ELECTRICAL POWER QUALITY

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Syllabus

ELECTRICAL POWER QUALITY

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Terms & Definitions: General Classes of Power Quality Problems, Transients, Long Duration Voltage Variations, Short-Duration Voltage Variations, Voltage Imbalance, Waveform Distortion, Voltage Fluctuations, Power Frequency Variations, Power Quality Terms.

Voltage Sags & Interruptions: Sources of Sags and Interruptions, Estimating Voltage Sag Performance, Fundamental Principles of Protection, Solutions at the End-User Level, Evaluating the Economics of Different Ride-Through Alternatives, Motor Starting Sags, Utility System Fault-Clearing Issues.

UNIT-II

Transient Over Voltages: Sources of Transient Over Voltages, Principle of Over Voltage Protection, Devices for Over Voltage Protection, Utility Capacitor-Switching Transients, Utility System Lightning Protection, Managing Ferro-resonance, Switching Transient Problems with Loads, Computer Tools for Transient Analysis.

Fundamentals of Harmonics: Harmonic Distortion, Voltage Versus Current Distortion, Harmonics Versus Transients, Power System Quantities under Non-sinusoidal Conditions, Harmonic Indices, Harmonic Sources from Commercial Loads, Locating Harmonic Sources, System Response Characteristics, Effects of Harmonic Distortion, Inter-harmonics.

UNIT-III

Long Duration Voltage Variations: Principles of Regulating the Voltage, Devices for Voltage Regulation, Utility Voltage Regulator Application, Capacitors for Voltage Regulation, End-User Capacitor Application, Regulating Utility Voltage with Distributed resources, Flicker.

Power Quality Monitoring: Monitoring Considerations, Historical Perspective of Power Quality Measuring Instruments, Power Quality Measurement Equipments, Assessment of Power Quality Measurement Data, Application of Intelligent Systems, Power Quality Monitoring Standards.

UNIT- 1

TERMS AND DEFINITIONS

1.1 Power Quality

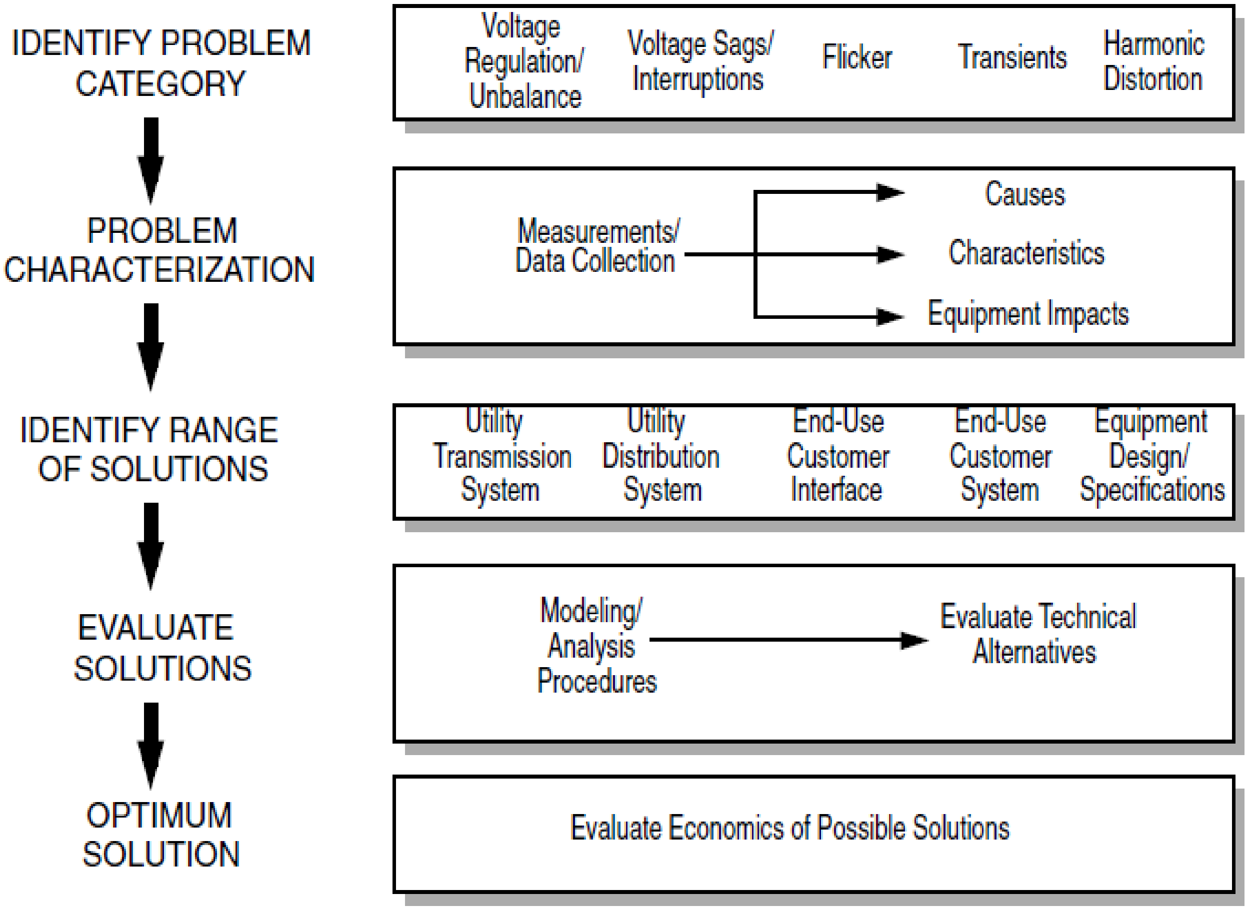
There are different definitions for power quality.

- According to Utility, power quality is reliability.
- According to load aspect, it is defined as the power supplied for satisfactory performance of all equipment i.e., all sensitive equipment.
- This depends upon the end user. According to end user point of view, it is defined as, "any power problem manifested in voltage, current, or frequency deviations thatresult in failure or misoperation of customer equipment"
- In IEEE dictionary, power quality is defined as "the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment".
- IEC (International Electrotechnical Commission), it is defined as, " set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (magnitude, frequency, waveform).

The power supply system can only control the quality of the voltage; it has no control over the currents that particular loads might draw. Therefore, the standards in thepower quality are related to maintaining the supply voltage within certain limits.

1.2 The Power Quality Evaluation Procedure

The following gives the general steps that are often required in a power quality investigation, along with the major considerations that must be addressed at each step.



1.3General Classes of Power Quality Problems

The IEEE Standards Coordinating Committee 22 (IEEE SCC22) has led the main effort in the United States to coordinate power quality standards.

The IEC classifies electromagnetic phenomena into the groups as given below.

(i) Conducted low-frequency phenomena
    Harmonics, interharmonics
    Signal systems (power line carrier)
    Voltage fluctuations (flicker)
    Voltage dips and interruptions
    Voltage imbalance (unbalance)
    Power frequency variations
    Induced low-frequency voltages

  - DC in ac networks
- (ii) Radiated low-frequency phenomena
  - Magnetic fields
  - Electric fields
- (iii)Conducted high-frequency phenomena
  - Induced continuous-wave (CW) voltages or currents
  - Unidirectional transients
  - Oscillatory transients
- (iv)Radiated high-frequency phenomena
  - Magnetic fields
  - Electric fields
  - Electromagnetic fields
  - Continuous waves
  - Transients
- (v) Electrostatic discharge phenomena (ESD)
- (vi)Nuclear Electromagnetic Pulse (NEMP)

1.4 Categories and Characteristics of Power System ElectromagneticPhenomena

Categories	**Typical Spectral Content**	**Typical Duration**	**Typical voltage Magnitude**
1. Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1-µs rise	50 ns–1 ms	
1.1.3 Millisecond	0.1-ms rise	>1 ms	
1.2 Oscillatory			
1.2.1 Low frequency	<5 kHz	0.3–50 ms	0–4 pu
1.2.2 Medium frequency	5–500 kHz	20 µs	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 µs	0–4 pu
2. Short-duration variations			
2.1 Instantaneous			
2.1.1 Interruption		0.5–30 cycles	<0.1 pu
2.1.2 Sag (dip)		0.5–30 cycles	0.1–0.9 pu
2.1.3 Swell		0.5–30 cycles	1.1–1.8 pu
2.2 Momentary			
2.2.1 Interruption		30 cycles–3 s	<0.1 pu
2.2.2 Sag (dip)		30 cycles–3 s	0.1–0.9 pu
2.2.3 Swell		30 cycles–3 s	1.1–1.4 pu
2.3 Temporary			
2.3.1 Interruption		3 s–1 min	<0.1 pu
2.3.2 Sag (dip)		3 s–1 min	0.1–0.9 pu

2.3.3 Swell		3 s–1 min	1.1–1.2 pu
3. Long-duration variations			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Under voltage		>1 min	0.8-0.9 pu
3.3 Overvoltage		>1 min	1.1-1.2 pu
4. Voltage unbalance		Steady state	0.5–2%
5. Waveform distortion			
5.1 DC offset		Steady state	0–0.1%
5.2 Harmonics	0–100th harmonic	Steady state	0–20%
5.3 Interharmonics	0–6 kHz	Steady state	0–2%
5.4 Notching		Steady state	
5.5 Noise	Broadband	Steady state	0–1%
6. Voltage fluctuations	<25 Hz	Intermittent	0.1–7%
7.0 Power frequencyVariations		<10 s	

1.5 Transients

It is an event that is undesirable and momentary in nature. It is the sudden change in one steady state operating condition to another.

Transients can be classified into two categories:

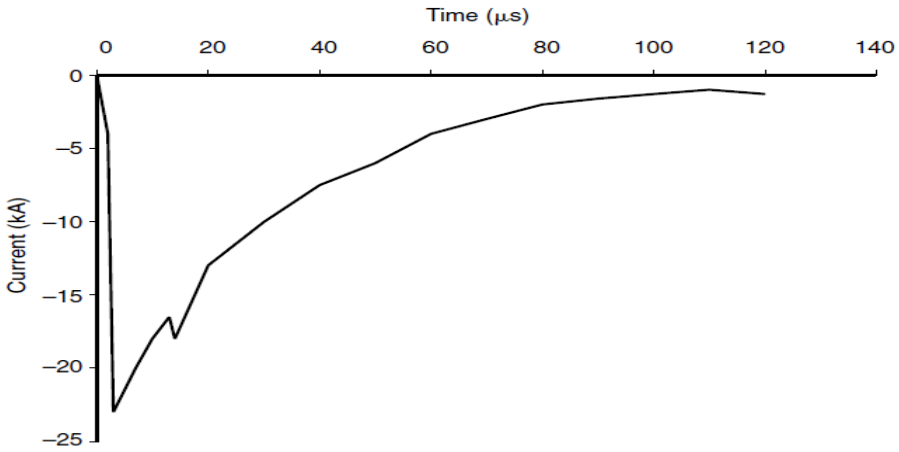
1. Impulsive and
2. Oscillatory

1.5.1 Impulsive Transient

- An impulsive transientis a sudden non–power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity (either positive or negative).
- Impulsive transients are normally characterized by their rise and decay times.
- Due to high frequency nature, the shape of impulsive transients may be changed quickly by circuit components and may have significant different characteristics when viewed from different partsof the power system. They are generally not conducted far from thesource.
- Impulsive transients can excite the natural frequency of power systemcircuits and produce oscillatory transients.

Source: lightning

The following shows a typical current impulsive transient caused by lightning.



[Fig.Lightning stroke current impulsive transient]

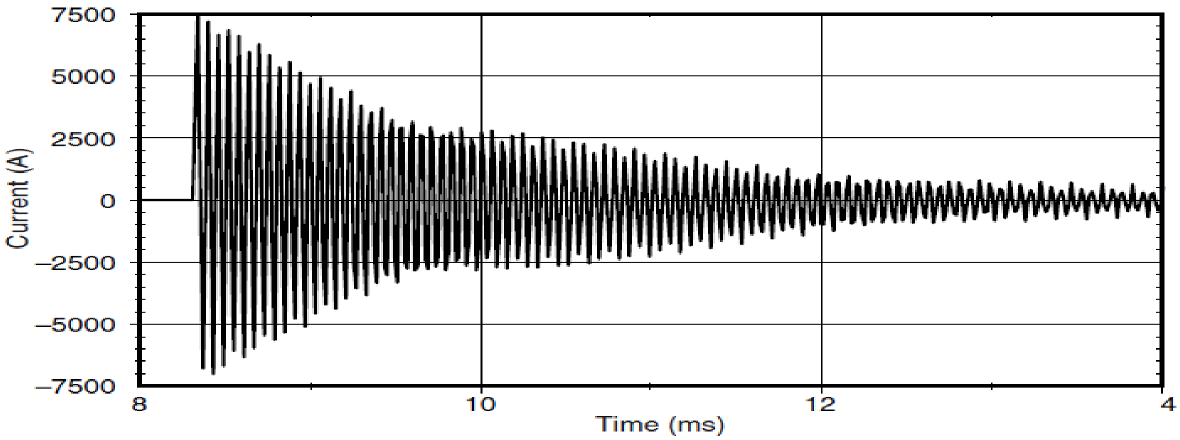
1.5.2 Oscillatory Transient

- An oscillatory transient is a sudden, non–power frequency change in the steady-state condition of voltage, current, or both, that includes both positive and negative polarity values.
- Instantaneous value of oscillatory transient changes polarity rapidly.

It can be classified into 3 types,

1. High-frequency Transients: These have frequency components greaterthan 500 kHz and a typical duration measured in microseconds (or severalcycles of the principal frequency).
2. Medium-frequency Transients: These have frequency components between 5 and 500kHz with duration measured in the tens of microseconds (or severalcycles of the principal frequency).
3. Low-frequency Transients: These have frequency components less than 5 kHz,and a duration from 0.3 to 50 ms .

Sources: Back-to-back capacitor switching, Transformer energization.



[Fig. Oscillatory Transient caused due to back-to-back capacitor switching]

1.6Long-Duration Voltage Variations

When the rms value of voltage deviates for duration more than 1 minute, it is termed as long duration voltage variation.

Sources: Load variations, System switching operation.

It may be categorized into following types.

1. **Over Voltage:** An overvoltage is an increase in the rms ac voltage greater than 110 percent at the power frequency for duration longer than 1 min.
   Sources: (a) Overvoltage is usually the result of load switching (e.g., switchingoff a large load or energizing a capacitor bank).
   (b) Incorrect tap settings on transformers can also result in system over voltages.
2. **Under Voltage:** An under voltageis a decrease in therms ac voltage to less than 90 percentat the power frequency for a duration longer than 1 min.
   Sources: A load switching on or a capacitor bank switching off.
3. **Sustained Interruptions:** When the supply voltage becomes zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a sustained interruption.

1.7 Short-Duration Voltage Variations

When the rms value of voltage deviates for duration less than 1 minute, it is termed as long duration voltage variation.

Each type of variation can be designated as *instantaneous*,*momentary*, or *temporary*, depending on its duration.

It may be categorized into following types.

1. **Interruption:**An *interruption* occurs when the supply voltage or load currentdecreases to less than 0.1 pu for a period of time not exceeding 1 min.
   Sources:Interruptions can be the result of power system faults, equipment failures, and control malfunctions.
2. **Sags(dips):** A *sag*is a decrease in rms voltage or currentbetween 0.1 and 0.9 pu at the power frequency for durations from 0.5 cycle to 1 min.
   Sources:Voltage sags are result of system faults and also can be caused by energization of heavy loads or starting of large motors.
3. **Swells:** A*swell* is defined as an increase to between 1.1 and 1.8 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min.
   Sources:Voltage swells occur from temporary voltage rise on the unfaulted phases duringan SLG fault. Swells can also be caused by switching off a large load or energizing large capacitor bank.

1.8 Voltage Imbalance

- Voltage imbalance (also called voltage unbalance) is defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent.
- The ratio of either the negative- or zero-sequence component to the positive-sequence component can be used to specify the percent unbalance.
- The source of voltage unbalances is single-phase loads on a three-phase circuit.
- Voltage unbalance can also be the result of blown fuses in one phase of a three-phase capacitor bank.
- Severe voltage unbalance (greater than 5 percent) can result from single-phasing conditions.

1.9 Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency.

There are five primary types of waveform distortion:

1. DC offset
2. Harmonics
3. Interharmonics
4. Notching
5. Noise

1. DC offset:

The presence of a dc voltage or current in an ac power system is termed dc offset.

Effects: (a) It may saturate the transformer core causing additional heating and loss of transformer life.

(b) Direct current may also cause the electrolytic erosion of grounding electrodes and other connectors.

