current characteristics of electric arcs are nonlinear. Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system. This gives the arc the appearance of having a negative resistance for a portion of its operating cycle such as in fluorescent lighting applications.

In electric arc furnace applications, the limiting impedance is primarily the furnace cable and leads with some contribution from the power system and furnace transformer. Currents in excess of 60,000 A are common.

The electric arc itself is actually best represented as a source of voltage harmonics. If a probe were to be placed directly across the arc, one would observe a somewhat trapezoidal waveform. Its magnitude is largely a function of the length of the arc. However, the impedance of ballasts or furnace leads acts as a buffer so that the supply voltage is only moderately distorted. The arcing load thus appears to be a relatively stable harmonic current source, which is adequate for most analyses. The exception occurs when the system is near resonance and a Thevenin equivalent model using the arc voltage waveform gives more realistic answers.

The harmonic content of an arc furnace load and other arcing devices is similar to that of the magnetic ballast shown in Fig. 4.3. Three phase arcing devices can be arranged to cancel the triplen harmonics through the transformer connection. However, this cancellation may not work in three-phase arc furnaces because of the frequent unbalanced operation during the melting phase. During the refining stage when the arc is more constant, the cancellation is better.

4.3.3 Saturable devices

Equipment in this category includes transformers and other electromagnetic devices with a steel core, including motors. Harmonics are generated due to the nonlinear magnetizing characteristics of the steel (see Fig. 4.11).

Power transformers are designed to normally operate just below the “knee” point of the agnetizing saturation characteristic. The operating flux density of a transformer is selected based on a complicated optimization of steel cost, no-load losses, noise, and numerous other factors. Many electric utilities will penalize transformer vendors by various amounts for no-load and load losses, and the vendor will try to meet the specification with a transformer that has the lowest evaluated cost. A high-cost penalty on the no-load losses or noise will generally result in more steel in the core and a higher saturation curve that yields lower harmonic currents.

Although transformer exciting current is rich in harmonics at normal operating voltage (see Fig.4.12), it is typically less than 1 percent of rated full load current. Transformers are not as much of a concern as electronic power converters and arcing devices which can produce harmonic currents of 20 percent of their rating, or higher. However, their effect will be noticeable, particularly on utility distribution systems, which have hundreds of transformers. It is common to notice a significant increase in triplen harmonic currents during the early morning hours when the load is low and the voltage rises. Transformer exciting current is more visible then because there is insufficient load to obscure it and the increased voltage causes more current to be produced. Harmonic voltage distortion from transformer over excitation is generally only apparent under these light load conditions.

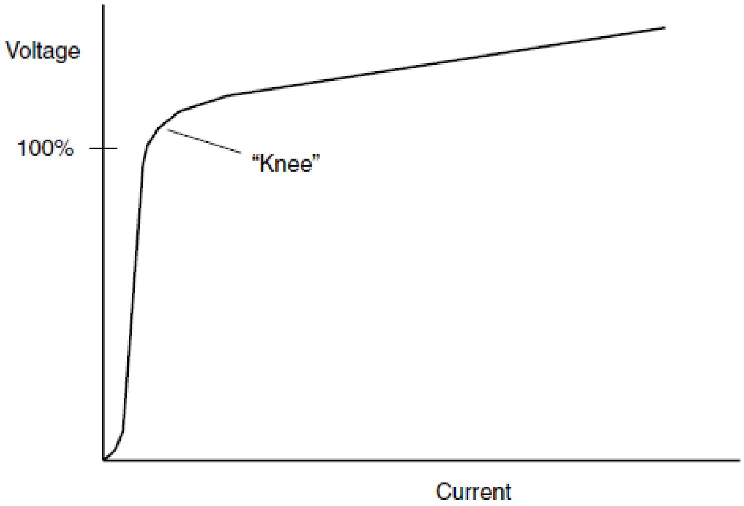


Figure 4.11. Transformer magnetizing characteristic.

Some transformers are purposefully operated in the saturated region. One example is a triplen transformer used to generate 180 Hz for induction furnaces. Motors also exhibit some distortion in the current when overexcited, although it is generally of little consequence. There are, however, some ractional horsepower, single-phase motors that have a nearly triangular waveform with significant third-harmonic currents.

The waveform shown in Fig. 4.12 is for single-phase or wye-grounded three-phase ransformers. The current obviously contains a large amount of third harmonic. Delta connections and ungrounded-wye connections prevent the flow of zero-sequence harmonic, which triplens tend to be. Thus, the line current will be void of these harmonics unless there is an imbalance in the system.

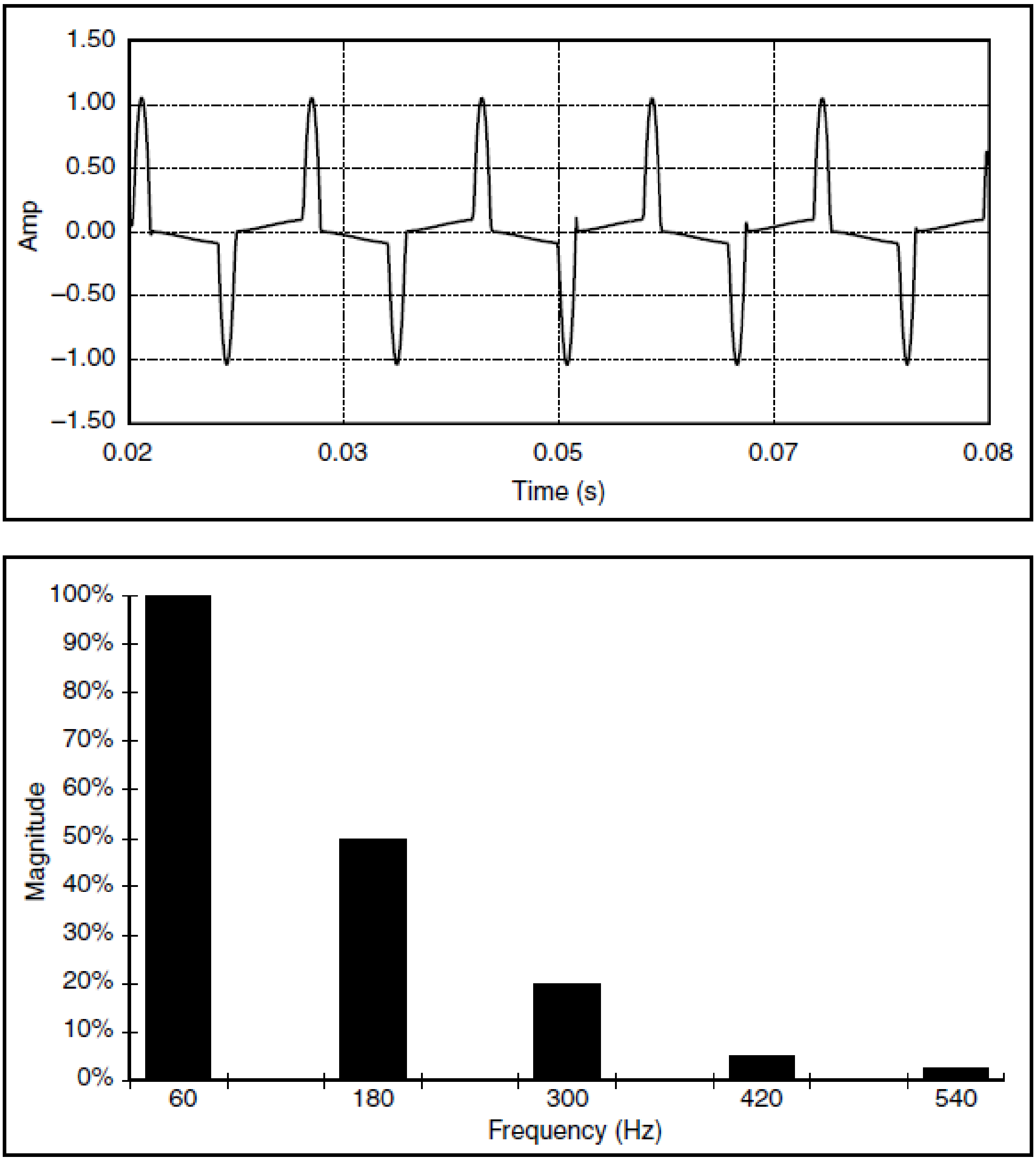


Figure 4.12. Transformer magnetizing current and harmonic spectrum.

4.4. Harmonics controlling Devices:

- In- line reactors or chokes
- Zigzag transformer.
- Active filters
  - -series active filter
  - -shunt active filter
- Passive filters
  - -shunt passive filter
  - -series passive filter
- c- type filter

4.4.1. In–Line reactors or chokes

Simply a series inductance which represents a series impedance that is directly proportional to frequency. Relatively small reactor or choke inserted at the line input side of the drive the inductance slows the rate at which the capacitor on the DC bus can be charged and forces the drive to draw current over a longer time period. The net effect is a lower magnitude current with much less harmonics.

4.4.2. Zigzag Transformer

A zigzag transformer is a special purpose transformer. It has primary windings but no secondary winding. One application is to derive an earth reference point for an ungrounded electrical system. Another is to control harmonic currents. Consider a three-phase Y (wye) transformer with an earth connection on the neutral point. Cut each winding in the middle so that the winding splits into two. Turn the outer winding around and rejoin the outer winding to the next phase in the sequence (i.e. outer A phase connects to inner B phase, outer B phase connects to inner C phase, and outer C phase connects to inner A phase). This device is the zigzag transformer.

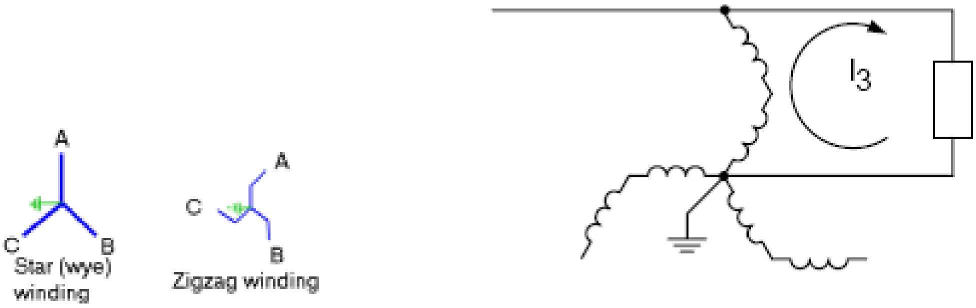


Figure 4.13. Zigzag transformer winding diagram

These transformers are 3-phase, dry-type autotransformers that are wound on a common core and are designed for very low zero-sequence impedance. The zero-sequence impedance is usually less than 1%, and the reactance component is very small.

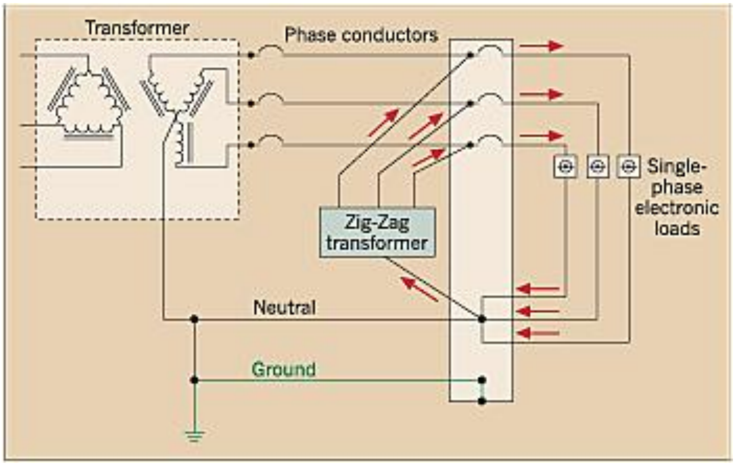


Figure.4.14. Zigzag Transformer connections

They're designed for 3-phase, 4-wire systems, and they provide a low-impedance path for the zero sequence harmonic currents. They should be installed in parallel and typically at a panel or bus duct that is as close as possible to the harmonic producing load see fig 15 above.

- Zig-zag transformers offer the following benefits for controlling the harmonic voltages and currents.
- There are no capacitors. The magnetic-only solution eliminates concerns about resonance or magnification of other harmonic components.
- They reduce third harmonic current components flowing in both the phase conductors and the neutral conductors up-line (back towards the supply) from the zig-zag transformer installation. By providing a shorter path.
- This reduces neutral conductor loading problem and losses in all of the conductors and the supply transformer. It also reduces transformer heating for the supply transformer

4.4.3. Active filters

An active filter removes harmonics from the supply current by injecting the opposite harmonics that are produced by the load. An example of the active filter system is shown in the Figure 4.15.

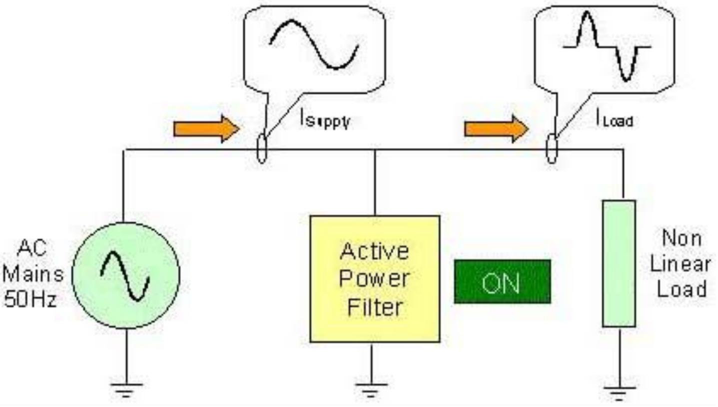


Figure 4.15 Active filters for harmonic elimination

(i) Harmonic cancellation-active filters

This technique uses an insulated gate bipolar transistor (IBGT) based device. The basic operation of this type of filter involves measurement and analysis of the input current waveform, with the injection of the inverse harmonic current waveform. You typically select the active filter capacity based upon harmonic cancellation current requirements, which is accomplished by determining the magnitude of harmonic current desired to be removed from the system. When properly selected, an active filter will typically reduce harmonics to residual levels of about 5% THD_I. You connect a standalone active filter in parallel with the power system. It is suitable for a mixture of both nonlinear and linear loads.

(ii) Active Harmonic Filter

An active harmonic filter is something like a boost regulator. The concept used in an active filter is the introduction of current components using power electronics to remove the harmonic distortions produced by the non-linear load.

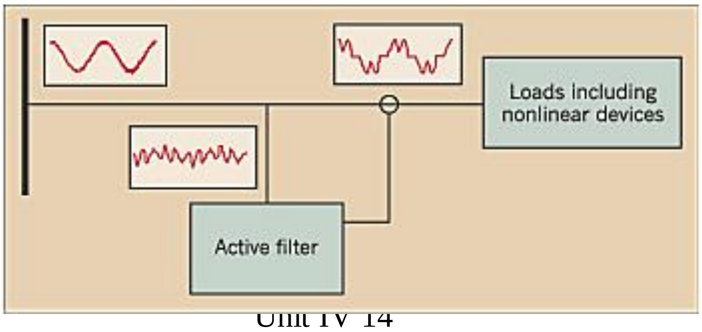


Figure 4.16 Active Harmonics filter used for elimination of Harmonics due to non-linear loads

These filters correct harmonic distortion levels by monitoring the current waveform that includes the nonlinear loads, and by creating a current waveform that results in cancellation of the harmonic components. Several different control strategies are possible in the nonlinear load current. Active filters for commercial applications have the following advantages:

Active harmonic filters are mostly used for low-voltage networks.

There are mainly two types of active harmonic filters based on the way they are connected to the AC distribution network.

a) The series filter is connected in series with the AC distribution network. It serves to offset harmonic distortions caused by the load as well as that present in the AC system.

b) The parallel/ shunt filter is connected in parallel with the AC distribution network and offset the harmonic distortions caused by the non-linear load.

4.4.4. Passive Harmonic Filter

A passive harmonic filter is built using an array of capacitors, inductors, and resistors. It can take the form of a simple line reactor or may use a series of parallel resonant filters to eliminate harmonics. Passive harmonic filters are also divided based on the way they are connected with the load.

a) A series filter: Here the filter is placed in series with the load and uses parallel components, i.e. inductors and capacitors are in parallel. This filter is a current rejecter.

Unlike a notch filter which is connected in shunt with the power system, a series passive filter is connected in series with the load. The inductance and capacitance are connected in parallel and are tuned to provide high impedance at a selected harmonic frequency. The high impedance then blocks the flow of harmonic currents at the tuned frequency only. At fundamental frequency, the filter would be designed to yield a low impedance, thereby allowing the fundamental current to follow with only minor additional impedance and losses. Figure 4.16 shows a typical series filter arrangement. Series filters are used to block a single harmonic current (such as the third harmonic) and are especially useful in a single-phase circuit where it is not possible to take advantage of zero-sequence characteristics. The use of the series filters is limited in blocking multiple harmonic currents. Each harmonic current requires a series filter tuned to that harmonic. This arrangement can create significant losses at the fundamental frequency. Furthermore, like other series components in power systems, a series filter must be designed to carry a full rated load current and must have an over current protection scheme. Thus, series filters are much less commonly applied than shunt filters.

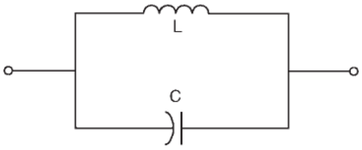


Figure 4.16. A series passive filter.

4.4.5. C-type filter

It is used for complex loads, Cyclo-converters and electric arc furnaces and is a special variation of the high pass filter. This filter will provide the load with reactive power and avoid forming parallel resonance circuits with the load.

4

HARMONICS

(SHORT TYPE QUESTIONS AND ANSWERS)

What is in Unit 4?

- **Harmonic Concept, Harmonic Resonance Etc.**
- **Quantitative Expression, Indices Or Evaluation.**
- **Sources Of Harmonics.**
- **Controlling Or Mitigating Devices.**
- **Harmonic Standards.**

1. Define Harmonics.

A sinusoidal component of a periodic wave having a frequency that is an integral multiple of the fundamental frequency. Thus for a power system with f_0 (50 Hz)fundamental frequency, the frequency of the h-th (if 2nd)order of harmonic is hf_0 2x50) Harmonics are usually defined as periodic steady state distortions of voltage and/or current waveforms in power systems.

2. What causes harmonics?

One common source of harmonics is iron core devices like transformers. The magnetic characteristics of iron are almost linear over a certain range of flux density, but quickly saturate as the flux density increases. This nonlinear magnetic characteristic is described by a hysteresis curve. Because of the nonlinear hysteresis curve, the excitation current waveform isn't sinusoidal.

Generators themselves produce some 5th harmonic voltages due to magnetic flux distortions that occur near the stator slots and non-sinusoidal flux distribution across the air gap. Other producers of harmonics include nonlinear loads like rectifiers, inverters, adjustable-speed motor drives, welders, arc furnaces, voltage controllers, and frequency converters.

Semiconductor switching devices produce significant harmonic voltages as they abruptly chop voltage waveforms during their transition between conducting and cutoff states. Inverter circuits are notorious for producing harmonics, and are in widespread use today. An adjustable-speed motor drive is one application that makes use of inverter circuits, often using pulse width modulation (PWM) synthesis to produce the AC output voltage.

3. What is a non- linear load.? Why a non-linear load is more significant from harmonic point of view?

A non linear devices is one in which the current is not proportional to the applied voltage.

Nonlinear load- Electrical load that draws currents discontinuously or whose impedance varies during each cycle of the input AC voltage wave form.

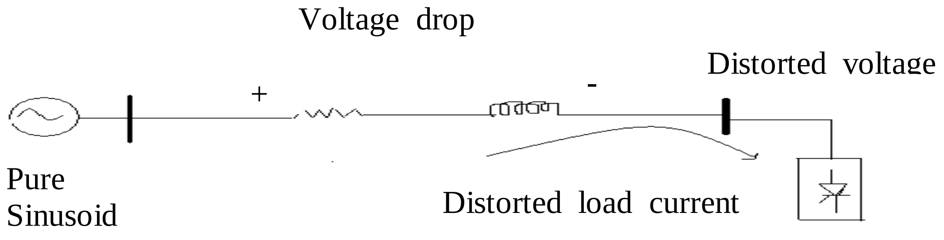
4. What is IEEE standard 519-1992?

IEEE 519 Explains about Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

5. What is harmonic distortion

Harmonic distortion is caused by non-linear devices in the power system. (A non linear devices is one in which the current is not proportional to the applied voltage). Harmonics occur in the steady state, and are integer multiples of the fundamental frequency.

6. Explain briefly voltage verses current distortions.



Harmonic current flowing through the system impedance result in harmonic voltage at the load

7. What is the significance of Harmonic Indices? Name some common harmonic indices

The two most commonly used indices (fig showing the relative level) for measuring the harmonics are

- Total harmonic distortion(thd)
- Total demand distortion(tdd)

8. Define Total Harmonic Distortion (THD).What does it indicate?

The ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity expressed expressed as a percent of the fundamental

$$THD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty} (M_h)^2}}{M_{fundamenta\ l}} \times 100\ \%$$

Where, M_h is the magnitude of either the voltage or current harmonic component and $M_{fundamental}$ is the magnitude of either the fundamental voltage or current.

Significance of THD

- THD provides a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load
- Gives indication of additional losses caused by the current flowing through a conductor.

9. Define Total demand distortion (TDD). Why it is preferred over total harmonic distortion?(TDD)

The Total Demand Distortion (TDD) shall be defined as the ratio of the RMS value of the harmonic content to the RMS value of the rated or maximum fundamental quantity. A small current may have a high THD but not be significant threat to the system. Even though relative current distortion may be high but magnitude of harmonic current can be low. To avoid this difficulty we go for Total Demand Distortion (TDD) instead of THD.

10. Define Telephone Influence Factor

Telephone influence factor (TIF) is a measure used to describe the telephone noise originating from harmonic currents and voltages in power systems.

11. Give few harmonic - producing commercial loads.

- Single phase power supplies.
- Fluorescent lighting
- Adjustable speed drives for HVAC and elevators

12. Give few harmonic - producing industrial loads.

Three phase power converters

- D.C drives
- AC drives
- Arcing devices (Furnace arc welders, discharge -type lightning like fluorescent, sodium vapor mercury vapor)
- Saturable devices(transformers and other electromagnetic devices with a steel core)

13. What is harmonic resonance?

Harmonic resonance is caused when the electrical system reactances (capacitive and inductive) combine to form a tank circuit (LC circuit) with its natural resonant frequency near any frequency where electrical energy may be present. Harmonic resonance can appear in two different forms,

- Parallel resonance
- Series resonance

14. Name the devices for controlling harmonics

- In- line reactors or chokes
- Zigzag transformer.
- Passive filters

- shunt passive filter
- series passive filter

- Active filters

15. What is IEC standard on harmonics?

The IEC (International Electrotechnical Commission) standard on harmonics, Explains about the Electromagnetic compatibility standard that deals with power quality issues. The Electromagnetic compatibility includes concerns for both radiated and conducted interference with end use equipment's. The IEC standards are broken down in to six parts.

16. Define interharmonic frequency.

the sum of two or more pure sine waves with different amplitudes where the frequency of each sinusoid is not an integer multiple of the fundamental frequency does not necessarily result in a periodic waveform. This noninteger multiple of the fundamental frequency is commonly known as an interharmonic frequency.

17. Define Triplen Harmonics.

The triplen harmonics are defined as the odd multiples of the 3rd harmonic (ex. 3rd, 9th, 15th, 21st etc.).

18. What are the bad effects of harmonics?

In general, harmonics present on a distribution system can have the following effects:

- Overheating of transformers & rotating equipment
- Increased Hysteresis losses
- Decreased kVA capacity
- Neutral overloading
- Unacceptable neutral-to-ground voltages
- Distorted voltage and current waveforms
- Failed capacitor banks
- Breakers and fuses tripping
- Interference on phone and communications systems
- Unreliable operation of electronic equipment

- Erroneous register of electric meters
- Wasted energy/height electric bills - kW & kWh
- Wasted capacity - Inefficient distribution of power

19. What is a harmonic filter?

A harmonic filter is used to eliminate the harmonic distortion caused by appliances. Harmonic filters isolate harmonic current to protect electrical equipment from damage due to harmonic voltage distortion. They can also be used to improve power factor.

20.What are passive harmonic filters?

