

## UNIT I

## INTRODUCTION TO POWER QUALITY

Terms and definitions: Overloading - under voltage - over voltage. Concepts of transients - short duration variations such as interruption - long duration variation such as sustained interruption. Sags and swells - voltage sag - voltage swell - voltage imbalance - voltage fluctuation - power frequency variations. International standards of power quality. Computer Business Equipment Manufacturers Associations (CBEMA) curve.

**General Definition:** Power quality is any abnormal behavior on a power system arising in the form of voltage or current, which affects the normal operation of electrical or electronic equipment.

**Standard Definition:** Any power problem manifested in voltage, current, or frequency deviations that results in failure or misoperation of customer equipment.

### Reasons for power quality issues:

1. Newer-generation load equipment, with microprocessor-based controls and power electronic devices, is more sensitive to power quality variations than was equipment used in the past.
2. The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This is resulting in increasing harmonic levels on power systems and has many people concerned about the future impact on system capabilities.
3. End users have an increased awareness of power quality issues. Utility customers are becoming better informed about such issues as interruptions, sags, and switching transients and are challenging the utilities to improve the quality of power delivered.
4. Many things are now interconnected in a network. Integrated processes mean that the failure of any component has much more important consequences.

### Examples for power quality issues:

AC power systems are designed to operate at a sinusoidal voltage of a given frequency [typically 50 or 60 hertz (Hz)] and magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem.

For example,

1. The current resulting from a short circuit causes the voltage to sag or disappear completely, as the case may be.
2. Currents from lightning strokes passing through the power system cause high-impulse voltages that frequently flash over insulation and lead to other phenomena, such as short circuits.
3. Distorted currents from harmonic-producing loads also distort the voltage as they pass through the system impedance. Thus a distorted voltage is presented to other end users.

Therefore, while it is the voltage with which we are ultimately concerned, we must also address phenomena in the current to understand the basis of many power quality problems.

### Importance of power quality:

The ultimate reason that we are interested in power quality is economic value. There are economic impacts on utilities, their customers, and suppliers of load equipment.

The quality of power can have a direct economic impact on many industrial consumers. There has recently been a great emphasis on revitalizing industry with more automation and more modern equipment. This usually means electronically controlled, energy-efficient equipment that is often much more sensitive to deviations in the supply voltage than were its electromechanical predecessors.

## Impacts of power quality:

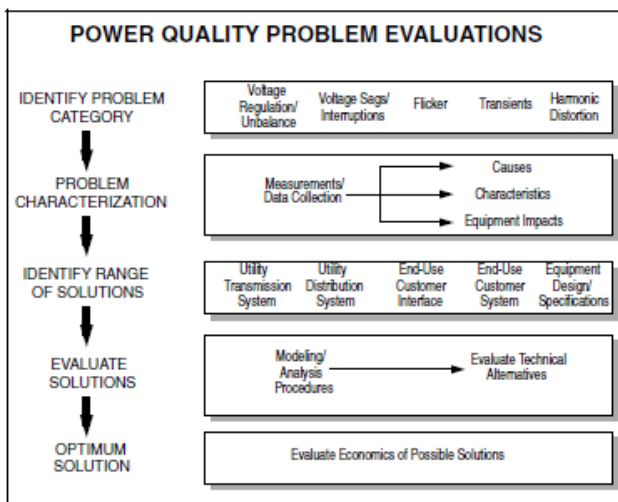
1. Throughout the world, many governments have revised their laws regulating electric utilities with the intent of achieving more cost-competitive sources of electric energy. Deregulation of utilities has complicated the power quality problem. In many geographic areas there is no longer tightly coordinated control of the power from generation through end-use load. While regulatory agencies can change the laws regarding the flow of money, the physical laws of power flow cannot be altered. In order to avoid deterioration of the quality of power supplied to customers, regulators are going to have to expand their thinking beyond traditional reliability indices and address the need for power quality reporting and incentives for the transmission and distribution companies.

2. There has been a substantial increase of interest in distributed generation (DG), that is, generation of power dispersed throughout the power system. There are a number of important power quality issues that must be addressed as part of the overall interconnection evaluation for DG. Therefore, we have added a chapter on DG.

3. The globalization of industry has heightened awareness of deficiencies in power quality around the world. Companies building factories in new areas are suddenly faced with unanticipated problems with the electricity supply due to weaker systems or a different climate. There have been several efforts to benchmark power quality in one part of the world against other areas.

4. Indices have been developed to help benchmark the various aspects of power quality. Regulatory agencies have become involved in performance-based rate-making (PBR), which addresses a particular aspect, reliability, which is associated with interruptions. Some customers have established contracts with utilities for meeting a certain quality of power delivery.

## The Power Quality Evaluation Procedure



The general procedure must also consider whether the evaluation involves an existing power quality problem or one that could result from a new design or from proposed changes to the system. Measurements will play an important role for almost any power quality concern. This is the primary method of characterizing the problem or the existing system that is being evaluated. When performing the measurements, it is important to record impacts of the power quality variations at the same time so that problems can be correlated with possible causes.

**Categories and Characteristics of Power System Electromagnetic Phenomena**

Categories	Typical spectral content	Typical duration	Typical voltage magnitude
1.0 Transients			
1.1 Impulsive			
1.1.1 Nanosecond	5-ns rise	<50 ns	
1.1.2 Microsecond	1- $\mu$ s 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 $\mu$ s	0–8 pu
1.2.3 High frequency	0.5–5 MHz	5 $\mu$ s	0–4 pu
2.0 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
3.0 Long-duration variations			
3.1 Interruption, sustained		>1 min	0.0 pu
3.2 Undervoltages		>1 min	0.8–0.9 pu
3.3 Overvoltages		>1 min	1.1–1.2 pu
4.0 Voltage unbalance		Steady state	0.5–2%
5.0 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%
6.0 Voltage fluctuations	<25 Hz	Intermittent	0.1–7% 0.2–2 Pst
7.0 Power frequency variations		<10 s	

All the power quality issues are comprised into following categories

- Transients
- Long-Duration Voltage Variations
- Short-Duration Voltage Variations
- Voltage Imbalance
- Waveform Distortion
- Voltage Fluctuation
- Power Frequency Variations

### ➤ Transients

The term transients has long been used in the analysis of power system variations to denote an event that is undesirable and momentary in nature. The notion of a damped oscillatory transient due to an RLC network is probably what most power engineers think of when they hear the word transient.

Types of transients:

- Impulsive transient
- Oscillatory transient

### Impulsive transient

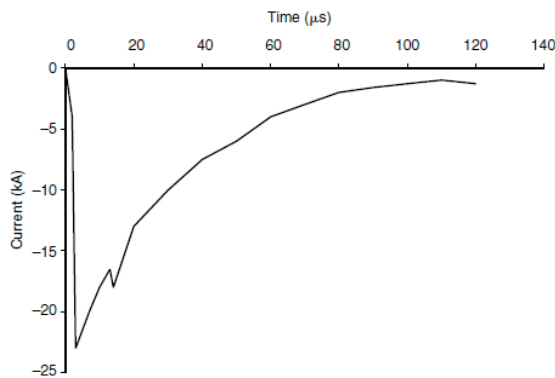
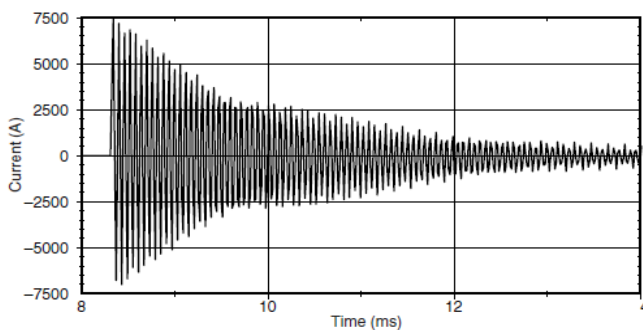


Figure illustrates a typical current impulsive transient caused by lightning.

An impulsive transient is a sudden, non-power frequency change in the steady-state condition of voltage, current, or both that is unidirectional in polarity (primarily either positive or negative).

Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. For example, a 1.2 X 50-μs 2000-volt (V) impulsive transient nominally rises from zero to its peak value of 2000 V in 1.2 μs and then decays to half its peak value in 50 μs. The most common cause of impulsive transients is lightning.

### 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.

An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content (predominate frequency), duration, and magnitude. The spectral content subclasses are high, medium, and low frequency. The frequency ranges for these

classifications are chosen to coincide with common types of power system oscillatory transient phenomena.

### ➤ Long-Duration Voltage Variations

Long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min. ANSI C84.1 specifies the steady-state voltage tolerances expected on a power system. A voltage variation is considered to be long duration when the ANSI limits are exceeded for greater than 1 min.

Long-duration variations can be either overvoltages or undervoltages. Overvoltages and undervoltages generally are not the result of system faults, but are caused by load variations on the system and system switching operations. Such variations are typically displayed as plots of rms voltage versus time.

#### Overvoltage

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

Causes: switching off a large load or energizing a capacitor bank, Incorrect tap settings on transformers

#### Undervoltage

An undervoltage is a decrease in the rms ac voltage to less than 90 percent at the power frequency for a duration longer than 1 min. Undervoltages are the result of switching events that are the opposite of the events that cause overvoltages.

Causes: A load switching on or a capacitor bank switching off Overloaded circuits

The term **brownout** is often used to describe sustained periods of undervoltage initiated as a specific utility dispatch strategy to reduce power demand.

### **Sustained interruptions**

When the supply voltage has been zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a sustained interruption. Voltage interruptions longer than 1 min are often permanent and require human intervention to repair the system for restoration.

The term sustained interruption refers to specific power system phenomena and, in general, has no relation to the usage of the term outage.

### **➤ Short-Duration Voltage Variations**

This category encompasses the IEC category of voltage dips and short interruptions. Each type of variation can be designated as instantaneous, momentary, or temporary, depending on its duration.

Short-duration voltage variations are caused by fault conditions, the energization of large loads which require high starting currents, or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause either temporary voltage drops (sags), voltage rises (swells), or a complete loss of voltage (interruptions).

### **Interruption**

An interruption occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min.

Causes: Power system faults, equipment failures, and control malfunctions.