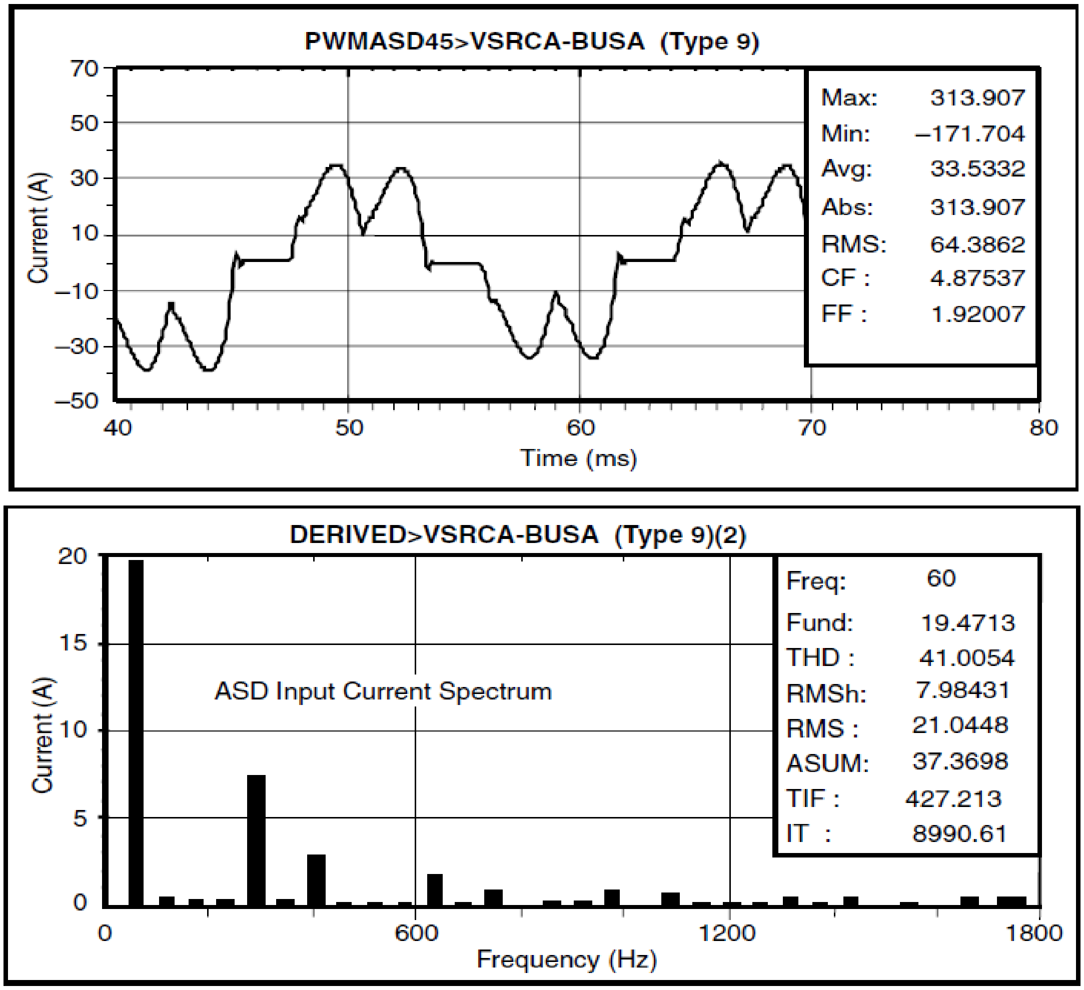
2.Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the supply frequency (fundamental frequency).

Sources: Non-linear loads

Total Harmonic Distortion is used to measure the effective value of harmonic distortion.

The following figureillustrates the waveform and harmonic spectrum for a typical adjustable-speed-drive (ASD) input current.



[Fig.Current waveform and harmonic spectrum for an ASD input current]

3. Interharmonics

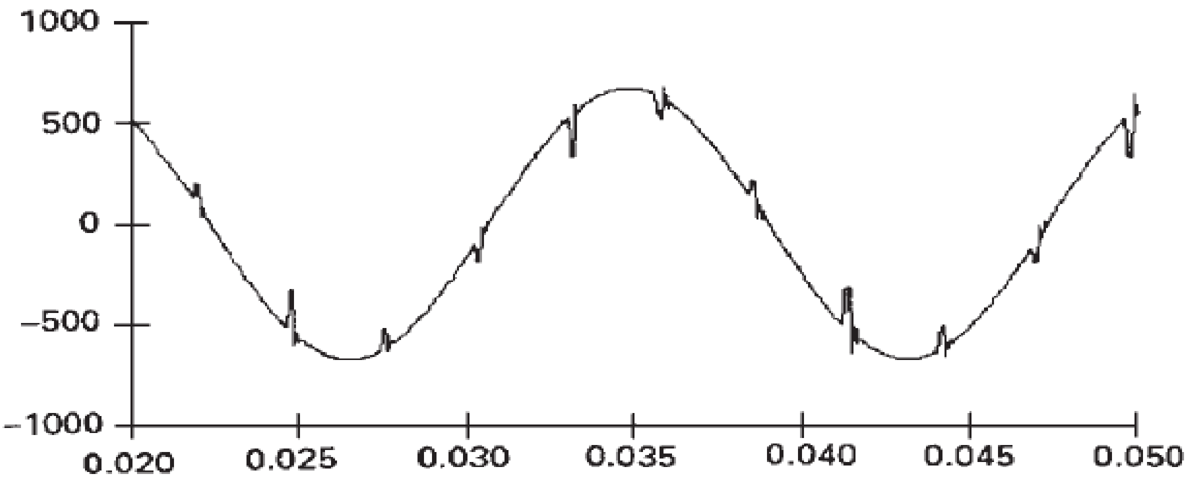
Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 or 60 Hz) are called interharmonics.

Sources: Static frequency converter, cycloconverters, induction furnaces, and arcing devices.Power line carrier signals can also be considered as interharmonics.

4. Notching

Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another.

The following figure shows an example of voltage notching from a three-phase converter that produces continuous dc current. The notches occur when the current commutates from one phase to another. During this period, there is a momentary short circuit between two phases, pulling the voltage as close to zero as permitted by system impedances.



[Fig.Voltage notching caused by a three-phase converter]

5. Noise

Noise is the unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines.

Sources: Power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies.

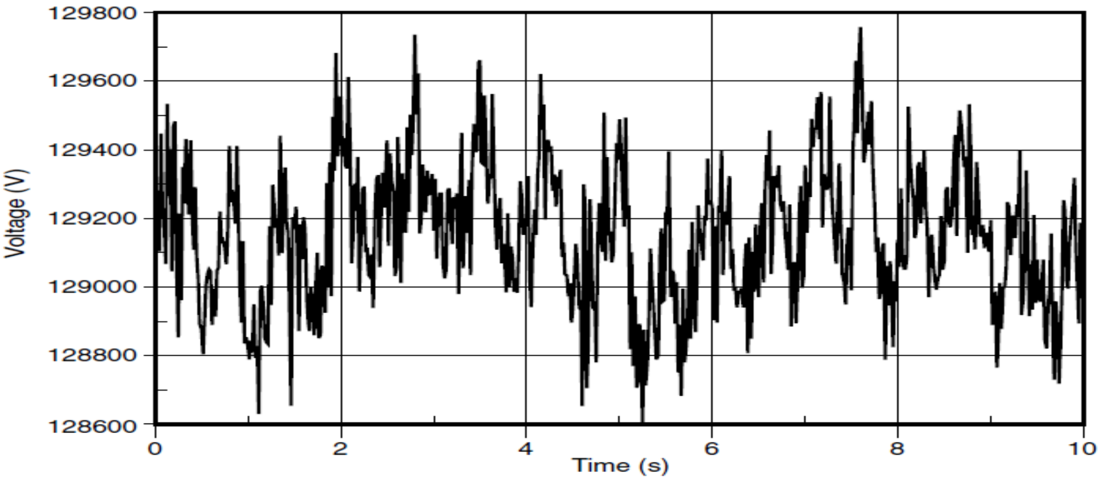
The problem can be mitigated by using filters, isolation transformers, and line conditioners.

1.10 Voltage Fluctuation

Voltage fluctuations are systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage range 0.9 to 1.1 pu.

- Voltage fluctuations are characterized as a series of random or continuous voltage fluctuations.
- Loads that can exhibit continuous, rapid variations in the load current magnitude can cause voltage variations that are often referred to as flicker.
- The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker. To be technically correct, voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltagefluctuation in some loads.

The following fig. shows voltage fluctuations caused by an arc furnace operation.



[Fig. voltage fluctuations caused by an arc furnace operation]

1.11 Power Frequency Variations

Power frequency variations are defined as the deviation of the power system fundamental frequency from it specified nominal value (50 or 60 Hz).

Sources: Due to faults on the bulk power transmission system, a large block of load being disconnected, or a large source of generation going off-line.

On modern interconnected power system, frequency variations are rare.

1.12 Power Quality Terms

Some power quality terms are described below.

Active filter: Consists of a number of power electronic devices for eliminating harmonic distortion.

CBEMA curve:A set of curves representing the withstand capabilities of computers in terms of the magnitude and duration of the voltage disturbance. It is developed by the Computer Business Equipment Manufacturers Association (CBEMA).It became standard for measuring the performance of all types of equipment and power systems and is commonly referred to by this name.CBEMAhas been replaced by the Information Technology IndustryCouncil (ITI), and a new curve has been developed that is commonly referred to as the ITI curve.

Common mode voltage: The noise voltage that appears equally from current carrying conductor to ground.

Coupling:A circuit element, or elements, or a network that may be considered common to the input mesh and the output mesh and through which energy may be transferred from one to another.

Crest factor:A value reported by many power quality monitoring instruments representing the ratio of the crest value of the measured waveform to the root mean square of the fundamental. For example, the crest factor of a sinusoidal wave is 1.414.

Critical load: Devices and equipment whose failure to operate satisfactorily jeopardizes the health or safety of personnel, and/or results in loss of function, financial loss, or damage to property deemed critical by the user.

Current distortion: Distortion in the ac line current.

Differential mode voltage: The voltage between any two of a specified set of active conductors.

Distortion: Any deviation from the normal sine wave for an AC quantity.

Distributed generation (DG): Generation dispersed throughout the power system as opposed to large, central station power plants. DG typically refers to units less than 10 megawatts (MW) in size that are interconnected with the distribution system rather than the transmission system.

Dropout:A loss of equipment operation (discrete data signals) due to noise, sag, or interruption.

Dropout voltage: The voltage at which a device will release to its deenergized position (for this document, the voltage at which a device fails to operate).

Electromagnetic Compatibility(EMC): The ability of a device, equipment, or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment.

Equipment grounding conductor: The conductor used to connect the non–current carrying parts of conduits, raceways, and equipment enclosures to the grounded conductor (neutral) and the grounding electrode at the service equipment (main panel) or secondary of a separately derived system (e.g., isolation transformer).

Failure mode: The effect by which failure is observed.

Fast tripping: Refers to the common utility protective relaying practice in which the circuit breaker or line recloser operates faster than a fuse can blow.

Fault: Generally refers to a short circuit on the power system.

Fault, transient:A short circuit on the power system usually induced by lightning, tree branches, or animals, which can be cleared by momentarily interrupting the current.

Ferro resonance: An irregular, often chaotic type of resonance that involves the nonlinear characteristic of iron-core (ferrous) inductors. It is nearly always undesirable when it occurs in the power delivery system, but it is exploited in technologies such as constant-voltage transformers to improve the power quality.

Flicker: An impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.

Frequency deviation: An increase or decrease in the power frequency. The duration of a frequency deviation can be from several cycles to several hours.

Frequency response: In power quality usage, generally refers to the variation of impedance of the system, or a metering transducer, as a function of frequency.

Fundamental (component): The component of order one (50 to 60 Hz) of the Fourier series of a periodic quantity.

Ground:A conducting connection, whether intentional or accidental, by which an electric circuit or electrical equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth. It is used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting ground currents to and from earth (or the conducting body).

Ground electrode: Aconductor or group of conductors in intimate contact with the earth for the purpose of providing a connection with the ground.

Ground grid:A system of interconnected bare conductors arranged in a pattern over a specified area and on or buried below the surface of the earth. The primary purpose of the ground grid is to provide safety for workers by limiting potential differences within its perimeter to safe levels in case of high currents that could flow if the circuit being worked became energized for any reason or if an adjacent energizedcircuit faulted. Metallic surface mats and gratings are sometimes utilized for the same purpose.This is not necessarily the same as a signal reference grid.

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

Ground window: The area through which all grounding conductors, including metallic raceways, enter a specific area. It is often used in communications systemsthrough which the building grounding system is connected to an area that would otherwise have no grounding connection.

Harmonic (component): Integer multiple of fundamental frequency.

Harmonic content: The quantity obtained by subtracting the fundamental component from an alternating quantity.

Harmonic distortion: Periodic distortion of the sine wave.

Harmonic filter: On power systems, a device for filtering one or more harmonics from the power system. Most are passive combinations of inductance, capacitance, and resistance. Newer technologies include active filters that can also address reactive power needs.

Harmonic number: The integral number given by the ratio of the frequency of a harmonic to the fundamental frequency.

Harmonic resonance:A condition in which the power system is resonating near one of the major harmonics being produced by nonlinear elements in thesystem, thus exacerbating the harmonic distortion.

Impulse:A pulse that, for a given application, approximates a unit pulse or aDirac function.When used in relation to monitoring power quality, it is preferableto use the term impulsive transient in place of impulse.

Impulsive transient:A sudden, nonpower frequency change in the steady state condition of voltage or current that is unidirectional in polarity (primarilyeither positive or negative).

Instantaneous: When used to quantify the duration of a short-duration variation as a modifier, this term refers to a time range from one-half cycle to 30 cycles of the power frequency.

Instantaneous reclosing:A term commonly applied to reclosing of a utility breaker as quickly as possible after an interrupting fault current. Typical times are 18 to 30 cycles.

Interharmonic (component):A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is designed to operate (e.g., 50 or 60 Hz).

Interruption, momentary (electrical power systems): An interruption of a duration limited to the period required to restore service by automatic or supervisory controlled switching operations or by manual switching at locations where an operator is immediately available. Such switching operations must be completed in a specified time not to exceed 5 min.

Interruption, momentary (power quality monitoring):A type of short-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 30 cycles and 3 s.

Interruption, sustained (electrical power systems): Any interruption not classified as a momentary interruption.

Interruption, sustained (power quality):A type of long-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time greater than 1 min.

Interruption, temporary:A type of short-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between3 s and 1 min.

Inverter:A power electronic device that converts direct current to alternating current of either power frequency or a frequency required by an industrialprocess. Common inverters today employ pulse-width modulation to create the desired frequency with minimal harmonic distortion.

Islanding: Refers to a condition in which distributed generation is isolated on a portion of the load served by the utility power system. It is usually an undesirablesituation, although there are situations where controlled islands can improve the system reliability.

Isolated ground: An insulated equipment grounding conductor run in the same conduit or raceway as the supply conductors. This conductor is insulatedfrom the metallic raceway and all ground points throughout its length. It originates at an isolated ground-type receptacle or equipment input terminal block and terminates at the point where neutral and ground are bonded at the power source.

Isolation: Separation of one section of a system from undesired influences of other sections.

ITI curve:A set of curves published by the Information Technology Industry Council (ITI) representing the withstand capabilities of computers connected to120-V power systems in terms of the magnitude and duration of the voltage disturbance. The ITI curve replaces the curves originally developed by the ITI's predecessor organization, the Computer Business Equipment Manufacturers Association (CBEMA).

Linear load: An electrical load device that, in steady-state operation, presents an essentially constant load impedance to the power source throughout the cycle of applied voltage.

Long-duration variation:A variation of the rms value of the voltage from nominal voltage for a time greater than 1 min. Usually further described using amodifier indicating the magnitude of a voltage variation (e.g., undervoltage, overvoltage, or voltage interruption).

Low-side surges:A term coined by distribution transformer designers to describe the current surge that appears to be injected into the transformer secondary terminals during a lightning strike to grounded conductors in the vicinity.

Momentary: When used to quantify the duration of a short-duration variation as a modifier, refers to a time range at the power frequency from 30 cycles to 3 s.

Noise: Unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur.

Nominal voltage:A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class.

Nonlinear load: Electrical load that draws current discontinuously or whose impedance varies throughout the cycle of the input ac voltage waveform.

Normal mode voltage: Avoltage that appears between or among active circuit conductors.

Notch:A switching (or other) disturbance of the normal power voltage waveform, lasting less than a half-cycle, which is initially of opposite polarity thanthe waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half-cycle.

Oscillatory transient:A sudden, nonpower frequency change in the steady state condition of voltage or current that includes both positive- or negative polarity value.

Overvoltage: When used to describe a specific type of long-duration variation, refers to a voltage having a value of at least 10 percent above the nominal voltagefor a period of time greater than 1 min.

Passive filter:A combination of inductors, capacitors, and resistors designed to eliminate one or more harmonics. The most common variety is simply aninductor in series with a shunt capacitor, which short-circuits the major distorting harmonic component from the system.

Phase shift: The displacement in time of one voltage waveform relative to other voltage waveform(s).

Power factor, displacement: The power factor of the fundamental frequency components of the voltage and current waveforms.

Power factor (true): The ratio of active power (watts) to apparent power (volt-amperes).

Plt: The long-term flicker severity level as defined by IEC 61000-4-15, based on an observation period of 2 h.

Pst: The short-term flicker severity level as defined by IEC 61000-4-15, based on an observation period of 10 min. A Pst value greater than 1.0 corresponds to the level of irritability for 50 percent of the persons subjected to the measured flicker.