Passive harmonic filters are built with a series of passive components such as resistors, inductors and capacitors. Passive filters are most common and available for all voltage levels. They are built-up by combinations of capacitors, inductors (reactors) and resistors.

21.What are active harmonic filters?

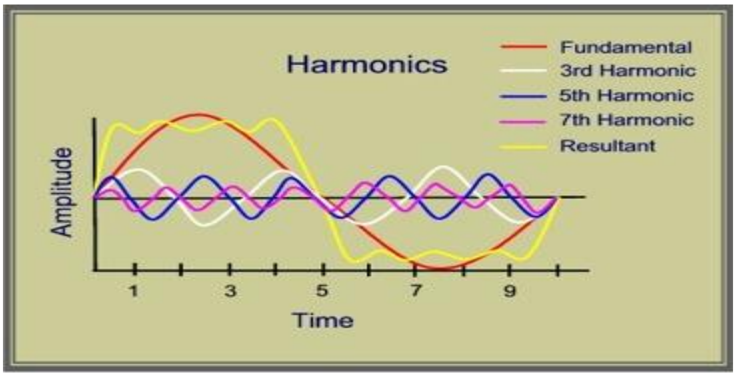
Active filters are available mainly for low voltage networks. Active harmonic filters are very fast electronic devices that will insert negative harmonics into the network, thus eliminating the undesirable harmonics on the network. The filters are built with active components such as IGBT-transistors and can eliminate many different harmonic frequencies. Signal types can be single phase AC, three phase AC, or DC.

4

HARMONICS

(LONG TYPE QUESTIONS AND ANSWERS)

1. Explain Harmonics



Harmonics: Harmonics by definition are a steady state distortion of the fundamental frequency (50 Hz). Harmonic distortion of current occurs when sinusoidal voltage is applied to a non-linear load (ex. electronic ballast, PLC, adjustable-speed drive, arc furnace, any ac/dc converter). The result is a distortion of the fundamental current waveform. This distortion occurs in integer multiples of the fundamental frequency (50 Hz). Hence, the 2nd Harmonic has a frequency = 2 x 50= 100 Hz, the 3rd Harmonic = 150 Hz and so on. Voltage distortion, on the other hand, is generated indirectly as result of harmonic currents flowing through a distribution system.

It is important to note that the vast majority of harmonic currents found in a distribution system are odd-order harmonics (3rd, 5th, 7th, etc.). Secondly, more often than not, the sources of the harmonic currents in a distribution system are the loads in operation within that facility. Interestingly, these are frequently the types of loads that are the most sensitive to distortion in the current and/or voltage.

2. Explain. Harmonic distorsion, Voltage versus current distorsion

(OR)

What is harmonic distortion and what are it’s effects? Explain voltage & current distortion.

distortion: Any deviation from the normal sine wave of an AC quantity.

Harmonic distortion is caused by non-linear devices in the power system. (A non linear devices is one in which the current is not proportional to the applied voltage). Harmonics occur in the steady state, and are integer multiples of the fundamental frequency.

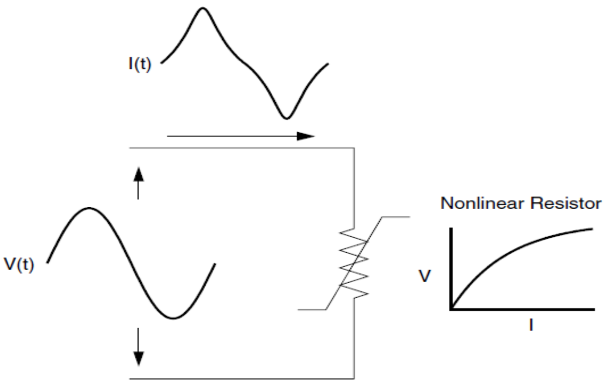


Fig 4.1. current distortion caused by non linear resistor

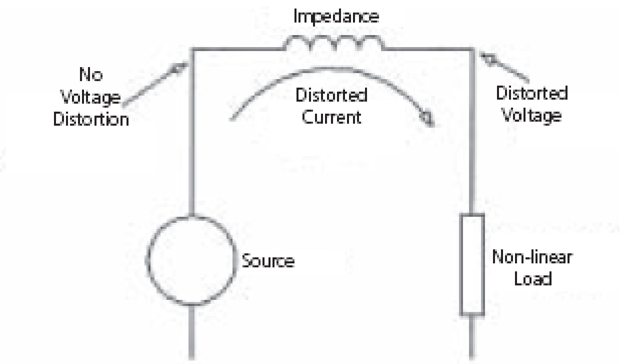


Fig 4.2 Distorted current-induced voltage distortion.

Voltage Versus Distortion

When a non-linear load draws current, that current passes through all of the impedance that is between the load and the system source (see Figure 4.2 As a result of the current flow, harmonic voltages are produced by impedance in the system for each harmonic. These voltages sum and, when added to the nominal voltage, produce voltage distortion. The magnitude of the voltage distortion depends on the source impedance and the harmonic voltages produced.

If the source impedance is low, then the voltage distortion will be low. If a significant portion of the load becomes non-linear (harmonic currents increase) and/or when a resonant condition prevails (system impedance increases), the voltage can increase dramatically. Power systems are able to absorb a considerable amount of current distortion without problems, and the distortion produced by a facility may be below levels recommended in IEEE 519. Fig 4.3 shows that voltage distortion is the result of distorted currents passing through the linear, series impedance of the power delivery system.

Although we have assumed here that the source bus contains only fundamental frequency voltage, the harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic. This results in voltage harmonics appearing at the load bus. The amount of voltage distortion depends on the impedance and the current. Assuming the load bus distortion stays within reasonable limits(less than 5 percent), the amount of harmonic current produced by the load is nearly constant for each load level. Voltage waveform distortion typically relates to electronic equipment, which has an internal switch-mode power supply (SMPS) that draws a nonlinear current waveform. Whereas a linear load produces a sine wave current, the SMPS draws current pulses at only one portion of the applied voltage waveform. This nonlinear current increases with each added device.

The nonlinear current, combined with the impedance of the circuit conductors and the power source, creates a voltage drop you see at the peak portions of the voltage waveform. The heavier the loading, the greater the root-means-square (rms) voltage drop. Recent changes in SMPS design and efficiency decreased the amplitude of current and, therefore, the amount of voltage waveform distortion

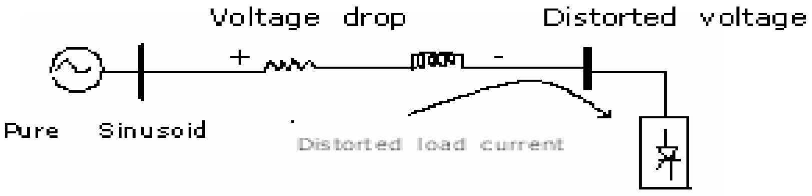


Fig 4.3 harmonic current flowing through the system impedance result in harmonic voltage at the load

3. Explain the harmonic indices THD & TDD in detail.
(OR)
Common Harmonic Indices.

In harmonic analysis there are several important indices used to describe the effects of harmonics on power system components and communication systems but the two most commonly used indices for measuring the harmonics are,

- Total harmonic distortion(THD)
- Total demand distortion(TDD)

i. Total harmonic distortion(THD)

The ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity expressed as a percent of the fundamental

$$THD\ \% = \frac{\sqrt{\sum_{h=2}^{h=\infty} (M_h)^2}}{M_{fundamental}} \times 100\ \%$$

Where, M_h is the magnitude of either the voltage or current harmonic component and $M_{fundamental}$ is the magnitude of either the fundamental voltage or current.

Significance of THD

- THD provides a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load
- Gives indication of additional losses caused by the current flowing through a conductor.

Derivation

The THD is a measure of the effective value of the harmonic components of a distorted waveform. That is, it is the potential heating value of the harmonics relative to the fundamental. This index can be calculated for either voltage or current:

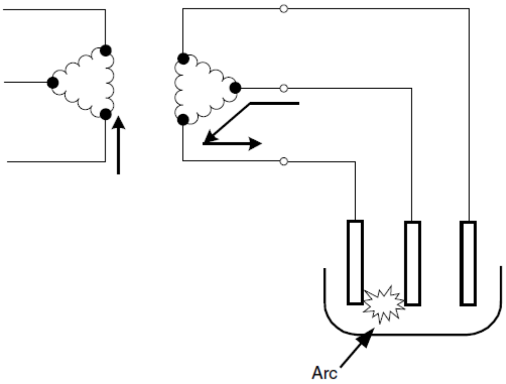


Figure 5.8 Arc furnace operation in an unbalanced mode allows triplen harmonics to reach the power system despite a delta connected transformer.

$$\mathrm{THD} = \frac{\sqrt{\sum_{h>1}^{h_{\max}} M_h^{\,2}}}{M_1}$$

Where, M_h is the rms value of harmonic component h of the quantity M. The rms value of a distorted waveform is the square root of the sum of the squares as shown in Eqs. (5.3) and (5.4). The THD is related to the rms value of the waveform as follows:

$$\mathrm{RMS} = \sqrt{\sum_{h=1}^{h_{\max}} M_h^{\,2}} = M_1\sqrt{1+\mathrm{THD}^2}$$

The THD is a very useful quantity for many applications, but its limitations must be realized. It can provide a good idea of how much extra heat will be realized when a distorted voltage is applied across a resistive load. Likewise, it can give an indication of the additional losses caused by the current flowing through a conductor. However, it is not a good indicator of the voltage stress within a capacitor because that is related to the peak value of the voltage waveform, not its heating value. The THD index is most often used to describe voltage harmonic distortion. Harmonic voltages are almost always referenced to the fundamental value of the waveform at the time of the sample. Because fundamental voltage varies by only a few percent, the voltage THD is nearly always a meaningful number. Variations in the THD over a period of time often follow a distinct pattern representing nonlinear load activities in the system. Figure 5.9 shows the voltage THD variation over a 1-week period where a daily cyclical pattern is obvious. The voltage THD shown in Fig. 5.9 was taken at a 13.2-kV distribution substation supplying a residential load. High-voltage THD occurs at night and during the early morning hours since the nonlinear loads are relatively high compared to the amount of linear load during these hours. A 1-week observation period is often required to come up with a meaningful THD pattern since it is usually the shortest period to obtain representative and reproducible measurement results.

ii. Total demand distortion(TDD)

The total demand distortion (TDD) is the total harmonic current distortion defined as the ratio of the RMS value of the harmonic content to the RMS value of the rated or maximum fundamental quantity.

WHY TDD? A small current may have a high THD but not be significant threat to the system. Even though relative current distortion may be high but magnitude of harmonic current can be low. To avoid this difficulty we go for Total Demand Distortion (TDD) instead of THD.

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} I_h^2}}{I_L}$$

Where, I_L is the maximum demand load current (15- or 30-minute demand) at fundamental frequency at the point of common coupling (PCC), calculated as the average current of the maximum demands for the previous twelve months.

4. Discuss the various industrial & commercial loads as sources of harmonics.

Harmonic - producing commercial loads.

- Single phase power supplies.
- Fluorescent lighting. (it contains a ballast which is responsible for harmonics, 186)
- Adjustable speed drives for HVAC and elevators (page 188)

I. Single-phase power supplies

Electronic power converter loads with their capacity for producing harmonic currents now constitute the most important class of nonlinear loads in the power system. Advances in semiconductor device technology have fueled a revolution in power electronics over the past decade, and there is every indication that this trend will continue. Equipment includes adjustable-speed motor drives, electronic power supplies, dc motor drives, battery chargers, electronic ballasts, and many other rectifier and inverter applications. A major concern in commercial buildings is that power supplies for single-phase electronic equipment will produce too much harmonic current for the wiring. DC power for modern electronic and microprocessor- based office equipment is commonly derived from single-phase full-wave diode bridge rectifiers. The percentage of load that contains electronic power supplies is increasing at a dramatic pace, with the increased utilization of personal computers in every commercial sector. There are two common types of single-phase power supplies. Older technologies use ac-side voltage control methods, such as transformers, to reduce voltages to the level required for the dc bus. The inductance of the transformer provides a beneficial side effect by smoothing the input current waveform, reducing harmonic content.

Newer-technology switch-mode power supplies (see Fig. 5.10) use dc-to-dc conversion techniques to achieve a smooth dc output with small, lightweight components. The input diode bridge is directly connected to the ac line, eliminating the transformer. This results in a coarsely regulated dc voltage on the capacitor. This direct current is then converted back to alternating current at a very high frequency by the switcher and subsequently rectified again. Personal computers, printers, copiers, and most other single-phase electronic equipment now almost universally employ switch-mode power supplies. The key advantages are the light weight, compact size, efficient operation, and lack of need for a transformer. Switch-mode power supplies can usually tolerate large variations in input voltage. Because there is no large ac-side inductance, the input current to the power supply comes in very short pulses as the capacitor C1 regains its charge on each half cycle. Figure 5.11 illustrates the current waveform and spectrum for an entire circuit supplying a variety of electronic equipment with switch-mode power supplies. A distinctive characteristic of switch-mode power supplies is a very high third-harmonic content in the current. Since third-harmonic current

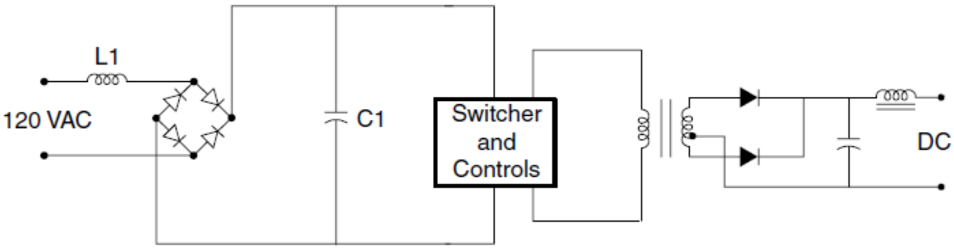


Figure 5.10 Switch-mode power supply.

components are additive in the neutral of a three-phase system, the increasing application of switch-mode power supplies causes concern for overloading of neutral conductors, especially in older buildings where an undersized neutral may have been installed. There is also a concern for transformer overheating due to a combination of harmonic content of the current, stray flux, and high neutral currents.

II. Fluorescent lighting

Lighting typically accounts for 40 to 60 percent of a commercial building load. According to the 1995 Commercial Buildings Energy Consumption study conducted by the U.S. Energy Information Administration, fluorescent lighting was used on 77 percent of commercial floor spaces, while only 14 percent of the spaces used incandescent lighting.1 Fluorescent lights are a popular choice for energy savings. Fluorescent lights are discharge lamps; thus they require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube. Once the discharge is established, the voltage decreases as the arc current increases.

It is essentially a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, a ballast is also a current-limiting device in lighting applications. There are two types of ballasts, magnetic and electronic. A standard magnetic ballast is simply made up of an iron-core transformer with a capacitor encased in an insulating material. A single magnetic ballast can drive one or two fluorescent lamps, and it operates at the line fundamental frequency, i.e., 50 or 60 Hz. The iron-core magnetic ballast contributes additional heat losses, which makes it inefficient compared to an electronic ballast. An electronic ballast employs a switch-mode–type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz. This high frequency has two advantages. First, a small inductor is sufficient to limit

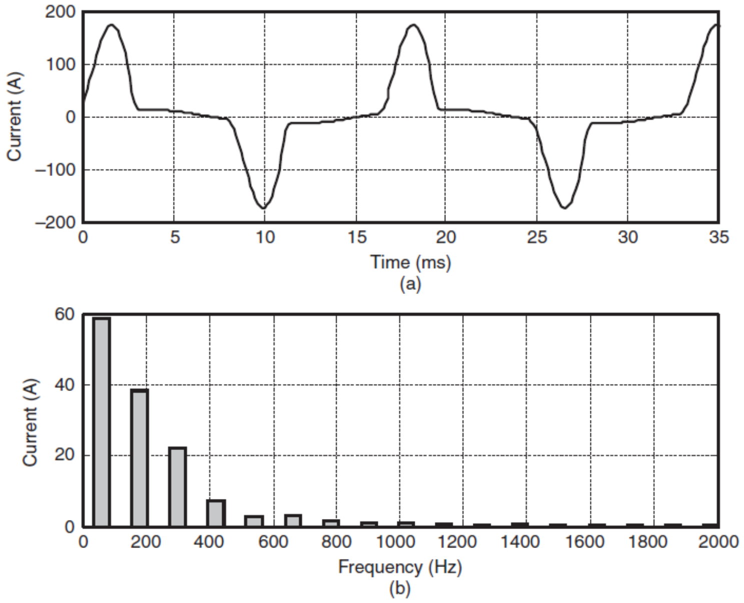


Figure 5.11 SMPS current and harmonic spectrum.

the arc current. Second, the high frequency eliminates or greatly reduces the 100- or 120-Hz flicker associated with an iron-core magnetic ballast. A single electronic ballast typically can drive up to four fluorescent lamps. Standard magnetic ballasts are usually rather benign sources of additional harmonics themselves since the main harmonic distortion comes from the behavior of the arc. Figure 5.12 shows a measured fluorescent lamp current and harmonic spectrum.

The current THD is a moderate 15 percent. As a comparison, electronic ballasts, which employ switch-mode power supplies, can produce double or triple the standard magnetic ballast harmonic output. Figure 5.13 shows a fluorescent lamp with an electronic ballast that has a current THD of 144. Other electronic ballasts have been specifically designed to minimize harmonics and may actually produce less harmonic distortion than the normal magnetic ballast-lamp combination. Electronic ballasts typically produce current THDs in the range of between 10 and 32 percent. A current THD greater than 32 percent is considered excessive according to ANSI C82.11-1993, High-Frequency Fluorescent Lamp Ballasts. Most electronic ballasts are equipped with passive filtering to reduce the input current harmonic distortion to less than 20 percent. the arc current. Second, the high frequency eliminates or greatly reduces the 100- or 120-Hz flicker associated with an iron-core magnetic ballast.

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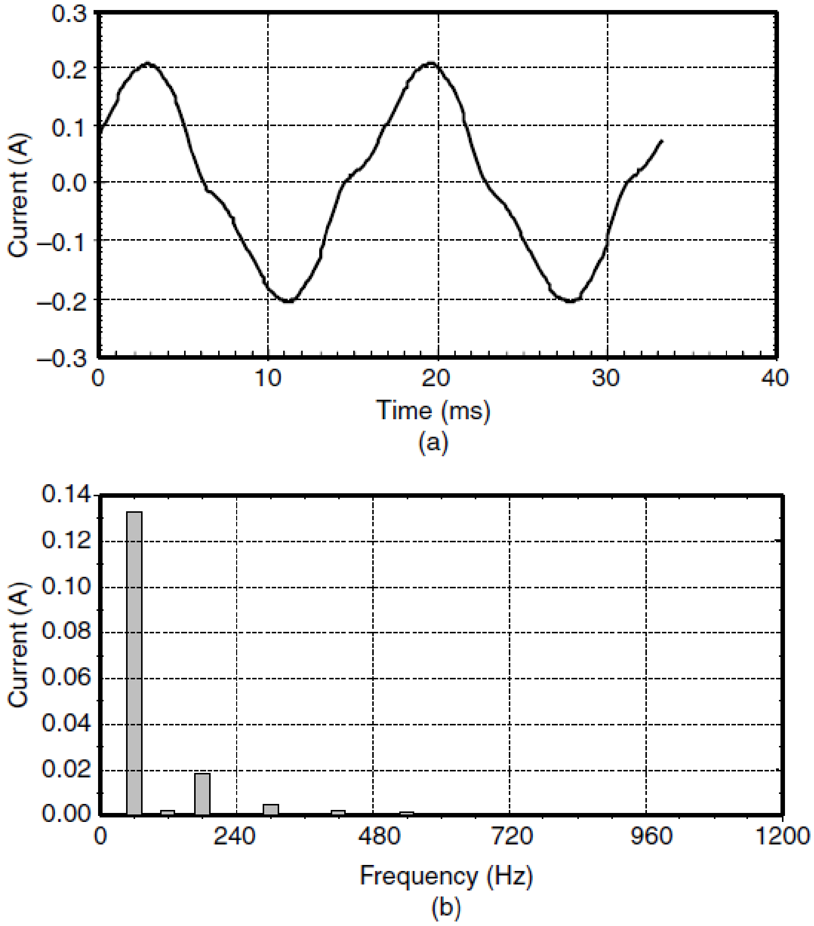


(a)

(b)

Figure 5.12 Fluorescent lamp with (a) magnetic ballast current waveform and (b) its harmonic spectrum.

Since fluorescent lamps are a significant source of harmonics in commercial buildings, they are usually distributed among the phases in a nearly balanced manner. With a delta-connected supply transformer, this reduces the amount of triplen harmonic currents flowing onto the power supply system. However, it should be noted that the common wye-wye supply transformers will not impede the flow of triplen harmonics regardless of how well balanced the phases are.

III. Adjustable-speed drives for HVAC and elevators

Common applications of adjustable-speed drives (ASDs) in commercial loads can be found in elevator motors and in pumps and fans in HVAC systems. An ASD consists of an electronic power converter that converts ac voltage and frequency into variable voltage and frequency. The variable voltage and frequency allows the ASD to control motor speed to match the application requirement such as slowing a pump or fan. ASDs also find many applications in industrial loads.

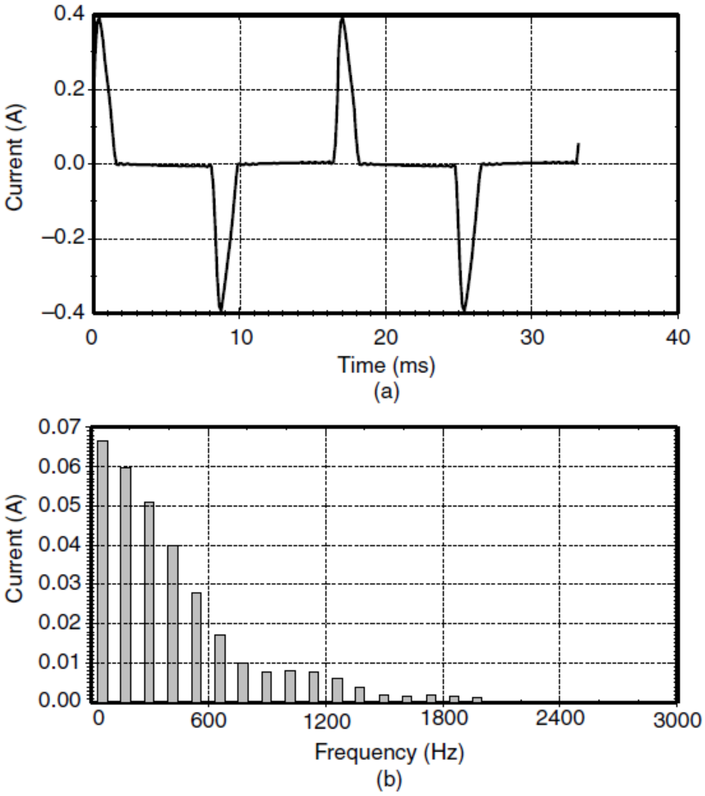


Figure 5.13 Fluorescent lamp with (a) electronic ballast current waveform and (b) its harmonic spectrum.

Harmonic - producing industrial loads.

- Three phase power converters.
- D.C drives.
- AC drives.
- Arcing devices.
- Saturable devices.

I. Three-phase power converters

Three-phase electronic power converters differ from single-phase converters mainly because they do not generate third-harmonic currents. This is a great advantage because the third-harmonic current is the largest component of harmonics. However, they can still be significant sources of harmonics at their characteristic frequencies, as shown in Fig. 5.14. This is a typical current source type of adjustable-speed drive. The harmonic spectrum given in Fig. 5.14 would also be typical of a dc motor drive input current. Voltage source inverter drives (such as PWM-type drives) can have much higher distortion levels as shown in Fig. 5.15.

The input to the PWM drive is generally designed like a three-phase version of the switch-mode power supply in computers. The rectifier feeds directly from the ac bus to a large capacitor on the dc bus. With little intentional inductance, the capacitor is charged in very short pulses, creating the distinctive “rabbit ear” ac-side current waveform with very high distortion. Whereas the switch-mode power supplies are generally for very small loads, PWM drives are now being applied for loads up to 500 horsepower (hp). This is a justifiable cause for concern from power engineers.