<b>Interruption</b>	<b>Magnitude</b>	<b>Duration</b>
<b>Instantaneous</b>	<0.1 pu	0.5 to 30 cycles
<b>Momentary</b>	<0.1 pu	30 cycles to 3 sec
<b>Temporary</b>	<0.1 pu	3 sec to 1 min

### **Sags (dips)**

A sag is a decrease to between 0.1 and 0.9 pu in rms voltage or current at the power frequency for durations from 0.5 cycle to 1 min.

Sag durations are subdivided here into three categories—instantaneous, momentary, and temporary

Causes: Energization of heavy loads or starting of large motors.

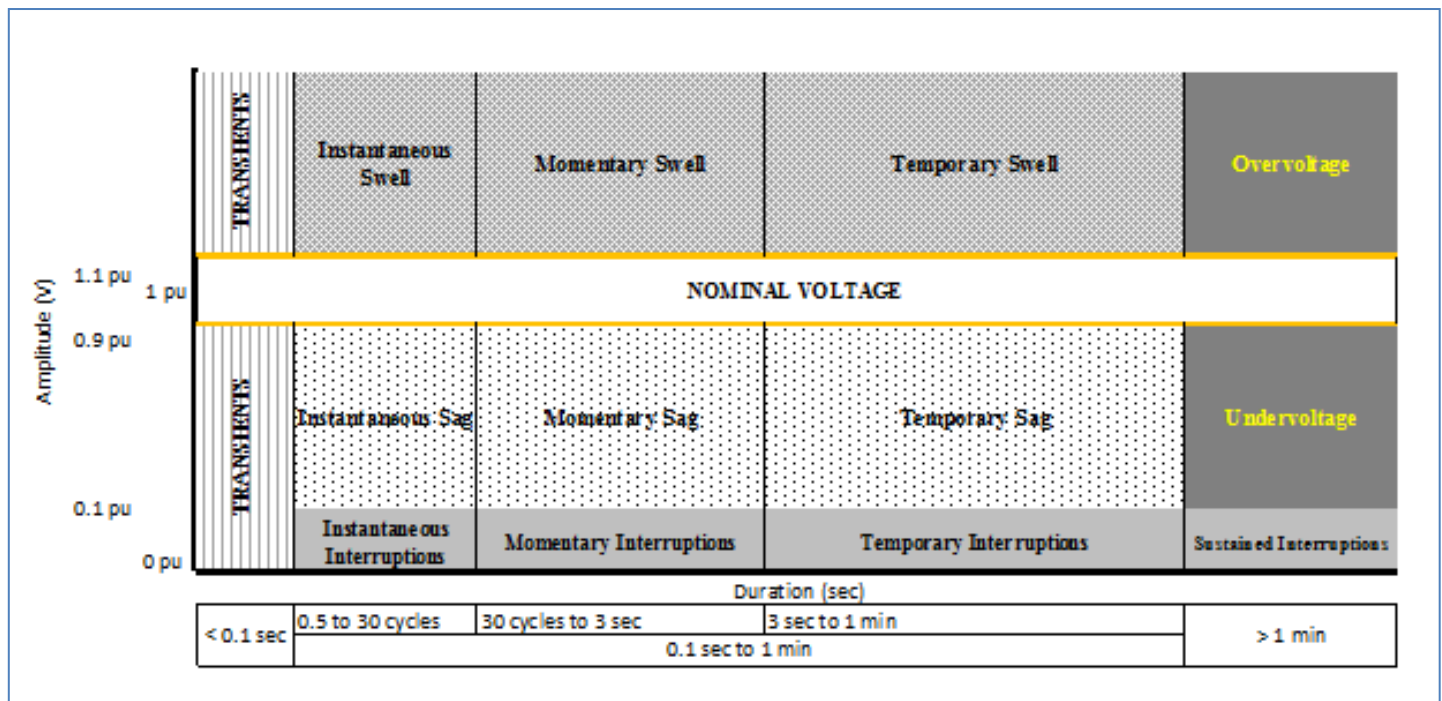
<b>Voltage Sag</b>	<b>Magnitude</b>	<b>Duration</b>
<b>Instantaneous</b>	0.1 to 0.9 pu	0.5 to 30 cycles
<b>Momentary</b>	0.1 to 0.9 pu	30 cycles to 3 sec
<b>Temporary</b>	0.1 to 0.9 pu	3 sec to 1 min

### **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.

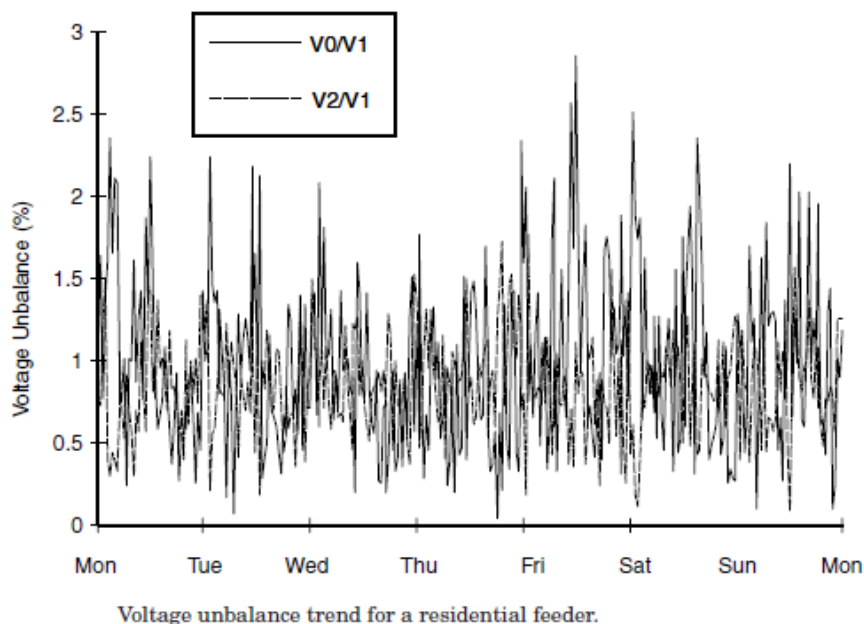
Causes: temporary voltage rise on the unfaulted phases during an SLG fault and switching off a large load or energizing a large capacitor bank.

<b>Voltage Swell</b>	<b>Magnitude</b>	<b>Duration</b>
<b>Instantaneous</b>	1.1 to 1.8 pu	0.5 to 30 cycles
<b>Momentary</b>	1.1 to 1.4 pu	30 cycles to 3 sec
<b>Temporary</b>	1.1 to 1.2 pu	3 sec to 1 min



### ➤ Voltage Imbalance

Voltage imbalance (also called voltage unbalance) is sometimes 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.



Imbalance is more rigorously defined in the standards using symmetrical components. The ratio of either the negative- or zero sequence component to the positive-sequence component can be used to specify the percent unbalance.

Causes: The primary source of voltage unbalances of less than 2 percent 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.

### ➤ Waveform Distortion

Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

There are five primary types of waveform distortion:

- DC offset
- Harmonics
- Interharmonics
- Notching
- Noise

### **DC offset.**

The presence of a dc voltage or current in an ac power system is termed dc offset. This can occur as the result of a geomagnetic disturbance or asymmetry of electronic power converters.

*Examples:* Incandescent light bulb life extenders may consist of diodes that reduce the rms voltage supplied to the light bulb by half-wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life.

### **Harmonics.**

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (termed the fundamental frequency; usually 50 or 60 Hz). Periodically distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics.

The total harmonic distortion (THD), is a measure of the effective value of harmonic distortion. IEEE Standard 519-1992 defines another term, the total demand distortion (TDD).

**Total harmonic distortion (THD)** The ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity, expressed as a percent of the fundamental

**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 fundamental current, expressed as a percent.

*Causes:* Originates in the nonlinear characteristics of devices and loads on the power system.

*Example:* Adjustable-speed drives (ASD) will exhibit high THD values for the input current when they are operating at very light loads.

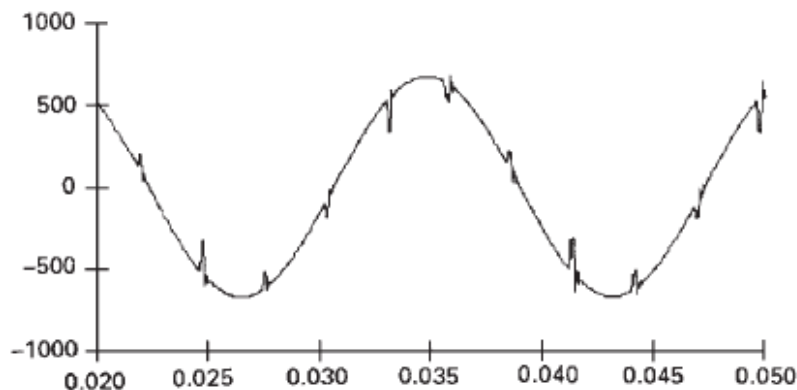
### **Interharmonics.**

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. They can appear as discrete frequencies or as a wideband spectrum. Interharmonics can be found in networks of all voltage classes.

*Causes:* Static frequency converters, cycloconverters, induction furnaces, and arcing devices.

Power line carrier signals can also be considered as interharmonics.

### **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. Since notching occurs continuously, it can be characterized through the harmonic spectrum of the affected voltage. However, it is generally treated as a special case. The frequency components associated with

notching can be quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis.



### Noise.

Noise is defined as 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.

Causes: 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.

### ➤ 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 ranges specified by ANSI C84.1 of 0.9 to 1.1 pu. IEC 61000-2-1 defines various types of 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 voltage fluctuation in some loads. However, the two terms are often linked together in standards.

IEC 61000-4-15 defines the methodology and specifications of instrumentation for measuring flicker. The IEEE Voltage Flicker Working Group has recently agreed to adopt this standard as amended for 60-Hz power systems for use in North America. This standard devises a simple means of describing the potential for visible light flicker through voltage measurements. The measurement method simulates the lamp/eye/brain transfer function and produces a fundamental metric called short-term flicker sensation (Pst). This value is normalized to 1.0 to represent the level of voltage fluctuations sufficient to cause noticeable flicker to 50 percent of a sample observing group. Another measure called long-term flicker sensation (Plt) is often used for the purpose of verifying compliance with compatibility levels established by standards bodies and used in utility power contracts. This value is a longer-term average of Pst samples.