Pulse: An abrupt variation of short duration of a physical quantity followed by a rapid return to the initial value.

Pulse Width Modulation (PWM): Acommon technique used in inverters to create an ac waveform by controlling the electronic switch to produce varying width pulses. Minimizes power frequency harmonic distortion in someapplications, but care must be taken to properly filter out the switching frequencies, which are commonly 3 to 6 kHz.

Reclosing: The common utility practice used on overhead lines of closing the breaker within a short time after clearing a fault, taking advantage of the fact that most faults are transient, or temporary.

Recovery time: The time interval needed for the output voltage or current to return to a value within the regulation specification after a step load or linechange.Also may indicate the time interval required to bring a system back to its operating condition after an interruption or dropout.

Recovery voltage: The voltage that occurs across the terminals of a pole of a circuit-interrupting device upon interruption of the current.

Rectifier:A power electronic device for converting alternating current to direct current.

Resonance:A condition in which the natural frequencies of the inductances and capacitances in the power system are excited and sustained by disturbing phenomena. This can result in excessive voltages and currents. Waveform distortion,whether harmonic or nonharmonic, is probably the most frequent excitation source. Also, various short-circuit and open-circuit faults can result in resonant conditions.

Sag:A decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations of 0.5 cycle to 1 min.

Shield: As normally applied to instrumentation cables, refers to a conductive sheath (usually metallic) applied, over the insulation of a conductor or conductors,for the purpose of providing means to reduce coupling between the conductors so shielded and other conductors that may be susceptible to, or which may be generating, unwanted electrostatic or electromagnetic fields (noise).

Shielding: Shielding is the use of a conducting and/or ferromagnetic barrier between a potentially disturbing noise source and sensitive circuitry. Shieldsare used to protect cables (data and power) and electronic circuits. They maybe in the form of metal barriers, enclosures, or wrappings around source circuitsand receiving circuits.

Shielding (of utility lines): The construction of a grounded conductor or towerover the lines to intercept lightning strokes in an attempt to keep the lightningcurrents out of the power system.

Short-duration variation: Avariation of the rms value of the voltage from nominal voltage for a time greater than one-half cycle of the power frequency butless than or equal to 1 min. (e.g., sag, swell, or interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, or temporary).

Signal reference grid (or plane):A system of conductive paths among interconnected equipment, which reduces noise-induced voltages to levels that minimizeimproper operation. Common configurations include grids and planes.

Sustained: Refers to the time frame associated with a long-duration variation (i.e., greaterthan 1 min).

Swell:A temporary increase in the rms value of the voltage of more than 10 percent of the nominal voltage, at the power frequency, for durations from 0.5cycle to 1 min.

Sympathetic tripping: When a circuit breaker on an unfaulted feeder section trips unnecessarily due to backfeed into a fault elsewhere. Most commonlyoccurs when sensitive ground fault relaying is employed.

Synchronous closing: Generally used in reference to closing all three poles of a capacitor switch in synchronism with the power system to minimize transients.

Temporary: When used to quantify the duration of a short-duration variation as a modifier, refers to a time range from 3 s to 1 min.

Total Demand Distortion (TDD): The ratio of the root mean square of the harmonic current to the rms value of the rated or maximum demand fundamentalcurrent, expressed as a percent.

Total disturbance level: The level of a given electromagnetic disturbance caused by the superposition of the emission of all pieces of equipment in a given system.

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 percentof the fundamental.

Transient: Pertaining to or designating a phenomenon or a quantity that varies between two consecutive steady states during a time interval that is short compared to the time scale of interest. Atransient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity.

Triplen harmonics:A term frequently used to refer to the odd multiples of the third harmonic, which deserve special attention because of their natural tendencyto be zero sequence.

Undervoltage: When used to describe a specific type of long-duration variation, refers to a measured voltage having a value at least 10 percent below thenominal voltage for a period of time greater than 1 min. In other contexts, such as distributed generation protection, the time frame of interest would be measured in cycles or seconds.

Voltage change:A variation of the root mean square or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations.

Voltage dip: sag.

Voltage distortion: Distortion of the ac line voltage.

Voltage fluctuation: A series of voltage changes or a cyclical variation of the voltage envelope.

Voltage imbalance (unbalance):A condition in which the three-phase voltages differ in amplitude or are displaced from their normal 120 degree phase relationship or both. Frequently expressed as the ratio of the negative sequence or zero-sequence voltage to the positive-sequence voltage, in percent.

Voltage interruption: Disappearance of the supply voltage on one or morephases. Usually qualified by an additional term indicating the duration of theinterruption (e.g., momentary, temporary, or sustained).

Voltage regulation: The degree of control or stability of the rms voltage at the load. Often specified in relation to other parameters, such as input-voltagechanges, load changes, or temperature changes.

Voltage magnification: The magnification of capacitor switching oscillatory transient voltage on the primary side by capacitors on the secondary side of a transformer.

Waveform distortion: A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

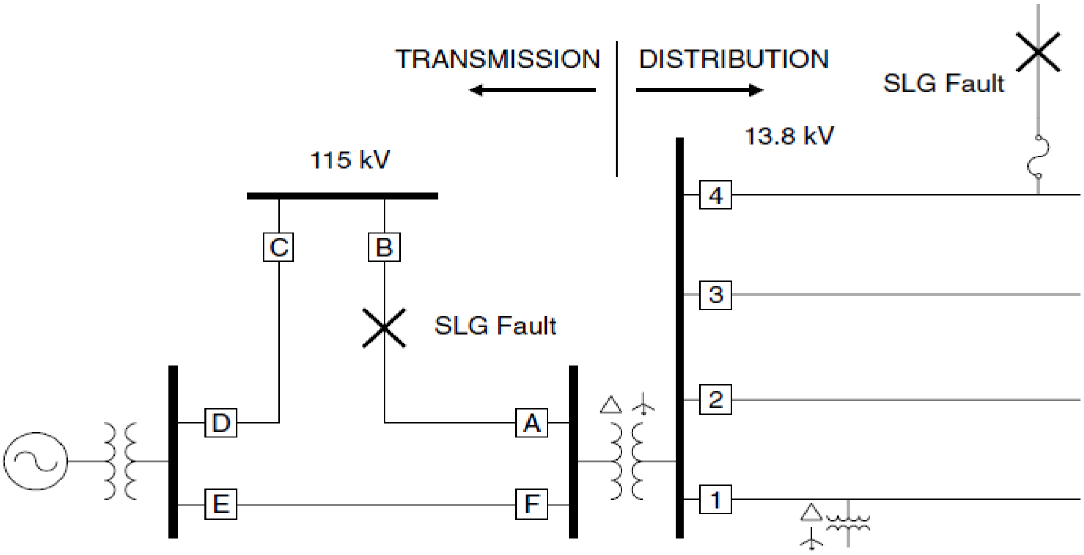
UNIT- 2

Transient Over Voltages

2.1Sources of Sags and Interruptions

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

Consider a customer that is suppliedfrom the feeder supplied by circuit breaker 1 on the diagram shown in Fig.



[Fig.2.1Fault locations on the utility power system]

If there is a fault on the same feeder, the customer will experience a voltage sag during the fault followed by an interruption whenthe breaker opens to clear the fault. If the fault is temporary in nature, a reclosing operation on the breaker should be successful and the interruption will only be temporary.

To clear the fault shown on the transmission system, both breakers A and B must operate. Transmission breakers will typicallyclear a fault in 5 or 6 cycles. In this case there are two lines supplying the distribution substation and only one has a fault. Therefore, customers supplied from the substation should expect to see only a sag and not an interruption. The distribution fault on feeder 4 may be cleared either by the lateral fuse or the breaker, depending on the utility's fuse saving practice.

2.2 Estimating Voltage Sag Performance

It is important to estimate voltage sag performance so that facilities can be designed and equipment specifications developed to assure the optimum operation of production facilities.

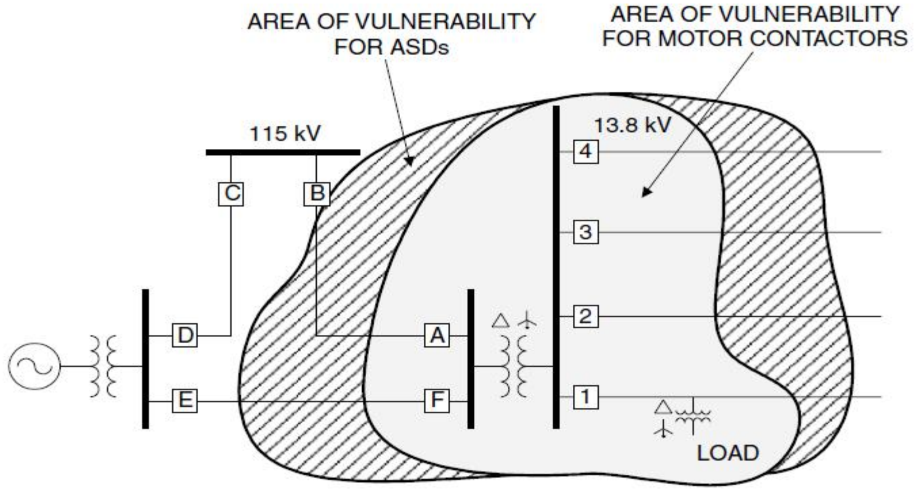
For the estimation of voltage sag performance, the following procedure is considered.

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) orwithin the customer facility (better immunity).

2.2.1 Area of vulnerability

It is defined as the likelihood of sensitive equipment being subjected to voltage lower than its minimum voltage sag ride-through capability.

An area of vulnerability is determined by the total circuit miles of exposure to faults that can cause voltage magnitudes at an end-user facilityto drop below the equipment minimum voltage sag ride-through capability.



[Fig.2.2 Illustration of an area of vulnerability]

The actual 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. The expected fault performance is usually determined from historical data.

2.2.2 Minimum Voltage Sag Ride-Through Capability

It is defined as the minimum voltage magnitude a piece of equipment can withstand or tolerate without misoperation or failure. This is also known as the equipment voltage sag immunity or susceptibility limit.

2.2.3 Equipment Sensitivity to Voltage Sags

The equipments within an end user facility that are sensitive to voltage sags are very dependent on specific load type, control settings, and applications.

The most commonly used characteristics are the duration and magnitude of the sag.

Generally, equipment sensitivity to voltage sags can be divided into following three categories:

1. **Equipment sensitive to only the magnitude of a voltage sag**: Devices in this group are sensitive to the minimum (or maximum) voltage magnitude experienced during a sag (or swell). This group includes devices such as under-voltage relays, process controls, motor drive controls, and many types of automated machines (e.g., semiconductor manufacturing equipment). The duration of the disturbance is usually of secondary importance for these devices.
2. **Equipment sensitive to both the magnitude and duration of a voltage Sag**: This group includes 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.
3. **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.

2.2.4 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.

<u>Importance:</u>

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 transmission networks. These faults may 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.

The following facts should be considered for evaluation of voltage sag;

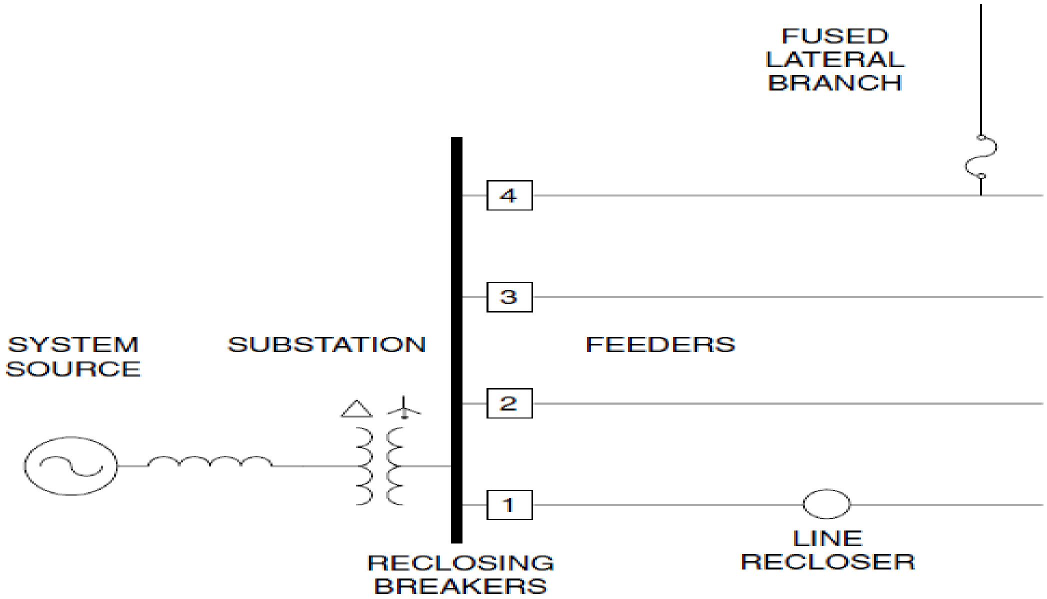
- Most utilities have detailed short-circuit models of the interconnected transmission system available for programs such as ASPEN. These programs can calculate the voltage throughout the system resulting from faults around the system.
- Utilities can also apply faults at locations along the transmission 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.

2.2.5 Utility Distribution System Sag Performance Evaluation

The 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.

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.

The following figure shows a typical distribution system with multiple feeder sand fused branches, and protective devices.



[Fig.2.3 Typical distribution system illustrating protection devices]

The utility protection scheme plays an important role in the voltage sag and momentary interruption performance.

The information needed to compute voltage sag performances are as follows:

- Number of feeders supplied from the substation.
- Average feeder length.

- Average feeder reactance.
- Short-circuit equivalent reactance at the substation.
- Feeder reactors, if any.
- Average feeder fault performance which includes three-phase-line-to-ground (3LG) faults and single-line-to-ground (SLG) faults in faults per mile per month.

There are two possible locations for faults on the distribution systems;

(a) on the same feeder and

(b) on parallel feeders.

The computation of the expected voltage sag performance can be performed as follows:

Faults on parallel feeders:

The voltage at the end-user facility can be due to 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.

The voltage sag performance for a specific sensitive equipment having the minimum ride-through voltage of $v_s$can be calculated as :

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

Where,N_1 and N_3 are the fault performance data for SLG and 3LG faults in faults per miles per month, and E_{p1} and E_{p3} 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 v_s at the end-user location.

Faults on the same feeder:

Here the expected voltage sag magnitude at the end-user location is computed as a function of fault location on the same feeder. 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.

The voltage sag performance for a specific sensitive equipment having the minimum ride-through voltage of $v_s$can be calculated as:

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

Where, E_{s1} and E_{s3} are the total circuit miles of exposure to SLG and 3LG on the same feeders that result in voltage sags below v_s at the end-user location.

The total expected voltage sag performance for the minimum ride through voltage v_s would be the addition of expected voltage sag performance on the parallel and the same feeders, i.e.,

$$E_{parallel}(v_s) + E_{same}(v_s)$$

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.

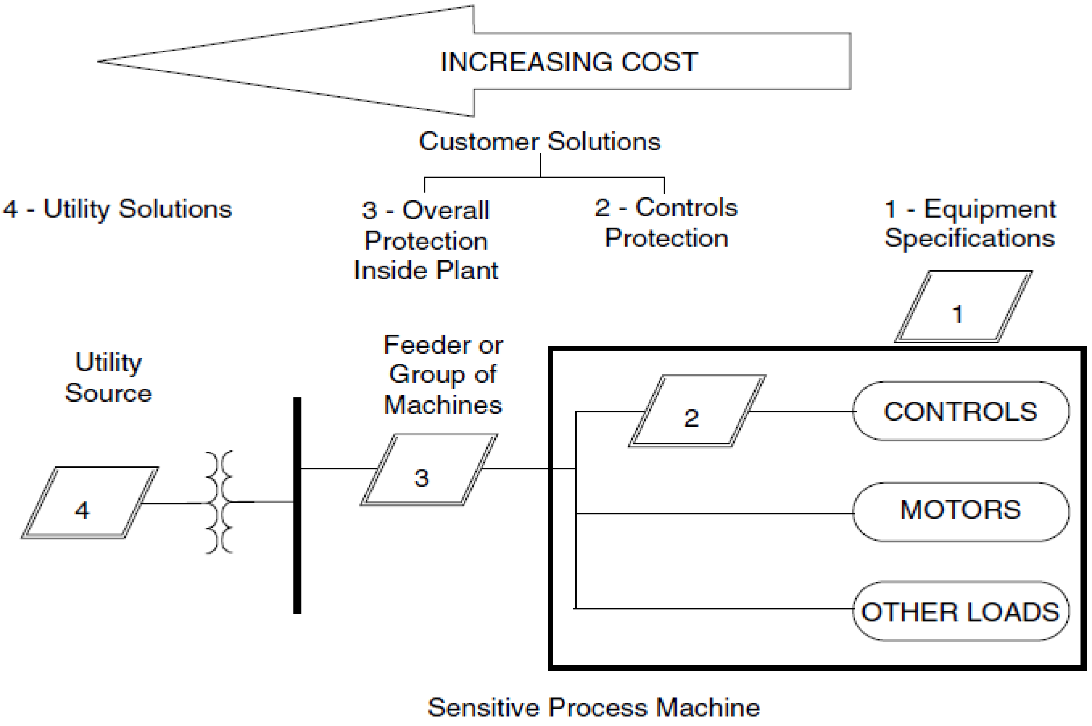
The expected number of interruptions can be computed as follows:

$$E_{int} = L_{int}(N_1 X N_3)$$

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

2.3 Fundamental Principles of Protection

The utility, end user, and equipment manufacturer can do many things to reduce the number and severity of voltage sags and to reduce the sensitivity of equipment to voltage sags. Figure The following figure shows voltage sag solution alternatives and their relative costs.