II. DC drives

Rectification is the only step required for dc drives. Therefore, they have the advantage of relatively simple control systems. Compared with ac drive systems, the dc drive offers a wider speed range and higher starting torque. However, purchase and maintenance costs for dc motors are high, while the cost of power electronic devices has been dropping year after year. Thus, economic considerations limit use of the dc drive to applications that require the speed and torque characteristics of the dc motor. Most dc drives use the six-pulse rectifier shown in Fig. 5.16. Large drives may employ a 12-pulse rectifier. This reduces thyristor current duties and reduces some of the larger ac current harmonics. The two largest harmonic currents for the six-pulse drive are the fifth and seventh. They are also the most troublesome in terms of system response. A 12-pulse rectifier in this application can be expected to eliminate about 90 percent of the fifth and seventh harmonics, depending on system imbalances. The disadvantages of the 12-pulse drive are that there is more cost in electronics and another transformer is generally required.

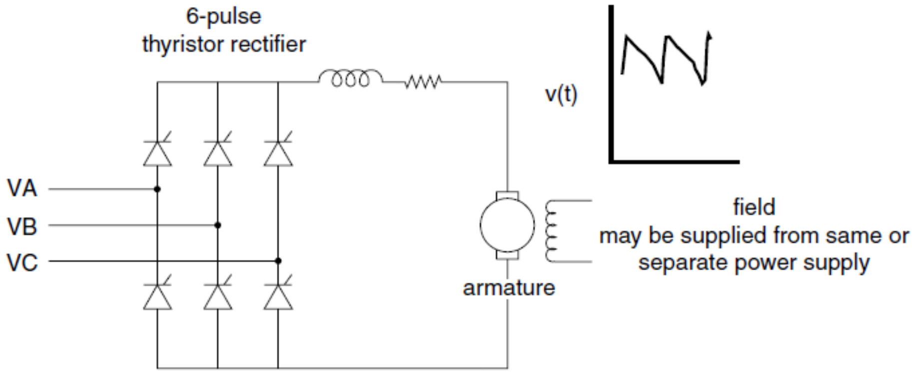


Figure 5.16 Six-pulse dc ASD.

III. AC drives

In ac drives, the rectifier output is Inverted to produce a variable-frequency ac voltage for the motor. Inverters are classified as voltage source inverters (VSIs) or current source inverters (CSIs). A VSI requires a constant dc (i.e., low-ripple) voltage input to the inverter stage. This is achieved with a capacitor or LC filter in the dc link. The CSI requires a constant current input; hence, a series inductor is placed in the dc link. AC drives generally use standard squirrel cage induction motors. These motors are rugged, relatively low in cost, and require little maintenance. Synchronous motors are used where precise speed control is critical.

A popular ac drive configuration uses a VSI employing PWM techniques to synthesize an ac waveform as a train of variable-width dc pulses (see Fig. 5.17). The inverter uses either SCRs, gate turnoff (GTO) thyristors, or power transistors for this purpose. Currently, the VSI PWM drive offers the best energy efficiency for applications over a wide speed range for drives up through at least 500 hp. Another advantage of PWM drives is that, unlike other types of drives, it is not necessary to vary rectifier output voltage to control motor speed. This allows the rectifier thyristors to be replaced with diodes, and the thyristor control circuitry to be eliminated.

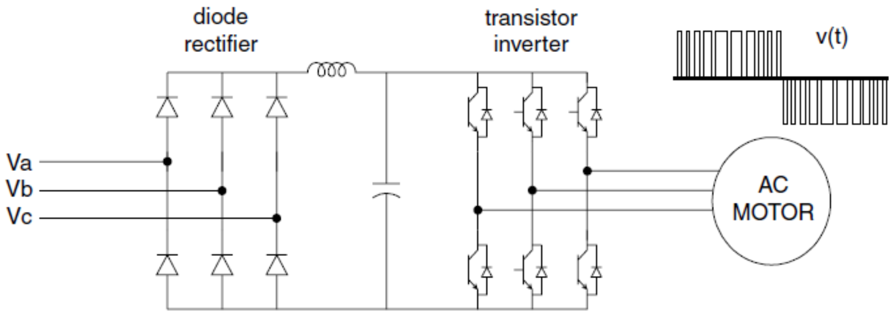


Figure 5.17 PWM ASD.

Very high power drives employ SCRs and inverters. These may be 6- pulse, as shown in Fig. 5.18, or like large dc drives, 12-pulse. VSI drives (Fig. 5.18a) are limited to applications that do not require rapid changes in speed. CSI drives (Fig. 5.18b) have good acceleration/deceleration characteristics but require a motor with a leading power factor (synchronous or induction with capacitors) or added control circuitry to commutate the inverter thyristors. In either case, the CSI drive must be designed for use with a specific motor.

IV. Arcing devices

This category includes arc furnaces, arc welders, and discharge-type lighting (fluorescent, sodium vapor, mercury vapor) with magnetic (rather than electronic) ballasts. As shown in Fig. 5.20, the arc is basically a voltage clamp in series with a reactance that limits current to a reasonable value. The voltage-current characteristics of electric arcs are nonlinear. Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system. This gives the arc the appearance of having a negative resistance for a portion of its operating cycle such as in fluorescent lighting applications. In electric arc furnace applications, the limiting impedance is primarily the furnace cable and leads with some contribution from the power system and furnace transformer. Currents in excess of 60,000 A are common.

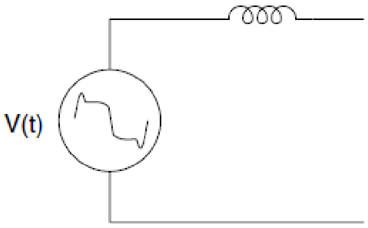


Figure 5.20 Equivalent circuit for an arcing device.

V. Saturable devices

Equipment in this category includes transformers and other electromagnetic devices with a steel core, including motors. Harmonics are generated due to the nonlinear magnetizing characteristics of the steel (see Fig. 5.21). Power transformers are designed to normally operate just below the “knee” point of the magnetizing saturation characteristic. The operating flux density of a transformer is selected based on a complicated optimization of steel cost, no-load losses, noise, and numerous other factors. Many electric utilities will penalize transformer vendors by various amounts for no-load and load losses, and the vendor will try to meet the specification with a transformer that has the lowest evaluated cost. A high-cost penalty on the no-load losses or noise will generally result in more steel in the core and a higher saturation curve that yields lower harmonic currents.

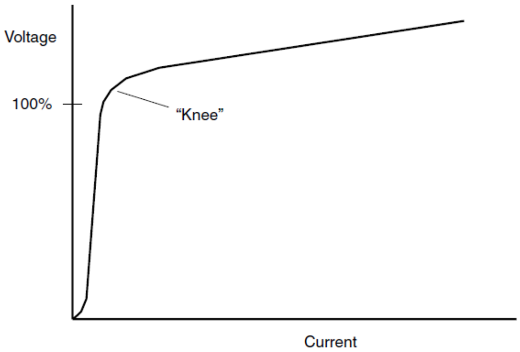


Figure 5.21 Transformer magnetizing characteristic.

Although transformer exciting current is rich in harmonics at normal operating voltage (see Fig. 5.22), it is typically less than 1 percent of rated full load current. Transformers are not as much of a concern as electronic power converters and arcing devices which can produce harmonic currents of 20 percent of their rating, or higher. However, their effect will be noticeable, particularly on utility distribution systems, which have hundreds of transformers. It is common to notice a significant increase in triplen harmonic currents during the early morning hours when the load is low and the voltage rises. Transformer exciting current is more visible then because there is insufficient load to obscure it and the increased voltage causes more current to be produced. Harmonic voltage distortion from transformer overexcitation is generally only apparent under these light load conditions. Some transformers are purposefully operated in the saturated region. One example is a triplen transformer used to generate 180 Hz for induction furnaces. Motors also exhibit some distortion in the current when overexcited, although it is generally of little consequence. There are, however, some fractional horsepower, single-phase motors that have a nearly triangular waveform with significant third-harmonic currents. The waveform shown in Fig. 5.22 is for single-phase or wye-grounded three-phase transformers. The current obviously contains a large amount of third harmonic. Delta connections and ungrounded-wye connections prevent the flow of zero-sequence harmonic, which triplens tend to be. Thus, the line current will be void of these harmonics unless there is an imbalance in the system.

5. What is harmonic resonance? Explain the phenomena of series and parallel harmonic resonance with neat diagrams.

The operation of nonlinear loads in a power distribution system creates harmonic currents that flow throughout the power system. The inductive reactance of that power system increases and the capacitive reactance decreases as the frequency increases, or as the harmonic order increases. At a given harmonic frequency in any system where a capacitor exists, there will be a crossover point where the inductive and capacitive reactances are equal.

In short, harmonic resonance can result if both of the following are true:

- Harmonic loads, such as AC/DC drive systems, induction heaters, arcing devices, switch mode power supplies, and rectifiers, are operating on the system.

- A capacitor or group of capacitors and the source impedance have the same reactance (impedance) at a frequency equal to one of the characteristic frequencies created by the loads.

A common problem that occurs when power factor correction capacitors are installed on a system is harmonic resonance. Harmonic resonance is caused when the electrical system reactances (capacitive and inductive) combine to form a tank circuit(LC network) with its natural resonant frequency near any frequency where electrical energy may be present.

Conditions under which series and parallel harmonic resonance occurs

Parallel resonance occurs when the parallel combination of system inductance and capacitance tune close to a harmonic frequency.

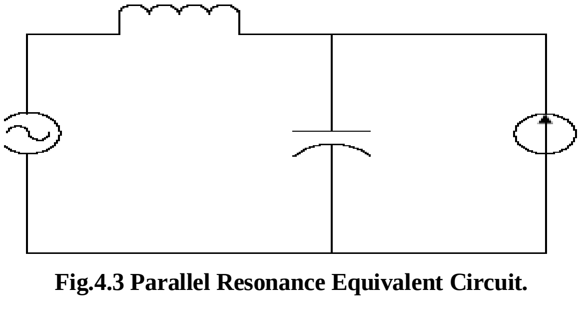


Fig.4.3 Parallel Resonance Equivalent Circuit.

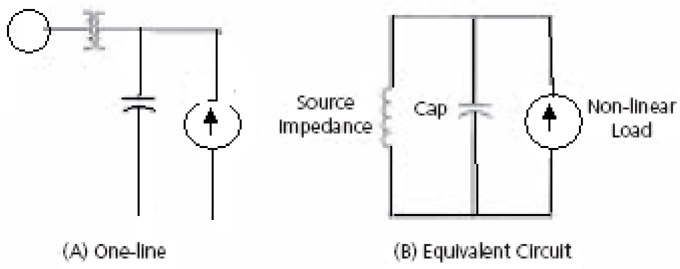


fig 4.4 Parallel Resonance.

When parallel resonant condition exist, the shunt capacitor bank appear to the harmonic source as being in parallel with the system source reactance (or short circuit reactance, Fig.4.4.). This means that for parallel resonance, the combined impedance will be very high, so any harmonic current present may cause large harmonic voltages to be present. The resonant frequency of this combination can be calculated as follows,

$$h= \sqrt{\frac{\text{kVA x 100}}{\text{kVAR x Z\%}}}$$

Where, h is harmonic number referred to the fundamental.
KVA is transformer KVA.
Z% is transformer impedance.
KVAR is rating of a connected capacitors.

Series Resonance

When series resonant conditions occur, the capacitor appears to be in series with line impedance, as seen from the harmonic source (see Figure 5). This presents a low-impedance path to the flow of harmonic currents.

For series resonance, where the L and C components appear electrically in series with each other, $X_L = X_C$ and therefore the combined impedance is very low. This means that if harmonic voltage is present at a frequency, the harmonic current into the network can be equal to the harmonic voltage divided by the LC network impedance (near zero), causing excessive current at a specific harmonic frequency.

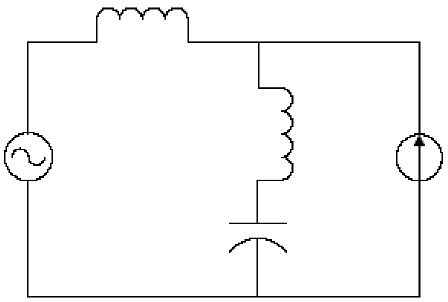


Fig.5 series resonance equivalent circuit

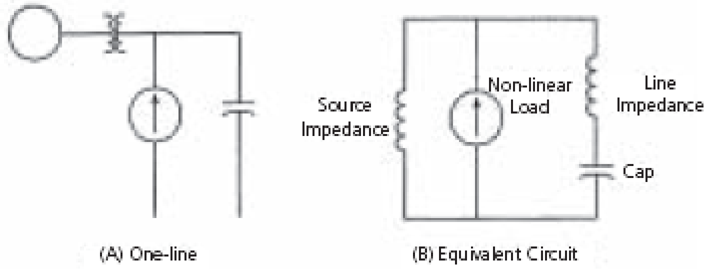


Fig.4.5 Series Resonance.

6. Discuss the devices for controlling harmonic distortions?

- In- line reactors or chokes
- zigzag transformer.
- Active filters
  - -series active filter
  - -shunt active filter
- Passive filters
  - -shunt passive filter
  - -series passive filter
- c- type filter

i. In–Line reactors or chokes

Simply a series inductance which represents a series impedance that is directly proportional to frequency. Relatively small reactor or choke inserted at the line input side of the drive the inductance slows the rate at which the capacitor on the DC bus can be charged and forces the drive to draw current over a longer time period. The net effect is a lower magnitude current with much less harmonics.

ii. Zigzag Transformer

A zigzag transformer is a special purpose transformer. It has primary windings but no secondary winding. One application is to derive an earth reference point for an ungrounded electrical system. Another is to control harmonic currents. Consider a three-phase Y (wye) transformer with an earth connection on the neutral point. Cut each winding in the middle so that the winding splits into two. Turn the outer winding around and rejoin the outer winding to the next phase in the sequence (i.e. outer A phase connects to inner B phase, outer B phase connects to inner C phase, and outer C phase connects to inner A phase). This device is the zigzag transformer.

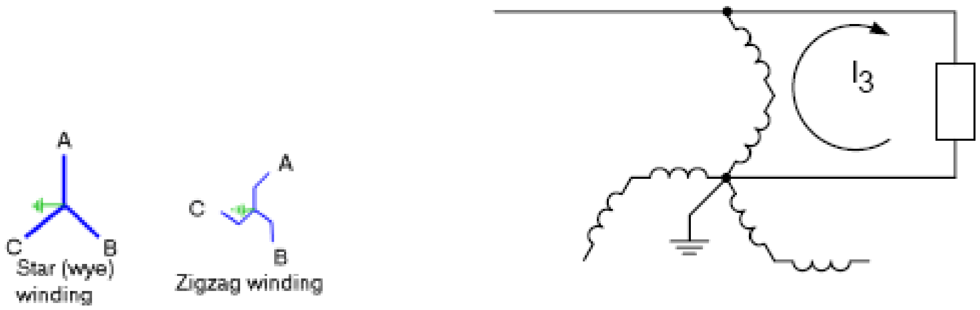


fig 4.6. conceptual diagram

These transformers are 3-phase, dry-type autotransformers that are wound on a common core and are designed for very low zero-sequence impedance. The zero-sequence impedance is usually less than 1%, and the reactance component is very small.

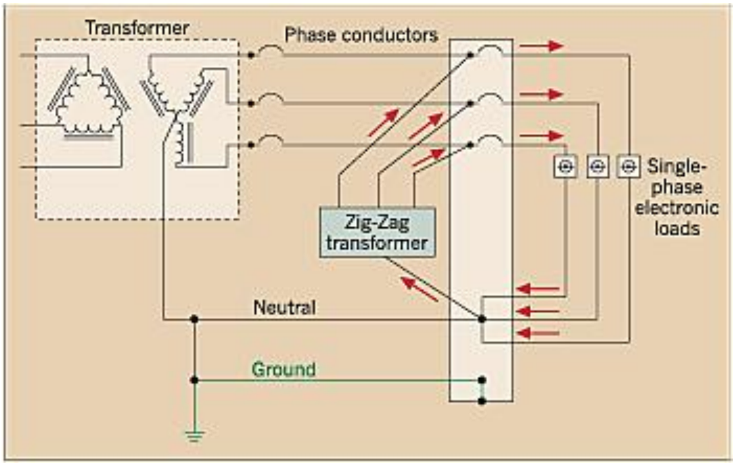


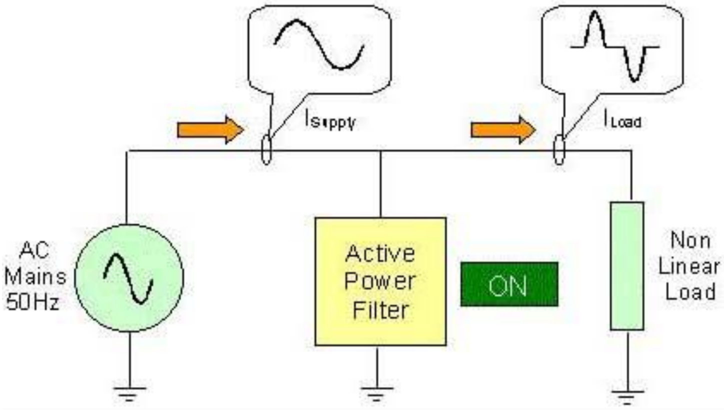
Fig.4.7. Zigzag Transformer

They're designed for 3-phase, 4-wire systems, and they provide a low-impedance path for the zero sequence harmonic currents. They should be installed in parallel and typically at a panel or bus duct that is as close as possible to the harmonic producing load see fig 4.7 above.

- Zig-zag transformers offer the following benefits for controlling the harmonic voltages and currents.
- There are no capacitors. The magnetic-only solution eliminates concerns about resonance or magnification of other harmonic components.
- They reduce third harmonic current components flowing in both the phase conductors and the neutral conductors up-line (back towards the supply) from the zig-zag transformer installation. By providing a shorter path.
- This reduces neutral conductor loading problem and losses in all of the conductors and the supply transformer. It also reduces transformer heating for the supply transformer

iii. Active filters

An active filter removes harmonics from the supply current by injecting the opposite harmonics that are produced by the load. An example of the active filter system is shown in the Next graphic.

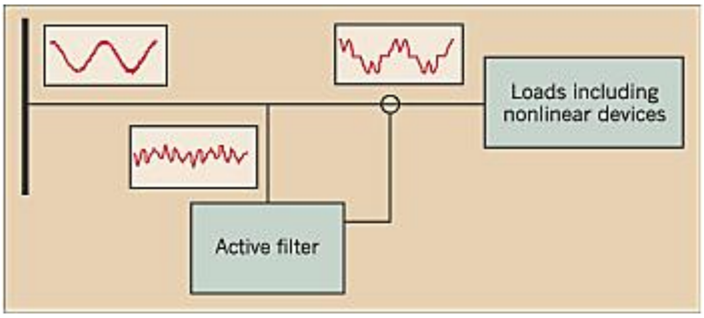


Harmonic cancellation-active filters

This technique uses an insulated gate bipolar transistor (IBGT) based device. The basic operation of this type of filter involves measurement and analysis of the input current waveform, with the injection of the inverse harmonic current waveform. You typically select the active filter capacity based upon harmonic cancellation current requirements, which is accomplished by determining the magnitude of harmonic current desired to be removed from the system. When properly selected, an active filter will typically reduce harmonics to residual levels of about 5% THD_I. You connect a standalone active filter in parallel with the power system. It is suitable for a mixture of both nonlinear and linear loads.

Active Harmonic Filter

An active harmonic filter is something like a boost regulator. The concept used in an active filter is the introduction of current components using power electronics to remove the harmonic distortions produced by the non-linear load.



These filters correct harmonic distortion levels by monitoring the current waveform that includes the nonlinear loads, and by creating a current waveform that results in cancellation of the harmonic components. Several different control strategies are possible in the nonlinear load current. Active filters for commercial applications have the following advantages:

Active harmonic filters are mostly used for low-voltage networks.

There are mainly two types of active harmonic filters based on the way they are connected to the AC distribution network.

a) The series filter is connected in series with the AC distribution network. It serves to offset harmonic distortions caused by the load as well as that present in the AC system.

b) The parallel/ shunt filter is connected in parallel with the AC distribution network and offset the harmonic distortions caused by the non-linear load.

iv. Passive Harmonic Filter

A passive harmonic filter is built using an array of capacitors, inductors, and resistors. It can take the form of a simple line reactor or may use a series of parallel resonant filters to eliminate harmonics. Passive harmonic filters are also divided based on the way they are connected with the load.

a) A series filter: Here the filter is placed in series with the load and uses parallel components, i.e. inductors and capacitors are in parallel. This filter is a current rejecter.

Unlike a notch filter which is connected in shunt with the power system, a series passive filter is connected in series with the load. The inductance and capacitance are connected in parallel and are tuned to provide a high impedance at a selected harmonic frequency. The high impedance then blocks the flow of harmonic currents at the tuned frequency only. At fundamental frequency, the filter would be designed to yield a low impedance, thereby allowing the fundamental current to follow with only minor additional impedance and losses. Figure 6.16 shows a typical series filter arrangement. Series filters are used to block a single harmonic current (such as the third harmonic) and are especially useful in a single-phase circuit where it is not possible to take advantage of zero-sequence characteristics. The use of the series filters is limited in blocking multiple harmonic currents. Each harmonic current requires a series filter tuned to that harmonic. This arrangement can create significant losses at the fundamental frequency. Furthermore, like other series components in power systems, a series filter must be designed to carry a full rated load current and must have an overcurrent protection scheme. Thus, series filters are much less commonly applied than shunt filters.

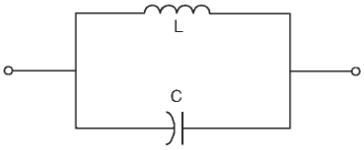


Figure 6.16 A series passive filter.

v. C-type filter

It is used for complex loads, cyclo converters and electric arc furnaces and is a special variation of the high pass filter. This filter will provide the load with reactive power and avoid forming parallel resonance circuits with the load.

7. Explain the role & types of active filters for harmonic control

It is covered in previous question

8. Explain the role of passive filters for harmonic control

It is covered in previous question

9. Discuss IEEE & IEC standard on harmonics in detail.
(Or)
Write a note on harmonic standards.

Harmonic standards are needed for the following reasons.

- Compatibility between the power system and end-user equipment.
- For utilities: Provides measurable limits that can be used as the basis for system design.
- For equipment manufacturers: Describes the electrical environment the equipment may be expected to operate in. Helps manufacturers design equipment to operate acceptably.

IEEE 519-1992
Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems:

Requirements

- Limits harmonic current produced by loads.
- Limits voltage distortion on the utility system.

Reference Material

- Describes harmonic generation by power converters, arc furnaces, SMPSs, etc.
- Covers effects on motors, transformers, capacitors, conductors, and other equipment.

Practices

- Covers analysis methods for,
  - System frequency response
  - System modeling
  - Telephone interference
  - And more…

- Covers measurements.
- Describes a methodology for evaluating new harmonic sources.

Overall IEEE standard 519-1992 represents a consensus of guidelines and recommended practices by the utilities and their customers in minimizing and controlling the impact of harmonics generated by nonlinear loads.

IEC (International Electrotechnical Commission) standard on harmonics

The IEC (International Electrotechnical Commission) standard on harmonics explains about the Electromagnetic compatibility standard that deals with power quality issues. The Electromagnetic compatibility includes concerns for both radiated and conducted interference with end use equipments

The IEC standards are broken down in to six parts

- General – definitions, terms
- Environment – description and characteristics
- Limits – Allowable disturbances caused by equipment
- Testing and measurement techniques – guidelines for measurement equipment and test procedures
- Installation and mitigation guidelines – define equipment immunity levels.
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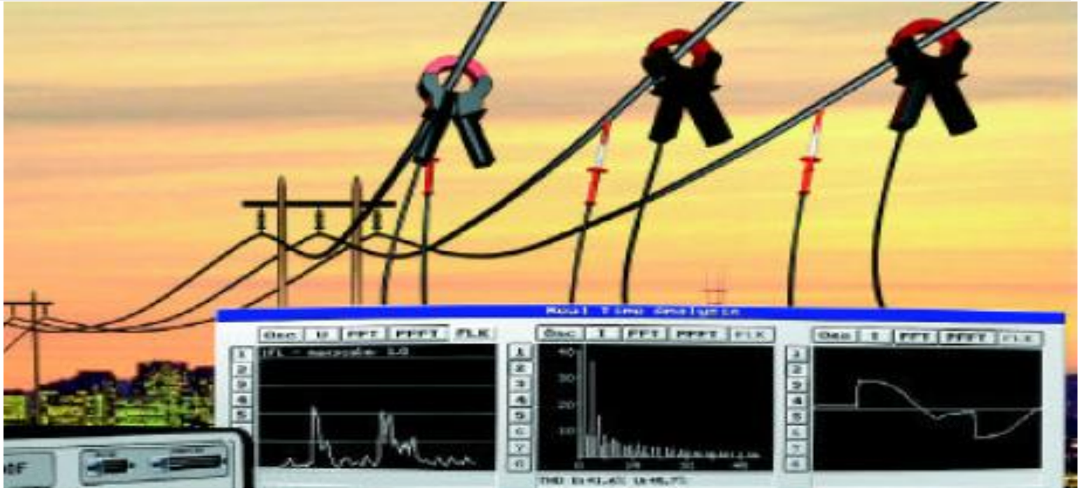
UNIT-5

POWER QUALITY MONITORING



5.1 Introduction

Power-quality monitoring has become increasingly common as the capabilities of commercially available monitoring systems have increased and costs have fallen. Power-quality engineers have used various power-monitoring tools for many years. In recent years, several trends have converged, resulting in the wide application of power-monitoring systems beyond power quality or power-management specialists.