*\*IEC TR 61000-2-1:1990 >>>Electromagnetic compatibility (EMC) - Part 2:Environment-Section 1*

*\*IEC 61000-4-15:2010 >>>Electromagnetic compatibility (EMC) - Part 4-15: Testing and measurement techniques*

### ➤ Power Frequency Variations

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

The power system frequency is directly related to the rotational speed of the generators supplying the system. There are slight variations in frequency as the dynamic balance between load and generation changes. The size of the frequency shift and its duration depend on the load characteristics and the response of the generation control system to load changes.

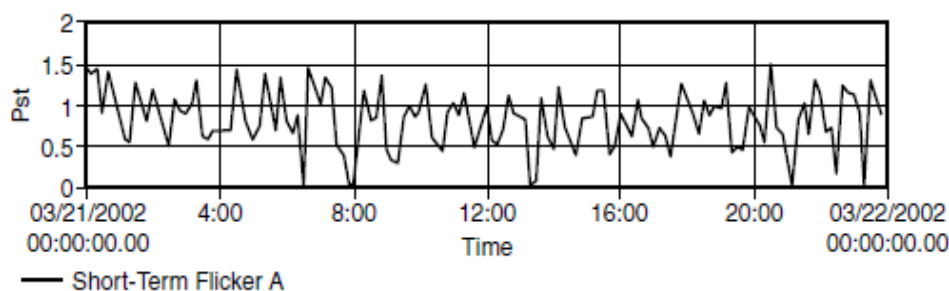


Figure illustrates frequency variations for a 24-h period on a typical 13-kV substation bus.



Frequency variations that go outside of accepted limits for normal steady-state operation of the power system can be caused by 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 systems, significant frequency variations are rare. Frequency variations of consequence are much more likely to occur for loads that are supplied by a generator isolated from the utility system. In such cases, governor response to abrupt load changes may not be adequate to regulate within the narrow bandwidth required by frequency-sensitive equipment.

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### ➤ **International Standards of power quality:**

#### **IEEE Standards:**

IEEE power quality standards: Institute Of Electrical and Electronics Engineer.

IEEE power quality standards: International Electro Technical Commission.

IEEE power quality standards: Semiconductor Equipment and Material International.

IEEE power quality standards: The International Union for Electricity Applications

IEEE Std 519-1992: IEEE Recommended practices and requirements for Harmonic control in Electric power systems.

IEEE Std 1159-1995: IEEE Recommended practices for monitoring electrical power

IEEE std 141-1993, IEEE Recommended practice for electric power distribution for industrial plants.

IEEE std 1159-1995, IEEE recommended practice for Monitoring electrical power quality.

#### **IEC Standards:**

The International Electrotechnical Commission (IEC), currently with headquarters in Geneva, Switzerland, has defined a category of electromagnetic compatibility (EMC) standards that deal with power quality issues. The term electromagnetic compatibility includes concerns for both radiated and conducted interference with end-use equipment. The IEC standards are broken down into six parts:

#### **Part 1: General.**

These standards deal with general considerations such as introduction, fundamental principles, rationale, definitions, and terminologies. They can also describe the application and interpretation of fundamental definitions and terms.

Their designation number is **IEC 61000-1-x**.

#### **Part 2: Environment.**

These standards define characteristics of the environment where equipment will be applied, the classification of such environment, and its compatibility levels.

Their designation number is **IEC 61000-2-x**.

#### **Part 3: Limits.**

These standards define the permissible levels of emissions that can be generated by equipment connected to the environment. They set numerical emission limits and also immunity limits.

Their designation number is **IEC 61000-3-x**.

#### **Part 4: Testing and measurement techniques.**

These standards provide detailed guidelines for measurement equipment and test procedures to ensure compliance with the other parts of the standards.

Their designation number is **IEC 61000-4-x**.

## **Part 5: Installation and mitigation guidelines.**

These standards provide guidelines in application of equipment such as earthing and cabling of electrical and electronic systems for ensuring electromagnetic compatibility among electrical and electronic apparatus or systems. They also describe protection concepts for civil facilities against the high-altitude electromagnetic pulse (HEMP) due to high altitude nuclear explosions.

They are designated with **IEC 61000-5-x**.

## **Part 6: Miscellaneous.**

These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment.

Their designation number is **IEC 61000-6-x**.

IEC standards relating to harmonics generally fall in parts 2 and 3. Unlike the IEEE standards on harmonics where there is only a single publication covering all issues related to harmonics, IEC standards on harmonics are separated into several publications. There are standards dealing with environments and limits which are further broken down based on the voltage and current levels. These key standards are as follows:

**IEC 61000-2-2 (1993):** Electromagnetic Compatibility (EMC). Part 2: Environment. Section 2: Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Public Low-Voltage Power Supply Systems.

**IEC 61000-3-2 (2000):** Electromagnetic Compatibility (EMC). Part 3: Limits. Section 2: Limits for Harmonic Current Emissions (Equipment Input Current Up to and Including 16 A per Phase).

**IEC 61000-3-4 (1998):** Electromagnetic Compatibility (EMC). Part 3: Limits. Section 4: Limitation of Emission of Harmonic Currents in Low-Voltage Power Supply Systems for Equipment with Rated Current Greater Than 16 A.

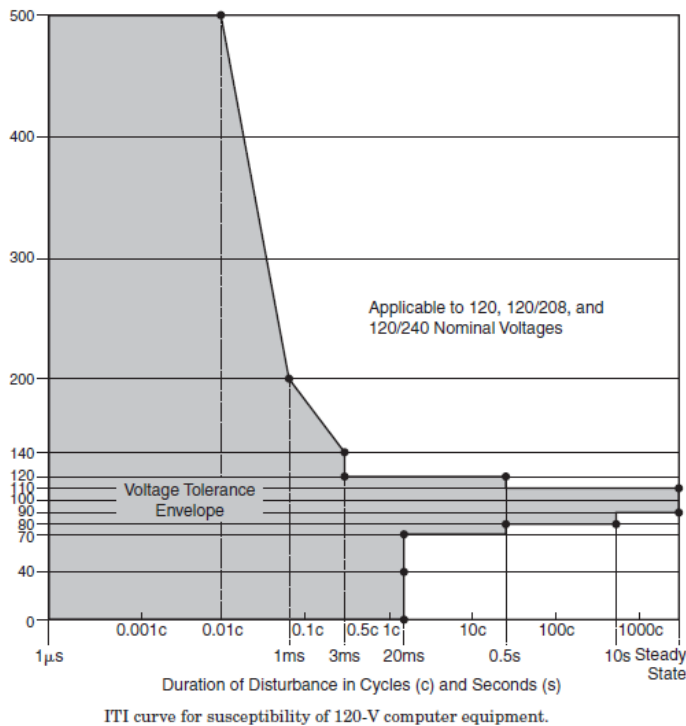
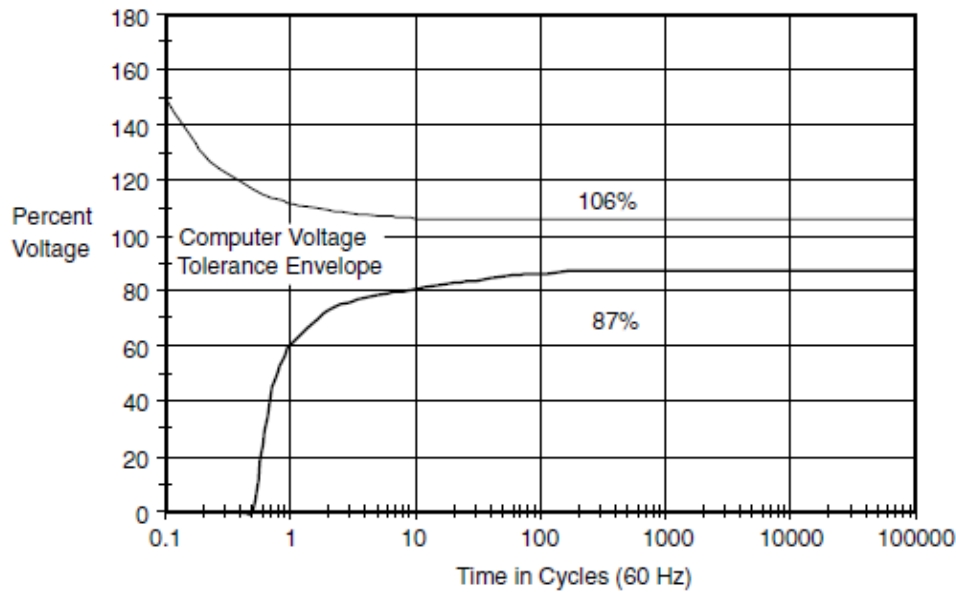
**IEC 61000-3-6 (1996):** Electromagnetic Compatibility (EMC). Part 3: Limits. Section 6: Assessment of Emission Limits for Distorting Loads in MV and HV Power Systems. Basic EMC publication.

### **CBEMA and ITI Curves**

A set of curves published by the Information Technology Industry Council (ITI) representing the withstand capabilities of computers connected to 120-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).

One of the most frequently employed displays of data to represent the power quality is the so-called CBEMA curve. A portion of the curve adapted from IEEE Standard 4469 that we typically use in our analysis of power quality monitoring results is shown in Fig. This curve was originally developed by CBEMA to describe the tolerance of mainframe computer equipment to the magnitude and duration of voltage variations on the power system. While many modern computers have greater tolerance than this, the curve has become a standard design target for sensitive equipment to be applied on the power system and a common format for reporting power quality variation data.

The axes represent magnitude and duration of the event. Points below the envelope are presumed to cause the load to drop out due to lack of energy. Points above the envelope are presumed to cause other malfunctions such as insulation failure, overvoltage trip, and over-excitation. The upper curve is actually defined down to 0.001 cycle where it has a value of about 375 percent voltage. We typically employ the curve only from 0.1 cycle and higher due to limitations in power quality monitoring instruments and differences in opinion over defining the magnitude values in the subcycle time frame.



The CBEMA organization has been replaced by ITI and a modified curve has been developed that specifically applies to common 120-V computer equipment. The concept is similar to the CBEMA curve. Although developed for 120-V computer equipment, the curve has been applied to general power quality evaluation like its predecessor curve. Both curves are used as a reference in this book to define the withstand capability of various loads and devices for protection from power quality variations. For display of large quantities of power quality monitoring data, we frequently add a third axis to the plot to denote the number of events within a certain predefined cell of magnitude and duration. If restricted to just the two-dimensional views shown in Fig below, the plot tends to turn into a solid mass of points over time, which is not useful.