[Fig.2.4. Sensitive Process Mavhine]

- From the above chart, it is seen that, it is generally less costly to tackle the problem at its lowest level, close to the load.
- The best solution is to incorporate ride through capability into the equipment specifications.

The following outlined ideas could easily be incorporated into any company's equipment procurement specifications to help alleviate problems associated with voltage sags:

1. Equipment manufacturers should have voltage sag ride-through capability curve available to their customers so that an initial evaluation of the equipment can be performed.
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.
3. Equipment should at least be able to ride through voltage sags with a minimum voltage of 70 percent. The relative probability of experiencing a voltage sag to 70 percent or less of nominal is much less than experiencing a sag to 90 percent or less of nominal. A more ideal ride-through capability for short-duration voltage sags would be 50 percent.

Solutions at higher levels of available power become more costly. If the required ride-through cannot be obtained at the specification stage, it may be possible to apply an uninterruptible power supply (UPS) system or some other type of power conditioning to the machine control.

2.4 Solutions at the End-User Level

For the improvement of reliability and performance of a facility, solutions can be applied at many different levels. The different available technologies should be evaluated based on the specific requirements of the facility to determine the optimum solution for improving the overall voltage sag performance.

As illustrated in above figure, the solutions can be discussed at the following different levels of application:

1.Protection for small loads [less than 5 kV]:

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

2. Protection for individual equipment or groups of equipment up to about 300 kVA:

This usually represents applying power conditioning technologies within the facility for protection of critical equipment that can be grouped together conveniently. Since usually not all the loads in a facility need protection, this can be a very economical method of dealing with the critical loads, especially if the need for protection of these loads is addressed at the facility design stage.

3. Protection for large groups of loads or whole facilities at the low-voltage level:

Sometimes, 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). New technologies are available for consideration when large groups of loads need protection.

4. 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.

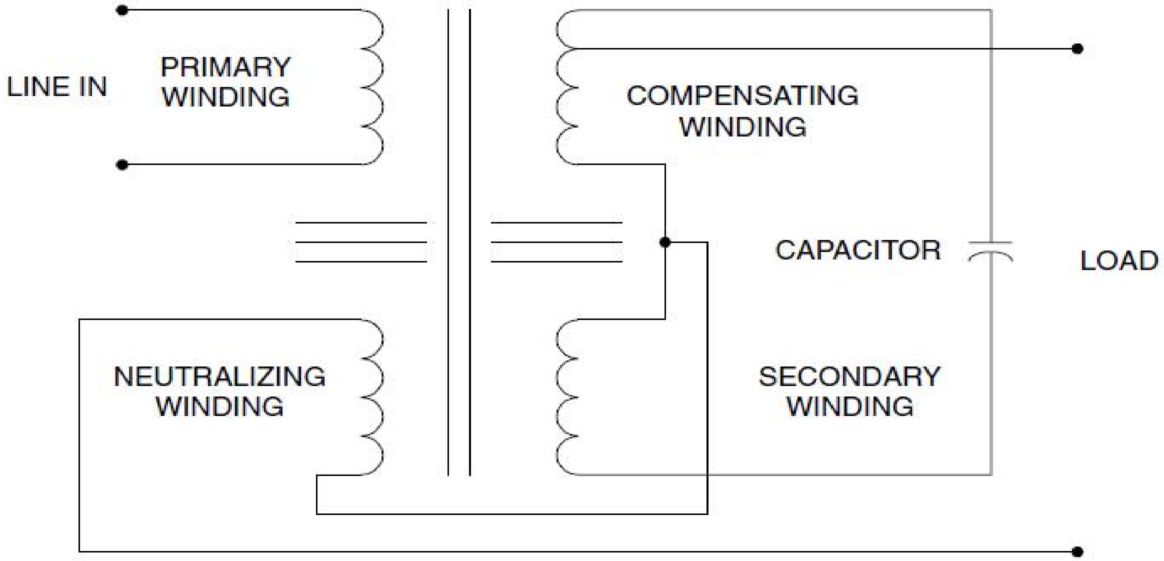
The followings describe the major technologies available and the levels where they can be applied.

2.4.1 Ferroresonant Transformers

It is also called constant-voltage transformers (CVTs). It can handle most voltage sag conditions. CVT sare especially attractive for constant, low-power loads. Variable loads, especially with high inrush currents, present more of a problem for CVTs, because of the tuned circuit on the output.

Ferroresonant 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.

A typical ferroresonant transformer schematic circuit diagram is shown in following Fig.

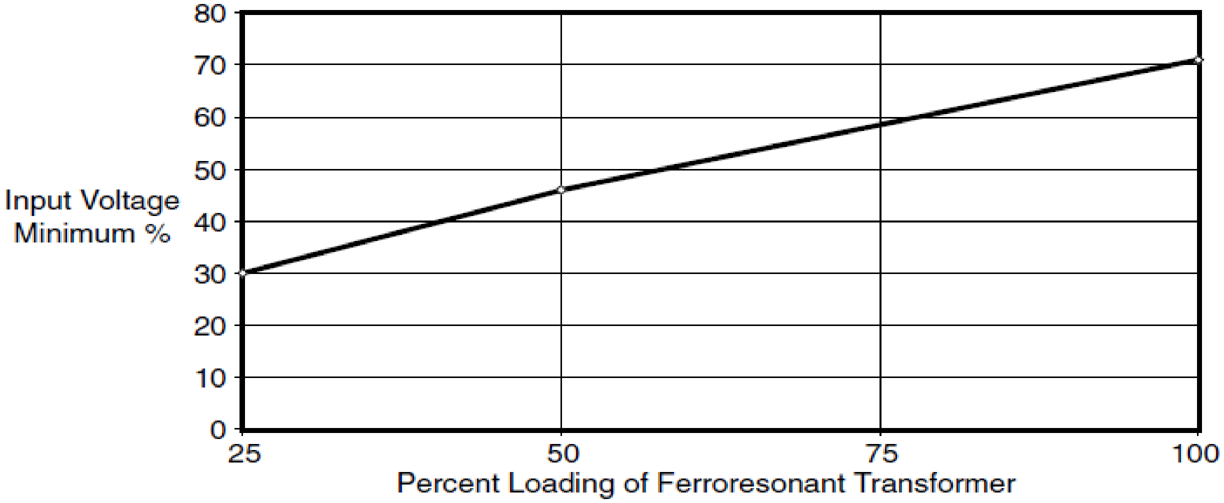


[Fig.2,5 schematic circuit diagram of ferroresonant transformer]

With the CVT, the ride through a voltage sag is 30 percent of nominal, whereas 82 percent without one

Ferroresonant transformers should be sized significantly larger than the load.

The following figure shows the allowable voltage sag as a percentage of nominal voltage (that will result in at least 90 percent voltage on the CVT output) versus ferroresonant transformer loading, as specified by the manufacturer.



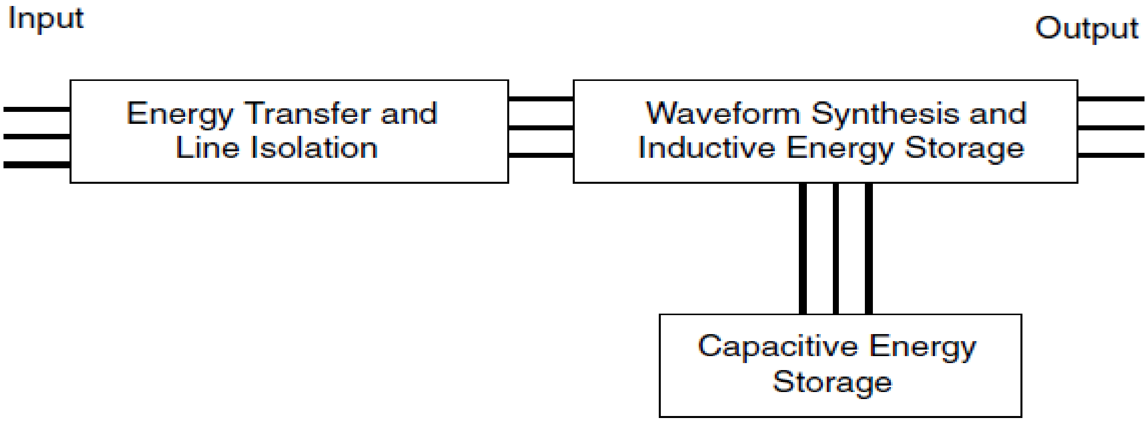
[Fig.2.6 Plot between Input Voltage minimum % vs % load of Ferroresonant Transformer]

At 25 percent of loading, the allowable voltage sag is 30 percent of nominal, which means that the CVT will output over 90 percent normal voltage as long as the input voltage is above 30 percent. This is important since the plant voltage rarely falls below 30 percent of nominal during voltage sag conditions. As the loading is increased, the corresponding ride-through capability is reduced, and when the ferroresonant transformer is overloaded (e.g., 150 percent loading), the voltage will collapse to zero.

2.4.2 Magnetic Synthesizers

- Magnetic synthesizers use a similar operating principle to CVTs except they are three-phase devices and take advantage of the three-phase magnetics to provide improved voltage sag support and regulation for three-phase loads.
- They are applicable over a size range from about 15 to 200 kVA and are typically applied for process loads of larger computer systems where voltage sags or steady-state voltage variations are important issues.

A block diagram of the process is shown in following figure.



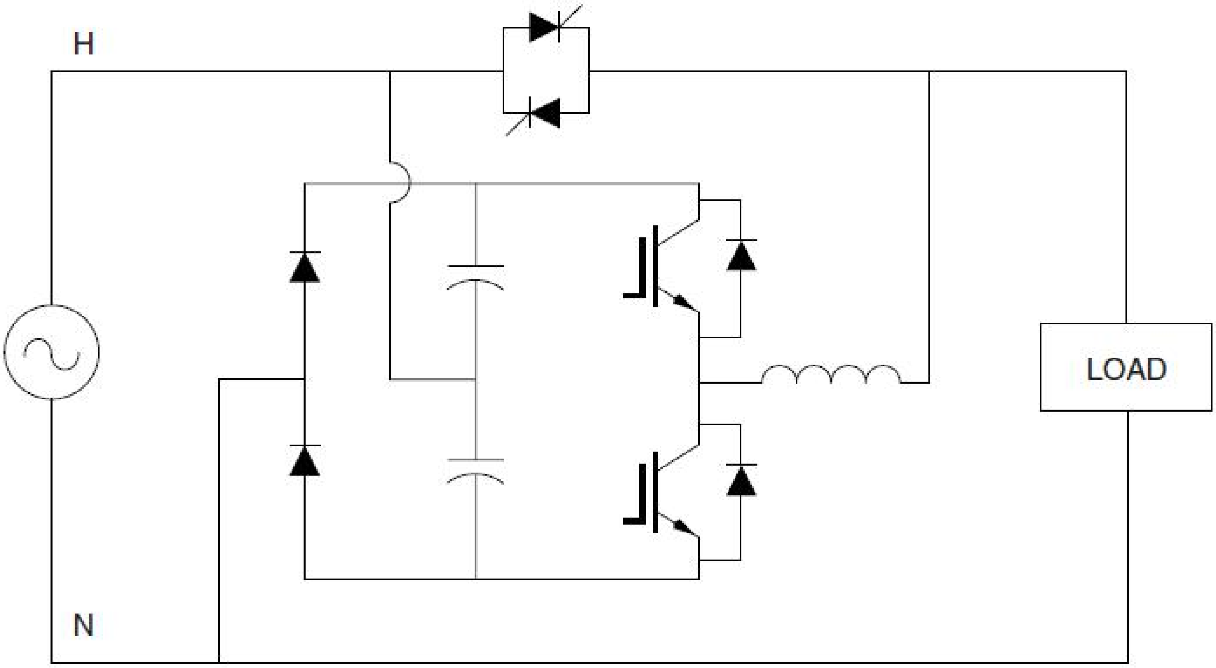
[Fig.2.7 block diagram of a magnetic synthesizer]

- Energy transfer and line isolation are accomplished through the use of nonlinear chokes. This eliminates problems such as line noise.
- The ac output waveforms are built by combining distinct voltage pulses from saturated transformers.
- The waveform energy is stored in the saturated transformers and capacitors as current and voltage. This energy storage enables the output of a clean waveform with little harmonic distortion.
- Finally, three-phase power is supplied through a zig-zag transformer.

2.4.3 Active Series Compensators

These are one of the new technologies using power electronic component that can boost the voltage by injecting a voltage in series with the remaining voltage during a voltage sag condition. They are available in size ranges from small single-phase devices (1 to 5 kVA) to very large devices that can be applied on the medium-voltage systems (2 MVA and larger).

A one-line diagram illustrating the power electronics that are used to achieve the compensation is shown in the following figure.



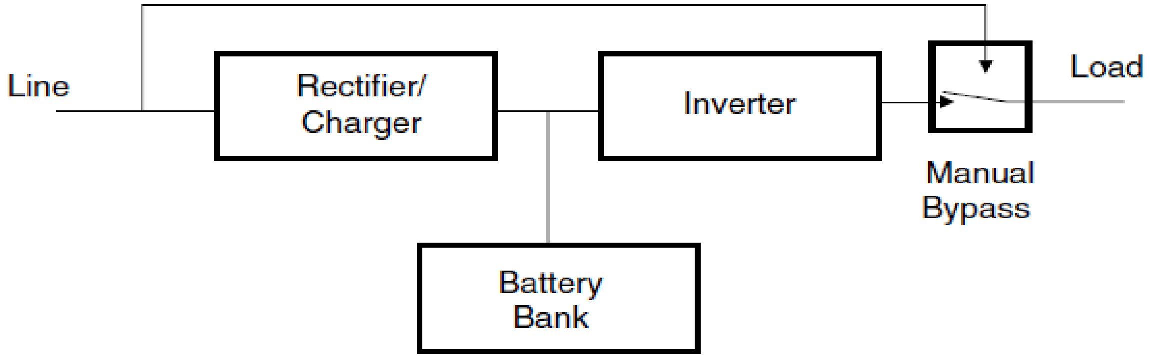
[Fig.2.8 Topology illustrating the operation of the active series compensator]

- When a disturbance to the input voltage is detected, a fast switch opens and the power is supplied through the series-connected electronics. This circuit adds or subtracts a voltage signal to the input voltage so that the output voltage remains within a specified tolerance during the disturbance.
- The switch is very fast so that the disturbance seen by the load is less than a quarter cycle in duration. This is fast enough to avoid problems with almost all sensitive loads.

- The circuit can provide voltage boosting of about 50 percent, which is sufficient foral most all voltage sag conditions.

2.4.4 On-line UPS

The following figure shows a typical configuration of an on-line UPS.



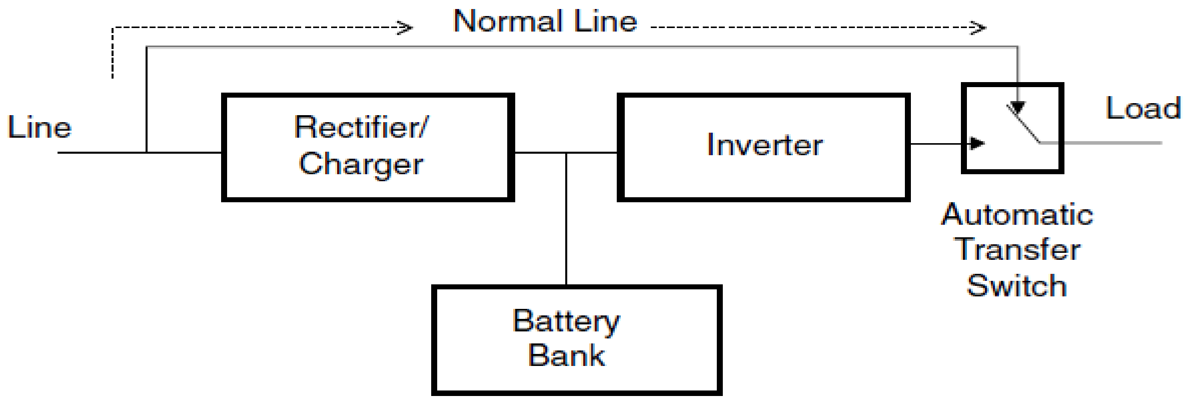
[Fig.2.9 on-line UPS]

- In this design, 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 into ac power, to feed the load.
- If the in coming ac power fails, the inverter is fed from the batteries and continues to supply the load.
- In addition to providing ride-through for power outages, an on-line UPS provides very high isolation of the critical load from all power line disturbances. However, the on-line operation increases the losses and may be unnecessary for protection of many loads.