Today, power monitors can track virtually any electrical parameter of interest. With all of the monitoring options available, a number of questions need to be asked: "What should we monitor?" "Which type of power-monitoring system should be selected: permanent or portable?" "What does my power-monitoring system need to measure, how fast does it need to sample, and how accurate does it need to be?"

When the lights flicker in a building, the first question a facility manager typically asks is: "What happened?" Unfortunately, in most cases, he/she does not know. The facility manager knows that the power went out momentarily - or did it? Characterizing the event by the voltage magnitude and duration, and evaluating the current coincidentally, helps identify the root cause and quantify the solution required to fix the problem.

If the company is adversely affected by such power-system events, corrective action may be warranted. But, without knowing exactly what happened (not only during this event, but over a period of time), the company probably doesn't have enough information to make a well-informed decision about which corrective action to pursue. For example, the company might invest in an uninterruptible power supply (UPS), which can ride through outages and interruptions for minutes, but the problem might actually have to do with transients (short-term, high over-voltage conditions).

Basic considerations when selecting a monitoring system and analyzing power-quality issues include:

Monitoring at the incoming service (from the utility) and downstream (near critical loads) to help distinguish where problems may have originated. Monitoring for a complete business cycle at a time when the problem is likely to occur (typically for a 1-week minimum). High sampling speeds, preferably 10 times the frequency of interest, to characterize fast transients caused by utility switching events or lightning. Often, transients occur, but the monitoring equipment may not sample fast enough to capture the event.

While portable monitors are more suitable for troubleshooting measurements, permanent monitors offer several important benefits: They're always monitoring, they're proactive and can help notify users of problems in advance, and they capture power quantities useful for energy-saving opportunities. Many companies track energy usage, peak demand, power factor, etc. in order to minimize their power bills. They may also compare their measurements with their power bills to make sure there isn't a discrepancy.

Remote communications with power-monitoring systems are essential to log data from such systems and communicate with users (paging the facility manager following an event, for example). Remote access via the Web is the preferred choice so that facility managers can access data remotely at any time and, secondly, so that experts can support the analysis from virtually anywhere in the world.

Site surveys are generally initiated to evaluate the quality of the power available at a specific location with the aim of avoiding equipment disturbances in a planned installation or of explaining (and correcting) disturbances in an existing installation. In either case, survey results constitute one of the inputs in the decision-making process of providing supplementary line conditioning equipment, either before or after power disturbances have become a problem. Depending on the reliability requirements of the load equipment, its susceptibility, and the severity of the disturbances, various line conditioning methods have been proposed: surge suppressor (with or without filter), isolation transformer, voltage regulator, magnetic synthesizer, motor-generator set, or uninterruptible power supply (,U-P-S),. Because this additional line conditioning equipment may require significant capital investment, the choice of corrective measures is generally made by economic tradeoff which is the prerogative and responsibility of the end user. However, if technical inputs to this trade-off are incorrect because erroneous conclusions were drawn as a result of a faulty site survey, the whole process is worthless - or worse yet, misleading. For this reason, a good understanding of the merits and limitations of site surveys is essential for reconciling expectation with reality before expensive line conditioning equipment is called for; one should deal, not with fiction or fallacies, but with facts. Power disturbances that affect sensitive electronic loads have a variety of sources. Lightning, utility switching, and utility outages are often-cited sources of power disturbances. However, power disturbances are frequently caused by users themselves, through switching of loads, ground faults, or normal operation of equipment. As one example, computer systems are not only sensitive loads, but can also generate disturbances themselves. Their nonlinear load characteristics can cause interactions with the power system such as unusual voltage drops, overloaded neutral conductors, or distortion of the line voltage. Utility systems are designed to provide reliable bulk power. However, it is not feasible for them to provide continuous power of the quality required for a completely undisturbed computer operation. Because normal use of electricity generates disturbances, and because unexpected power system failures will occur, every site will experience some power disturbances, but their nature, severity, and incidence rates will vary from site to site.

Measurement (power quality monitoring) is a good way of assessing the performance of a site or system, in the end measurement is the only exact method. But measurements have limited predictive value due to the large year-to-year and site-to-site differences. To predict voltage-dip performance a large number of monitors are needed for a long period of time. Stochastic prediction methods are much more suitable for performance prediction, e.g. for comparing different mitigation methods.

5.1.1 Confusion in Term Definitions

As will become painfully apparent in next month's review of site surveys, the terms used by the workers reporting their measurements do not have common definitions. An effort is being made within the IEEE to resolve this problem, as described later in this paper, but consensus has yet to be reached. In this paper, terms describing disturbances are consistent with the IEEE Standard Dictionary of Electrical and Electronics Terms 111 and with established usage within the community of surge protective devices engineers. The generally accepted meaning of surge voltage, in the context of power systems, is a short-duration overvoltage, typically less than 1 ms or less than one half-cycle of the t' were frequency. This meaning is not that which has been established by manufacturers and users of monitoring instruments and line conditioners. This unfortunate second meaning is a momentary overvoltage at the fundamental frequency with a duration of typically a few cycles.

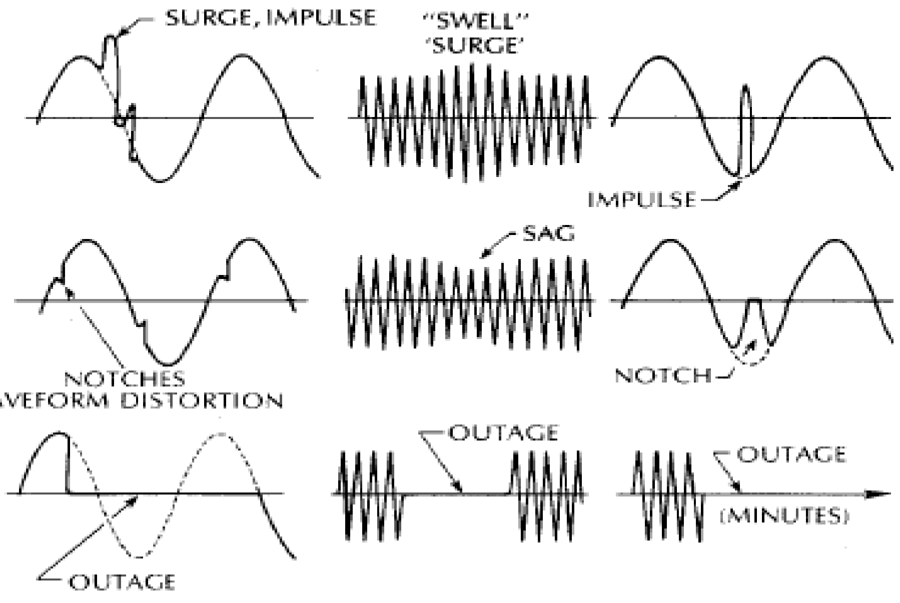


Figure 1.
Graphic depictions of disturbances with multiple meanings

5.2 SOLUTIONS TO POWER QUALITY PROBLEMS

Many compensation methods are developed to mitigate these power quality problems in distribution systems. The technology of the application of power electronics to power distribution networks for the benefit of a customer or a group of customers is known as custom power. Under this scheme, a customer receives a pre-specified quality power.

Maintaining a power distribution bus voltage near sinusoidal at rated magnitude and frequency is known as power quality. It can be classified into three types, they are

- Distribution STATCOM (DSTATCOM)
- Dynamic Voltage Regulator (DVR)
- Unified Power Quality Conditioner (UPQC)

5.3 Dynamic Voltage Restorer (DVR)

A dynamic voltage restorer is one of the custom power devices which is used to protect sensitive loads from sag/swell or disturbances in the supply voltage. The DVR consists of a voltage source inverter (VSI), a switching control scheme, a DC energy storage device and a coupling transformer is connected in series with the ac system as illustrated in Fig.5.1

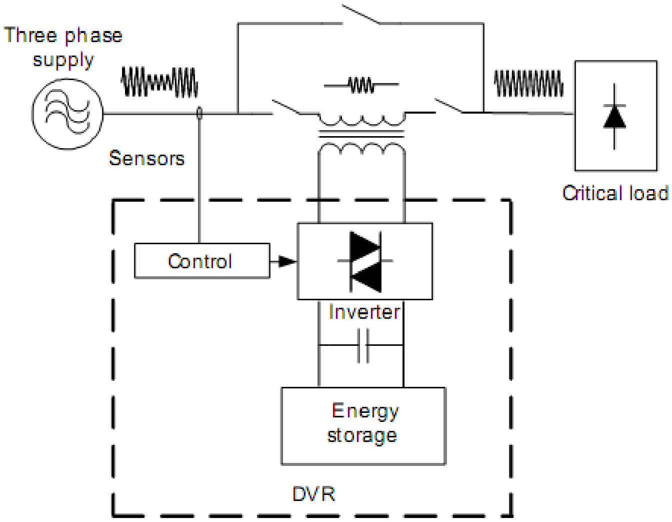


Fig. 5.1 DVR in distribution system

The DVR injects a set of three phase ac voltage in series and synchronized with the distribution feeder voltages of the ac system. The amplitude and phase angle of the injected voltages are variable thereby allowing control of the active and reactive power exchange between DVR and the ac system. The DVR control system compares the input voltage with a reference voltage and injects voltage so that the output voltage remains within specified value.

5.3.1 BASIC CONTROL STRATEGIES

To avoid tripping of the load, only the amplitude of the load voltage has to be restored by the DVR. Different strategies can be used to achieve this goal. The three basic strategies studied here are the pre-sag compensation, the in-phase compensation] and the energy-optimized compensation.

a) Pre-Sag Compensation

The standard solution for compensating voltage sags is to reestablish the exact voltage before the sag. Therefore, the amplitude and the phase of the voltage before the sag have to be exactly restored. The resulting vector is shown in Fig. 5.2. In this figure, the dashed quantities (V'_{Load} ; $V'_{DVR;}$ V'_{Grid}) indicate variables after the sag. The phasors prior to the sag are represented by V_{Load}, V_{Grid}, and $I_{Gri.d}$

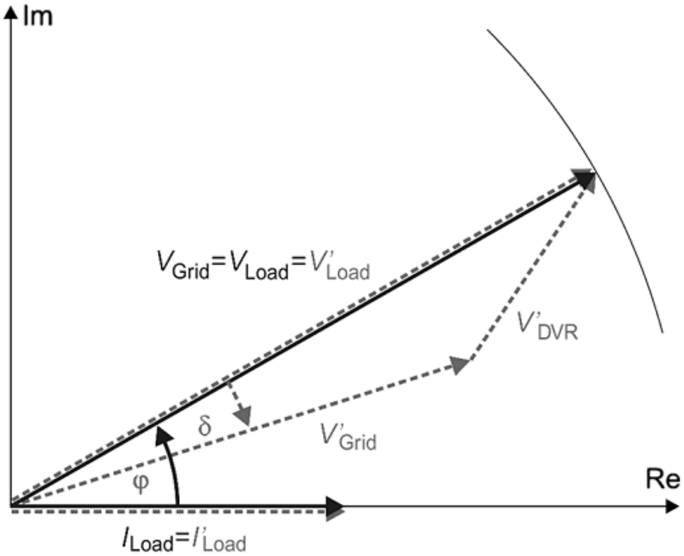


Fig. 5.2. Pre-sag compensation, showing current and voltage phasors before and after the voltage sag.

This compensation leads to the lowest distortions at the load, because the phase of the voltage at the load is not changed during the sag. For this strategy, a phase-locked loop (PLL) will be synchronized with the load voltage. As soon as a failure occurs, the PLL will be locked, and therefore, the phase angle can be restored.

Depending on the phase angle of the grid voltage during the sag, the DVR has to deliver a higher voltage amplitude to restore the correct voltage magnitude, because the phase jump of the grid has also to be compensated by the DVR. Therefore, the system has to be designed for a higher maximum voltage V_{DVR}.. In addition, less energy from the DC-link can be extracted.

b) In-Phase Compensation

As already mentioned, the pre-sag compensation does not lead to a minimized voltage amplitude. This can be realized with the in-phase strategy, which is designed to control the DVR with a minimum output voltage. In Fig. 5.3, the voltages for this strategy are depicted. In contrast to the pre-sag version, the voltage is now compensated in phase to the grid voltage after the sag. Hence, the required voltage amplitude is minimized, but the phase jump is not compensated.

In most cases, a voltage sag leads to a phase jump, therefore the distortions due to phase changes are not minimized. As a consequence, a phase jump will be applied to at the load, leading to transients and circulating currents. Thus, if a sensitive load must be secured, the in-phase compensation cannot be used, because it could lead to the tripping of sensitive loads. Note that, to realize this strategy, the PLL has to be synchronized to the grid voltage itself, and therefore, must not be locked to the pre-sag grid voltage during the compensation.

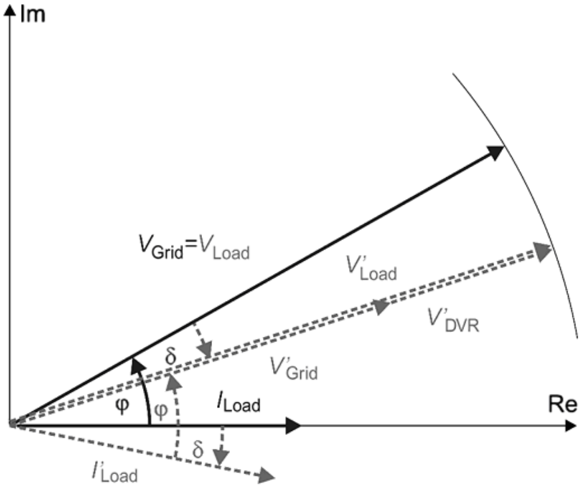


Fig. 5.3 In phase compensation, showing current and voltage phasors before and after the voltage sag.

c) Energy Optimized Compensation

Another existing strategy is to use as much reactive power as possible to compensate the sag. Therefore, the DVR voltage is controlled in such a way that the needed compensation voltage of the DVR is controlled perpendicular to the load current. The basic idea of this strategy is to draw as much active power from the grid as possible and thus to reduce the amount of active power needed from the DC-link. As long as the voltage sag is quite shallow, it is possible to compensate a sag with pure reactive power and therefore the compensation time is not limited. In Fig. 6, the voltages for the energy optimized compensation are depicted.

Beside the enormous advantage of not requiring active power, this strategy has in most cases two major disadvantages. On the one hand, a phase jump occurs and, on the other hand, the required DVR voltage amplitude can become quite high. Furthermore, the compensation with pure reactive power is only possible for shallow sags. If deep sag occurs, a large amount of active power is also needed with this strategy.

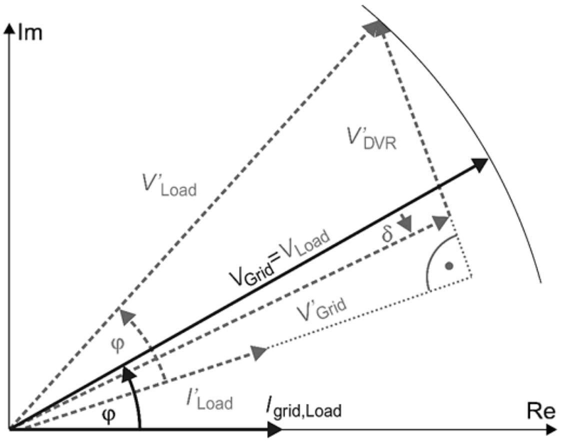


Fig. 5.4 Energy optimized compensation, showing current and voltage phasors before and after the voltage sag.

Advantages

- Energy storage options include batteries, capacitors, flywheels, superconductors etc.

- Only the missing energy needs to be stored.
- May also be used for harmonics filtering.

Disadvantage

- cannot (usually) mitigate interruptions.

5.4 Distribution Static Synchronous Compensator (D-STATCOM)

D-STATCOM is the most important controller for distribution networks. It has been widely used since the 1990s to precisely regulate system voltage, improve voltage profile, reduce voltage harmonics, reduce transient voltage disturbances and load compensation. Rather than using conventional capacitors and inductors combined with fast switches, the D-STATCOM uses a power-electronics converter to synthesise the reactive power output. A D-STATCOM converter is controlled using pulse width modulation (PWM) or other voltage/current-shaping techniques. D-STATCOMs are used more often than STATCOM controllers. Compared to STATCOM, D-STATCOMs have considerably lower rated power and, in consequence, faster power-electronics switches, thus the PWM carrier frequency used in a distribution controller can be much higher then in a FACTS controller. It has a substantial positive impact on the dynamics of the D-STACOM.

5.4.1 D-STATCOM Topology

D-STATCOM controllers can be constructed based on both voltage source inverter (VSI) topology and current source inverter (CSI) topology shown in fig.7. Regardless of topology, a controller is a compound of an array of semiconductor devices with turn off capability (*i.e.* IGBT, GTO, IGCT *etc.*) connected to the feeder via a relative small reactive filter. The VSI converter is connected to the feeder via reactor L_F and has a voltage source (capacitor C_D) on the DC side. On the other side, the CSI converter is connected on the AC side via capacitor C_F and has a current source (inductor L_D) on the DC side. In practice, CSI topology is not used for D-STATCOM. The reason for this is related to the higher losses on the DC reactor of CSI compared to the DC capacitor of VSI. Moreover, a CSI converter requires reverse-blocking semiconductor switches, which have higher loses than reverse-conducting switches of VSI. And finally, the VSI-based topology has the advantage because an inductance of a coupling transformer *Tr* (if present) can constitute, partially or completely, the inductance of AC filter.

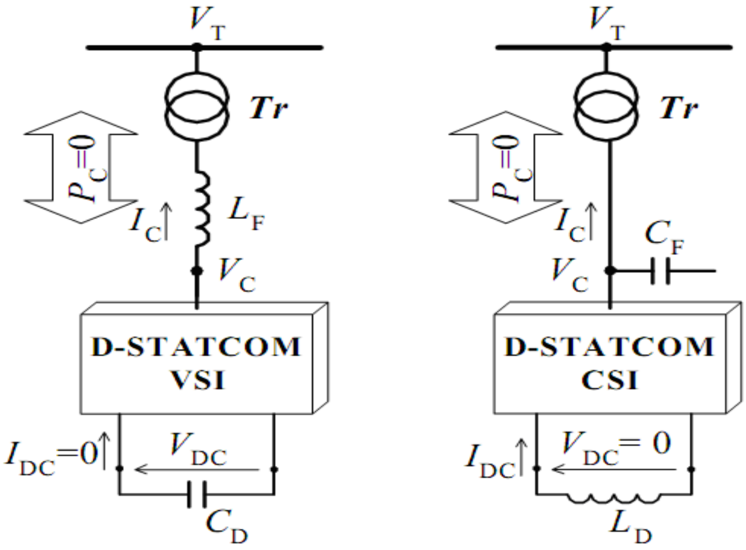


Fig 5.5 General Topology of VSI- based and CSI-based D-STATCOM

5.4.2 Principle of Operation

For the operation analysis of the D-STATCOM converter, it is possible to represent its PWM-controlled VSI with an instantaneous (averaged for PWM period) voltage source. The principle of generating instantaneous active and reactive powers by D-STATCOM is shown in Figure 8. In this figure, voltages and currents are represented with instantaneous space vectors obtained using a power-invariant Clarke transform. In Figure 8 are presented three cases: the general one, for reactive power equal to zero and for active power equal to zero. From this figure it is clear that by generating an appropriate AC voltage it is possible to generate arbitrary instantaneous vectors of both active and reactive power. The real component of currents is related to the equivalent series resistance modelling losses on the AC side. The possible active and reactive powers that can be generated or absorbed by D-STATCOM are limited. This limitation is related to circuit parameters and maximum ratings of VSI components. In Figure 8 there is presented an exemplary limit for AC voltage, which depends on VSI DC voltage V_{DC}. This limit, together with filter inductance L_F and terminal voltage V_T, define the operating region of a D-STATCOM controller. The operating voltage V_T, define the operating region of a D-STATCOM controller.

The active power is consumed by the D-STATCOM only to cover internal losses. Assuming lossless operation, the averaged (but not instantaneous) active power has to be zero. There are no similar limitations for reactive power, because it is only exchanged between phases, and is not converted between the AC and DC sides of D-STATCOM VSI. Fig. 9 shown V-I characteristic of D-STATCOM.

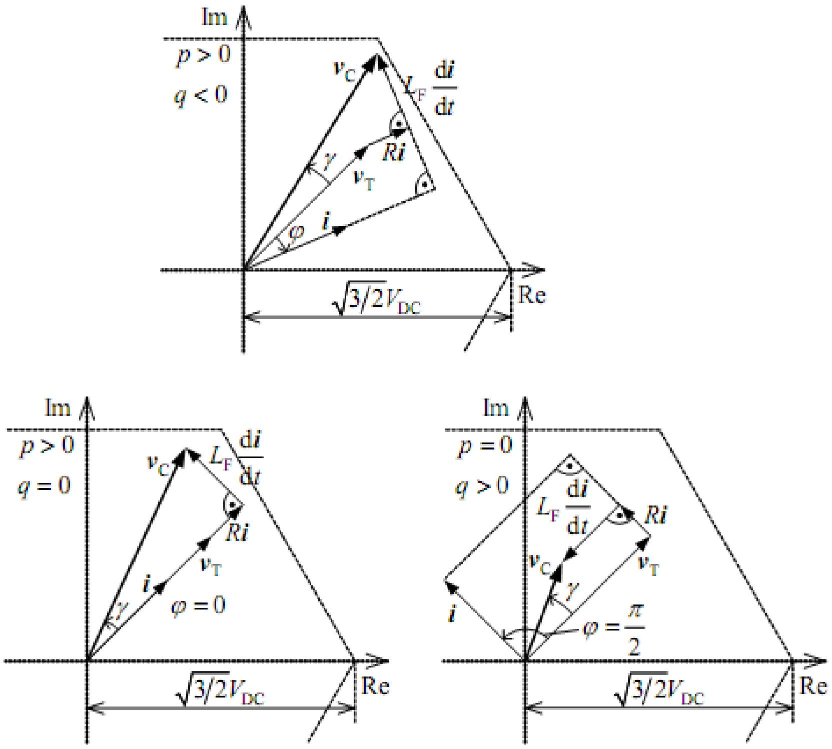


Fig.5.6 Principle of control of D-STATCOM instantaneous active and reactive power

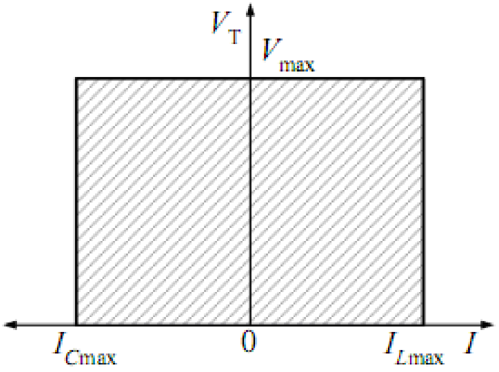


Fig.5.7 V-I characteristic of D-STATCOM

5.4.3 Compensation of DSTATCOM

The DSTATCOM is a DC/AC switching power-converter composed of an air-cooled voltage source converter. Basically, the DSTATCOM is used to suppress voltage variations and control reactive power in phase with the system voltage. The DSTATCOM produces phase- synchronized output voltage, therefore, it can compensate for inductive and capacitive currents linearly and continuously.