UNIT II	VOLTAGE SAGS AND INTERRUPTIONS
Sources of sags and interruptions - estimating voltage sag performance. Thevenin's equivalent source - analysis and calculation of various faulted condition. Voltage sag due to induction motor starting. Estimation of the sag severity - mitigation of voltage sags, active series compensators. Static transfer switches and fast transfer switches.	

A voltage sag is a short-duration (typically 0.5 to 30 cycles) reduction in rms voltage caused by faults on the power system and the starting of large loads, such as motors. Momentary interruptions (typically no more than 2 to 5 s) cause a complete loss of voltage and are a common result of the actions taken by utilities to clear transient faults on their systems. Sustained interruptions of longer than 1 min are generally due to permanent faults.

### ➤ Sources of Sags and Interruptions

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

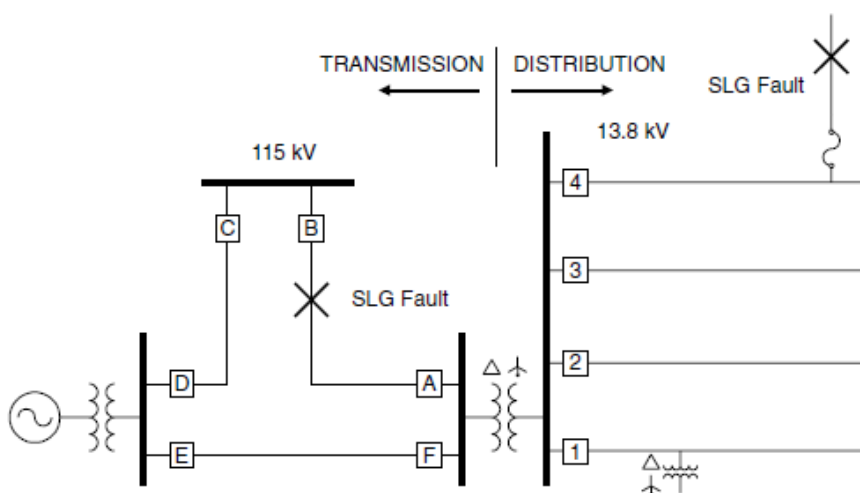


Figure 3.1 Fault locations on the utility power system.

Consider a customer that is supplied from the feeder supplied by circuit breaker 1 on the diagram shown. If there is a fault on the same feeder, the customer will experience voltage sag during the fault followed by an interruption when the breaker opens to clear the fault. If the fault is temporary in nature, a reclosing operation on the breaker should be successful and the

interruption will only be temporary. It will usually require about 5 or 6 cycles for the breaker to operate, during which time a voltage sag occurs. The breaker will remain open for typically a minimum of 12 cycles up to 5 s depending on utility reclosing practices.

Sensitive equipment will almost surely trip during this interruption. A much more common event would be a fault on one of the other feeders from the substation, i.e., a fault on a parallel feeder, or a fault somewhere on the transmission system. In either of these cases, the customer will experience voltage sag during the period that the fault is actually on the system. As soon as breakers open to clear the fault, normal voltage will be restored at the customer.

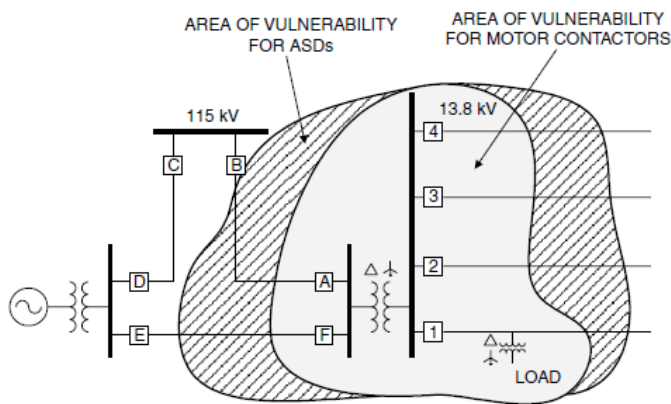
### ➤ Estimating Voltage Sag Performance

It is important to understand the expected voltage sag performance of the supply system so that facilities can be designed and equipment specifications developed to assure the optimum

operation of production facilities. The following is a general procedure for working with industrial customers to assure compatibility between the supply system characteristics and the facility operation:

1. Determine the number and characteristics of voltage sags that result from transmission system faults.
2. Determine the number and characteristics of voltage sags that result from distribution system faults (for facilities that are supplied from distribution systems).
3. Determine the equipment sensitivity to voltage sags. This will determine the actual performance of the production process based on voltage sag performance calculated in steps 1 and 2.
4. Evaluate the economics of different solutions that could improve the performance, either on the supply system (fewer voltage sags) or within the customer facility (better immunity).

### **Area of vulnerability**



The concept of an area of vulnerability has been developed to help evaluate the likelihood of sensitive equipment being subjected to voltage lower than its minimum voltage sag ride-through capability.

*\*The minimum voltage sag ride-through capability 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.*

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

### **Equipment sensitivity to voltage sags**

Equipment within an end-user facility may have different sensitivity to voltage sags.<sup>8</sup> Equipment sensitivity to voltage sags is very dependent on the specific load type, control settings, and applications.

The most commonly used characteristics are the duration and magnitude of the sag. Other less commonly used characteristics include phase shift and unbalance, missing voltage, three-phase voltage unbalance during the sag event, and the point-in-the-wave at which the sag initiates and terminates.

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

*Equipment sensitive to only the magnitude of a voltage sag.*

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

*Equipment sensitive to characteristics, other than magnitude and duration.*

***Equipment sensitive to only the magnitude of a voltage sag.***

Includes devices such as undervoltage relays, process controls, motor drive controls, <sup>6</sup> and many types of automated machines

Devices in this group are sensitive to the minimum voltage magnitude experienced during a sag.

The duration of the disturbance is usually of *secondary importance* for these devices.

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

Includes virtually all equipment that uses electronic power supplies.

Such equipment misoperates or fails when the power supply output voltage drops below specified values.

The important characteristic for this type of equipment is the duration that the rms voltage is below a specified threshold at which the equipment trips.

***Equipment sensitive to characteristics, other than magnitude and duration.***

Some devices are affected by other sag characteristics such as the phase unbalance during the sag event, the point-in-the wave at which the sag is initiated, or any transient oscillations occurring during the disturbance.

These characteristics are more subtle than magnitude and duration, and their impacts are much more difficult to generalize.

For end users with sensitive processes, the voltage sag ride-through capability is usually the most important characteristic to consider. These loads can generally be impacted by very short duration events, and virtually all voltage sag conditions last at least 4 or 5 cycles (unless the fault is cleared by a current-limiting fuse). Thus, one of the most common methods to quantify equipment susceptibility to voltage sags is using a magnitude-duration plot as shown in Fig. 2.6. It shows the voltage sag magnitude that will cause equipment to misoperate as a function of the sag duration.

## **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.

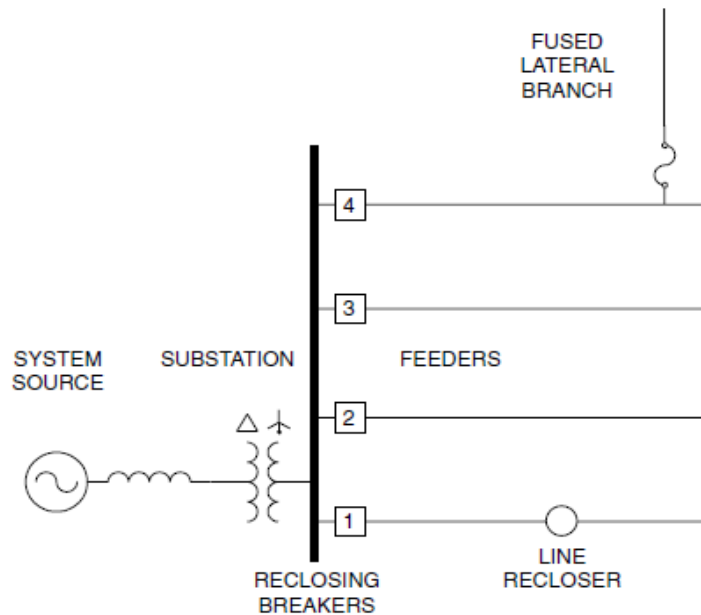
Transmission line faults and the subsequent opening of the protective devices rarely cause an interruption for any customer because of the interconnected nature of most modern-day transmission networks. These faults do, however, causes voltage sags. Depending on the equipment sensitivity, the unit may trip off, resulting in substantial monetary losses.

Most utilities have detailed short-circuit models of the interconnected transmission system available for programs such as ASPEN\* One Liner. ASPEN (Advanced System for Power Engineering) programs can calculate the voltage throughout the system resulting from fault around the system.

The fault performance is usually described in terms of faults per 100 miles/year (mi/yr). Most utilities maintain statistics of fault performance at all the different transmission voltages. These

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

## Utility distribution system sag performance evaluation



Typical distribution system illustrating protection devices.

Customers that are supplied at distribution voltage levels are impacted by faults on both the transmission system and the distribution system. The analysis at the distribution level must also include momentary interruptions caused by the operation of protective devices to clear the faults.

Figure shows a typical distribution system with multiple feeders and fused branches, and protective devices. The utility protection scheme plays an important role in the voltage sag and momentary interruption performance.

The critical information needed to compute voltage sag performance can be summarized as follows:

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

*\*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.*

They are two possible locations for faults on the distributed system (i.e) On the same feeder and on parallel feeder.

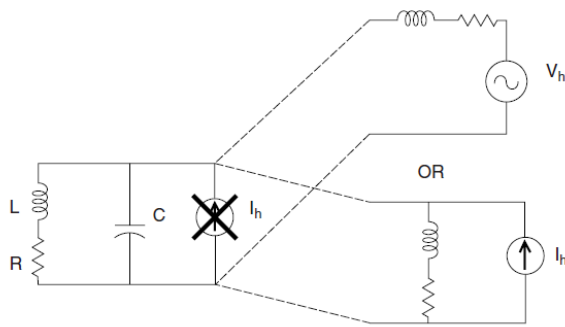
The computation of the expected voltage sag performance can be performed as follows:

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

**Faults on the same feeder:** The expected voltage sag magnitude at the end-user location is computed as a function of fault location on the same feeder



## ➤ Thevenin's equivalent source



EQUIVALENT CIRCUIT

Replacing the simple current source model with a Thevenin or Norton equivalent for better source models of resonant conditions.