2.4.5 Standby UPS

A standby power supply is sometimes termed as ***off-line*** *UPS.*

The following figure shows the configuration of a standby UPS.

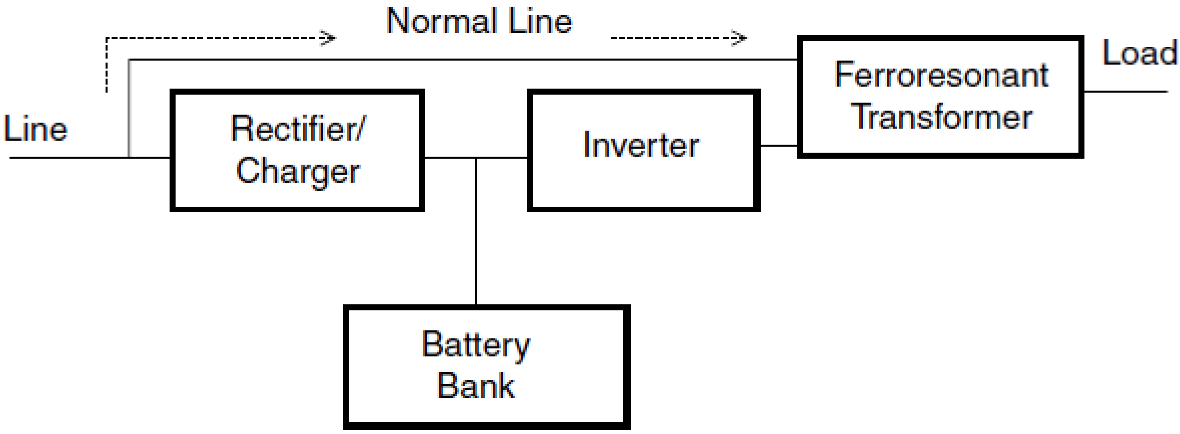


[Fig.2.10 standby UPS]

- It is referred as offline, since the normal line power is used to power the equipment until a disturbance is detected and a switch transfers the load to the battery backed in verter.
- The transfer time from the normal source to the battery-backed inverter is important.
- The CBEMA curve shows that 8ms 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.
- A standby power supply does not typically provide any transient protection or voltage regulation as does an on-line UPS.
- This is the most common configuration for commodity UPS units available at retail stores for protection of small computer loads.
- UPS specifications include kVA capacity, dynamic and static voltage regulation, harmonic distortion of the input current and output voltage, surge protection, and noise attenuation.
- The specifications should indicate, or the supplier should furnish, the test condition sunder which the specifications are valid.
-

2.4.6 Hybrid UPS

It is similar in design to the standby UPS.
The following figure shows the configuration of a hybrid UPS.



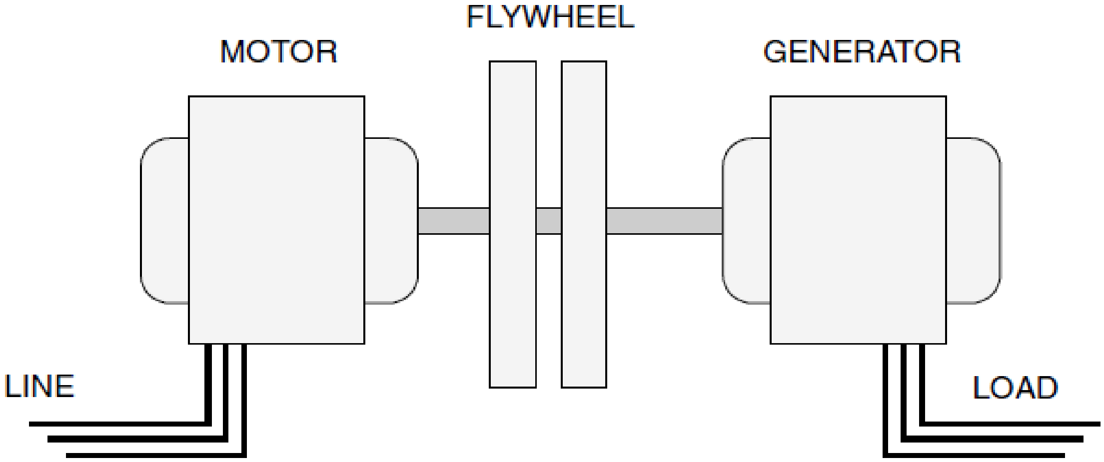
[Fig.2,11 hybrid UPS]

The hybrid 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.

2.4.7 Motor-generator sets

Motor-generator (M-G) sets come in a wide variety of sizes and configurations. This is a mature technology that is still useful for is olatingcritical loads from sags and interruptions on the power system. The concept is very simple.

The following figure shows block diagram of a M-G set.



[Fig.2.12 block diagram of a M-G set]

- A motor powered by the line drives a generator that powers the load. Flywheels on the same shaft provide greater inertia to increase ride-through time.
- When the line suffers a disturbance, the inertia of the machines and the fly wheels maintains the power supply for several seconds.
- This arrangement may also be used to separate sensitive loads from other classes of disturbances such as harmonic distortion and switching transients.

While simple in concept, M-G sets have disadvantages for some types of loads:

1. There are losses associated with the machines, although they are not necessarily larger than those in other technologies described here.
2. Noise and maintenance may be issues with some installations.
3. The frequency and voltage drop during interruptions as the machine slows. This may not work well with some loads.

- 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 between3150 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.

2.4.8 Flywheel Energy Storage Systems

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.

- M-G sets typically operate in the open and are subject to aerodynamic friction losses and these flywheels operate in a vacuum and employ magnetic bearings to substantially reduce standby losses.
- Designs with steel rotors may spin at approximately10,000 rpm, while those with composite rotors may spin at much higher speeds.
- Since the amount of energy stored is proportional to the square of the speed, a great amount of energy can be stored in a small space.
- The rotor serves as a one-piece storage device, motor, and generator.
- To store energy, the rotor is spun up to speed as a motor.
- When energy is needed, the rotor and armature act as a generator.
- As the rotor slows when energy is extracted, the control system automatically in creases the field to compensate for the decreased voltage.
- The high-speed fly wheel energy storage module would be used in place of the battery in any of the UPS concepts.

2.4.9 Superconducting Magnetic Energy Storage (SMES) devices

It can be used to reduce the 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 super conducting magnet.
- Since the coil is lossless, the energy can be released almost instantaneously.
- Through voltage regulator and inverter banks, this energy can be injected into the protected electrical system in less than 1cycle to compensate for the missing voltage during a voltage sag event.

The SMES-based system has several advantages over battery-based UPS systems:

1. SMES-based systems have a much smaller footprint than batteries for the same energy storage and power delivery capability.
2. The stored energy can be delivered to the protected system more quickly.
3. The SMES system has virtually unlimited discharge and charge duty cycles. The discharge and recharge cycles can be performed thousands of times without any degradation to the superconducting magnet.

The recharge cycle is typically less than 90 s from full discharge.

The following figure shows the functional block diagram of a common system.

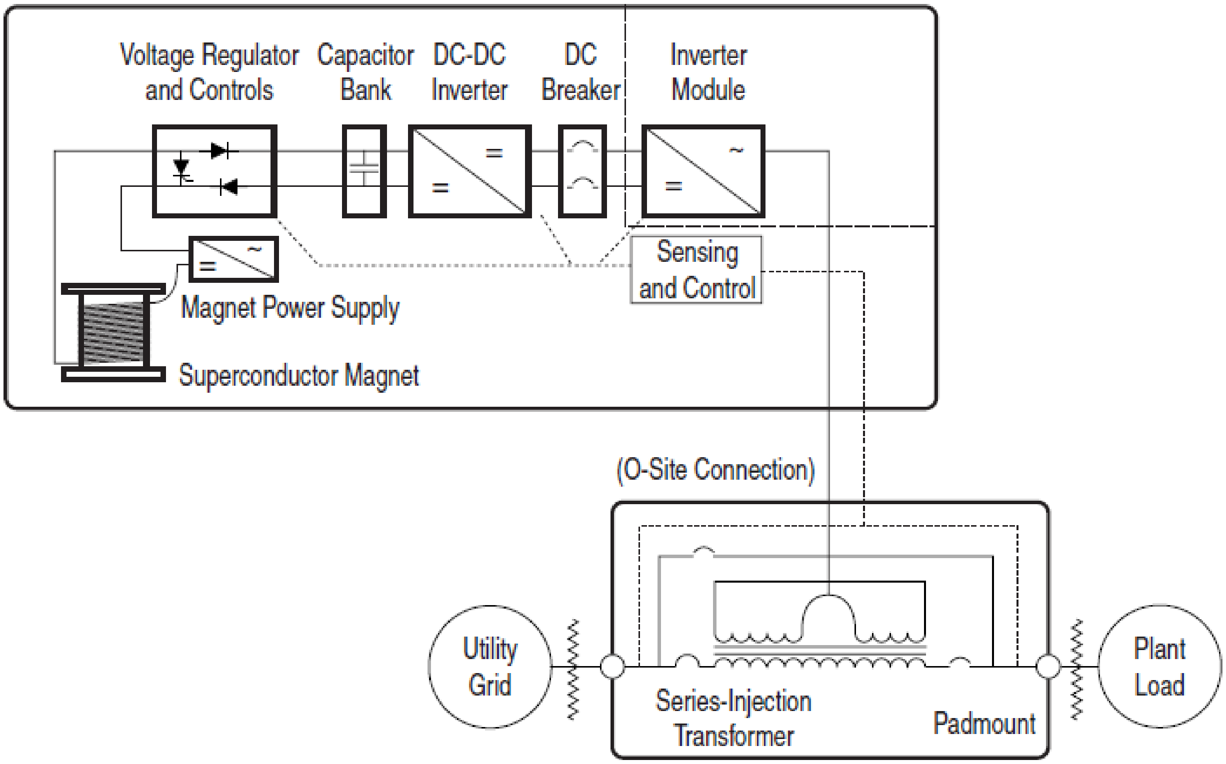


Fig.2.13 Functional block diagram of common system

- It consists of a superconducting magnet, voltage regulators, capacitor banks, a dc-to-dc converter, dc breakers, inverter modules, sensing and control equipment, and a series-injection transformer.
- The superconducting magnet is constructed of a niobium titanium (NbTi) conductor and is cooled to approximately 4.2 K by liquid helium.
- The cryogenic refrigeration system is based on a two-stage recondenser.
- The magnet electrical leads use high-temperature superconductor (HTS) connections to the voltage regulator and controls.
- The magnet might typically store about 3 MJ.

Example:

- In the example system shown, energy released from the SME Spasses through a current-to-voltage converter to charge a 14 mF dc capacitor bank to 2500 V_{dc}.
- The voltage regulator keeps the dc voltage at its nominal value and also provides protection control to the SMES.
- The dc-to-dc converter reduces the dc voltage down to 750V_{dc}.
- The inverter subsystem module consists of six single-phase inverter bridges. Two IGBT inverter bridges rated 450 Arms are paralleled in each phase to provide a total rating of 900 A per phase.
- The switching scheme for the inverter is based on the pulse-width modulation (PWM) approach where the carrier signal is a sine-triangle with a frequency of 4 kHz.

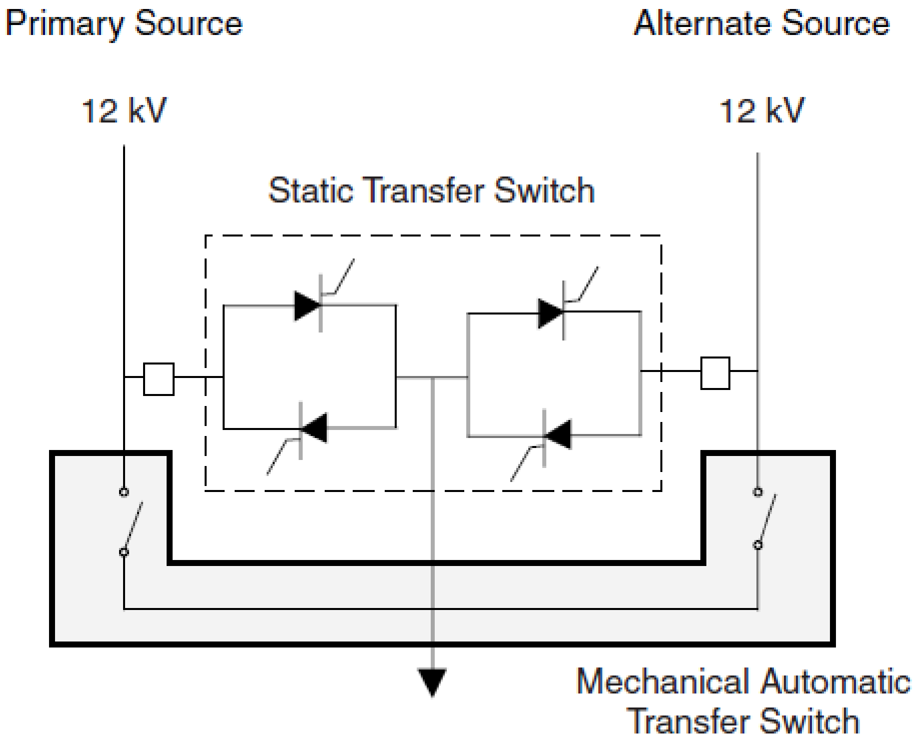
A typical SMES system can protect loads of up to 8 MVA for voltage sags as low as 0.25 pu. It can provide up to 10 s of voltage sag ride-through depending on load size.

2.4.10 Static Transfer Switches and Fast Transfer Switches

For protection of an entire facility that supposed be sensitive to voltage sags, dynamic voltage restorers (DVRs) and UPS systems can be applied at the medium-voltage level.
Another alternative that can be applied at either the low-voltage level or the medium-voltage level is the automatic transfer switch.

- Automatic transfer switches can be of various technologies, ranging from conventional breakers to static switches.
- Conventional transfers witches 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.

The transfer switch configuration is shown in the following figure.



[Fig.2.14 Configuration of a static transfer switch]

- The most important consideration in the effectiveness of a transfer switch for protection of sensitive loads is that it requires two independent supplies to the facility.

- For instance, if both supplies come from the same substation bus, then they will both be exposed to the same voltage sags when there is a fault condition somewhere in the supply system.
- If a significant percentage of the events affecting the facility are caused by faults on the transmission system, the fast transfer switch might have little benefit for protection of the equipment in the facility.

2.5 Evaluating the Economics of Different Ride-Through Alternatives

To find the best option for improving voltage sag performance, the economic evaluation procedure consists of the following steps:

1. Characterize the system power quality performance.
2. Estimate the costs associated with the power quality variations.
3. Characterize the solution alternatives in terms of costs and effectiveness.
4. Perform the comparative economic analysis.

The methodology for characterizing the expected voltage sag performance, and the major technologies that can be used to improve the performance of the facility are described in previous sections. Here, evaluation of the economics of the different options is presented.

2.5.1 Estimating the costs for the Voltage Sag events

The costs associated with sag events can vary significantly from nearly zero to several million dollars per event.

- The cost will vary not only among different industry types and individual facilities but also with market conditions.
- Higher costs are typically experienced if the end product is in short supply and there is limited ability to make up for the lost production.

The cost of a power quality disturbance can be captured primarily through three major categories:

1. Product-related losses, such as loss of product and materials, lost production capacity, disposal charges, and increased inventory requirements.
2. Labor-related losses, such as idled employees, overtime, cleanup, and repair.
3. Ancillary costs such as damaged equipment, lost opportunity cost, and penalties due to shipping delays.

Focusing on these three categories will facilitate the development of a detailed list of all costs and savings associated with a power quality disturbance.

Costs will typically vary with the severity (both magnitude and duration)of the power quality disturbance.

- This relationship can often be defined by a matrix of weighting factors.
- The weighting factors are developed using the cost of a momentary interruption as the base.

- Usually, a momentary interruption will cause a disruption to any load or process that is not specifically protected with some type of energy storage technology.
- Voltage sags and other power quality variations will always have an impact which is some portion of this total shutdown.
- After the weighting factors are applied to an event, the costs of the event are expressed in per unit of the cost of a momentary interruption.
- The weighted events can then be summed and the total is the total cost of all the events expressed in the number of equivalent momentary interruptions.

Example:

If a voltage sag to 40 percent causes 80 percent of the economic impact that a momentary interruption causes, then the weighting factor for a 40 percent sag would be 0.8. Similarly, if a sag to 75 percent only results in 10 percent of the costs that an interruption causes, then the weighting factor is 0.1.

The following table combines the weighting factors with expected performance to determine a total annual cost associated with voltage sags and interruptions.

Category of Event	**Weighting for Economic analysis**	**Number of Events per year**	**Total equivalent interruptions**
Interruption	1	5	5
Sag with minimum voltage below 50%	0.8	3	2.4
Sag with minimum voltage below 50% and 70%	0.4	15	6
Sag with minimum voltage below 70% and 90%	0.1	35	3.5
Total			16.9

The cost is 16.9 times the cost of an interruption. If an interruption costs $40,000, the total costs associated with voltage sags and interruptions would be $676,000 per year.