Active and reactive power trade between the power system and the DSTATCOM is accomplished by controlling the phase angle difference between the two voltages. If the output voltage of the DSTATCOM V_1 is in phase with the bus terminal voltage V_T and V_I is greater than V_T the DSTATCOM provides reactive power to the system. If V_1 is smaller than V_T, the DSTATCOM absorbs reactive power from the power system. Ideally, V_T and V_I have the same phase, but actually V_T and V_1 have a little phase difference to compensate for the loss of transformer winding and inverter switching, so it absorbs some real power from system. Fig. 10 shows the DSTATCOM vector diagrams, which show the inverter output voltage V_I, system voltage V_T, reactive voltage V_L and line current I in correlation with the magnitude and phase α. Fig. a and Fig. b explain how V_1 and V_T produce inductive or capacitive power by controlling the magnitude of the inverter output voltage V_I in phase with each other. Fig. c and Fig. d show that the DSTATCOM produces or absorbs real power with V_I and V_T having a phase difference ±α.

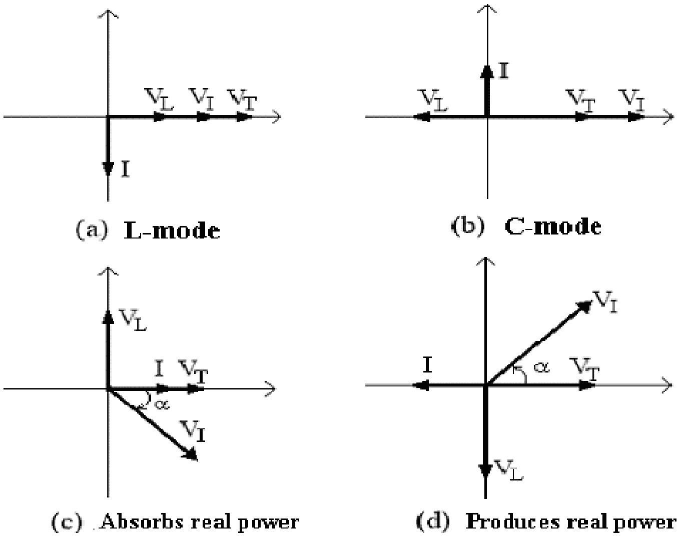


Fig. 5.8 Vector diagrams of DSTATCOM

5.5 Unified Power Quality Conditioner (UPQC)

5.5.1 Introduction

UPQC is based on combination of two 3-phase series and parallel active power filters. A UPQC can be installed to protect the sensitive load inside the plant as well as to restrict entry of any distortion from load side. This dual functionality makes the UPQC as one of the most suitable devices that could solve the problems of both consumers as well as of utility. UPQC thus can help to improve voltage profile and hence the overall health of power distribution system. Thus, UPQC is a versatile device that can compensate almost all types of perturbations such as voltage harmonics, voltage unbalance, voltage flicker, voltage sag and swell, current harmonics, current unbalance, reactive current, etc.

5.5.2 Principle of operation

The basic circuit of UPQC (Fig. 5.9) consists of two back to back connected IGBT based voltage source bi-directional converters with a common dc bus. One inverter is connected in series, while the other one is placed in shunt with the nonlinear load. The inverter connected in shunt with the load acts as a current source for injecting compensating current, i_c. While, the supply side inverter connected in series with the load acts as a voltage source feeding compensating voltage, v_c through an insertion transformer. A thyristor bridge rectifier feeding R-L load is considered as nonlinear load. The best protect for sensitive loads from voltage sources with inadequate quality, is shunt-series connection power conditioner (UPQC), in which the shunt part supplies the required power of the series part in the condition of voltage sags.

Shunt converter in spite of supplying the required active power by in series converters, they also can have applying DSTATCOM modes. Series converter injects a series voltage to the supply voltage and can posses DVR advantages.

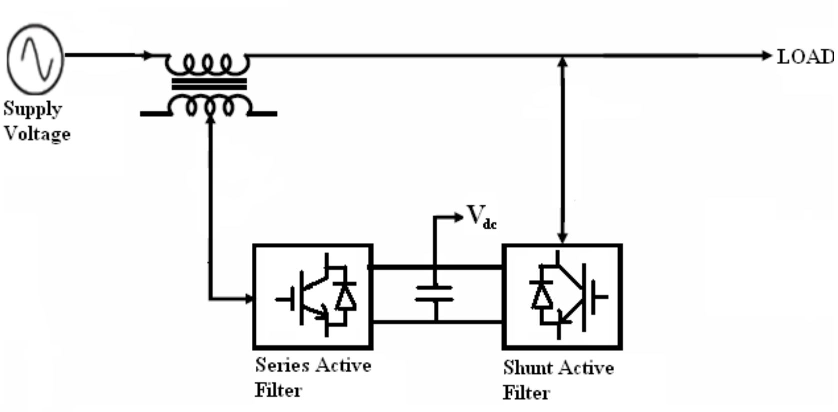


Figure 5.9. Schematic diagram of UPQC

5.6 ACTIVE FILTERING SYSTEM

The philosophy of active filtering system addresses the load current distortion from a time domain rather than a frequency domain approach. The most effective way to import the distortive power factor in a non-sinusoidal situation is to use a nonlinear active device that directly compensates for the load current distortion. The performance of these active filters is based on three basic design criteria. They are:

- Design of power inverter (semiconductor switches, inductances, capacitors, dc voltage);
- PWM control method (hysteresis, triangular carrier, periodical sampling); and
- Method used to obtain the current reference or the control strategy used to generate the reference template.

5.6.1 SERIES ACTIVE POWER FILTER (SAPF)

Series active power filter (Fig. 5.10) is connected in series with the incoming utility supply through a low pass filter and a voltage injecting transformer. The low pass filter eliminates the high switching frequency ripple of the inverter. The filter may inject some phase shift, which could be load dependent, but suitable feedback control is designed to dynamically adjust this shift. SAPF is responsible for compensating the deficiency in voltage quality of the incoming supply; such that the load end voltage remains insensitive to the variation of utility supply.

Different solutions are being proposed to improve the practical utilization of active filters. One of them is the use of a combined system of shunt passive filters and series active filters. This solution allows one to design the active filter for only a fraction of the total load power, reducing costs and increasing overall system efficiency.

The series active filter is controlled as a sinusoidal current source, instead of a harmonic voltage source. This approach presents the following advantages:

1) The control system is simpler, because only a sinusoidal waveform has to be generated.

2) This sinusoidal waveform to control the current can be generated in phase with the main

supply, allowing unity power-factor operation.

3) It controls the voltage at the load node, allowing excellent regulation characteristics.

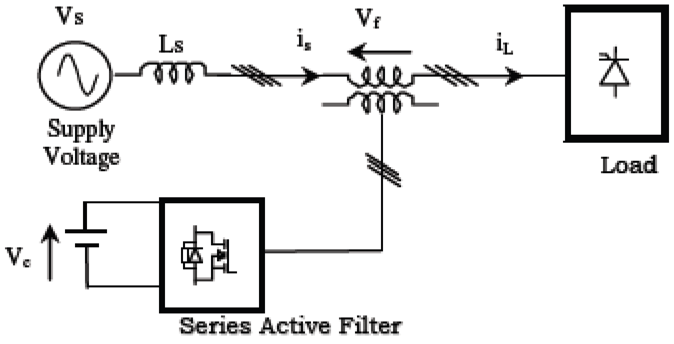


Figure 5.10 Global diagram of series active power filter (SAPF)

5.6.2 PARALLEL ACTIVE POWER FILTER (PAPF)

Parallel active power filter (PAPF) (Fig.5.11) is connected in parallel with the nonlinear load through a boost inductor Lf, which can boost up the common dc link voltage to the desired value through appropriate control. The size of the inductor has to be chosen carefully, bigger size would cause slower response to current control and smaller size would cause the high switching frequency ripple of the inverter to be injected into the distribution system. The main purpose of the PAPF is to provide required VAR support to the load, and to suppress the load current harmonics from flowing towards the utility and it is operated in current controlled mode.

The DC link capacitor C provides the common dc link voltage to both SAPF and PAPF. Ideally once charged, the dc link voltage should not fall off its charge, but due to finite switching losses of the inverters, inductor and capacitor, some active power is consumed and the charge of the dc link voltage needs to be maintained in a closed loop control, through the PAPF. The choice of the reference dc link voltage depends upon the percentage of voltage sag to be mitigated and amount of VAR to be shared.

The higher of the two values is to be chosen to comply with all needs. It is to be noted that as the C is charged continuously through PAPF, it does not require additional source of voltage support. The online charging also helps UPQC in mitigating voltage unbalance or under-voltage situations for longer durations, as it is not limited by the storage capacity of a separate voltage source.

Shunt active power filter compensate current harmonics by injecting equal-but-opposite harmonic compensating current. In this case the shunt active power filter operates as a current source injecting the harmonic components generated by the load but phase shifted by 180 degree. This principle is applicable to any type of load considered a harmonic source. Moreover, with an appropriate control scheme, the active power filter can also compensate the load power factor. In this way, the power distribution system sees the non linear load and the active power filter as an ideal resistor.

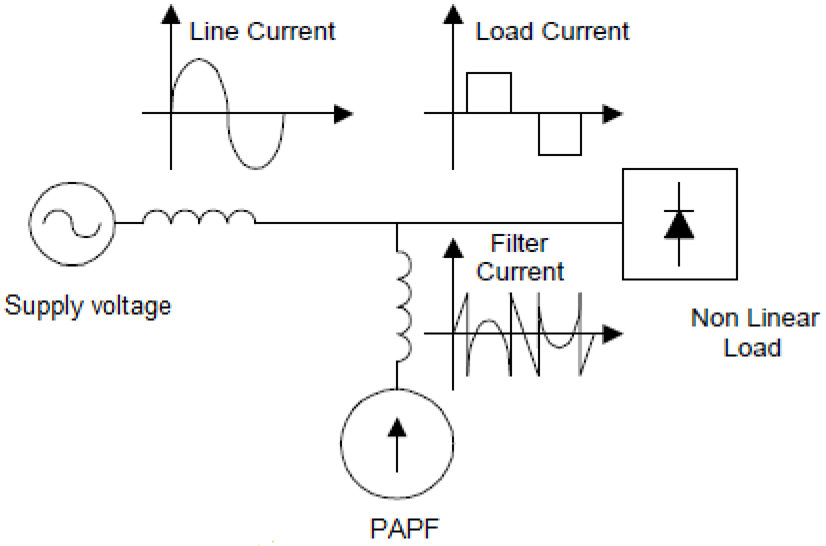


Figure 5.11 Compensation characteristics of a PAPF.

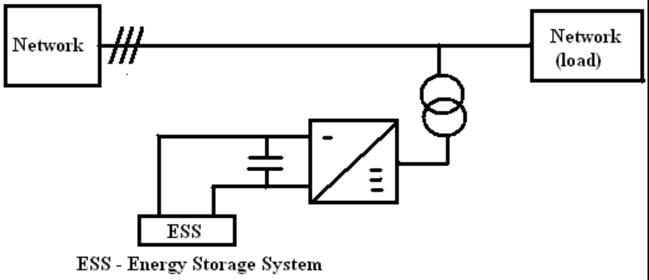
a) CAPACITOR:

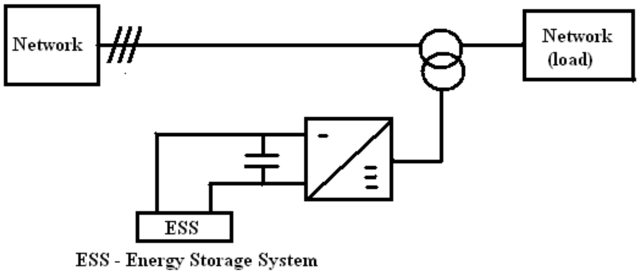
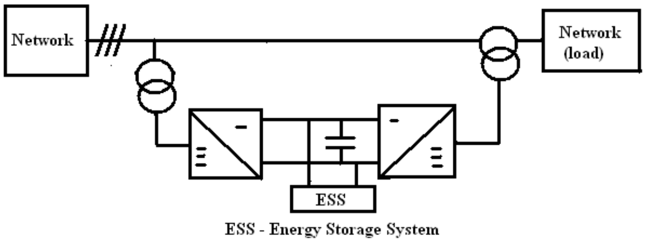
Capacitor is used as an interface between the two back to back connected inverters and the voltage across it acts as the dc voltage source driving the inverters.

b) POWER INVERTERS:

Both series voltage control and shunt current control involve use of voltage source converters. Both these inverters each consisting of six IGBTs with a parallel diode connected in reverse with each IGBT are operated in current control mode employing PWM control technique.

5.7 Comparison FACTS Equipment in Distribution System

NAME	TOPOLOGY	PREFERRED TASKS
DSTATCOM (Distribution STATCOM)		• Flicker compensation • Reactive power compensation • Harmonic filter
DVR (Dynamic Voltage Restorer)		• Sag/swell compensation

		
UPQC (Unified Power Quality Conditioner)		• Under voltage/ over voltage compensation • DSTATCOM and DVR advantages

5.8 Voltage Dip Mitigation methods

What has to be mitigated here is the tripping of equipment due to voltage dips. This can be done in a number of ways:

. ***Reducing the number of faults.*** *There are several well known methods for this like tree-trimming, animal guards, and shielding wires, but also replacing overhead lines by underground cables. As most of the severe dips are due to faults, this will directly affect the dip frequency.*

. ***Faster fault clearing****. This requires improved protection techniques. Much gain can be obtained in distribution networks, but at transmission level the fault-clearing time is already very short. Further improvement at transmission level would require the development of a new generation of circuit breakers and relays.*

. ***Improved network design and operation****. The network can be changed such that a fault will not lead to a severe dip at a certain location. This has been a common practice in the design of industrial power systems, but not in the public supply. Possible options are to remove long overhead feeders from busses supplying sensitive customers, and connecting on-site generators at strategic locations. Also the use of very fast transfer switches can be seen as a network-based solution.*

. ***Mitigation equipment at the interface****. The most commonly-used method of mitigating voltage dips is connecting a UPS or a constant-voltage transformer between the system and the sensitive load. For large loads the static series compensator of DVR (dynamic voltage restorer) is a possible solution..*

. ***Improved end-user equipment****. Making the equipment immune against all voltage dips would also solve the problem, but it is for most equipment not (yet) feasible. Methods of improving equipment behaviour will be discussed in more detail in [4]*

5.9 Future research

Research on voltage dips includes development-related research on mitigation equipment and improved end-user equipment. It also includes education-related research on the relation between voltage-dip frequency and system design and operation. Fundamental research is needed on voltage dip characteristics and indices, especially on methods for extracting system indices with a limited number of monitors and on suitable single-index methods. Related work is needed on the extraction of additional information from voltage-dip recordings. This is one of the possible applications for signal-processing techniques as are discussed in [7].

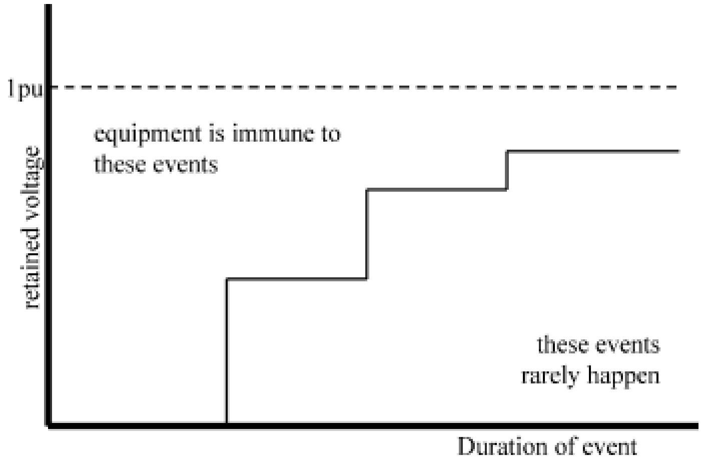


Figure 5.12 Distinction between events that are the responsibility of the customer and those that are the responsibility of the network operator

Fundamental research is also needed on stochastic prediction methods, including a large number of comparisons with monitoring results to find the limitations of stochastic prediction. Most of the work on consequences of voltage dips has been directed towards adjustable-speed drives. With the increase in embedded (renewable) generation more work should be done on the effect of voltage dips on generation, especially on inverter-based interfaces.

5.9 Harmonics

Mitigation is in the harmonic context often seen as synonym to reduction of harmonic voltage or current distortion. However the problem can also be mitigated by improving the immunity of equipment. De-rating of transformers and motors is a way of mitigating the harmonic problem, albeit not necessarily the most economic solution. A more common way of tackling the harmonic problem is by installing filters, typically LC-series connections that shunt the unwanted harmonic current components back to the load. The harmonic currents remain high but they do not spread through the system and do not cause much harmonic voltage distortion. The disadvantages of these so-called passive filters (high risk of overload, introduction of new resonances) has led to the development of so-called active filters where the current is fully controlled and adjusted to the existing voltage or current distortion.

Other mitigation methods include improvements in the network (de-rating of transformers, splitting sensitive and polluting loads) and improvements in the load. The latter includes a more sinusoidal current waveform (reduced emission) but also an increased immunity to voltage distortion. Reduced emission is seen by many as the preferred long-term solution of the harmonic distortion problem. One may however wonder if this is indeed the cheapest solution. As the number of concrete problems due to harmonic distortion remains relatively small, keeping the distortion at its current level or even allowing a further increase may be a cheaper overall solution. An important component in addressing harmonic problems is in defining limits to harmonic voltage and current distortion. The limits on harmonic voltage distortion as mentioned in various national and international standards are mainly a formalisation of the already existing distortion. For harmonic current limits, IEC and IEEE use two principally different approaches. The IEC standards set limits to the amount of emission of individual equipment, whereas the IEEE harmonic standard limits the emission per customer. Under the IEEE standard the responsibility lies with the customer who may decide to install filters instead of buying better equipment. Under the IEC standards the responsibility lies with the manufacturers of polluting equipment. The difference can be traced back to the aim of the documents: the IEEE standard aimed at regulating the connection of large industrial customers, whereas the IEC document mainly aims at small customers that do not have the means to choose between mitigation options.

5

POWER QUALITY MONITORING

(SHORT TYPE QUESTIONS AND ANSWERS)

UNIT 5 : WHAT IT IS?

- PQ Monitoring- It’s Objectives, Aspects.
- Various Monitoring.
- Equipment’s And Analyzers : Single and with Combined Features.
- One Intelligent Technique: That is Expert System Applications to Power
- Quality Monitoring.

1. Specify important aspects of the power quality monitoring effort.

The important aspects are

- Monitoring as a part of the facility site survey.
- Determining what to monitor
- Choosing monitoring location
- Options for permanent power quality monitoring equipment
- Disturbance monitor connections
- Setting monitor thresholds
- Quantities and duration to measure
- Finding the source of a disturbance

2. Name the different power quality monitoring need.

- Monitoring the supply at a number of positions at the same time, aimed at estimating an average " average power quality": a so – called power quality survey.
- Monitoring the supply at one site, aimed at estimating the power quality at that specific site.

3. Specify the common objectives of power quality monitoring

common objectives are

- Monitoring to characterize system performance
- Monitoring to characterize specific problem
- Monitoring as a part of an enhanced power quality service
- Monitoring as a part of predictive maintenance

4. What are the power quality monitoring consideration?

Power quality monitoring consideration includes the common objectives and aspects of power quality monitoring . (combine Q.no1 &3)

5. Name the permanent power quality monitoring equipment

- Digital fault recorder (DFRs)
- Smart relays and other IEDs (Intelligent .electronic . Device)
- Voltage recorders
- In plant power monitor
- Special purpose power quality monitor
- revenue meters

6. Name the basic categories of instruments which may be applicable for monitoring power quality.

- Wiring and grounding test devices.
- Multimeters
- Oscilloscope
- Disturbance analyzers
- Harmonic analyzer/spectrum analyzers.
- Flicker meters
- Energy monitors.

7. Mention the factors to be considered while selecting instruments for power quality monitoring

- Number of channels.
- Temperature specifications of the instrument.
- Ruggedness of the instrument.
- Input voltage range.
- Power requirements.
- Ability to measure currents.
- Housing of the instrument.
- Ease of use.
- Documentation.
- Communication capability.
- Analysis software.

8. Specify Important capabilities for a wiring and grounding test device

The Important capabilities are,

- Detection of isolated ground shorts and neutral-ground bonds.
- Ground impedance and neutral impedance measurement or indication.
- Detection of open grounds, open neutral or open hot wire.
- Detection of hot/neutral reversals or neutral/ground reversals.

9. Name the various signals checked with multimeters.

- Phase to ground voltage
- Phase to neutral voltage
- Neutral to ground voltage
- Phase to phase voltage.
- Phase currents
- Neutral currents

10. What important factor is considered while selecting a multimeter for PQ measurement

The most important factor to consider when selecting and using a multimeter is the method of calculation used in the meter.

11. Name the methods used for calculating the rms value using multimeters.

- Peak method
- Averaging method
- True rms.

12. Mention and brief the two categories of Disturbance analyzer.

- Conventional Analyzers that summaries events with specific information such as magnitudes, sags/surge magnitude and duration, transient magnitude and duration, etc.
- Graphics-based Analyzers that save and print the actual waveform along with the descriptive information which would be generated by one of the conventional analyzers.

13. Name the important capabilities for useful harmonic measurement

- Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained.
- Capability to measure both magnitude and phase angle of individual harmonic components
- Synchronization and a sampling rate fast enough to obtain accurate measurement of harmonic components up to at a least the 37th harmonic.
- Capability to characterize the statistical nature of harmonic distortion levels.

14. Name the categories of instruments used for harmonic analysis.

There are basically three categories of instrument to consider for harmonic analysis. They are

- Simple meters.
- General purpose meters.
- Special purpose meters

15. Define Voltage flicker.

A fluctuation in system voltage that can result in observable changes in light output. Voltage is called flicker. Flicker is rapidly occurring voltage sags caused by sudden and large increases in load current. Voltage flicker is most commonly caused by rapidly varying loads that require a large amount of reactive power such as welders, rock-crushers, sawmills, wood chippers, metal shredders, and amusement rides. It can cause visible flicker in lights and cause other processes to shut down or malfunction

When an electrical apparatus presents a changing load to the AC power network it draws fluctuating power from the supply. A good example of such an apparatus is a washing machine, since it contains electrical heaters and electric motors both of which draw significant current. As the machine runs through its washing cycle, the load presented to the supply changes as the program progresses. This changing load draws fluctuating current from the supply via the supply wiring which has an impedance. A fluctuating voltage drop is therefore seen across the supply wiring. If the wiring provides power to other electrical apparatus in the locality this fluctuating voltage can affect the function of the co-located apparatus. If the co-located apparatus is incandescent lighting, the fluctuating can manifest itself as a modulation of the light output from the luminaire, i.e. flicker.

16. Explain flicker standards

The two different standards used by utilities to evaluate the severity of flicker within their systems and flicker measurement are

- IEEE 141-1993 & 519- 1992 (both presents a borderline of visibility and a borderline of irritation curve with each related to the continuity, the amplitude, and the frequency aspects of the voltage fluctuations.)
- IEC 61000-4-15 (in principle all flicker meters built according to the IEC61000-4-15 Standard should provide the same results when connected to the same signal source) (In Europe and other countries, however, the International Electrotechnical Commission (IEC) has developed a group of standards which systematically account for many of the difficulties in the "flicker curve" methods. The IEEE Task Force on Light Flicker is presently considering modifications to these IEC standards that are required for them to be considered for adoption in the United States and Canada.)

17. Name the various flicker measurement technique

- RMS strip chart method
- Fast Fourier transform method.
- Flicker meters

18. Explain flicker meter

A flicker meter provides a convenient and standardized method of evaluating flicker levels. It is essentially a device that demodulates the flicker signal , weights it according to the established flicker curves and perform statistical analysis on the processed data It calculates the short term flicker indicator **(P_{st})** by processing through its five blocks.

19. Give the significance of flicker curve.

"flicker curves" derived from controlled experiments, offer thresholds of perception and/or irritability when periodic rectangular voltage fluctuations occur continuously. where the percent of the total change in voltage with respect to the average voltage (ΔV/V) is expressed along Y-axis and frequency of changes per minute (fluctuation rate) is taken along x axis **(**flicker sensitivity curve are drawn on the basis of the response of the human eye and brain to variations in the light output from a 60W incandescent bulb caused by fluctuations in the supply voltage.)