A Thevenin equivalent is obtained in a straightforward manner for many nonlinear loads. For example, an arc furnace is well represented by a square-wave voltage of peak magnitude approximately 50 percent of the nominal ac system voltage. The series impedance is simply the short-circuit impedance of the furnace transformer and leads (the lead impedance is the larger of the two). Unfortunately, it is difficult to determine clear-cut equivalent impedances for many nonlinear devices. In these cases, a detailed simulation of the internals of the

harmonic-producing load is necessary. This can be done with computer programs that iterate on the solution or through detailed time-domain analysis. Fortunately, it is seldom essential to obtain such great accuracy during resonant conditions and analysts do not often have to take these measures. However, modeling arcing devices with a Thevenin model is recommended regardless of need.

## ➤ Analysis and calculation of various faulted condition

### Fault locating

Finding faults quickly is an important aspect of reliability and the quality of power.

**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 expedite locating 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.

**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 a detailed description of each is beyond the scope of this report. Some of the general classes of methods follow.

**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.

**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.

**Tone.** A tone system injects a high-frequency signal on the cable, and the route of the cable can be followed by a special receiver. This technique is 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.

**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. This can be an expensive and time-consuming procedure that some consider to be the least effective of fault-locating methods and one that should be used only as a last resort.

The traditional reliability indices for utility distribution systems are defined as follows:

**SAIFI:** System average interruption frequency index

$$\text{SAIFI} = \frac{(\text{no. customers interrupted}) (\text{no. of interruptions})}{\text{total no. customers}}$$

**SAIDI:** System average interruption duration index

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

**CAIFI:** Customer average interruption frequency index

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

**CAIDI:** Customer average interruption duration index

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

**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.

Typical target values for these indices are

Index	Target
SAIFI	1.0
SAIDI	1.0–1.5 h
CAIDI	1.0–1.5 h
ASAI	0.99983

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### ➤ **Voltage sag due to induction motor starting.**

Motors have the undesirable effect of drawing several times their full load current while starting. This large current will, by flowing through system impedances, cause a voltage sag which may dim lights, cause contactors to drop out, and disrupt sensitive equipment. The

situation is made worse by an extremely poor starting displacement factor—usually in the range of 15 to 30 percent. The time required for the motor to accelerate to rated speed increases with the magnitude of the sag, and an excessive sag may prevent the motor from starting successfully. Motor starting sags can persist for many seconds

### **Motor-starting methods**

**Full-voltage starting :** Energizing the motor in a single step (full-voltage starting) provides low cost and allows the most rapid acceleration. It is the preferred method unless the resulting voltage sag or mechanical stress is excessive.

**Autotransformer starting:** Autotransformer 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.

**Resistance and reactance starting:** Resistance and reactance 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 autotransformer starters, but provide higher starting torque. Reactors are typically provided with 50, 45, and 37.5 percent taps.

**Part-winding starting:** Part-winding 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

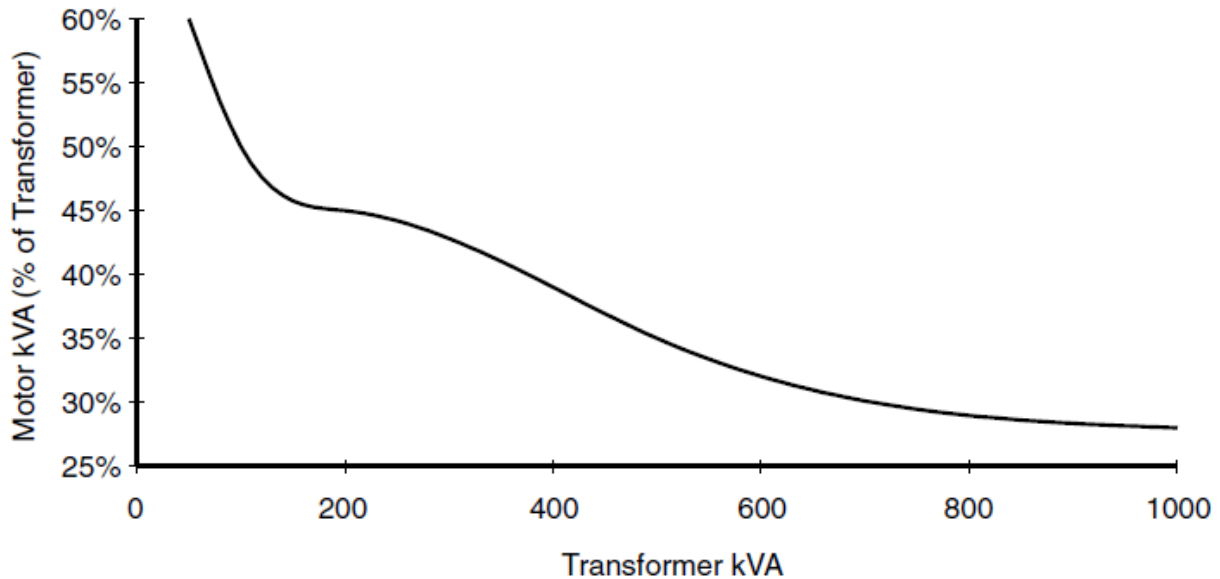
**Delta-wye starting:** Delta-wye starters connect the stator in wye for starting and then, after a time delay, reconnect the windings in delta. The wye connection reduces the starting voltage to 57 percent of the system line-line voltage; starting current and starting torque are reduced to 33 percent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

### ➤ **Estimating the sag severity during full-voltage starting**

Starting an induction motor results in a steep dip in voltage, followed by a gradual recovery. If full-voltage starting is used, the sag voltage, in per unit of nominal system voltage, is

$$V_{\text{Min}}(\text{pu}) = \frac{V(\text{pu}) \text{ kVA}_{\text{SC}}}{\text{kVA}_{\text{LR}} + \text{kVA}_{\text{SC}}}$$

where,  $V(\text{pu})$  = actual system voltage, in per unit of nominal  
 $\text{kVA}_{\text{LR}}$  = motor locked rotor kVA  
 $\text{kVA}_{\text{SC}}$  = system short-circuit kVA at motor



Typical motor versus transformer size for full-voltage starting sags of 90 percent.

Figure illustrates the results of this computation for sag to 90 percent of nominal voltage, using typical system impedances and motor characteristics. 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:

- Parameter values for the standard induction motor equivalent circuit:  $R_1$ ,  $X_1$ ,  $R_2$ ,  $X_2$ , and  $X_M$ .
- Number of motor poles and rated rpm (or slip).
- WK2 (inertia constant) values for the motor and the motor load.
- Torque versus speed characteristic for the motor load.

## ➤ Mitigation of Voltage Sags

### Solutions at the End-User Level

Solutions to improve the reliability and performance of a process or facility can be applied at many different levels. The different technologies available should be evaluated based on the specific requirements of the process to determine the optimum solution for improving the overall voltage sag performance. The solutions can be discussed at the following different levels of application:

#### **1. Protection for small loads [e.g., less than 5 kilovoltamperes (kVA)].**

This usually involves 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 such a large portion of the facility is critical or needs protection that it is reasonable to consider protecting large groups of loads at a convenient location (usually the service entrance). 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.

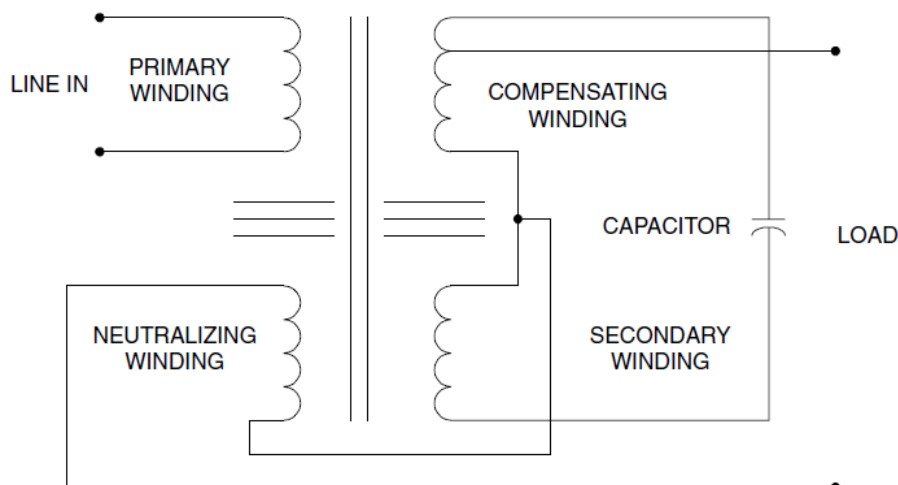
The size ranges in these categories are quite arbitrary, and many of the technologies can be applied over a wider range of sizes. The following are the major technologies available that can be applied.

- Ferroresonant transformers
- Magnetic synthesizers
- Active series compensators
- On-line UPS
- Standby UPS
- Hybrid UPS
- Motor-generator sets
- Flywheel energy storage systems
- Superconducting magnetic energy storage (SMES) devices
- Static transfer switches and fast transfer switches
- Static Var Compensator (SVC)
- Dynamic voltage restorer

## **Ferroresonant transformers**

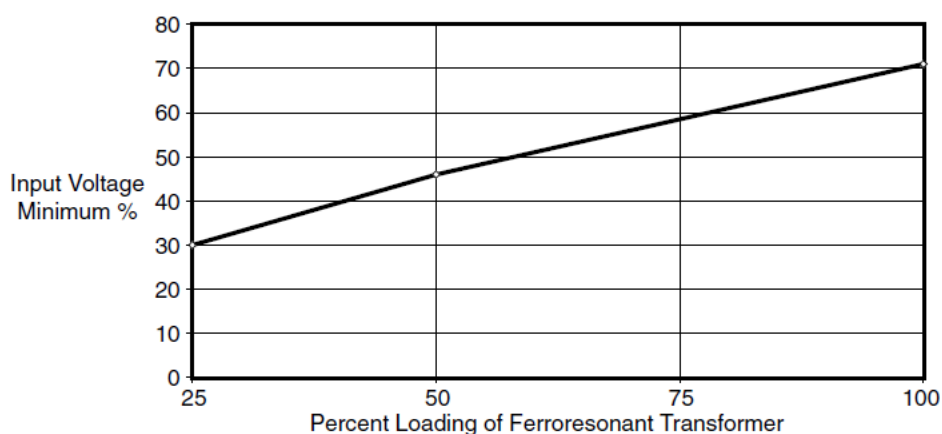
Ferroresonant transformers, also called constant-voltage transformers (CVTs), can handle most voltage sag conditions. CVTs are especially attractive for constant, low-power loads.