2.5.2 Characterizing the cost and effectiveness for solution alternatives

Each solution technology needs to be characterized in terms of cost and effectiveness.

- The solution cost should include initial procurement and installation expenses, operating and maintenance expenses, and any disposal and/or salvage value considerations.
- A thorough evaluation would include less costs such as real estate or space-related expenses and tax considerations.
- The cost of the extra space requirements can be incorporated as a space rental charge and included with other annual operating expenses.

- Tax considerations may have several components, and the net benefit or cost can also be included with other annual operating expenses.
- These costs are provided for use in the example and should not be considered indicative of any particular product.
- Besides the costs, the solution effectiveness of each alternative needs to be quantified in terms of the performance improvement that can be achieved.
- Solution effectiveness, like power quality costs, will typically vary with the severity of the power quality disturbance.

2.5.3 Performing Comparative Economic Analysis

The process of comparing the different alternatives for improving performance involves determining the total annual cost for each alternative, including both the costs associated with the voltage sag sand the annualized costs of implementing the solution.

- The objective is to minimize these annual costs (power quality costs + solution costs).
- Comparing the different power quality solution alternatives in terms of their total annual costs (annual power quality costs + annual power quality solution costs) identifies those solution(s) with lower costs that require more detailed investigations.
- The do-nothing solution is generally included in the comparative analysis and is typically identified as the base case. The do-nothing solution has a zero annual power quality solution cost but has the highest annual power quality costs.
- Many of the costs (power quality and operation and maintenance) are annual costs by their nature.

2.6 Motor Starting Sags

Motors draw several times their full load current while starting. This large current will cause voltage sag, by flowing through system impedances, which may dim lights, cause contactors to drop out, and disrupt sensitive equipment.

The time required for the motor to accelerate to rated speed increases with the magnitude of the sag, and excessive sag may prevent the motor from starting successfully. Motor starting sags can persist form any seconds.

2.6.1 Motor Starting Methods

Single step (*full-voltage starting*) energization of motors provides low cost and allows the most rapid acceleration. It is the preferred method unless the resulting voltage sag or mechanical stress is excessive.

(a) Autotransformer starters:

- These starters have two autotransformers connected in open delta.
- Taps provide a motor voltage of 80, 65, or 50 percent of system voltage during start-up.

- Line current and starting torque vary with the square of the voltage applied to the motor, so the 50 percent tap will deliver only 25 percent of the full-voltage starting current and torque.
- The lowest tap which will supply the required starting torque is selected.

(b) Resistance and reactance starters:

- These starters initially insert an impedance in series with the motor.
- After a time delay, this impedance is shorted out.
- Starting resistors may be shorted out over several steps; starting reactors are shorted out in a single step.
- Line current and starting torque vary directly with the voltage applied to the motor. So for a given starting voltage, these starters draw more current from the line than with a uto-transformer starters, but provide higher starting torque.
- Reactors are typically provided with 50, 45, and 37.5 percent taps.

(c)Part-winding starters:

- These starters are attractive for use with dual-rated motors (220/440 V or 230/460 V).
- The stator of a dual-rated motor consists of two windings connected in parallel at the lower voltage rating, or in series at the higher voltage rating.
- When operated with a part-winding starter at the lower voltage rating, only one winding is energized initially, limiting starting current and starting torque to 50 percent of the values seen when both windings are energized simultaneously.

(d) Delta-Wye starters:

- These starters connect the stator in wye for starting and then, after a time delay, reconnect the windings in delta.
- The wye connection reduces the starting voltage to 57 percent of the system line-line voltage; starting current and starting torque are reduced to 33 percent of their values for full-voltage start.

2.6.2 Estimating the Sag severity during full-voltage starting

If full-voltage starting is used, the sag voltage, in per unit of nominal system voltage is,

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

Where, V(pu) = actual system voltage, in per unit of nominal

kVA_{LR} = motor locked rotor kVA

kVA_{SC}= system short-circuit kVA at motor

- If the result is above the minimum allowable steady-state voltage for the affected equipment, then the full-voltage starting is acceptable.
- If not, then the sag magnitude versus duration characteristic must be compared to the voltage tolerance envelope of the affected equipment.
- The required calculations are fairly complicated and best left to a motor-starting or general transient analysis computer program.

The following data will be required for the simulation:

(i) Parameter values for the standard induction motor equivalent circuit: R_1, X_1, R_2, X_2, and X_M.

(ii) Number of motor poles and rated rpm (or slip).

(iii) WK^2 (inertia constant) values for the motor and the motor load.

(iv) Torque versus speed characteristic for the motor load.

2.7 Utility System Fault Clearing Issues

Utility feeder design and fault-clearing practices have a great influence on the voltage sag and interruption performance at a distribution-connected load.

Utilities have two basic options to reduce the number and severity of faults on their system:

1. Prevent faults
2. Modify fault clearing practices

- Fault prevention results in improved customer satisfaction and it also prevent costly damage to power system equipment.
- Fault prevention activities include tree trimming, adding line arresters, insulator washing, and adding animal guards.
- Tower footing resistance is an important factor in back flashovers from static wire to a phase wire.
- If the tower footing resistance is high, the surge energy from a lightning stroke will not be absorbed by the ground as quickly.
- Improved fault-clearing practices may include adding line reclosers, eliminating fast tripping, adding loop schemes, and modifying feeder design.

2.7.1 Over current Coordination Principles

It is important to understand the operation of the utility system during fault conditions. We should consider the issues relevant to utility fault clearing with both the end user (or load equipment designer) and the utility side.

There are two fundamental types of faults on power systems:

1. *Transient (temporary) faults*:

These are faults due to such things as overhead line flashovers that result in no permanent damage to the system insulation. Power can be restored as soon as the fault arc is extinguished. Automatic switchgear can do this within a few seconds. Some transient faults are self-clearing.

2. *Permanent faults:*

These are faults due to physical damage to some element of the insulation system that requires intervention by a line crew to repair. The impact on the end user is an outage that lasts from several minutes to a few hours.

The main objective of the utility system fault-clearing process is personnel safety and to limit the damage to the distribution system. Therefore, the detection and clearing of the faults must be done with the maximum possible speed without resulting in false operations for normal transient events.

- A radial distribution system is designed so that only one fault interrupter must operate to clear a fault.
- For permanent faults, that same device, or another, operates to *sectionalize* the feeder. That is, the faulted section is isolated so that power may be restored to the rest of the loads served from the sound sections. This is referred to as the ***coordination*** of the over current protection devices.
- All of the process is performed automatically by autonomous devices employing only local intelligence.
- Over current protection devices appear in series along a feeder.
- For permanent fault coordination, the devices operate progressively slower as one moves from the ends of the feeders toward the substation. This helps ensure the proper sectionalizing of the feeder so that only the faulted section is isolated. However, this principle is often violated for temporary faults, particularly if fuse saving is employed.

The typical hierarchy of over current protection devices on a feeder is,

1. **Feeder breaker in the substation:**
   This is a circuit breaker capable of interrupting typically 40 kA of current and controlled by separate relays. When the available fault current is less than 20 kA, it is common to find reclosers used in this application.
2. **Line reclosers mounted on poles at mid feeder:**
   The simplest are self-contained with hydraulically operated timing, interrupting, and reclosing mechanisms. Others have separate electronic controls.
3. Fuses on many lateral taps off the main feeder

2.7.2 Fuses

- It is the most basic over current protective element on the system is a fuse.
- Fuses are relatively inexpensive and maintenance-free. For those reasons, they are generally used in large numbers on most utility distribution systems to protect individual transformers and feeder branches.
- The fundamental purpose of fuses isto operate on permanent faults and isolate (sectionalize) the faulted section from the sound portion of the feeder. They are so placed so that the smallest practical section of the feeder is disturbed.
- Fuses detect over current by melting the fuse element, which generally is made of a metal such as tin or silver.
- This initiates some sort of arcing action that will lead to the interruption of the current.

There are two basic kinds of fuse technologies (on the basis of the way the arc is quenched) used in power systems:

1. Expulsion fuses
2. Current limiting fuse

Expulsion Fuse:

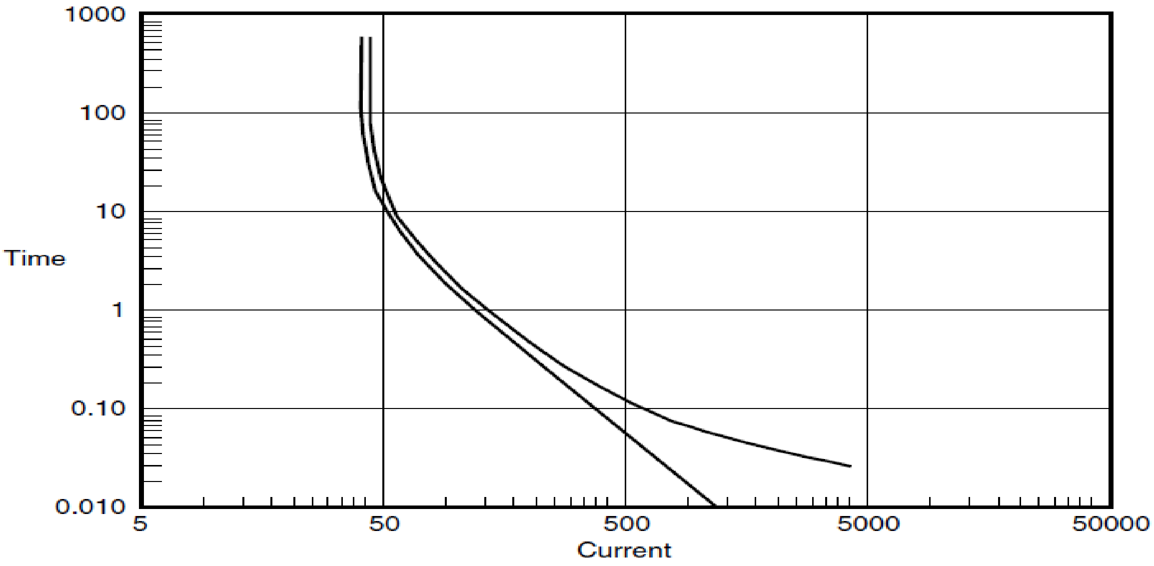
- It creates an arc inside a tube with an ablative coating. This creates high-pressure gases that expel the arc plasma and fuse remnants out the bottom of the cutout.
- This cools the arc such that it will not reignite after the alternating current naturally goes through zero.
- This can be as short as one-half cycle for high currents to several cycles for low fault currents. This determines the duration of the voltage sag observed at loads.
- An expulsion fuse is considerably less expensive than a current limiting fuse.

Current Limiting Fuse:

- A current-limiting fuse dissipates the energy in the arc in a closed environment, typically by melting a special sand within an insulating tube.
- This process actually quenches the arc very quickly forcing the current to zero before that would naturally occur.

Characteristics:

- A fuse takes different amounts of time to operate at different levels of fault current, because it is based on a piece of metal that must accumulate heat until it reaches its melting temperature.
- The time decreases as the current level increases, giving a fuse its distinctive inverse time-current characteristic (TCC), as shown in below figure.



[Fig. 2.15 Inverse Time Current Characteristic (TCC)]

- To achieve full-range coordination with fuses, all other over current protective devices in the distribution system must adopt this same basic shape.
- The fuse TCC is typically given as a band between two curves as shown.

- The leftmost edge represents the minimum melting time, while the rightmost edge represents the maximum clearing time for different current levels.

Some aspects of coordinating with the fuse characteristic relevant to power quality are as follows:

1. If the utility employs fuse saving on temporary faults, the coordinating fault interrupter must have a TCC to the left of the minimum melting curve.
2. For a permanent fault, the coordinating device must have a TCC to the right of the clearing curve to allow the fuse to melt and clear first. Otherwise, many other customers will be interrupted.
3. Repeated fault currents, inrush currents from reclosing, and lightning stroke currents can damage the fuse element, generally shifting the TCC to the left. This will result in inadvertent interruptions of customers down line from the fuse.
4. For high current values with operating time less than 0.1 s, it is difficult to guarantee that an upline mechanical fault interrupter will be able to save the fuse.

2.7.3 Reclosing

- As most of the faults on overhead lines are transient, the power can be successfully restored within several cycles after the current is interrupted.
- Thus, most automatic circuit breakers are designed to reclose 2or 3 times, if needed, in rapid succession.
- The multiple operations are designed to permit various sectionalizing schemes to operate and to give some more persistent transient faults a second chance to clear.
- There are special circuit breakers for utility distribution systems called, appropriately, ***reclosers***, that were designed to perform the fault interruption and reclosing function.
- The majority of faults will be cleared on the first operation.
- These devices are generally pole-mounted on overhead utility lines, although a pad-mounted version also exists.
- The oil-insulated designs are the most common, but sulfur hexafluoride (SF6) insulatedand encapsulated solid dielectric designs are also popular.
- These devices can be found in numerous places along distribution feeders and sometimes in substations.
- They are typically applied at the head of sections subjected to numerous temporary faults.

2.7.4 Fuse saving

- Blowing fuses is avoided as it requires changing them.
- Line reclosers were designed specifically to help save fuses.
- Substation circuit breakers can use instantaneous ground relaying to accomplish the same thing.
- The basic idea is to have the mechanical circuit-interrupting device operate very quickly on the first operation so that it clears before any fuses down line from it have a chance to melt.

- When the device closes back in, power is fully restored in the majority of the cases and no human intervention is required.
- The only inconvenience to the customer is a slight blink. This is called the ***fast*** operation of the device, or the ***instantaneous trip***.

If the fault is still there upon reclosing, the following two options are commonly used:

1. Switch to a slow or delayed tripping characteristics.
2. Try a second fast operation.

3.7.5 Reliability

The term reliability in the utility context usually refers to the amount of time end users are totally without power for an extended period of time (i.e., a sustained interruption).
Different indices are described below.

1. **SAIFI (System Average Interruption Frequency Index)**

   System Average Interruption Frequency Index (SAIFI) is the average number of times that a customer experiences outage during the year (or the time period under study).

$$\mathrm{SAIFI} = \frac{(\mathrm{no.\ \ cusomers\ interrupted})(\mathrm{no.\ of\ interruption})}{\mathrm{total\ no.\ of\ customers}}$$

2. **SAIDI (System Average Interruption Duration Index)**

   This index measures the total duration of an interruption for the average customer during a given period.

$$\mathrm{SAIDI} = \frac{\sum[(\mathrm{no.\ of\ customers\ affected})(\mathrm{duration\ of\ outage})]}{\mathrm{total\ no.\ of\ customers}}$$

3. **CAIFI (Customer Average Interruption Frequency Index)**

   It measures the average number of interruptions per customer interrupted per year (period under study).

$$\mathrm{CAIFI} = \frac{\mathrm{total\ no.\ customer\ interruptions}}{\mathrm{no.\ of\ customers\ affected}}$$

4. CAIDI (Customer Average Interruption Duration Index)

$$\text{CAIDI} = \frac{\sum \text{customer interruption durations}}{\text{total no. customer interruptions}}$$

5. ASAI (Average System Availability Index)

$$\text{ASAI} = \frac{\text{customer hours service availability}}{\text{customer hours service demand}}$$

Where, customer hours service demand = 8760 for an entire year.

Problem:

Calculate the reliability indices for the following PQ problem for 26th of the month where five outages occurred. The utility has 50000 customers.

Date	Time	Customers interrupted	Duration (min)
26th	9:53	10	90
26th	11:02	1000	20
26th	13:15	2	175
26th	20:48	1	120
26th	22:35	1	38

Solution:

Date	Time	Customers interrupted	Duration (min)	(customer) x (hours)
26th	9:53	10	90	15 [(90/60)x10]
26th	11:02	1000	20	333.33
26th	13:15	2	175	5.83
26th	20:48	1	120	2
26th	22:35	1	38	0.63
		$\sum = 1014$	$\sum = 443$	$\sum = 356.8$

The different indices are calculated below.

1. SAIDI $= \frac{356.8 \times 60}{50000} = 0.0428$ min
   i.e., average customer was out for 0.0428 min on 26th .

2. CAIDI $= \frac{356.8 \times 60}{1014} = 21.1$ min
   i.e., on average any customer who experienced an outage on 26th was out of service for 21.1 min.

3. SAIFI $= \frac{1014}{50000} = 0.02$

   i.e., on 26th of the month, the customers of this utility had a 0.02 probability of experiencing an outage.

4. CAIFI $= \frac{5}{1014} = 0.005$

   i.e., average no. of interruptions for a customer who was interrupted is 0.005 times.

5. ASAI $= 1 - \frac{356.8}{50000 \times 24} = 1 - 0.000297333 = 0.9997$

[As one day(26th) is under study, so hours service demand is 24 hrs.]

$\Longrightarrow \text{ASAI} = 99.97\ \%$

2.7.6 Impact of eliminating fuse saving

- Application of fuse provides interruption for the entire feeder.
- The penalty is that customers on the affected fused tap will suffer a sustained interruption until the fuse can be replaced.
- The solution is to prefer optimal technical and economical solutions which make use of fast trip capability of breakers and reclosers. This saves operating cost and improves reliability.
- The impact on the reliability indices is highly dependent on the structure of the feeder and sectionalization.
- A problem is when there are faults close to substation on other or same feeder. This causes deep sag.