24. Define flicker severity

Intensity of the nuisance caused by the flicker, measured as defined by UIE-CEI and evaluated as:

- Short term severity (P_{st}) measured in a 10 minute period
- Long term severity (P_{lt}) (2 hrs) defined as $P_{lt} = \sqrt[3]{\sum_{i=1}^{12} \frac{P_{st}^3}{12}}$

20. Explain spectrum analyzer.

An analysis of a complex waveform, prepared in terms of a graphic plot of the amplitude versus frequency is known as spectrum analysis. spectrum analysis recognizes the fact that waveforms are composed of the summation of a group of sinusoidal waves., each of an exact frequency and all existing simultaneously. The devices that does the work i ,e selects the different frequency (amplitude versus frequency) components of the input is called a Spectrum analyzer**.**

21. Explain harmonic analyzer?

A device that analyses a periodic function from its graph in terms of the Fourier Series corresponding to the function is called a harmonic analyzer A harmonic analyzer has the capability to simultaneously log, display and analyze the harmonic components of voltage and/or current. The DC components, fundamental components and harmonic components of voltage and current, up to the 50th harmonic as related to a fundamental frequency of 15 to 400 Hz (ours is 50 Hz), are continuously and uninterruptedly logged at all three phases, calculated and represented as numerical values or as a bar graph in a phase selective fashion in real-time by means of the fast Fourier transformation process (A fast Fourier transform (FFT) is an efficient algorithm to compute the discrete Fourier transform (DFT) and its inverse) Total Harmonic Distortion (THD) Analyzers calculate the total distortion introduced by all the harmonics of the fundamental frequency wave.

22. What is a disturbance analyzer?

Disturbance Analyzers and disturbance monitors form a category of instruments which have been developed specifically for power quality measurements. They typically measure a wide variety of system disturbances(number and type of voltage and frequency disturbances which have occurred within an adjustable time interval, number and type of current disturbances which have occurred within an adjustable time interval, list of events including time of occurrence, cause and measurement value etc.) from very short duration transient voltages to long-duration outages or under voltages.

The devices basically fall into two categories:

- Conventional Analyzers that summaries events with specific information
- Graphics-based Analyzers that save and print the actual waveform along with the descriptive information

23. What is an expert systems.

An expert system, also known as a knowledge based system, is a computer program that contains the knowledge and analytical skills of one or more human experts, related to a specific subject. An expert system is a software system that incorporates concepts derived from experts in a field and uses their knowledge to provide problem analysis to users of the software.

24. What is the need for applying / role of an expert system /intelligent system for power quality?

Expert systems are the intelligent systems that can automatically evaluate disturbances and system conditions, draw conclusions about their cause, and even predict problems before they occur." wave of the future. The implementation of intelligent systems within a monitoring instruments can significantly increase the value of a monitoring application since it can generate information rather than collecting data .Expert systems help engineers determine the system condition rapidly This is especially important when restoring service following major disturbances.

5

POWER QUALITY MONITORING

(LONG TYPE QUESTIONS AND ANSWERS)

1. Discuss the various power quality monitoring considerations.

(or)

Discuss the various important aspects of the power quality monitoring .

(here one should write about the objectives as well as aspects of power quality monitoring)
Before entering to any power quality monitoring effort one should clearly defined the monitoring objectives.
The common objectives are,

- Monitoring to characterize system performance
- Monitoring to characterize specific problem
- Monitoring as a part of an enhanced power quality service
- Monitoring as a part of predictive maintenance

The following are the important aspects of the power quality monitoring effort. They are,

i. Site survey :

Site surveys are performed to evaluate concerns for power quality and equipment performance throughout a facility. The survey includes inspection of wiring and grounding concerns , equipment connections and the voltage and current characteristics. And the other information obtained from initial site survey are,

- Nature of the problem.
- Characteristics of the equipment's.
- The time at which problem occurs.
- Possible sources of the particular problem (motor starting, capacitor switching etc.)
- Existing power conditioning equipment being used.
- Electrical system data.(single line diagram , transformer sizes. Load information cable data. Etc.)

ii. Choosing a monitoring location:

It is very important that monitoring locations should be selected carefully. Based on the monitoring objectives.

It is best to start monitoring as close as possible to the sensitive equipment being affected by power quality variations. It is important that the monitor sees the same variations that the sensitive equipment sees. High frequency transients, in particular, can be significantly different if there is significant separation between the monitor and the affected equipment. Another important location is the main service entrance. Transients and voltage variations measured at this location can be experienced by all of the equipment in the facility. This is also the best indication of disturbances caused by the utility system.

iii. Option for permanent power quality monitoring equipments.

The categories of instruments that can be incorporated permanently into overall monitoring system include the followings. By using permanent power quality monitoring equipments we can become less careful about the duration of monitoring. Because monitoring equipments will provide information as part of the system.

- Digital fault recorder (DFRs).
- Smart relays and other IEDs (Intelligent Electronic Device).
- Voltage recorders.
- In plant power monitor.
- Special purpose power quality monitor.
- revenue meters.

iv. Disturbance recording form

It is important that the customer maintain a log detailing equipment problems that occur during the measurement period with a disturbance recording, form this will permit correlation of disturbances and system switching events with actual equipment power quality problems. The log should also indicate any major changes in the system configuration that are implemented during the measurement period.

Date of disturbance:……………..
Time of disturbance:…………….
Company:……………………
Address:………………
Contact name:………………
Phone.No:……………….
Brief description of disturbance:………………
Equipment category:…………………
Equipment type:………………….
Manufacturers:………………….
Equipment limitation:……………….
Cost of equipment failure:……………….
Cost of down time:……………………….

Table 5.1 Sample disturbance recording form

v. Disturbance monitor (like spectrum analyzer harmonic analyzer power analyzer etc.) connections:

The grounding of the power disturbance monitor is an important consideration otherwise it will damage the instruments or invalidate the measurements. The disturbance monitor will have a ground connection for the signal to be monitored and a ground connection for the power supply of the instrument. Both of these grounds will be connected to the instrument chassis. For safety reasons, both of these ground terminals should be connected to earth ground. However, this has the potential of creating ground loops if different circuits are involved.

The recommended practice is to provide input power to the monitor from a circuit other than the circuit to be monitored. Some manufacturers include input filters and/or surge suppressors on their power supplies that can alter disturbance data if the monitor is powered from the same circuit that is being monitored

vi. Setting monitor thresholds (threshold means there will not be any response until some minimum value of the input is exceeded**):**

Disturbance monitors are designed to detect conditions that are abnormal. Therefore, it is necessary to define the range of condition that can be considered normal. Some disturbance monitors have pre-selected thresholds that can be used as a starting point. The best approach for selecting thresholds is to match them with the specifications of the equipment that is affected. This may not always be possible due to a lack of specifications or applications guidelines.

An alternative approach is to set the thresholds fairly tight for a period of time and then use the data collected to selected appropriate thresholds for longer duration monitoring.

vii. Quantities and duration to measure

When monitoring power disturbances, it is usually sufficient to monitor system voltages. In order to characterize harmonic concerns, it is critical to measure both voltages and currents. If you have to choose one or the other, the currents are generally more important.

Current measurement on feeder circuits or at the service entrance characterizes a group or the loads or the entire facility as a source of harmonics. Current measurements on the distribution system can be used to characterize groups of customers or an entire feeder.

Voltage measurements help characterize he system response to the generated harmonic currents. In order to determine system frequency response characterize from measurements, voltages and currents must be measured simultaneously. In order to measure harmonic power flows , all three phases must be sampled simultaneously.

Duration of monitoring depend on the monitoring objectives. For example harmonic distortion problems and flicker problems should be characterized over a period of one week to get a complete picture (idea) of how the load changes and how system variations may affect these levels.

viii. Interpreting the measuring results.

In order to analyze power quality problems using measurements, it is important to correlate the characteristics of a disturbance with possible causes of the disturbance. This requires knowledge of the characteristics which are typical for different types of disturbance. Once the cause of a disturbance is understood, the impacts on equipment and possible solutions must be determined.

ix. Finding the source of a disturbance.

The first step in identifying the source of a disturbance is to correlate the disturbance wave form with possible causes .Once the category for the cause has been determined , the identification becomes more straight-forward.

- High-frequency voltage will be limited to locations close to the source of the disturbance.
- Power interruptions close to the monitoring location will cause a very abrupt change in the voltage. Power interruptions remote from the monitoring will result in a decaying voltage due to stored energy in rotating equipment and capacitors.
- The highest harmonic voltage distortion levels will occur close to capacitors that are causing resonance problems.

2. Discuss the various categories of equipment that can be incorporated into an Overall monitoring system.

(or)

Discuss the various instruments used in Power quality measurements.

Power quality problems encompass a wide range of disturbances and conditions on the system. They include everything from very first transient over voltages to long duration outages. Power quality also includes steady-state phenomenon such as harmonic distortion, and intermittent phenomenon, such as voltages flicker.

Types of instruments:

Although instruments have been developed which measure a wide variety of disturbances, a number of different instruments are generally necessary, depending on the phenomenon being investigated. Basic categories of instruments which may be applicable include:

- Wiring and grounding test devices.
- Multimeters.
- Oscilloscopes.
- Disturbance analyzers.
- Harmonic analyzer/spectrum analyzers.
- Combination disturbance and harmonic analyzers.
- Flicker meters.
- Energy meters.

Besides these instruments, which measure steady-state signals or disturbances on the power system directly, other instruments can be used to help solve power quality problems by measuring ambient conditions:

- Infrared meters can be very valuable in detecting loose connections and overheating conductors.
- Magnetic gauss meters are used o measure magnetic field strengths for inductive coupling concerns.
- Electric field meters can measure the strength of electric fields for electrostatic coupling concerns.
- Noise problems related to electromagnetic radiation may require measurement of field strengths in the vicinity of affected equipment.
- Static electric meters are special purpose devices to measure static electricity in the vicinity of sensitive equipment.

i. Wiring and grounding testers

The great majority of power quality problems reported by customers are caused by problems with wiring and /or grounding within the facility. These problems can be identified by visual inspection of wiring, connections and panel boxes and also with special test devices for detecting wiring and grounding problems. Important capabilities for a wiring and grounding test device include,

- Detection of isolated ground shorts and neutral-ground bonds.
- Ground impedance and neutral impedance measurement or indication.
- Detection of open grounds, open neutral or open hot wire.
- Detection of hot/neutral reversals or neutral/ground reversals.

ii. Multimeters:

After initial tests if wiring integrity; it may also be necessary to make quick checks of the voltage and / or current levels within a facility. Overloading of circuits , under and over voltage problems and unbalances between circuits can be detected in this manner. These measurements just require a simple multimeter to check

- Phase-to-ground voltages
- Phase-to-neutral voltages
- neutral-to-ground voltages
- Phase-to-phase voltages(three phase system)
- Phase currents.
- Neutral currents.

The most important factor to consider when selecting and using a multimeter is the method of calculation used in the meter.

iii. Oscilloscopes:

An oscilloscope is used to perform real time tests. Without performing detailed harmonic analysis on the wave forms an oscilloscope can provide much information about what is happening, such as magnitude and distortion in the waveform

A digital oscilloscopes with data storage is valuable because the wave form can be saved and analyzed. Oscilloscope in this category often have waveform analysis capability also. In addition, digital oscilloscopes can usually be obtained with communications so that waveform data can be uploaded to a PC for additional analysis with a software package.

Hand-held oscilloscopes instruments with the capability to display waveforms as well as performing some signal processing are also there. These are quite useful for power quality investigations because they are very portable and can be operated like a volt – ohm meter, but yield much more information.

iv. Disturbance Analyzers:

Disturbance Analyzers and disturbance monitors typically measure a wide variety of system disturbances such as number and type of voltage and frequency disturbances which have occurred within an adjustable time interval, number and type of current disturbances which have occurred within an adjustable time interval, list of events including time of occurrence, cause and measurement value etc. from very short duration transient voltages to long-duration outages or under voltages.
The devices basically fall into two categories:

- **Conventional Analyzers** that summaries events with specific information such as magnitudes, sags/surge magnitude and duration, transient magnitude and duration, etc.

- **Graphics-based Analyzers** that save and print the actual waveform along with the descriptive information which would be generated by one of the conventional analyzers.

v. Spectrum Analyzers and Harmonic analyzers

An analysis of a complex waveform, prepared in terms of a graphic plot of the amplitude versus frequency is known as spectrum analysis. The devices that does the work i.e. selects the different frequency (amplitude versus frequency) components of the input is called a Spectrum analyzer.

A harmonic analyzer has the capability to simultaneously log, display and analyze the harmonic components of voltage and/or current, the DC components, fundamental components and harmonic components of voltage and current,

Some of the more powerful analyzers have add-on modules that can be used for computing fast Fourier transform (FFT) calculations to determine the lower order harmonics up to the 50th harmonic as related to a fundamental frequency of 15 to 400 Hz. However , any significant requirements will demand an instrument that is designed for spectral analysis or harmonic analysis. Important capabilities for useful harmonic measurements include.

- Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained.
- Capability to measure both magnitude and phase angle of individual harmonic components
- Synchronization and a sampling rate fast enough to obtain accurate measurement of harmonic components up to at a least the 37th harmonic.
- Capability to characterize the statistical nature of harmonic distortion levels.

There are basically three categories of instrument to consider for harmonic analysis. They are

- **Simple meters:** To make a quick check of harmonics levels at a problem location
- **General purpose meters**: Designed to perform spectrum analysis on waveforms for a wide variety of applications
- **Special purpose meters**: Designed specifically for power system harmonic analysis

vi. Combination disturbance and harmonic analyzers

These devices provide complete information about all types of disturbances. The most recent instruments combine limited harmonic sampling and energy-monitoring functions with complete disturbance-monitoring functions as well. The output is graphically based and the data are remotely gathered over telephone lines into a central database. Statistical analysis can then be performed on the data. The data are also available for input and manipulation into other programs such as spreadsheets and other graphical output processors.

vii. Flickermeter

A flicker meter provides a convenient and standardized method of evaluating flicker levels. It is essentially a device that demodulates the flicker signal , weights it according to the established flicker curves and perform statistical analysis on the processed data It calculates the short term flicker indicator **(**P_{st}**)** by processing through its five blocks.

Voltage flicker

It is rapidly occurring voltage sags caused by sudden and large increases in load current. The most accurate method for measuring flicker is to use what are known as flicker meters.

- A flicker meter provides a convenient and standardized method of evaluating flicker levels.
- It Records voltage fluctuations.
- It Converts voltage changes to an estimate of light variation from an incandescent bulb.
- Weights this estimate according to frequency to account for human perception.
- Determines an instantaneous flicker perceptibility reading (P_{INST}).
- Derives a short-term flicker indication (P_{ST}) over a 10-min period.
- Derives a long-term flicker indication (P_{LT}) over a 2-h period.
- Here both PST and PLT are called as the flicker level evaluator.

PST = short term perceptibility (the ability to observe with sense) index or short term evaluation of flicker severity. This index is calculated from a combination of five percentile values i.e. the P value exceeded 50%, 10%, 3%, 1%, 0.1% of the time during the ten minutes. simply We can say that PST express the degree of irritation. PST is calculated as the root sum of some weighted percentiles of the momentary flicker sensation level.

PLT = It is calculated as the cubic mean of twelve consecutive PST values of a time window of two hours. Both depend upon the load duty cycle. How the voltage changes such as $\Delta V/V$.

3. Discuss about the flicker meters for power quality monitoring.

(Or)

Explain IEC flicker meters.

A flicker meter provides a convenient and standardized method of evaluating flicker levels. It is essentially a device that demodulates the flicker signal , weights it according to the established flicker curves and perform statistical analysis on the processed data It calculates the short term flicker indicator **(**P_{st}**)** by processing through its five blocks

IEC Flicker standard

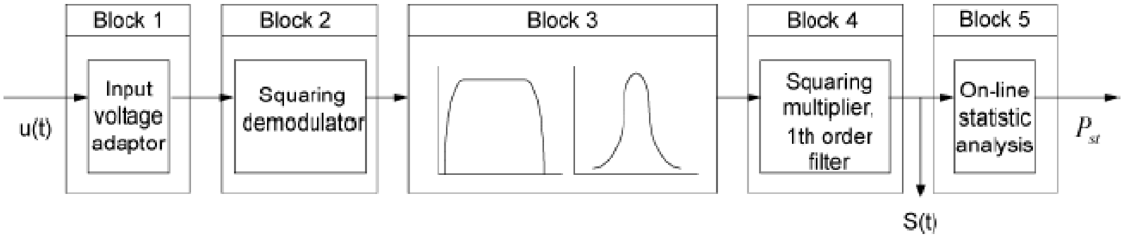


Fig 5.2 Functional diagram of IEC flicker meter.

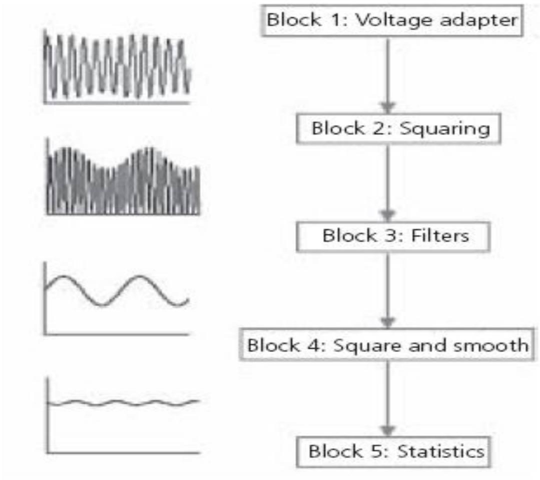


Fig 5.4 conceptual diagram of a flicker meter.

Block-1 Input Voltage Transformer.

This accepts a wide range of nominal mains voltages and adapts (scales the input voltage down to an internal reference level) them to a maximum level compatible with the operation of of the following circuitry. there is automatic gain control so that a range of input voltages can be tested. The output of the block is the RMS voltage modulated with the disturbance function. this block does not attenuate the flicker frequencies which are of interest.

Block-2 Squaring Demodulator.

Recovers the voltage fluctuation by squaring the input voltage to simulate the characteristics of a lightning device. This circuit gives a component of its output, a voltage linearly related to the amplitude of the fluctuation modulating the input .it is essentially simulating the flicker produced by a tungsten filament light bulb. part of output component is the flicker waveform to be analyzed, the other parts must be removed.

Block-3 Weighing Filters Or Cascade Filters.

It is composed of cascade of two filters. The first filter removes the D.C component and double main frequency component (component at twice the main frequency due to the squaring function involved.).) of the demodulator output (i,e output of block 2). The

output of this filter is solely the voltage flicker waveform. this filter comprises two filter back to back.

The second filter is a weighing filter that simulates frequency response to sinusoidal voltage variation of the coiled filament gas filled lamp combined with the human visual sensitivity response (eye- brain response).

About Eye Brain Response

The human eye/brain combination is especially sensitive such light variations particularly via peripheral vision. Flicker perception is a measure of this sensitivity and is based on the effect of supply variations at different rates when applied to a 60Watt incandescent light bulb. The response of human eye/brain combination is most sensitive to a flicker rate of about 1000 changes per minute (this equating to a square wave at 8.33Hz). In extreme cases this rate can trigger an epileptic fit in vulnerable people.

In order to make measurements of any phenomena one or more parameters have to be defined. In this case of flicker, two flicker indicators have been defined. These are Short Term (PSt) and Long Term (PLt). The short-term indicator is measured over a 110-minute period whilst the long term over a period of up to 2 hours.

Block-4 Squaring Multiplier

It consist of a squaring multiplier and sliding mean filter. The voltage signal is squared to simulate the non-linear eye-brain response, while the sliding mean averages the signal to simulate the short-term storage effect of the brain. The output of this block is considered to be the instantaneous flicker level. A level of one on the output of this block corresponds to perceptible flicker. It measures how intense the effect can be noticed by the average human beings

Block-5 Online Statistical Analysis

It consists of a statistical analysis of the instantaneous flicker level. The output of block-4 is divided into suitable classes, thus creating a histogram. A probability density function (PDF) is created based upon each class and from this a cumulative distribution function (CDF) can be formed.

Flicker Level Evaluation

Flicker level evaluation can be divided into two categories, short-term and long-term. Short-term evaluation of flicker severity PST is based upon an observation period of 10 min. This period is based upon assessing disturbances with a short duty cycle or those that produce continuous fluctuations. PST can be found using the equation,

$$P_{ST} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}}$$

where the percentages $P_{0.1}$, P_{1s}, P_{3s}, P_{10s} , and P_{50s} are the flicker levels that are exceeded 0.1, 1.0, 3.0, 10.0, and 50.0 percent of the time, respectively. These values are taken from the cumulative distribution curve discussed previously. A PST of 1.0 on the output of block 5 represents the objectionable (or irritable) limit of flicker. For cases where the duty cycle is long or variable, such as in arc furnaces, or disturbances on the system that are caused by multiple loads operating simultaneously, the need for the long-term assessment of flicker severity arises. Therefore, the long-

term flicker severity PLT is derived from PST using the equation

$$P_{LT} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{STi}^{3}}{N}}$$

where N is the number of PST readings and is determined by the duty cycle of the flicker-producing load. The purpose is to capture one duty cycle of the fluctuating load. If the duty cycle is unknown, the recommended number of PST readings is 12 (2-h measurement window).

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} P_{st_j}^{\ 3}}$$

Here, N=12 (P_{LT}) represents the long-term flicker severity. Each P_{lt} value is calculated from 12 successive P_{st} values using this formula)

4. Explain expert systems & Discuss the various applications of expert system for power quality monitoring

One of the most exciting developments in this field of Power quality monitoring systems is the implementation of intelligent systems that can

- automatically evaluate disturbances and system conditions,
- draw conclusions about their cause,
- predict problems before they occur.

An expert system, also known as a knowledge based system, is a computer program that contains the knowledge and analytical skills of one or more human experts

The implementation of intelligent systems within a monitoring instruments can significantly increase the value of a monitoring application since it can generate information rather than collecting data

The expert systems are packaged as individual autonomous expert systems module Where each module performs specific function. One or more autonomous expert system module can be implemented within an advanced power quality monitoring systems.

The few example applications of autonomous expert systems are

- Voltage sag direction module.
- Radial fault locator module
- Capacitor switching direction module.
- Capacitor switching operation inspection module
- Lightning correlation module

Voltage sag direction module.

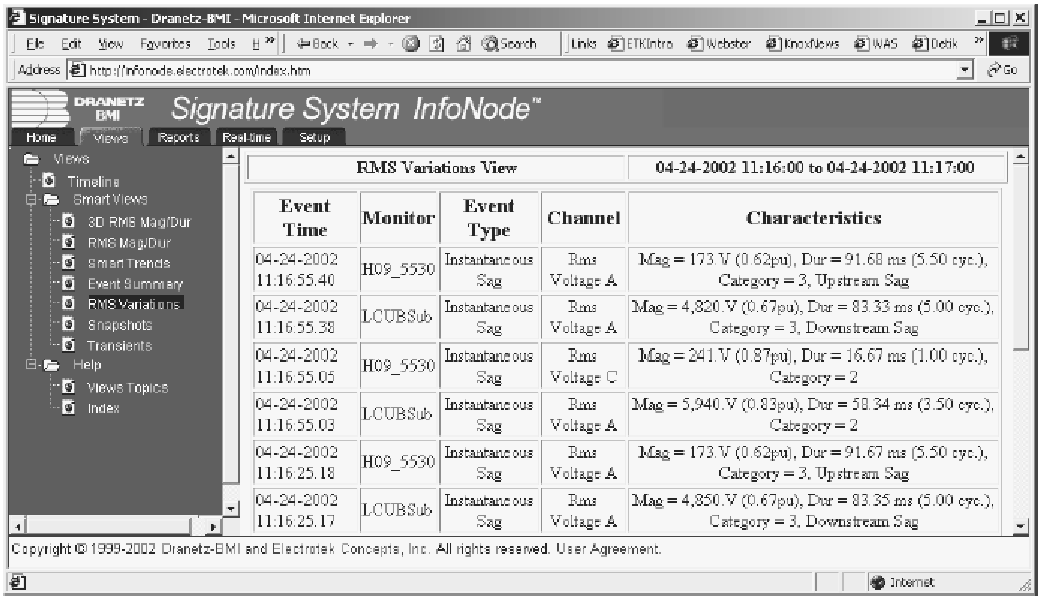
Voltage sags are some of the most important disturbances on utility systems. They are usually caused by a remote fault somewhere on the power system; however, they can also be caused by a fault inside end-user facilities. Determining the location of the fault causing the voltage sag can be an important step toward preventing voltage sags in the future and assigning responsibility for addressing the problem. For instance, understanding the fault location is necessary for implementing contracts that include voltage sag performance specifications.