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 Fig.

Ferroresonant transformers should be sized significantly larger than the load. 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



Voltage sag versus ferroresonant transformer loading.

one manufacturer.

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.

## **Magnetic synthesizers**

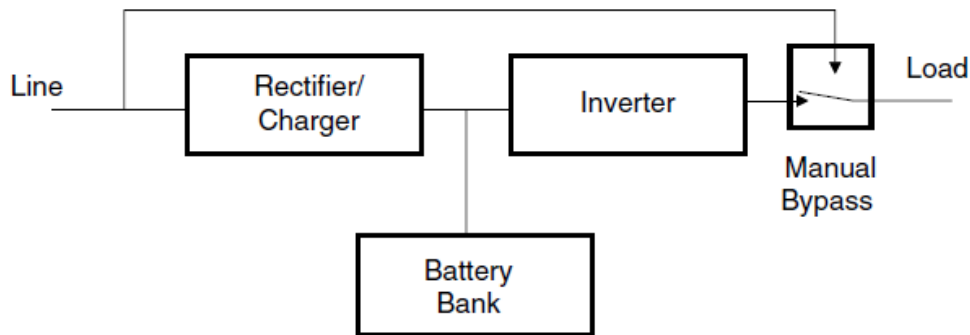
Magnetic synthesizers use a similar operating principle to CVTs except they are three-phase devices and take advantage of the three-phase magnetics to provide improved voltage sag support and regulation for three-phase loads. They are applicable over a size range from about 5 to 200 kVA and are typically applied for process loads of larger computer systems where voltage sags or steady-state voltage variations are important issues.

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 zigzag transformer.

## **On-line UPS**

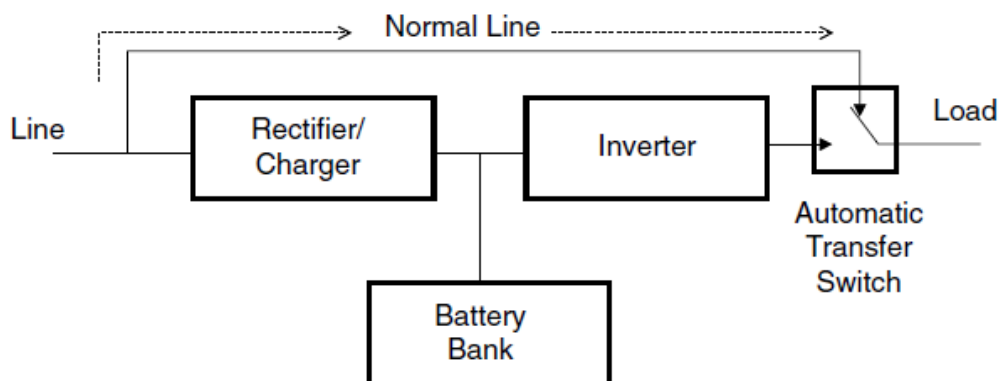
Figure shows a typical configuration of an on-line UPS. In this design, the load is always fed through the UPS. The incoming ac power is rectified into dc power, which charges a bank of batteries. This dc power is then inverted back into ac power, to feed the load. If the incoming ac power fails, the 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



## **Standby UPS**

A standby power supply is sometimes termed off-line UPS 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 inverter. The transfer time from the normal source to the battery-backed inverter is important. The CBEMA curve shows that rms 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.



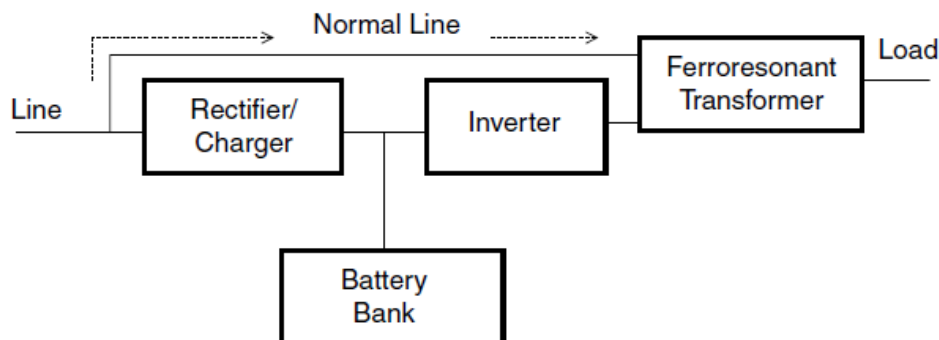
UPS

specifications include kilovoltampere 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 conditions under which the specifications are valid.

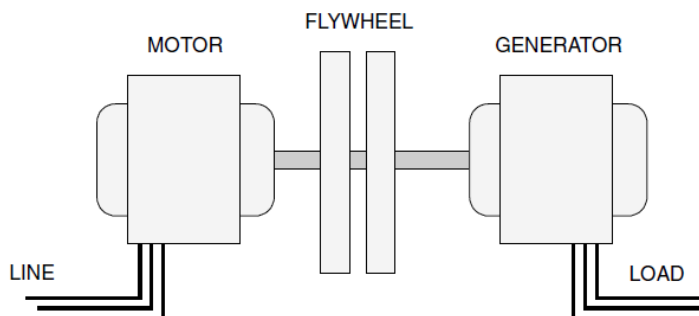
## **Hybrid UPS**



Similar in design to the standby UPS, the hybrid UPS 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 is made.



### **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 isolating critical loads from sags and interruptions on the power system.

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 flywheels 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.
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 between 3150 and 3600 revolutions per minute (rpm).

Flywheel inertia allows the generator rotor to keep rotating at speeds above 3150 rpm once power shuts off. The rotor weight typically generates enough inertia to keep it spinning fast enough to produce 60 Hz for 15 s under full load.

Another means of compensating for the frequency and voltage drop while energy is being extracted is to rectify the output of the generator and feed it back into an inverter. This allows more energy to be extracted, but also introduces losses and cost.

### **Flywheel energy storage systems**

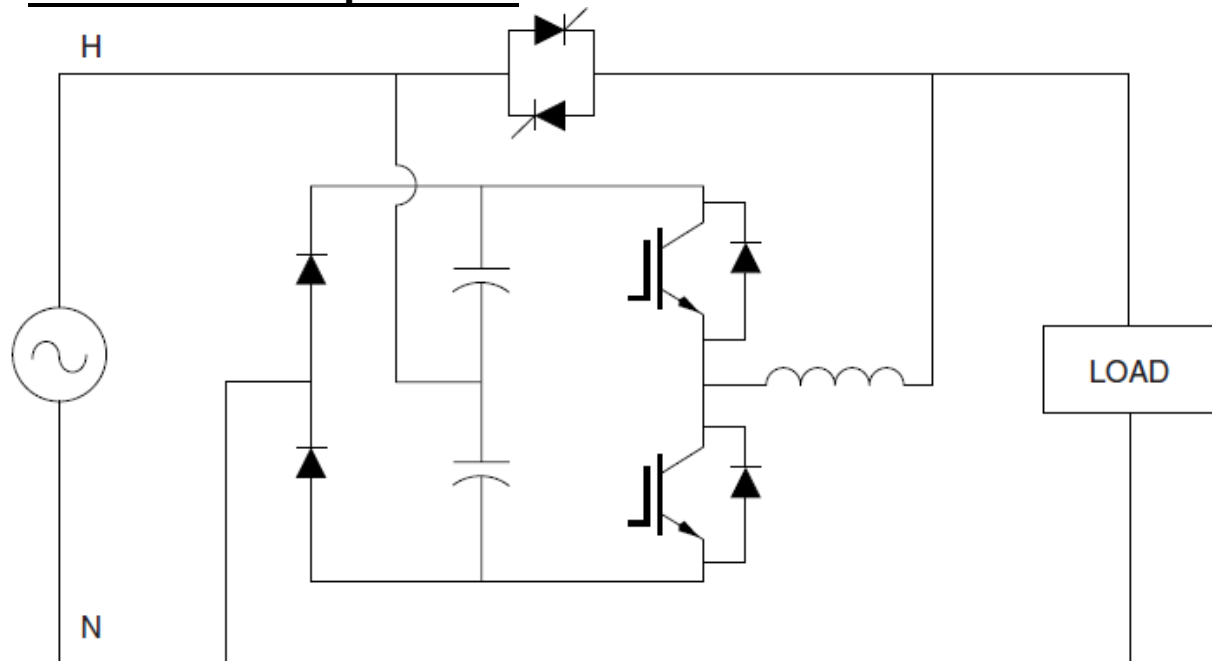
Motor-generator sets are only one means to exploit the energy stored in flywheels. A modern flywheel energy system uses high-speed flywheels and power electronics to achieve sag and interruption ride-through from 10 s to 2 min.

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

### **Superconducting magnetic energy storage (SMES) devices**

An SMES device can be used to alleviate voltage sags and brief interruptions. The energy storage in an SMES-based system is provided by the electric energy stored in the current flowing in a superconducting magnet. 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 1 cycle to compensate for the missing voltage during a voltage sag event.