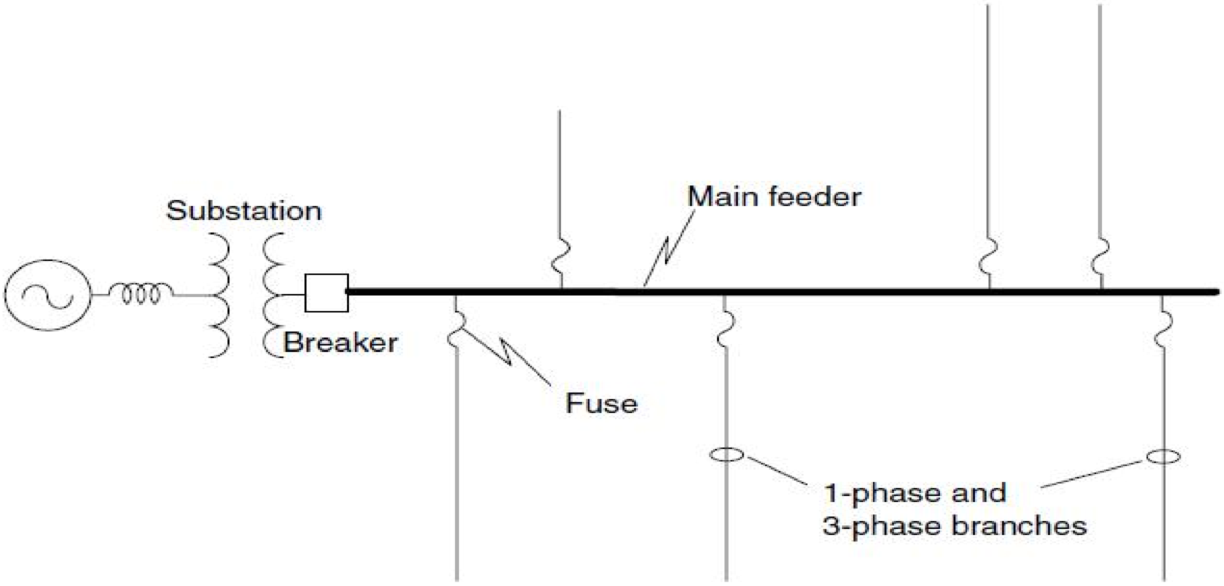
The approach to deal with this is,

(i) Install reactors on each line coming from the substation.
(ii) Install current limiting fuses.

- Residential complaints can be avoided by employing instantaneous reclosing on residential feeders.

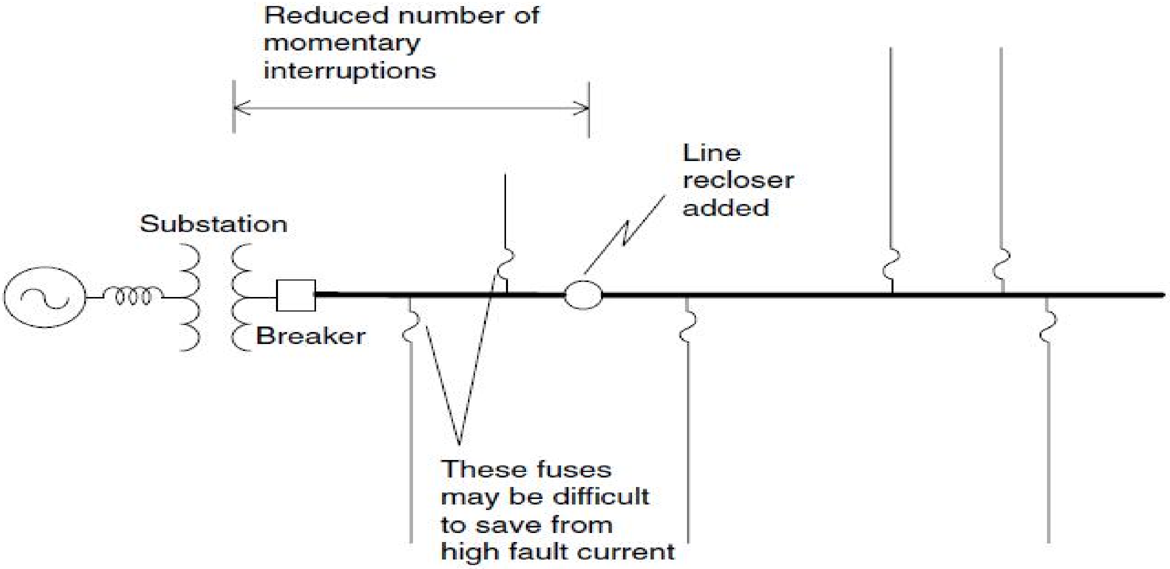
2.7.7 Increased Sectionalizing

The typical primary distribution feeder is a radial feeder. In simplest form, it consists of a main 3-Φ feeder with fused 1-Φ and 3-Φ taps as shown in the following figure.



[Fig.2.16 Typical main line feeder construction with fused taps]

The first step in sectionalization to improve overall reliability is to add line reclosers as shown below.



[Fig.2.17 Adding a line recloser to the main feeder as the first step in sectionalizing]

2.7.8 Midline or Tap Reclosers

- Addition of more line reclosers will accomplish greater sectionalizing of the feeder and perhaps, permit the use of fuse-saving practices on the bulk of the feeder again.
- This practice is very effective if the whole feeder is being interrupted for faults that are largely constrained to a particular region.

- By putting the recloser farther out on the feeder, it will attempt to clear the fault first so that the number of customers inconvenienced by a blink is reduced.
- If it is also necessary to eliminate fast tripping on the substation breaker, only a smaller portion of the feeder nearer the substation is threatened with the possibility of having a fuse blow on a transient fault, as explained previously.
- This is not much different than the normal case because of the difficulty in preventing fuse blowing in the high fault current regions near the substation anyway.

2.7.9 Instantaneous Reclosing

- Instantaneous reclosing is the practice of reclosing within 12 to 30 cycles after interrupting the fault, generally only on the first operation.
- This has been a standard feature of breakers and reclosers for sometime, and some utilities use it as standard practice, particularly on substation breakers.
- However, many utilities reclose no faster than 2 s (the standard reclosinginterval on a hydraulic recloser) and some wait even longer.
- After it was observed that many digital clocks and even some motor driven loads can successfully ride through a 12- to 30-cycle interruption, some utilities began to experiment with using instantaneous reclosing while retaining the fast tripping to save fuses.
- Instantaneous reclosing has had a bad reputation with some utility engineers. One risk is that there is insufficient time for the arc products to disperse and the fault will not clear. Some utilities have had this experience with higher distribution voltage levels and particular line constructions.
- When this happens, substation transformers are subjected to repeated through-faults unnecessarily. This could result in increased failures of the transformers. However, if there is no indication that instantaneous reclosing is causing increased breaker operations, it should be safe to use it.
- Another concern is that very high torques will be generated in rotating machines upon reclosing. This is a particular issue with distributed generation because 12 to 30 cycles may not be sufficient time to guarantee that the generator's protective relaying will detect a problem on the utility side and be off-line.
- Reclosing intervals on feeders with DG should be at least 1 to 2 s so that there is less chance theutility will reclose into the DG out of synchronism. Some utilities allow5 s.

2.7.10 Single Phase Tripping

- Most of the three-phase breakers and reclosers on the utility distribution system operate all three phases simultaneously.
- One approach that has been suggested to minimize the exposure of customers to momentary outages is to trip only the faulted phase or phases. Because many of the loads are single phase, this would automatically reduce the exposure by two-thirds for most faults.

- The main problem with this is that it is possible to damage some three-phase loads if they are single phased for a substantial length of time.
- Thus, it is generally considered to be undesirable to use single-phase reclosers on three-phase branches with significant three-phase loads. Of course, this is done quite commonly when only one-phase loads are being served.
- This problem is solved by a three-phase breaker, or recloser, that is capable of operating each phase independently until it is determined that the fault is permanent. Then, to prevent single-phasing of three- phase loads, all three phases are opened if the fault is permanent and the interrupter locks out.

3.7.11 Current-limiting fuses

- Current-limiting fuses are often used in electrical equipment where the fault current is very high and an internal fault could result in a catastrophic failure.
- Since they are more expensive than conventional expulsion links, their application is generally limited to locations where the fault current is in excess of 2000 to 3000 A.

Construction:

  - The basic configuration is that of a thin ribbon element or wire wound around a form and encased in a sealed insulating tube filled with a special sand.
  - The tube is constructed of stout material such as a fiber glass-epoxy resin composite to withstand the pressures during the places simultaneously and, with the aid of the melting sand, very quickly builds up a voltage drop that opposes the flow of current.
  - The current is forced to zero in about one-fourth of a cycle.
  - The main purpose of current-limiting fuses is to prevent damage due to excessive fault current.

When current-limiting fuses were first installed on utility systems in great numbers, there was the fear that the peak arc voltage transient, which exceeds system voltage, would cause damage to arresters and to insulation in the system. This has not proven to be a significant problem. The overvoltage is on the same order as capacitor-switching transient over voltages, which occur several times a day on most utility systems without serious consequences.

3.7.12 Adaptive Relaying

- Adaptive relaying is the practice of changing the relaying characteristics of the over current protective device to suit the present system conditions.
- One relevant thing that is currently being done with adaptive relaying is the enabling and disabling of fast tripping of breakers in response to weather conditions. This is generally done through a radio or telecommunications link to the utility control center.
- It could also bed one with local devices that have the ability to detect the presence of nearby lightning or rain.

- If a storm is approaching, fast tripping is enabled to save the fuses from the anticipated high incidence of temporary faults. End users are more understanding and less likely to complain about interruptions during storms. At other times, fast tripping is disabled and the fuses are allowed to blow.
- This does not mean there will be no temporary faults without storms. Animals can climb electrical structures at any time and cause a fault. Vegetation growth may be sufficient to cause faults. However, the public generally much less understands about an interruption on a clear day.

2.7.13 Ignoring Third Harmonic Currents

- The level of third-harmonic currents has been increasing due to the increase in the numbers of computers and other types of electronic loads on the system.
- The residual current (sum of the three-phase currents) on many feeders contains as much third harmonic as it does fundamental frequency.
- A common case is to find each of the phase currents to be moderately distorted with a THD of 7 to 8 percent, consisting primarily of the third harmonic.
- The third-harmonic currents sum directly in the neutral so that the third harmonic is 20 to 25 percent of the phase current, which is often as large, or larger, than the fundamental frequency current in the neutral.
- As the third-harmonic current is predominantly zero-sequence, it affects the ground-fault relaying.
- False trips and lockout occur due to excessive harmonic currents in the ground-relaying circuit.
- The simplest solution is to raise the ground-fault pickup level when operating procedures will allow. Unfortunately, this makes fault detection less sensitive, which defeats the purpose of having ground relaying, and some utilities are restrained by standards from raising the ground trip level.
- It has been observed that if the third harmonic could be filtered out, it might be possible to set the ground relaying to be more sensitive.
- The third-harmonic current is almost entirely a function of load and is not a component of fault current.
- When a fault occurs, the current seen by the relaying is predominantly sinusoidal. Therefore, it is not necessary for the relaying to be able to monitor the third harmonic for fault detection.

2.7.14 Utility fault prevention

The following things can be followed to reduce the incidence of faults.

Overhead line maintenance

1. **Tree trimming:**
   This is one of the more effective methods of reducing the number of faults on overhead lines. It is a necessity, although the public may complain about the environmental and aesthetic impact.
2. **Insulator washing:**
   Like tree trimming in wooded regions, insulator washing is necessary in coastal and dusty regions. Otherwise, there will be numerous insulator flashovers for even a mild rainstorm without lightning.
3. **Shield wires:**
   Shield wires for lightning are common for utility transmission systems. They are generally not applied on distribution feeders except where lines have an unusually high incidence of lightning strikes. Some utilities construct their feeders with the neutral on top,perhaps even extending the pole, to provide shielding.
4. **Improving pole grounds:**
   It makes the faults easier to detect. If shielding is employed, this will reduce the back flashoverrate.
5. **Modified conductor spacing:**
   Employing a different line spacing can sometimes increase the withstand to flashover or the susceptibility to getting trees in the line.
6. **Tree wire (insulated/covered conductor):**
   In areas where tree trimming is not practical, insulated or covered conductor can reduce the likelihood of tree-induced faults.

UD Cables

- Fault prevention techniques in underground distribution (UD) cables are generally related to preserving the insulation against voltage surges.
- The insulation degrades significantly as it ages, requiring increasing efforts to keep the cable sound.
- This generally involves arrester protection schemes to divert lightning surges coming from the overhead system, although there are some efforts to restore insulation levels through injecting fluids into the cable.
- Since nearly all cable faults are permanent, the power quality issue is more one of finding the fault location quickly so that the cable can be manually sectionalized and repaired.

Line Arresters

- To prevent overhead line faults, one must either raise the insulation level of the line, prevent lightning from striking the line, or prevent the voltage from exceeding the insulation level.
- The third idea is becoming more popular with improving surge arrester designs.

- To accomplish this, surge arresters are placed every two or three poles along the feeder as well as on distribution transformers.
- Some utilities place them on all three phases, while other utilities place them only on the phase most likely to be struck by lightning.
- To provide custom power with reliable main feeders, it will be necessary to put arresters one very phase of every pole.
- Presently, applying line arresters in addition to the normal arrester at transformer locations is done only on line sections.
- But recently, some utilities have claimed that applying line arresters is not only more effective than shielding, but it is more economical.
- Some sections of urban and suburban feeders will naturally approach the goal of an arrester every two or three poles because the density of load requires the installation of a distribution transformer at least that frequently. Each transformer will normally have a primary arrester in lightning-prone regions.

2.7.15 Fault Locating

Finding faults quickly is an important aspect of reliability and the quality of power. Here, some fault locating methods are described below.

Faulted circuit indicators:

- Finding cable faults is often quite a challenge. The cables are underground, and it is generally impossible to see the fault, although occasionally there will be a physical display.
- To locate the fault, many utilities use “faulted circuit indicators,” or simply “fault indicators,” to locate the faulted section more quickly.
- These are devices that flip a target indicator when the current exceeds a particular level. The idea is to put one at each pad-mount transformer; the last one showing a target will be located just before the faulted section.
- One way to choose the ratings of faulted circuit indicators can be 2 to 3 times the maximum expected load on the cable. This results in a fairly sensitive fault detection capability.
- The other way of choosing rating of indicator is too sensitive and is the reason that many fault indicators give a false indication. The solution to this problem is to apply the indicator with a rating based on the maximum fault current available rather than on the maximum load current. This is based on the assumption that most cable faults quickly develop into bolted faults. Therefore, the rating is selected allowing for a margin of 10 to 20 percent.
- Another issue impacting the use of fault indicators is DG. With multiple sources on the feeder capable of supplying fault current, there will be an increase in false indications.
- Fault indicators must be reset before the next fault event. Some must be reset manually, while others have one of a number of techniques for detecting, or assuming, the restoration of power and resetting automatically.
- Some of the techniques include test point reset, low-voltage reset, current reset, electrostatic reset, and time reset.

Locating cable faults without fault indicators:

Without fault indicators, the utility must rely on more manual techniques for finding the location of a fault. There are a large number of different types of fault-locating techniques and some of the general classes of methods are as follows.

1. **Thumping:**
    - This is a common practice with numerous minor variations.
    - The basic technique is to place a dc voltage on the cable that is sufficient to cause the fault to be reestablished and then try to detect by sight, sound, or feel the physical display from the fault.
    - One common way to do this is with a capacitor bank that can store enough energy to generate a sufficiently loud noise. Those standing on the ground on top of the fault can feel and hear the “thump” from the discharge.
    - Some combine this with cable radar techniques to confirm estimates of distance. Many are concerned with the potential damage to the sound portion of the cable due to thumping techniques.
2. **Cable RADAR and other Pulse Methods:**
    - These techniques make use of traveling wave theory to produce estimates of the distance to the fault.
    - The wave velocity on the cable is known. Therefore, if an impulse is injected into the cable, the time for the reflection to return will be proportional to the length of the cable to the fault.
    - An open circuit will reflect the voltage wave back positively while a short circuit will reflect it back negatively. The impulse current will do the opposite.
    - If the routing of the cable is known, the fault location can be found simply by measuring along the route. It can be confirmed and fine-tuned by thumping the cable.
    - On some systems, there are several taps off the cable. The distance to the fault is to be determined which branch it is on. This can be a very difficult problem that is still a major obstacle to rapidly locating a cable fault.
3. **Tone:**
    - Atone system injects a high-frequency signal on the cable, and the route of the cable can be followed by a special receiver.
    - This techniqueis sometimes used to trace the cable route while it is energized, but is also useful for fault location because the tone will disappear beyond the fault location.
4. **Fault chasing with a fuse:**
    - The cable is manually sectionalized, and then each section is reenergized until a fuse blows.
    - The faulted section is determined by the process of elimination or by observing the physical display from the fault.