The supplier would not be responsible for sags that are caused by faults within the customer facility. This is also important when trying to assess performance of the distribution system in comparison to the transmission system as the cause of voltage sag events that can impact customer operations. The fault locations can help identify future problems or locations where maintenance or system changes are required. An expert system to identify the fault location (at least upstream or downstream from the monitoring location) can help in all these cases. An autonomous expert system module called the voltage sag direction module is designed just for that purpose, i.e., to detect and identify a voltage sag event and subsequently determine the origin (upstream or downstream from the monitoring location) of the voltage sag event.

If a data acquisition node is installed at a customer PCC, the source of the voltage sag will be either on the utility or the customer side of the meter. If the monitoring point is at a distribution substation trans- former, the source of the voltage sag will be either the distribution system or the transmission system. The voltage sag direction module works by comparing current and voltage rms magnitudes both before and after the sag event. It tracks phase angle changes from prefault to postfault.

By assembling information from the rms magnitude comparison and the phase angle behavior, the origin of the voltage sag event can be accurately determined. In addition, the voltage sag direction module is equipped with algorithms to assess the quality of the knowledge or answer discovered. If the answer is deemed accurate, it will be sent as an output; otherwise, it will be neglected and no answer will be provided. In this way, inaccurate or false knowledge can be minimized. Inaccurate knowledge can be due to a number of factors, primarily to missing data and unresolved conflicting characteristics.

Outputs of the voltage sag direction module can be displayed on a computer screen using Web browser software, displayed in printed paper format, sent to a pager, or sent as an e-mail. Figure 11.31 shows an output of a voltage sag direction expert system module. The first column indicates the event time, the second column indicates the monitor identification, the third column indicates event types, the fourth column indicates the triggered channel, and finally the fifth column indicates the characteristics of the event and outputs of the answer module.



RMS Variations View | **04-24-2002 11:16:00 to 04-24-2002 11:17:00**

Event Time	Monitor	Event Type	Channel	Characteristics
04-24-2002 11:16:55.40	H09_5530	Instantaneous Sag	Rms Voltage A	Mag = 173.V (0.62pu), Dur = 91.68 ms (5.50 cyc.), Category = 3, Upstream Sag
04-24-2002 11:16:55.38	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 4,820.V (0.67pu), Dur = 83.33 ms (5.00 cyc.), Category = 3, Downstream Sag
04-24-2002 11:16:55.05	H09_5530	Instantaneous Sag	Rms Voltage C	Mag = 241.V (0.87pu), Dur = 16.67 ms (1.00 cyc.), Category = 2
04-24-2002 11:16:55.03	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 5,940.V (0.83pu), Dur = 58.34 ms (3.50 cyc.), Category = 2
04-24-2002 11:16:25.18	H09_5530	Instantaneous Sag	Rms Voltage A	Mag = 173.V (0.62pu), Dur = 91.67 ms (5.50 cyc.), Category = 3, Upstream Sag
04-24-2002 11:16:25.17	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 4,850.V (0.67pu), Dur = 83.35 ms (5.00 cyc.), Category = 3, Downstream Sag

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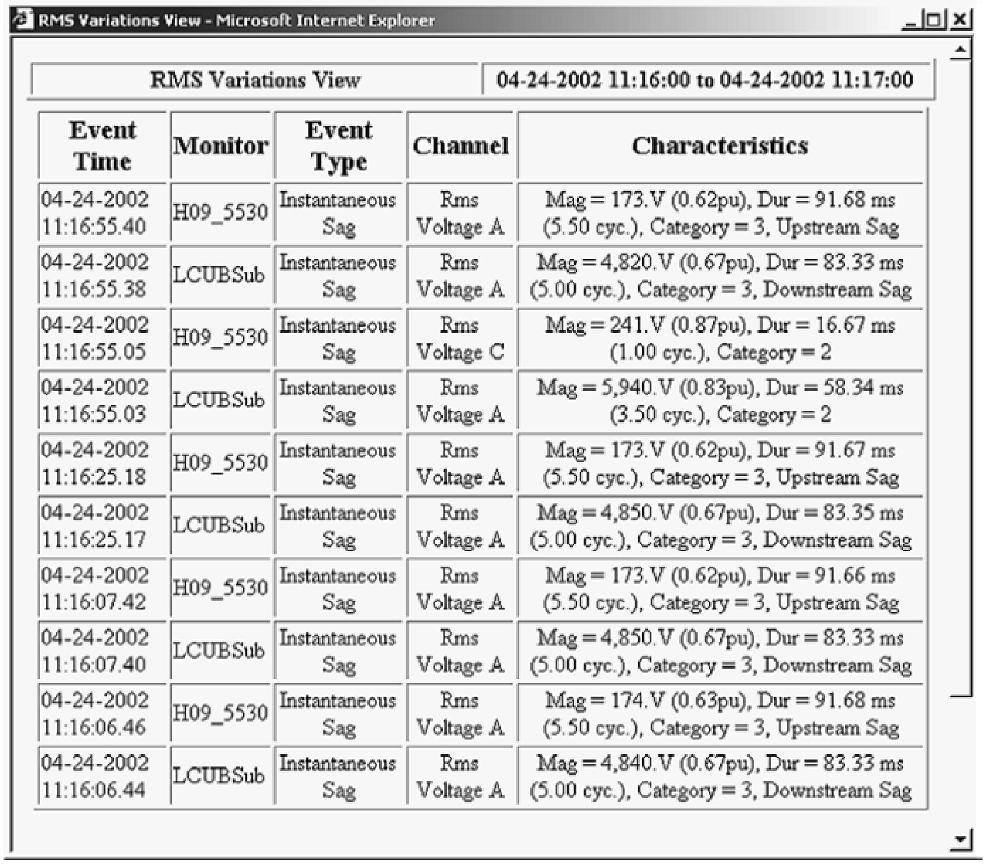
Figure 11.31 A standard Web browser is the interface between the monitoring system and users. Outputs of the voltage sag direction module are shown in the last column of the table.

Figure 11.31 shows an event table with several voltage sag events that occurred at 11:16:55 A.M. on April 24, 2002. A tree branch that fell across a 13-kV overhead line caused the sag events. A total of five automatic reclosure operations were performed before the breaker finally tripped and locked out.

There were two data acquisition nodes available to capture this disturbance: one at the substation, i.e., at the secondary of 161/13-kV transformer (LCUBSub), where the affected overhead line was served, and one at the service entrance of a Electrotek office complex (H09_5530) located about 0.5 mi from the substation. (See Fig. 11.38 for the geographical locations of these data acquisition nodes.) Obviously, the LCUBSub and H09_5530 data acquisition nodes should report that the directions or the relative origin of voltage sags are downstream and upstream, respectively.

Analysis provided by the voltage sag direction module reports the direction of the voltage sag correctly. Note that there are two voltage sag events where the module does not provide any knowledge about the origin of the sag event. This happens since the algorithms were unable to resolve conflicting characteristics extracted from the data. Figure 11.32 shows the table of the sag events associated with this fault.



RMS Variations View — 04-24-2002 11:16:00 to 04-24-2002 11:17:00

Event Time	Monitor	Event Type	Channel	Characteristics
04-24-2002 11:16:55.40	H09_5530	Instantaneous Sag	Rms Voltage A	Mag = 173.V (0.62pu), Dur = 91.68 ms (5.50 cyc.), Category = 3, Upstream Sag
04-24-2002 11:16:55.38	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 4,820.V (0.67pu), Dur = 83.33 ms (5.00 cyc.), Category = 3, Downstream Sag
04-24-2002 11:16:55.05	H09_5530	Instantaneous Sag	Rms Voltage C	Mag = 241.V (0.87pu), Dur = 16.67 ms (1.00 cyc.), Category = 2
04-24-2002 11:16:55.03	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 5,940.V (0.83pu), Dur = 58.34 ms (3.50 cyc.), Category = 2
04-24-2002 11:16:25.18	H09_5530	Instantaneous Sag	Rms Voltage A	Mag = 173.V (0.62pu), Dur = 91.67 ms (5.50 cyc.), Category = 3, Upstream Sag
04-24-2002 11:16:25.17	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 4,850.V (0.67pu), Dur = 83.35 ms (5.00 cyc.), Category = 3, Downstream Sag
04-24-2002 11:16:07.42	H09_5530	Instantaneous Sag	Rms Voltage A	Mag = 173.V (0.62pu), Dur = 91.66 ms (5.50 cyc.), Category = 3, Upstream Sag
04-24-2002 11:16:07.40	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 4,850.V (0.67pu), Dur = 83.33 ms (5.00 cyc.), Category = 3, Downstream Sag
04-24-2002 11:16:06.46	H09_5530	Instantaneous Sag	Rms Voltage A	Mag = 174.V (0.63pu), Dur = 91.68 ms (5.50 cyc.), Category = 3, Upstream Sag
04-24-2002 11:16:06.44	LCUBSub	Instantaneous Sag	Rms Voltage A	Mag = 4,840.V (0.67pu), Dur = 83.33 ms (5.00 cyc.), Category = 3, Downstream Sag

Figure 11.32 An event summary report detailing time of occurrence and event characteristics. There are five voltage sag events associated with the autoreclosure operation following a fault. The voltage sag direction module identifies the origin of the sag correctly.

Radial fault locator module

Radial distribution feeders are susceptible to various short-circuit events such as symmetrical faults (three-phase) and unsymmetrical faults, including single-line-to-ground, doubleline- to-ground, and line-to-line faults. These system faults arise from various conditions ranging from natural causes such as severe weather conditions and animal contacts to human intervention and errors, including equipment failure. Quickly identifying the source and location of faults is the key to cost-efficient system restoration.

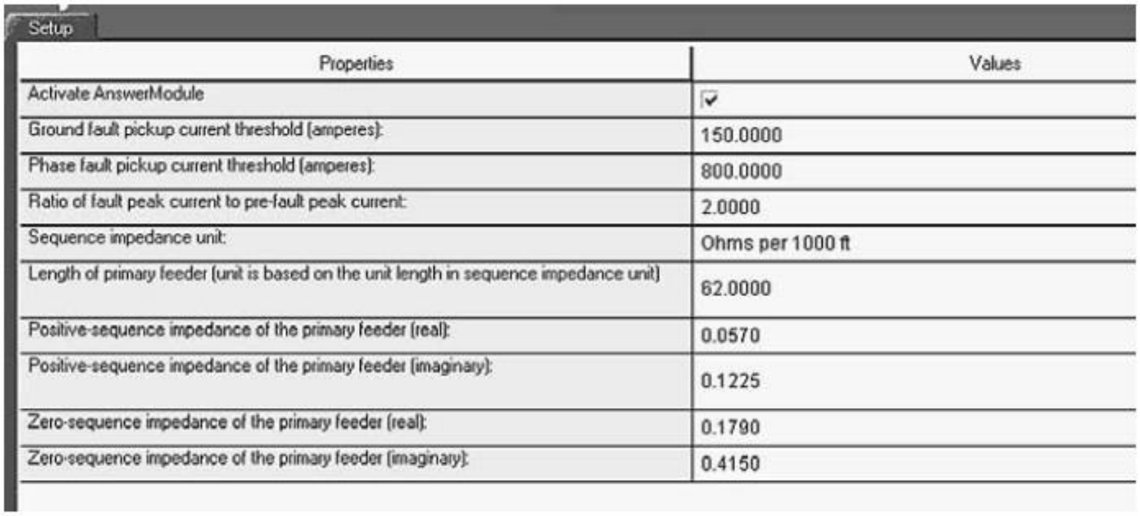
The current practice to locate the faults is to send a lineperson to patrol the suspected feeders. While this is a proven method, it is certainly not a costeffective way to restore power. An expert system module called the radial fault locator is developed to estimate the distance to a fault location from the location where the measurements were made. The unique feature of this module is that it only requires a set of three-phase voltages and currents from a single measurement location with the sequence impedance data of the primary distribution feeder.

The module works by first identifying a permanent fault event based on the ground fault and phase fault pickup current threshold. Users can enter these values in the answer module setup window shown in Fig. 11.33. Once a permanent fault event is identified, the distance to fault estimation is carried out based on the apparent impedance approach.13 Estimates of the distance to the fault are then displayed in a computer screen with the Web browser illustrated in Fig. 11.34 or sent to a

lineperson via a pager. The lineperson can quickly pinpoint the fault location. This example illustrates the emerging trend in smart power quality monitoring, i.e., collect power quality data and extract and formulate information for users to perform necessary actions.

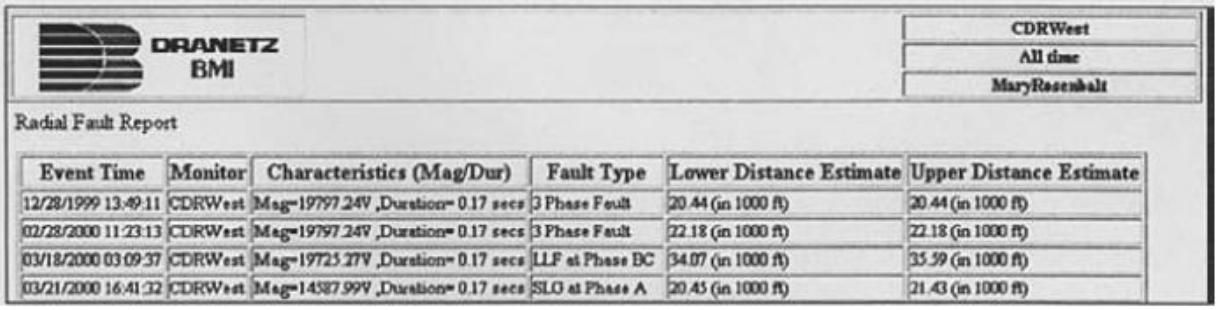
Capacitor switching direction module.

Capacitor-switching operations are the most common cause of transient events on the power system. When a capacitor bank is energized, it interacts with the system inductance, yielding oscillatory transients. The transient overvoltage in an uncontrolled switching is between 1.0 to 2.0 pu with typical overvoltages of 1.3 to 1.4 pu and frequencies of 250 to 1000 Hz. Transients due to energizing utility capacitor banks can propagate into customer facilities. Common problems associated with the switching transients include tripping off sensitive equipment such adjustable-speed drives and other electronically controlled loads. Some larger end-user facilities may also have capacitor banks to provide reactive power and voltage support as well. When a sensitive load trips off due to capacitor-switching transients, it is important to know where the capacitor bank is, whether it is on the utility side or in the customer facility.



Properties	Values
Activate AnswerModule	☑
Ground fault pickup current threshold (amperes):	150.0000
Phase fault pickup current threshold (amperes):	800.0000
Ratio of fault peak current to pre-fault peak current:	2.0000
Sequence impedance unit:	Ohms per 1000 ft
Length of primary feeder (unit is based on the unit length in sequence impedance unit)	62.0000
Positive-sequence impedance of the primary feeder (real):	0.0570
Positive-sequence impedance of the primary feeder (imaginary):	0.1225
Zero-sequence impedance of the primary feeder (real):	0.1790
Zero-sequence impedance of the primary feeder (imaginary):	0.4150

Figure 11.33 Setup window for the radial fault location answer module.



CDRWest
All time
MaryRosenbalt

Radial Fault Report

Event Time	Monitor	Characteristics (Mag/Dur)	Fault Type	Lower Distance Estimate	Upper Distance Estimate
12/28/1999 13:49:11	CDRWest	Mag=19797.24V ,Duration= 0.17 secs	3 Phase Fault	20.44 (in 1000 ft)	20.44 (in 1000 ft)
02/28/2000 11:23:13	CDRWest	Mag=19797.24V ,Duration= 0.17 secs	3 Phase Fault	22.18 (in 1000 ft)	22.18 (in 1000 ft)
03/18/2000 03:09:37	CDRWest	Mag=19725.27V ,Duration= 0.17 secs	LLF at Phase BC	34.07 (in 1000 ft)	35.59 (in 1000 ft)
03/21/2000 16:41:32	CDRWest	Mag=14587.99V ,Duration= 0.17 secs	SLG at Phase A	20.45 (in 1000 ft)	21.43 (in 1000 ft)

Figure 11.34 The distance estimates presented in tabular form.

A capacitor-switching direction expert system module is designed to detect and identify a capacitor switching event and determine the relative location of the capacitor bank from the point where measurements were collected. It only requires a set of three-phase voltages and currents to perform the tasks mentioned. This module is useful to determine the responsible parties, i.e., the utility or customer, and help engineers pinpoint the problematic capacitor bank. The capacitor-switching transient direction module works as follows. When an event is captured, the module will extract the information and represent it in domains where detection and identification are more favorable. The domains where the information is represented are in the time-, frequency-, and time-scale (wavelet) domains. If the root cause of the event is due to a capacitor bank energization, the answer module will proceed to determine the most probable location of the capacitor bank.

There are only two possible locations with respect to the monitoring location, i.e., upstream or downstream. The expert system module works well with grounded, ungrounded, delta-configured, and wye- (or star-) configured capacitor banks. It also works well for back-to-back capacitor banks. The capacitor-switching transient direction module is equipped with algorithms to determine the quality of the information it discovers. Thus, the module may provide an undetermined answer. This answer is certainly better than an incorrect one.

An example application of the answer module to analyze data capture from a data acquisition node installed at an office complex service entrance is shown in Fig. 11.35. The analysis results are shown in Fig. 11.36, which is a screen capture from a standard Web browser. Since the office complex has no capacitor banks, any capacitor-switching transients must originate from the utility side located upstream from the data acquisition node.

The module correctly determines the relative location of the capacitor bank. Note that there are some instances where the expert system was not able to determine the relative location of the capacitor bank. From the time stamp of the events, it is clear that capacitor bank energizations occur at about 5:00 A.M. and 7:00 P.M. each day.

Capacitor switching operation inspection module

As described, capacitor- switching transients are the most common cause of transient events on the power system and are results of capacitor bank energization operation. One common thing that can go wrong with a capacitor bank is for a fuse to blow. Some capacitor banks may not be operating properly for months before utility personnel notice the problem. Routine maintenance is usually performed by driving along the line and visually inspecting the capacitor bank. An autonomous expert system was developed for substation applications to analyze downstream transient data and determine if a capacitor- switching operation is performed successfully and display a warning message if the operation was not successful.

With the large number of capacitor banks on most power systems, this expert system module can be a significant benefit to power systems engineers in identifying problems and correlating them with capacitor-switching events. Successful capacitor bank energization is characterized by a uniform increase of kvar on each phase whose total corresponds to the capacitor kvar size. For example, when a 1200-kvar capacitor bank is energized, reactive power of approximately 400 kvar should appear on each phase. The total kvar increase can be determined by computing kvar changes in individual phases from the current and voltage waveforms before and after the switching operation. This total computed kvar change is then compared to the actual or physical capacitor bank kvar supplied by a user. If the expected kvar was not realized, the capacitor bank or its switching device may be having some problems. Figure 11.37 shows the application of the capacitor-switching operation inspector expert system in a commercial monitoring system. The monitoring location is at the substation; thus, all capacitor banks along the feeders are downstream from the monitoring location. The first capacitor-switching event indicates that two phases of the capacitor are out of service. Either the fuses have blown or the switch is malfunctioning. The second event shows a successful capacitor-switching operation.

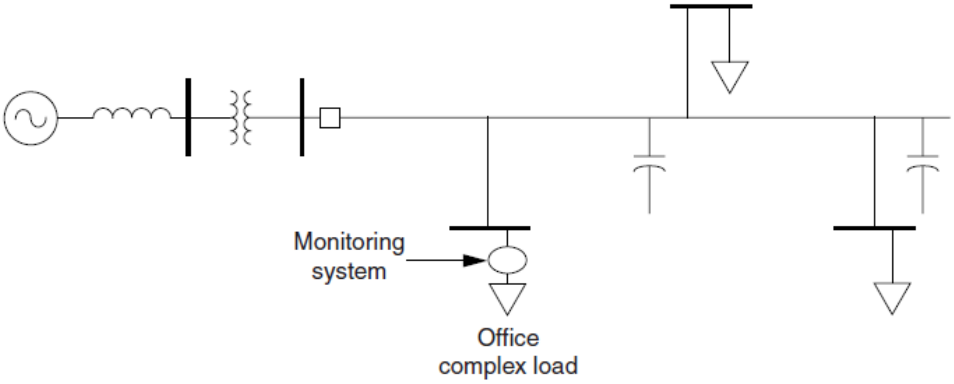


Figure 11.35 All capacitors are upstream from the monitoring location. Therefore, the answer module should report upstream capacitor switching when such an event is captured.

Transients View | 04-17-2002 00:00:00 to 04-19-2002 23:23:55

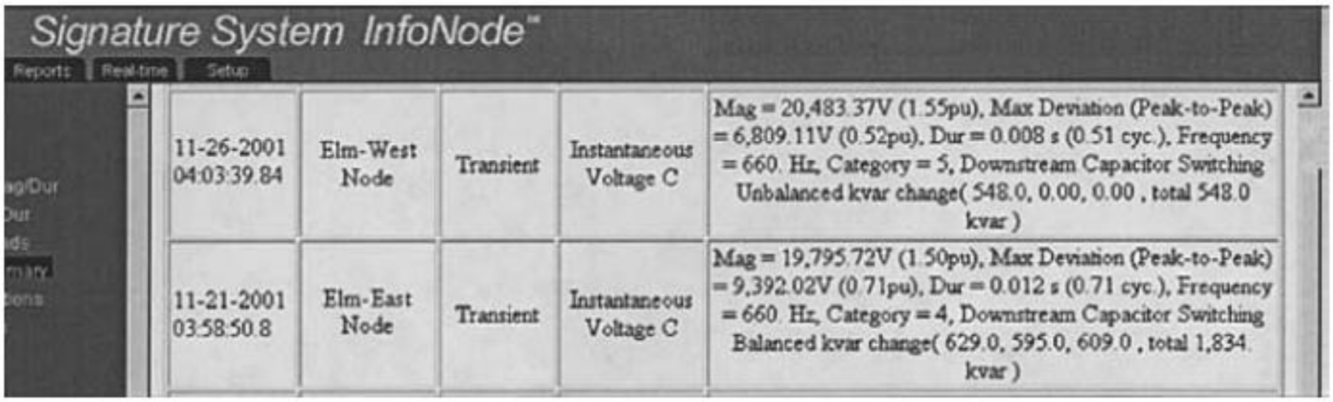
Event Time	Monitor	Event Type	Channel	Characteristics
04-19-2002 19:01:17.36	H09_5530	Transient	Instantaneous Voltage C	Mag = 448.V (1.14pu), Max Deviation (Peak-to-Peak) = 174.V (0.44pu), Dur = 1.692 ms (0.10 cyc.), Frequency = 420. Hz, Category = 2, Upstream Capacitor Switching
04-19-2002 05:03:48.96	H09_5530	Transient	Instantaneous Voltage A	Mag = 406.V (1.04pu), Max Deviation (Peak-to-Peak) = 92.V (0.24pu), Dur = 3.646 ms (0.22 cyc.), Upstream Capacitor Switching
04-19-2002 04:57:05.33	H09_5530	Transient	Instantaneous Voltage A	Mag = 474.V (1.21pu), Max Deviation (Peak-to-Peak) = 310.V (0.79pu), Dur = 3.516 ms (0.21 cyc.), Frequency = 3,218. Hz, Category = 3, Upstream Capacitor Switching
04-19-2002 04:57:04.84	H09_5530	Transient	Instantaneous Voltage B	Mag = 485.V (1.24pu), Max Deviation (Peak-to-Peak) = 270.V (0.69pu), Dur = 1.693 ms (0.10 cyc.), Frequency = 2,453. Hz, Category = 3, Upstream Capacitor Switching
04-19-2002 04:56:31.69	H09_5530	Transient	Instantaneous Voltage A	Mag = 412.V (1.05pu), Max Deviation (Peak-to-Peak) = 106.V (0.27pu), Dur = 5.079 ms (0.30 cyc.), Frequency = 1,013. Hz, Category = 1, Direction Unknown Capacitor Switching
04-18-2002 19:01:19.69	H09_5530	Transient	Instantaneous Voltage C	Mag = 408.V (1.04pu), Max Deviation (Peak-to-Peak) = 169.V (0.43pu), Dur = 2.343 ms (0.14 cyc.), Frequency = 795. Hz, Upstream Capacitor Switching
04-18-2002 04:57:06.26	H09_5530	Transient	Instantaneous Voltage A	Mag = 405.V (1.03pu), Max Deviation (Peak-to-Peak) = 121.V (0.31pu), Dur = 2.865 ms (0.17 cyc.), Direction Unknown Capacitor Switching
04-18-2002 04:57:05.81	H09_5530	Transient	Instantaneous Voltage A	Mag = 404.V (1.03pu), Max Deviation (Peak-to-Peak) = 168.V (0.43pu), Dur = 45.19 ms (2.71 cyc.), Upstream Capacitor Switching
04-17-2002 04:56:53.15	H09_5530	Transient	Instantaneous Voltage A	Mag = 422.V (1.08pu), Max Deviation (Peak-to-Peak) = 220.V (0.56pu), Dur = 2.735 ms (0.16 cyc.), Frequency = 3,180. Hz, Category = 1, Upstream Capacitor Switching
04-17-2002 04:56:52.73	H09_5530	Transient	Instantaneous Voltage B	Mag = 479.V (1.22pu), Max Deviation (Peak-to-Peak) = 125.V (0.32pu), Dur = 2.734 ms (0.16 cyc.), Category = 3, Direction Unknown Capacitor Switching
04-17-2002 04:56:52.65	H09_5530	Transient	Instantaneous Voltage B	Mag = 497.V (1.27pu), Max Deviation (Peak-to-Peak) = 230.V (0.59pu), Dur = 2.344 ms (0.14 cyc.), Frequency = 2,468. Hz, Category = 3, Direction Unknown Capacitor Switching

Figure 11.36 The output of the capacitor-switching answer module for the one-line diagram presented in Fig. 11.35.