#### **➤ Active series compensators**



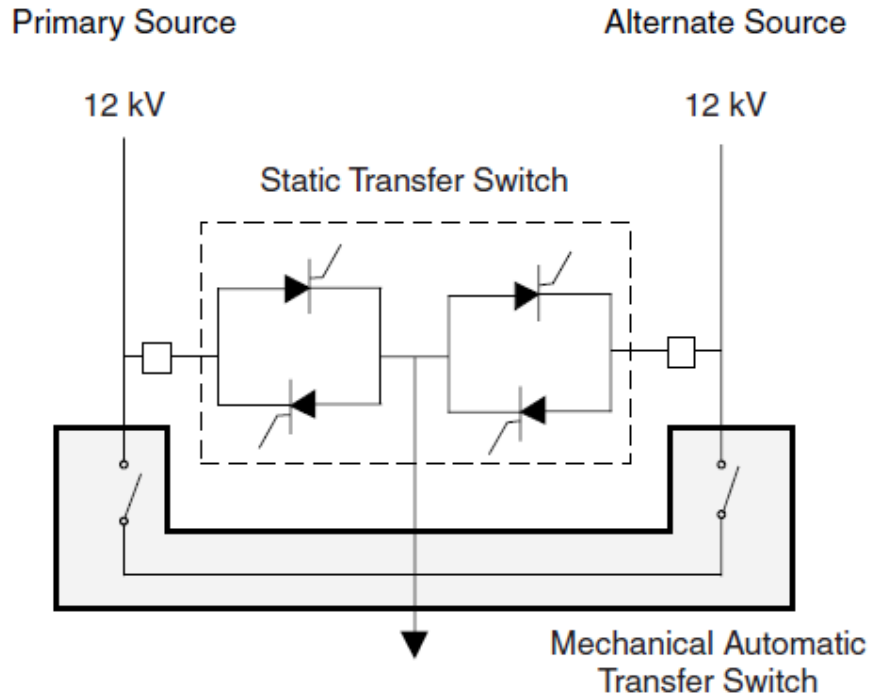
Advances in power electronic technologies and new topologies for these devices have resulted

in new options for providing voltage sag ride through support to critical loads. One of the important new options is a device that can boost the voltage by injecting a voltage in series with the remaining voltage during a voltage sag condition. These are referred to as active series compensation devices. 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 Fig. 3.20. 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 for almost all voltage sag conditions.

### ➤ **Static transfer switches and fast transfer switches.**

There are a number of alternatives for protection of an entire facility that may be sensitive to voltage sags. These include dynamic voltage restorers (DVRs) and UPS systems that use technology similar to the systems described previously but applied at the medium-voltage level.



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

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 transfer switches will switch from the primary supply to a backup supply in seconds. Fast transfer switches that use vacuum breaker technology are available that can transfer in about 2 electrical cycles. This can be fast enough to protect many sensitive loads. Static switches use power electronic switches to accomplish the transfer within about a quarter of an electrical cycle.

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.

### UNIT III      OVERVOLTAGES

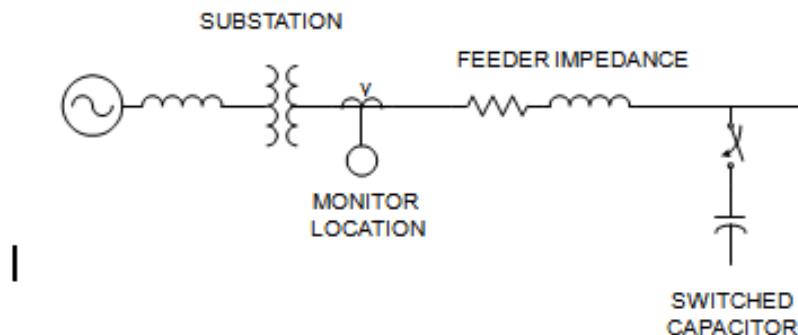
Sources of over voltages - Capacitor switching – lightning - ferro resonance. Mitigation of voltage swells - surge arresters - low pass filters - power conditioners. Lightning protection – shielding – line arresters - protection of transformers and cables. An introduction to computer analysis tools for transients, PSCAD and EMTP

#### ➤ Sources of over voltages

- There are two main sources of transient overvoltages on utility systems: capacitor switching and lightning.
- These are also sources of transient overvoltages as well as a myriad of other switching phenomena within end-user facilities.
- Some power electronic devices generate significant transients when they switch.
- Transient overvoltages can be generated at high frequency (load switching and lightning), medium frequency (capacitor energizing), or low frequency.

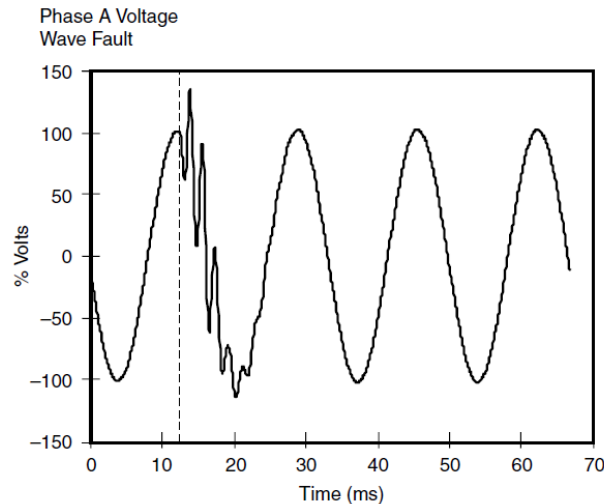
#### ➤ Capacitor switching

Capacitors are used to provide reactive power (in units of vars) to correct the power factor, which reduces losses and supports the voltage on the system. Some capacitors are energized all the time (a fixed bank), while others are switched according to load levels. During switching of shunt capacitor banks, high magnitude and high frequency transients can occur.



- 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.
- Several cases of power system component failures and malfunctions due to capacitor bank switching operations have been seen by the author.

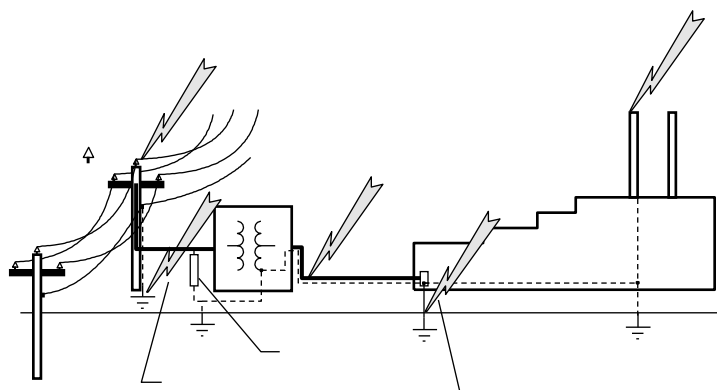
- Typically, the voltage rise due to capacitor switching operation can attain values 1.5 to 2 times the nominal voltage.



- Power equipment can withstand only a limited number of exposures to such rises in voltage magnitude.
- With time, the insulation systems of such devices weaken, and a point is reached when the devices can fail.
- In one particular instance, two power distribution transformers failed at the same time; the cause was traced to large capacitor bank switching operations by the utility at a substation located adjacent to the affected facility.
- Adjustable speed drives (ASDs) and solid-state motor controllers are quite sensitive to voltage rises resulting from capacitor bank switching operations.
- The ASD might shut down the motor due to voltage on the system rising beyond the maximum tolerance.
- In some cases, capacitor switching causes the voltage waveform to undergo oscillations and produce stray crossings of the time axis.
- This is unacceptable for devices that require the precise number of zero time crossings for proper performance.

### ➤ **Lightning**

Lightning is a potent source of impulsive transients. 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.



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

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

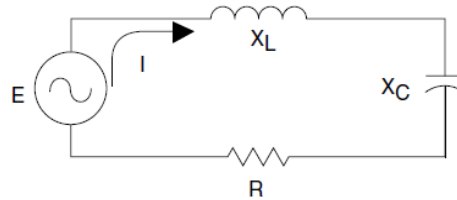
1. They raise the potential of the local ground above other grounds in the vicinity by several kilovolts. Sensitive electronic equipment that is connected between two ground references, such as a computer connected to the telephone system through a modem, can fail when subjected to the lightning surge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

### ➤ Ferroresonance

The resonance occurred in relation with the core of the transformer involved with the power systems is called as ferroresonance.

- The ferroresonance occurs when the magnetising impedance of the transformer is placed in series with a system capacitor. This happens when there is an open phase conductor.
- Ferroresonance result in magnification of harmonics, high voltages and currents, but resulting waveforms are usually irregular in shape.
- The concept of ferroresonance can be explained in terms of linear system resonance as follows.
- Consider a simple RLC series circuit. Neglecting the resistance R for the moment, the current flowing in the circuit can be expressed as,

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



where, E – Driving voltage

$X_L$  – Reactance of L

$X_C$  – Reactance of C

- When  $X_L = |X_C|$ , a series resonant circuit is formed, and the equation gives an infinitely large current that in reality would be limited by R.

The voltage across the inductor,  $v = jX_L I$

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

where  $v$  is a voltage variable.

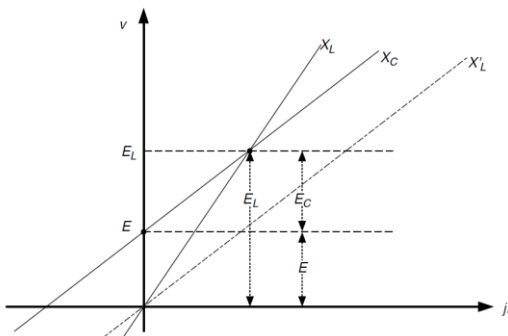
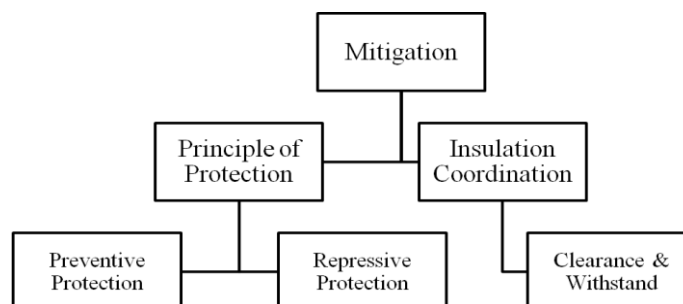


Fig. shows the graphical solution of these two equations for two different reactances,  $X_L$  and  $X_L'$ .  $X_L'$  represents the series resonant condition. The intersection of the capacitive and inductive lines gives the voltage across inductor  $E_L$ .



- At resonance, the two lines will intersect at infinitely large voltage and current since the  $|XC|$  the line is parallel to the  $XL'$  line.
- In practice, ferroresonance most commonly occurs when unloaded transformers become isolated on underground cables of a certain range of lengths.
- The capacitance of overhead distribution lines is generally insufficient to yield the appropriate conditions.
- The minimum length of cable required to cause ferroresonance varies with the system voltage level.
- The capacitance of cables is nearly the same for all distribution voltage levels, varying from 40 to 100 nF per 1000 feet (ft), depending on conductor size.
- However, the magnetizing reactance of a 35-kV-class distribution transformer is several times higher (the curve is steeper) than a comparably sized 15-kV-class transformer.
- Therefore, damaging ferroresonance has been more common at the higher voltages.
- For delta connected transformers, ferroresonance can occur for less than 100 ft of cable.
- For this reason, many utilities avoid this connection on cable-fed transformers.
- The grounded wye-wye transformer has become the most commonly used connection in Underground systems in North America.
- It is more resistant, but not immune, to ferroresonance because most units use a three-legged or five-legged core design that couples the phases magnetically.
- It may require a minimum of several hundred feet of cable to provide enough capacitance to create a ferroresonant condition for this connection.