- Because of the element of danger and the possibility of damaging cable components, some utilities strongly discourage this practice.
- Others require the use of small current-limiting fuses, which minimize the amount of energy permitted into the fault.
- Thiscan be an expensive and time-consuming procedure that some consider to be the least effective of fault-locating methods.
- This also subjects end users to nuisance voltage sags.

UNIT- 3

Long Duration Voltage Variations

Generally Transients are disturbances that occur for a very short duration (less than a cycle), and the electrical circuit is quickly restored to original operation provided no damage has occurred due to the transient. An electrical transient is a cause-and-effect phenomenon. For transients to occur, there must be a cause.

3.1

Sources of Transient Over voltages

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

i) capacitor switching
ii) lightning

These are also sources of transient over voltages as well as many of other switching phenomena within end-user facilities. Some power electronic devices generate significant transients when they switch.

Transient over voltages can be generated at high frequency (load switching and lightning), medium frequency (capacitor energizing), or low frequency.

3.1.1

Capacitor switching:

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. Switching of capacitor banks is accompanied by a surge of current which is initially limited by the characteristic impedance of the power system and resistance of the line. A sharp reduction in the voltage is followed by a voltage rise, which decays by oscillation at a frequency determined by the inductance and capacitance of the circuit.

One drawback to the use of capacitors is that they yield oscillatory transients when switched. Some capacitors are energized all the time (a fixed bank), while others are switched according to load levels.

Various control means, including time, temperature, voltage, current, and reactive power, are used to determine when the capacitors are switched. It is common for controls to combine two or more of these functions, such as temperature with voltage override.

Typically, the voltage rise due to capacitor switching operation can attain values 1.5 to 2 times the nominal voltage.

One of the common symptoms of power quality problems related to utility capacitor switching overvoltages is 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 adjustable-speed-drive trips and malfunctions of other electronically controlled load equipments.

Fig. 3.1 shows the one-line diagram of a typical utility feeder capacitor-switching situation.

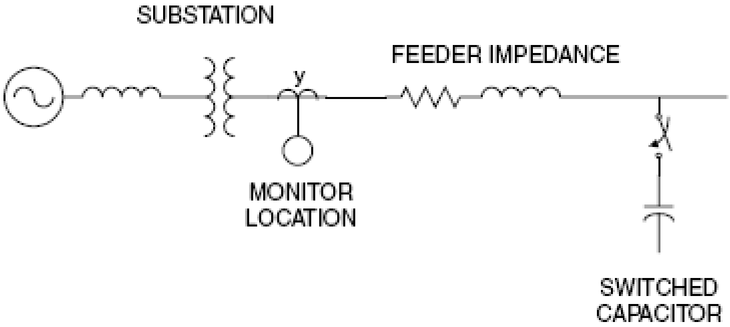


Fig. 3.1. One-line diagram of a capacitor-switching of utility feeder.

3.1.2
Lightning

Lightning is a powerful source of impulsive transients. We will concentrate on how lightning causes transient overvoltages to appear on power systems.

Figure 2.2 shows some of the places where lightning can strike that results in lightning currents being conducted from the power system into loads. 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, but some analysts question whether this is the most common way that lightning surges enter load facilities and cause damage. 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. 4.6, include the primary ground, the secondary ground, and the structure of the load facilities. Note also that strikes to the primary phase are conducted to the ground circuits through the arresters on the service transformer. Thus, many more lightning impulses may be observed at loads than one might think.

It is to be noted that grounds are never perfect conductors, especially for impulses. While most of the surge current may eventually be dissipated into the ground connection closest to the strike, there will be substantial surge currents flowing in other connected ground conductors in the first few microseconds of the strike.

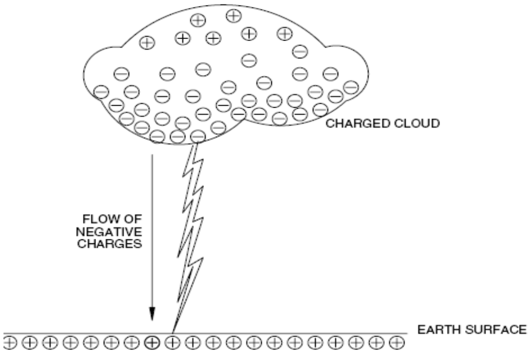


Fig. 3.2 Lightning discharge due to charge buildup in the clouds.

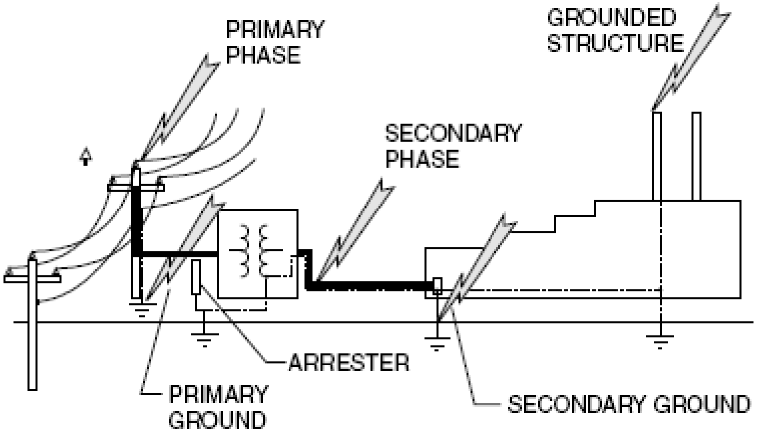


Fig. 3.3 Possible Lightning strike locations where lightning impulses will be conducted into load facilities.

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. The interception of the impulse from the phase wire is fairly straightforward if properly installed surge arresters are used. If the line flashes over at the location of the strike, the tail of the impulse is generally truncated. Depending on the effectiveness of the grounds along the surge current path, some of the current may find its way into load apparatus. Arresters near the strike may not survive because most lightning strokes are actually many strokes in rapid-fire sequence.

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.

Many researchers in this field postulate that lightning surges enter loads from the utility system through the inter-winding capacitance of the service transformer as shown in Fig. 2.3. 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 inter winding 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.

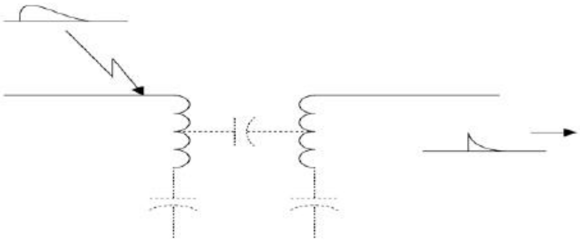


Fig.3.4 Coupling of impulses through the interwinding capacitance of transformers.

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.

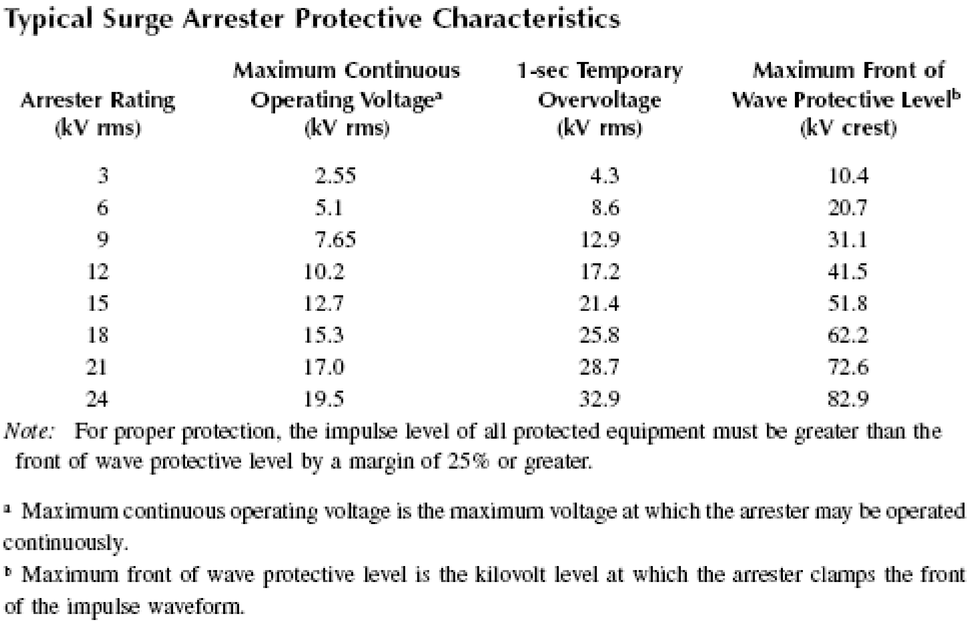
Arresters on the secondary winding should have no difficulty dissipating the energy in such a surge, but the rates of rise can be high. Thus, lead length becomes very important to the success of an arrester in keeping this impulse out of load equipment.

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

- 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.
- They induce high voltages in phase conductors as they pass through cables on the way to a better ground.

Lightning arresters, when properly applied, can provide protection against lightning- induced low voltages. Arresters have a well-defined conduction voltage below which they are ineffective. This voltage depends on the rating of the arrester itself. For optimum protection, the arrester voltage should be matched to the lightning impulse withstand of the equipment being protected. **Table 3.1** provides typical voltage discharge characteristics of arresters for various voltage classes.

Table. 3.1



Typical Surge Arrester Protective Characteristics

Arrester Rating (kV rms)	Maximum Continuous Operating Voltage[a] (kV rms)	1-sec Temporary Overvoltage (kV rms)	Maximum Front of Wave Protective Level[b] (kV crest)
3	2.55	4.3	10.4
6	5.1	8.6	20.7
9	7.65	12.9	31.1
12	10.2	17.2	41.5
15	12.7	21.4	51.8
18	15.3	25.8	62.2
21	17.0	28.7	72.6
24	19.5	32.9	82.9

Note: For proper protection, the impulse level of all protected equipment must be greater than the front of wave protective level by a margin of 25% or greater.

[a] Maximum continuous operating voltage is the maximum voltage at which the arrester may be operated continuously.

[b] Maximum front of wave protective level is the kilovolt level at which the arrester clamps the front of the impulse waveform.

3.1.3

Ferroresonance

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. 2.4. Neglecting the resistance R for the moment, the current flowing in the circuit can be expressed as follows:

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

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.

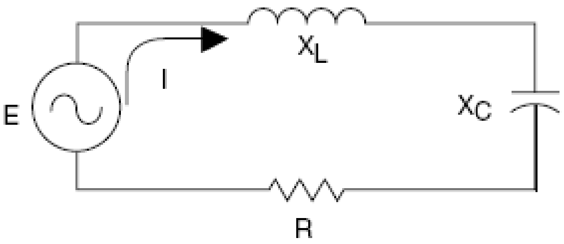


Fig. 3.4 Simple series RLC circuit.

An alternate solution to the series RLC circuit can be obtained by writing two equations defining the voltage across the inductor, as given below

$$v = jX_L I$$

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

Figure 2.5 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 Fig. 2.5.

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.

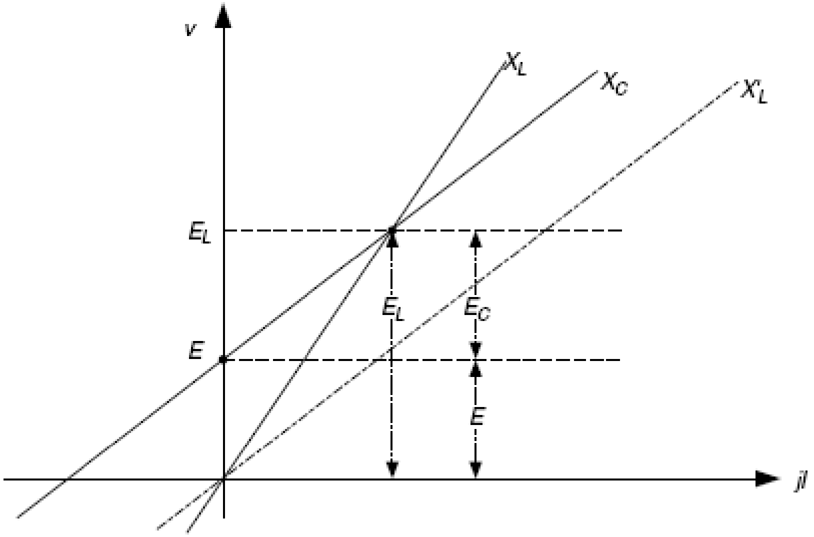


Fig. 3.5 Graphical solution to the linear LC circuit.

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. 2.6a). 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. 2.6b). 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.

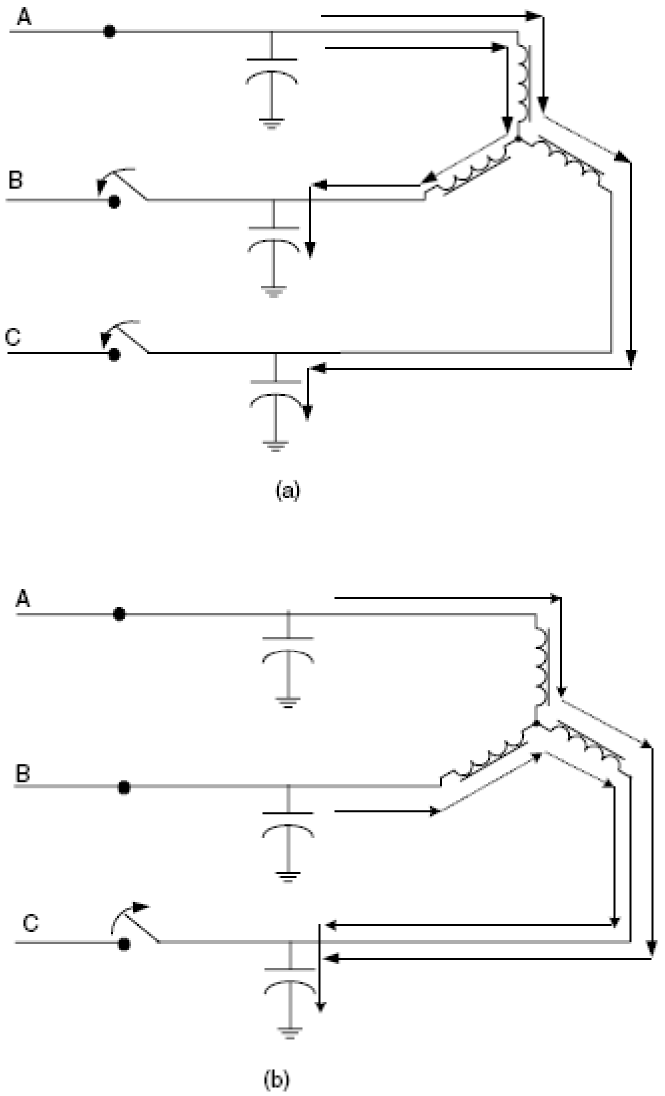


Fig. 3.6 Common system conditions where ferroresonance may occur: (a) one phase closed, (b) one phase open.

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-classsystems
- 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.

Common indicators of ferroresonance are as follows.

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

3.2
Principle of Over Voltage Protection

The fundamental principles of overvoltage protection of load equipments are as follows

1. Limit the voltage across sensitive insulation.
2. Divert the surge current away from the load.
3. Block the surge current from entering the load.
4. Bond grounds together at the equipment.
5. Reduce, or prevent, surge current from flowing between grounds.
6. Create a low-pass filter using limiting and blocking principles.

Figure 2.7 illustrates these principles, which are applied to protect from a lightning strike.

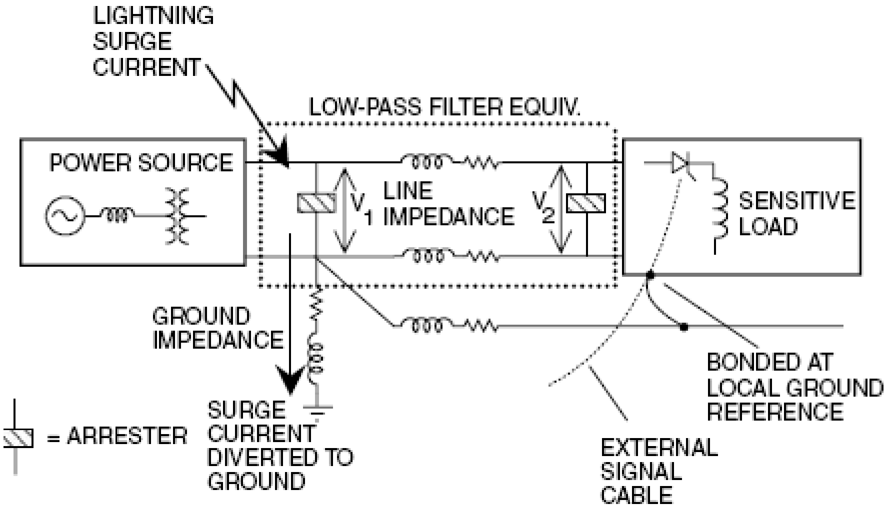


Fig. 3.7 Demonstrating the principles of overvoltage protection.

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. One of the points to which arresters, or surge suppressors, are connected is frequently the local ground, but this need not be the case. 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. 2.7 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 lowimpedance 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.