Lightning correlation module

The majority of voltage sags and outages in the United States are attributed to weather-related conditions such as thunderstorms. For example, TVA has approximately 17,000 mi of transmission lines where lightning accounts for as much as 45 percent of the faults on their system. The lightning correlation expert system module is designed to correlate lightning strikes with measured power quality events and make that information available in real time directly at the point of measurement.

Armed with the correlation results, engineers can evaluate the cause and impact of voltage sags for a specific customer at a specific monitoring point as well as evaluate the impact on all customers for a given event. When the lightning correlation module detects a voltage sag or transient event, it queries a lightning database via the Internet. The lightning data are provided by the U.S. National Lightning Detection Network operated by Global Atmospherics, Inc. If the query returns a result set, the lightning correlation module will store this information in the monitoring system database along with the disturbance data for information dissemination. The lightning data include the event time of the strike, the latitude and longitude of strike location, the current magnitude, and number of strokes.



11-26-2001 04:03:39.84	Elm-West Node	Transient	Instantaneous Voltage C	Mag = 20,483.37V (1.55pu), Max Deviation (Peak-to-Peak) = 6,809.11V (0.52pu), Dur = 0.008 s (0.51 cyc.), Frequency = 660. Hz, Category = 5, Downstream Capacitor Switching Unbalanced kvar change(548.0, 0.00, 0.00 , total 548.0 kvar)
11-21-2001 03:58:50.8	Elm-East Node	Transient	Instantaneous Voltage C	Mag = 19,795.72V (1.50pu), Max Deviation (Peak-to-Peak) = 9,392.02V (0.71pu), Dur = 0.012 s (0.71 cyc.), Frequency = 660. Hz, Category = 4, Downstream Capacitor Switching Balanced kvar change(629.0, 595.0, 609.0 , total 1,834 kvar)

Figure 11.37 Analysis results of the capacitor-switching inspector expert system.

The following example illustrates how the module performs its function. On Easter Sunday, March 31, 2002, in Knoxville, Tennessee, the location of the Electrotek Concepts primary engineering office, thunderstorms moved through the area around 11:00 A.M. Figure 11.38 shows the four lightning strikes in the Cedar Bluff area of Knoxville. The office complex, marked as "Electrotek," has a data acquisition node at the service entrance.

Another data acquisition node marked as "Cedar Bluff Substation" is connected at the 161/13-kV transformer on the 13-kV side at the substation that feeds the Electrotek office about 1⁄2 mi away. During the time of the storm, the power monitoring system captured a number of events. The strikes shown in Fig. 11.38 were all within several kilometers of the substation and are located directly on known distribution system right of way. Specifically, there were two events that correlated within 100 ms of lightning strikes during the storm as shown in the output of the lightning correlation module in Fig. 11.39. Lightning strike data are summarized in Table 11.4.

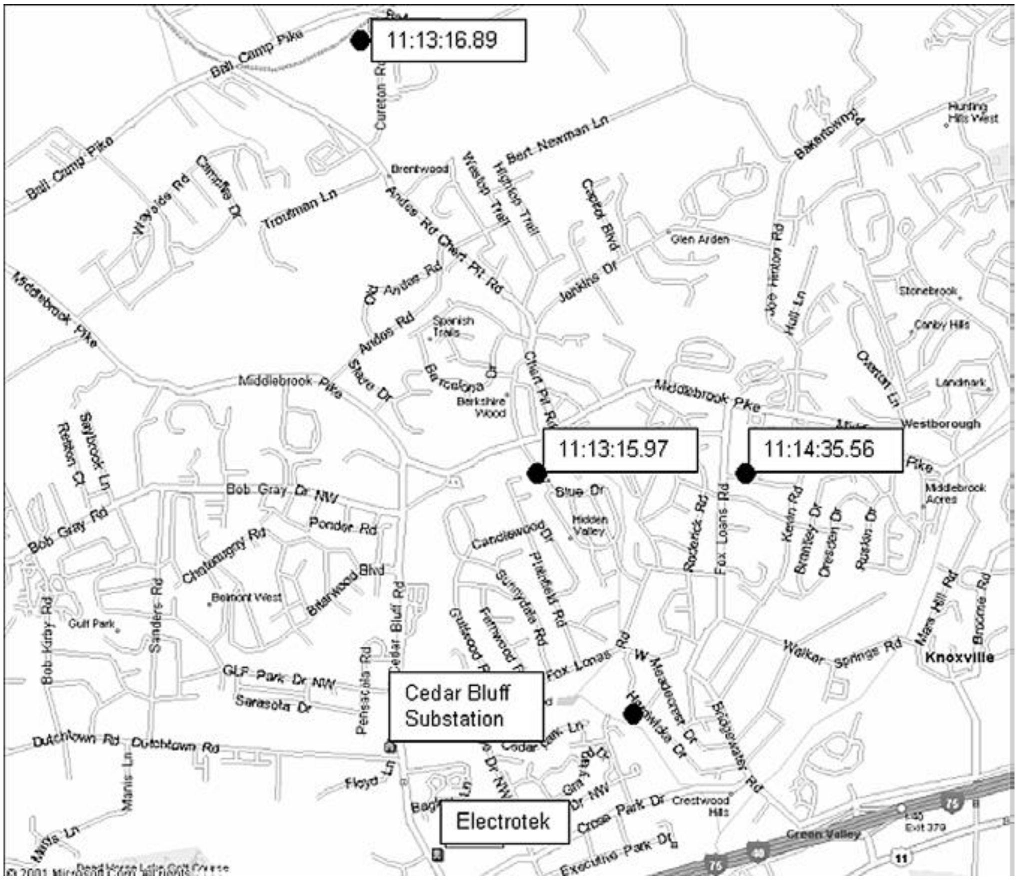
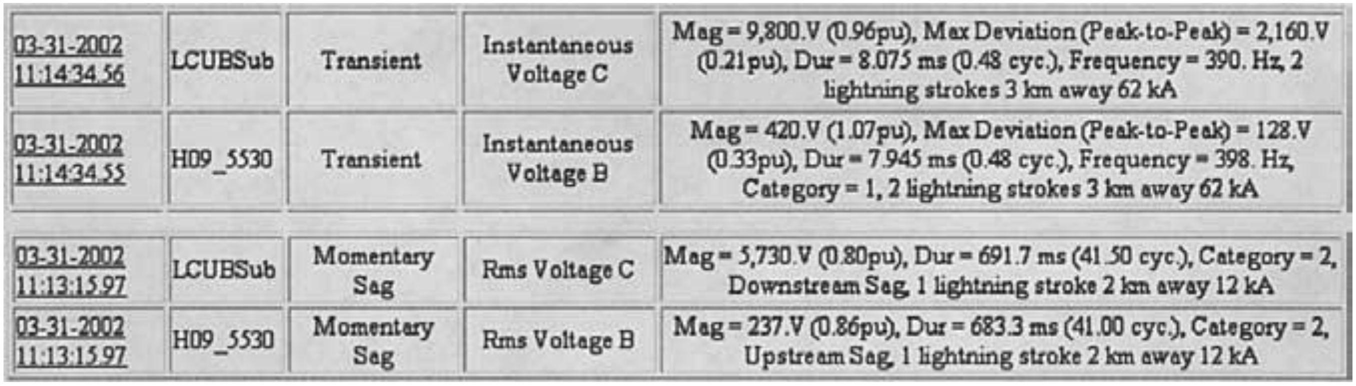


Figure 11.38 Lightning strikes near a substation serving the Electrotek office on Easter Sunday morning in 2002.



03-31-2002 11:14:34.56	LCUBSub	Transient	Instantaneous Voltage C	Mag = 9,800.V (0.96pu), Max Deviation (Peak-to-Peak) = 2,160.V (0.21pu), Dur = 8.075 ms (0.48 cyc.), Frequency = 390. Hz, 2 lightning strokes 3 km away 62 kA
03-31-2002 11:14:34.55	H09_5530	Transient	Instantaneous Voltage B	Mag = 420.V (1.07pu), Max Deviation (Peak-to-Peak) = 128.V (0.33pu), Dur = 7.945 ms (0.48 cyc.), Frequency = 398. Hz, Category = 1, 2 lightning strokes 3 km away 62 kA
03-31-2002 11:13:15.97	LCUBSub	Momentary Sag	Rms Voltage C	Mag = 5,730.V (0.80pu), Dur = 691.7 ms (41.50 cyc.), Category = 2, Downstream Sag, 1 lightning stroke 2 km away 12 kA
03-31-2002 11:13:15.97	H09_5530	Momentary Sag	Rms Voltage B	Mag = 237.V (0.86pu), Dur = 683.3 ms (41.00 cyc.), Category = 2, Upstream Sag, 1 lightning stroke 2 km away 12 kA

Figure 11.39 Outputs of the lightning correlation expert system module.

TABLE 11.4 Lightning Stroke Data

Time stamp	Latitude	Longitude	Mag (kA)	Distance (km)	Strokes	Type
3/31/2002 11:15:21.700	35.962	−84.048	−58	6	10	CG*
3/31/2002 11:14:42.700	31.335	−88.921	132	678	1	CG
3/31/2002 11:14:34.500	**35.941**	**−84.073**	**−62**	**3**	**2**	**CG**
3/31/2002 11:14:31.800	31.696	−88.760	42	638	1	CG
3/31/2002 11:14:11.100	31.549	−88.745	−32	649	2	CG
3/31/2002 11:14:09.800	31.885	−88.406	−10	600	1	CG
3/31/2002 11:14:08.900	31.705	−88.347	−10	612	1	CG
3/31/2002 11:13:36.300	31.739	−88.577	−14	623	1	CG
3/31/2002 11:13:36.300	31.887	−88.849	14	627	1	CG
3/31/2002 11:13:36.200	32.150	−88.553	42	587	1	CG
3/31/2002 11:13:36.000	31.725	−88.720	22	633	1	CG
3/31/2002 11:13:16.000	35.963	−84.097	−8	5	2	CG
3/31/2002 11:13:15.900	**35.941**	**−84.086**	**−12**	**2**	**1**	**CG**
3/31/2002 11:13:03.800	31.769	−88.768	−18	632	3	CG

*CG = cloud to ground.

The output of the lightning correlation module clearly shows the correlation between power quality events and lightning strikes. Note that the power monitoring system is equipped with GPS-based time synchronization; thus, it is capable of making precise multisource event correlation. Two lightning strikes, at 11:13:15 A.M. and 11:14:34 A.M., shown in Table 11.4 are captured in both data acquisition nodes installed at the Electrotek office and the substation.

5. Why monitor power quality?

Monitoring provides a number of benefits to utilities as well as customers. Some of these benefits are exclusively found in that realm defined as the utility-side of the meter, some are found exclusively on the customer side. However, power provider and power user share similar benefits. These can include:

- **Identification of problem conditions**. Monitoring can identify problem conditions on utility and customer power systems before they cause equipment misoperation or failures and customer complaints. Examples can include resonance conditions that can cause localized harmonic distortion problems, breaker problems that cause restrikes during capacitor switching, and fault performance problems resulting in excessive voltage sags and momentary interruptions.
- **Prioritize system improvements**. Utilities traditionally prioritize capital expenditures and system maintenance based on solving system problems and handling system growth. These expenditures are also related to maintaining an acceptable level of reliability.. Understanding the impacts of power quality variations on customers requires monitoring along with follow up with the customer to assess the impacts
- **Assess overall performance of utility and customer power systems**. This becomes important as utilities and customers move towards power supply contracts that specify a certain level of service reliability. An ongoing monitoring regime can enable power providers and users to assess system reliability under a wide range of conditions, including market volatility, weather conditions, and utility and customer operations.

- **Determine effectiveness of system maintenance activities and power conditioning technologies**. For utilities, monitoring can help determine the effectiveness of measures such as tree trimming and expansion of the distribution system. For customers, monitoring can verify the performance of ride through measures such as UPS systems and backup generation or power conditioning technologies such as harmonic filters. Many utilities, especially through their unregulated subsidiaries, are working with customers to implement mitigation measures to improve power quality. Monitoring is an essential component of the customer care process for this business.

While many of these benefits have long been recognized by utilities, the increasing attention by customers to power quality has leant them a greater prominence in both customer service and system operation activities.

6. Give a note on choosing power quality monitoring location.

Since the primary objective was to characterize power quality on primary distribution feeders, monitoring was done on the actual feeder circuits. One monitor was located near the substation and two additional sites were selected randomly.

When a monitoring project involves characterizing specific power quality problem that are actually being experienced by customers on the distribution systems, the monitoring locations should be at actual customer service entrance location because it includes the step down transformers supplying the customers data collected at the service entrance can also characterize customer load current variation and harmonic distortion level.

It is best to start monitoring as close as possible to the sensitive equipment being affected by power quality variations. It is important that the monitor sees the same variations that the sensitive equipment sees. High frequency transients, in particular, can be significantly different if there is significant separation between the monitor and the affected equipment. Another important location is the main service entrance. Transients and voltage variations measured at this location can be experienced by all of the equipment in the facility. This is also the best indication of disturbances caused by the utility system.

7. Mention the various important factors to be considered before selecting the type of instrument needed for a particular test.

Regardless of the type of instrument needed for a particular test , a number of important factors should be considered while selecting the instrument. Some of the more important factors include:

- Number of channels. (voltage and/or current)
- Temperature specifications of the instrument.
- Ruggedness of the instrument.
- Input voltage range. (i.e. 0 to 600 V)
- Power requirements.
- Ability to measure currents.
- Ability to measure three phase voltages.

- Input isolation (isolation between input channels and from each input to ground)
- Housing of the instrument.(whether potable or rack –mount (fixed) one)
- Ease of use. (user interface, graphic capability)
- Documentation.
- Communication capability. (whether modem or network interface)
- Analysis software.

The flexibility of the instrument is also important . The more functions that can be performed with a single instrument, the fewer the instruments required.

8. Discuss the various permanent power quality monitoring equipments.

The categories of instruments that can be incorporated permanently into overall monitoring system include the followings.

Digital fault recorder (DFRs): They trigger on fault events and record the voltage and current waveforms that characterize the event. This makes them valuable for characterizing rms disturbances such as voltage sags, DFRs also offer periodic wave form capture for calculating harmonic distortion levels.

9. Discuss the categories of instruments considered for harmonic analysis.

There are basically three categories of instruments to consider for harmonic analysis They are,

i. Simple meters.
ii. .General purpose meters.
iii. Special purpose meters.

i. Simple meters:

It may sometimes be necessary to make a quick of harmonics levels at a problem location. A simple, portable meter is ideal for this purpose. Now, there are several hand-held instruments of this type on the market. Each instrument has advantage and disadvantages in this operation and design. These devices generally use microprocessor-based circuitry to perform the necessary calculations to determine individual harmonics up to the 50th harmonic, as well as the rms, the THD, and the telephone influence factor (TIF). Some of these devices can calculate harmonics powers and can upload stored waveforms and calculated data to a pc.

ii. General-purpose spectrum analyzers:

Instruments in this category are designed to perform spectrum analysis on waveforms for a wide variety of applications. They are general signal analysis instruments. The advantage of these instruments is that they offer very powerful capabilities for a reasonable price since they are designed for a broader market than simply power system application. The disadvantage is that they are not designed especially for sampling power frequency waveforms and, therefore, must be used carefully to assure accurate harmonic analysis. There are a wide variety of instrument in this category.

iii. Special-purpose power system harmonic analyzers:

Besides the general –purpose spectrum analyzers described above, there are also a number of instrument and devices designed specifically for power system harmonic analysis. These are based on the FFT with sampling rates specifically designed for determining harmonic components in power signals. They can generally be left in the field and include communications capability for remote monitoring

A measure of the interference of power-line harmonics with telephone lines, it is the ratio of the square root of the sum of the squares of the weighted rms values of all the sine wave components (including alternating currents waves of both fundamental and harmonics) to the rms value (unweighted) of the entire wave.

10. Give a note on Power quality analyzer.

Power quality analyzer is used to measure electric power signals to determine the load's ability to function properly with that electric power. Without the proper electric power, an electrical device (or load) may malfunction, fail prematurely or not operate at all. There are many ways in which electric power can be of poor quality and many more causes of such poor quality power.

Power quality analyzer technology tracks several electrical parameters, which include AC voltage, AC current, and frequency. Electrical parameters include demand and peak demand. Electrical demand is the actual amount of power that the monitored system uses. Peak electrical demand is the maximum amount of electric power that can be used. Typically, power parameters are measured in watts (W), volt amperes (VA), and volt ampere reactive (VAR). Watts are units of electrical power that indicate the rate of energy produced or consumed by an electrical device. Volt amperes equal the current flowing in a circuit multiplied by the voltage of that circuit. Volt ampere reactive identify the reactive component of volt amperes.

Power quality analyzers detect mystery disturbances: those upsets to a process or sensitive equipment operation that don't seem to correspond to any identifiable source of power disturbance. Such things as ground loops, high speed transients, lightning, and common mode electrical noise come to mind. Many of these events are here and gone in such a short time frame that they are not easily identified, except with a power disturbance analyzer using high speed wave shape or event capture.

A power quality analyzer can also detect repetitive, cyclical disturbances both within and outside of a facility. These problems will be repetitive and cyclical in nature, definitely power-related, and line-to-line. Examples include voltage sags and surges, momentary interruptions by circuit breaker operations, and power interruptions.

A power quality analyzer can also measure harmonic distortion, a disturbance related to the integer multiples of the fundamental power frequency (60 Hz). It is widely recognized that this area is a subset of the power related area, since harmonic currents and voltages are recurring. However, there may need to be special tactics in searching out these problems and identifying our solution alternatives.

The chances of getting such a question is very less as in the book nowhere it is mentioned specifically the term Power quality analyzer. But the physical existence of such instrument is there. You go through it. it will help to write some other stories for some questions in case you forget what to write really.

11. Give a note on Spectrum analyzers and harmonic analyzers used as power quality measurement equipment's.

An analysis of a complex waveform, prepared in terms of a graphic plot of the amplitude versus frequency is known as spectrum analysis. The devices that does the work i.e. selects the different frequency (amplitude versus frequency) components of the input is called a Spectrum analyzer.

Harmonic analyzers are effective instruments for determining the waveshapes of voltage and current and measuring the respective frequency spectrum. Several types of harmonic measuring instruments are available, with each type having a different capability. The simplest ones measure single-phase harmonic voltage and current, and provide information on the harmonic spectrums. These handheld instruments are easy to carry around. In addition, power factor and phase angle information are also measured by the harmonic analyzer. Three-phase harmonic analyzers measure the harmonic characteristics of the three phases and the neutral simultaneously

In addition to harmonic measurement, some analyzers are capable of measuring power, power factor, and transient disturbance data to help assess power quality within the power system. Harmonic analyzer has the capability to simultaneously log, display and analyze the harmonic components of voltage and/or current, the DC components, fundamental components and harmonic components of voltage and current. Total Harmonic Distortion (THD) Analyzers calculate the total distortion introduced by all the harmonics of the fundamental frequency wave. In most cases THD is the amount that is required to calculate, rather than distortion caused by individual harmonics.

Some of the more powerful analyzers have add-on modules that can be used for computing fast Fourier transform (FFT) calculations to determine the lower order harmonics up to the 50th harmonic as related to a fundamental frequency of 15 to 400 Hz However , any significant requirements will demand an instrument that is designed for spectral analysis or harmonic analysis. Important capabilities for useful harmonic measurements include

- Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained.
- Capability to measure both magnitude and phase angle of individual harmonic components
- Synchronization and a sampling rate fast enough to obtain accurate measurement of harmonic components up to at a least the 37th harmonic.
- Capability to characterize the statistical nature of harmonic distortion levels.

There are basically three categories of instrument to consider for harmonic analysis.
They are,

i. .Simple meters.
ii. .General purpose meters.
iii. Special purpose meters.

i. Simple meters:

It may sometimes be necessary to make a quick of harmonics levels at a problem location. A simple, portable meter is ideal for this purpose. Now, there are several hand-held instruments of this type on the market. Each instrument has advantage and disadvantages in this operation and design. These devices generally use microprocessor-based circuitry to perform the necessary calculations to determine individual harmonics up to the 50th harmonic, as well as the rms, the THD, and the telephone influence factor (TIF). Some of these devices can calculate harmonics powers and can upload stored waveforms and calculated data to a pc.

ii. **General-purpose spectrum analyzers**:

Instruments in this category are designed to perform spectrum analysis on waveforms for a wide variety of applications. They are general signal analysis instruments. The advantage of these instruments is that they offer very powerful capabilities for a reasonable price since they are designed for a broader market than simply power system application. The disadvantage is that they are not designed especially for sampling power frequency waveforms and, therefore, must be used carefully to assure accurate harmonic analysis. There are a wide variety of instrument in this category.

iii. Special-purpose power system harmonic analyzers:

Besides the general –purpose spectrum analyzers described above, there are also a number of instrument and devices designed specifically for power system harmonic analysis. These are based on the FFT with sampling rates specifically designed for determining harmonic components in power signals. They can generally be left in the field and include communications capability for remote monitoring

12. Give a note on Disturbance analyzers used as power quality measurement equipment’s.

Disturbance Analyzers and disturbance monitors form a category of instruments which have been developed specifically for power quality measurements. They typically measure a wide variety of system disturbances from very short duration transient voltages to long-duration outages or under voltages, over voltages, surges and sags, impulses, frequency deviations and harmonic distortions. which measures, records, and reports power disturbances, aiding in the analysis of power quality for AC power in medical, commercial and industrial applications.

The Power Line Disturbance Analyzer can accomplish the above task and thus functions as a valuable tool for power quality analysis, as it can log critical power parameters. Thresholds can be set and the instruments left unattended to record disturbances over a period of time. The information is most commonly recorded on a paper tape but many devices have attachments so that it can be recorded on disk as well. Power disturbances detected on multiple channels are recorded by their time, date, magnitude, and duration in a nonvolatile RAM memory. This data is then retrieved from the analyzer through its serial communications port.

A PC-based data acquisition scheme is used, which is more flexible and easy to maintain compared to a hardware-oriented scheme.

The devices basically fall into two categories:

- **Conventional Analyzers** that summaries events with specific information such as magnitudes, sags/surge magnitude and duration, transient magnitude and duration, etc.

- **Graphics-based Analyzers** that save and print the actual waveform along with the descriptive information which would be generated by one of the conventional analyzers.