### ➤ Mitigation of voltage swells



#### **Principles of Protection**

##### ***1. Preventive protection:***

- To limit internal or lightning impulse overvoltages (overhead protection cable, neutral earthing, regulators, protection relays, switching-impulse-limiting circuit-breaker);

##### ***2. Repressive protection:***

- For draining the overvoltage to earth using special equipments (dischargers, surge arresters).

The fundamental principles of overvoltage protection of electrical equipment are:

- To limit the voltage for sensitive insulation.
- To reduce, or prevent, surge current from flowing between grounds.
- To drain the surge current away from the load.

- iv. To bond the ground and equipment.
- v. To create a low-pass filter using limiting and blocking principles.

### **Insulation Coordination**

Three basic elements to insulation coordination, which are:

- Determining the overvoltage stresses from the system.
- Knowing the strength of the insulation of specific equipment in the substation.
- Selecting surge arrester ratings and locations, or other mitigation equipment or operating restrictions, to ensure that the system-imposed overvoltages do not exceed the insulation strength of the equipment, including an appropriate protective margin.

Protection level is determined by three factors:

- Installation;
- Environment;
- Equipment used.

Final objective of insulation coordination is to ensure safe and optimized distribution of electric power, which means the best possible economic balance between the various costs, namely:

- Insulation;
- Protective devices;
- Failures (operating loss and repairs) weighted with their probabilities.

### **Clearance:**

- i. **Gas clearance:** Shortest path between two conductive parts (air, SF<sub>6</sub>, etc.)
- ii. **Creepage distance:** Shortest path between two conductors following the outer surface of a solid insulator.

### **Insulation Deterioration depends**

- Environmental conditions (humidity, pollution, UV radiation);
- Age (deterioration of the material);
- Permanent electrical stresses (local value of the electric field).

### **Gas Clearance depends**

- Air pressure with altitude;
- Device filling pressure.

### **Voltage Withstand**

**Power Frequency Withstand:** Voltage withstand monitored through the standard one-minute dielectric tests is generally sufficient.

### **Switching Impulse Voltage Withstand:**

- Characterized with the following properties:
- Non-linear relation with voltage;
- Unbalance, variation according to wave polarity;

- Passage through a minimum curve value of the withstand voltage as a function of front time;
- Dispersion withstand must be expressed in statistical terms.
- Standard tests of a wave of front time 250 ms and half-amplitude time 2500 ms

### **Lightning Overvoltage Withstand:**

- Positive and Negative Polarities – 1.2/50µS
- Two formulas can be used to evaluate withstand to a 1.2/50 µS positive-polarity impulse of an air gap for HV and MV networks:

$$V_{50} = \frac{d}{1.9}$$

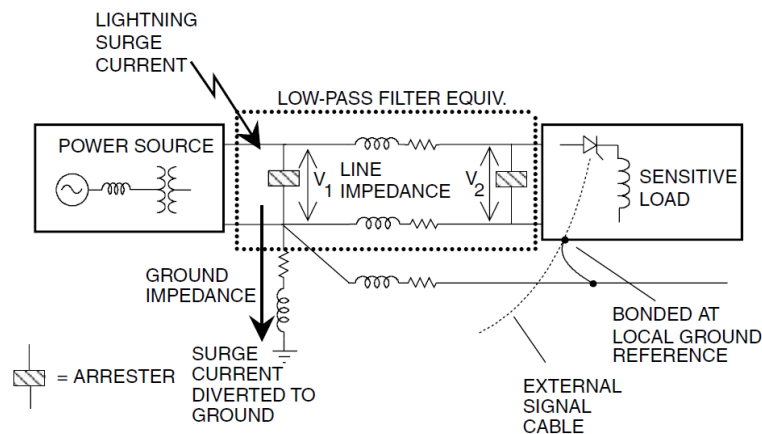
where  $V_{50}$  is the voltage for which the breakdown probability is 50 %; and

$$V_0 = \frac{d}{2.1}$$

where  $V_0$  is the withstand voltage and  $d$  is clearance in meters ( $V_{50}$  and  $V_0$  are in MV).

A lot of experimental studies have provided tools to evaluate the relation between clearance and withstand voltage, taking into account a variety of factors such as front and tail times, environmental pollution and insulator type.

### ➤ **Surge arresters**

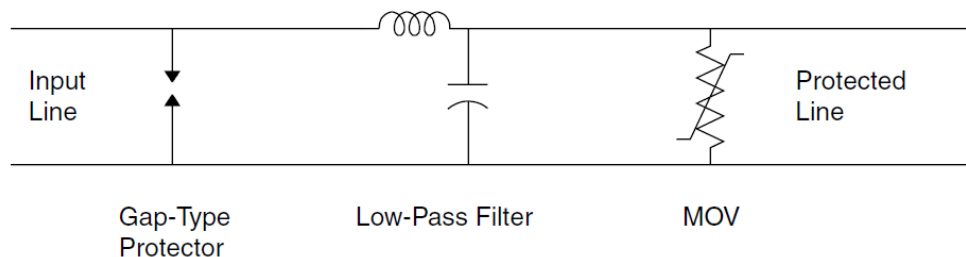


- TVSS have more surge-limiting elements than an arrester, which most commonly consists solely of MOV blocks.
- An arrester may have more energy-handling capability.
- Different modes of operation, *crowbar* and *clamping*.
- Crowbar devices are normally open devices that conduct current during overvoltage transients.

- Once the device conducts, the line voltage will drop to nearly zero due to the short circuit imposed across the line.
- These devices are usually manufactured with a gap filled with air or a special gas.
- The gap arcs over when a sufficiently high overvoltage transient appears.
- Once the gap arcs over, usually power frequency current, or “follow current,” will continue to flow in the gap until the next current zero.
- Thus, these devices have the disadvantage that the power frequency voltage drops to zero or to a very low value for at least one-half cycle.
- This will cause some loads to drop offline unnecessarily.
- Clamping devices for ac circuits are commonly nonlinear resistors (varistors) that conduct very low amounts of current until an overvoltage occurs.
- Then they start to conduct heavily, and their impedance drops rapidly with increasing voltage.
- These devices effectively conduct increasing amounts of current (and energy) to limit the voltage rise of a surge.
- They have an advantage over gap-type devices in that the voltage is not reduced below the conduction level when they begin to conduct the surge current.
- Zener diodes are also used in this application.
- MOV arresters have two important ratings.
- The first is maximum continuous operating voltage (MCOV), which must be higher than the line voltage and will often be at least 125 percent of the system nominal voltage.
- The second rating is the energy dissipation rating (in joules).
- MOVs are available in a wide range of energy ratings.

### ➤ **Low pass filters**

- LPF provides better protection against high frequency transients.
- Consists of series inductance and parallel capacitance. This circuit provides low impedance to the ground path.
- Voltage clamping devices are added in parallel with the capacitor in surge protection usage.



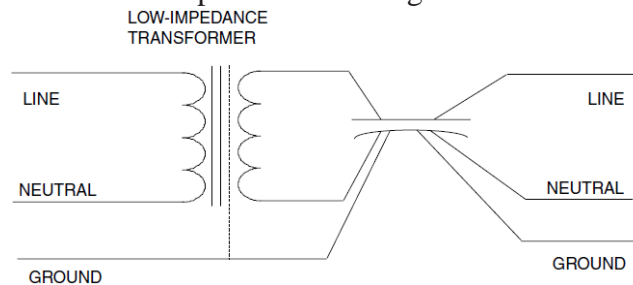
- High surge protector combines two surge suppressors and a LPF for maximum protection.
- It uses a gap-type protector on the front end to handle high-energy transients. The low-pass filter limits transfer of high-frequency transients.
- Inductor helps block high-frequency transients and forces them into the first suppressor.
- Capacitor limits the rate of rise, while the nonlinear resistor (MOV) clamps the voltage

magnitude at the protected equipment.

- Other variations on this design will employ MOVs on both sides of the filters and may have capacitors on the front end as well.

## ➤ Power conditioners

- Low-impedance power conditioners (LIPCs) are used primarily to interface with the switch-mode power supplies found in electronic equipment.
- LIPCs differ from isolation transformers in that these conditioners have much lower impedance and have a filter as part of their design

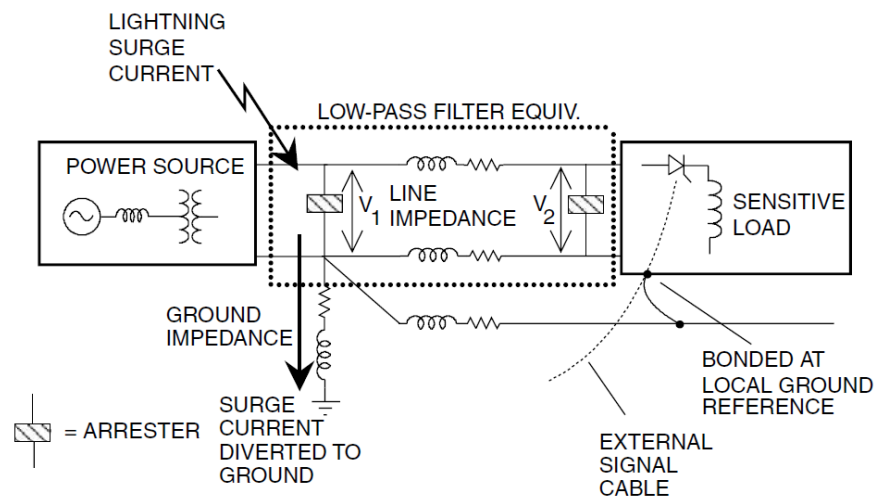


- The filter is on the output side and protects against high-frequency, source-side, common-mode, and normal-mode disturbances (i.e., noise and impulses).
- The new neutral-to-ground connection that can be made on the load side because of the existence of an isolation transformer.

### Drawbacks:

- Low- to medium-frequency transients (capacitor switching) can cause problems for LIPCs
- Transients can be magnified by the output capacitor.

## ➤ Lightning protection



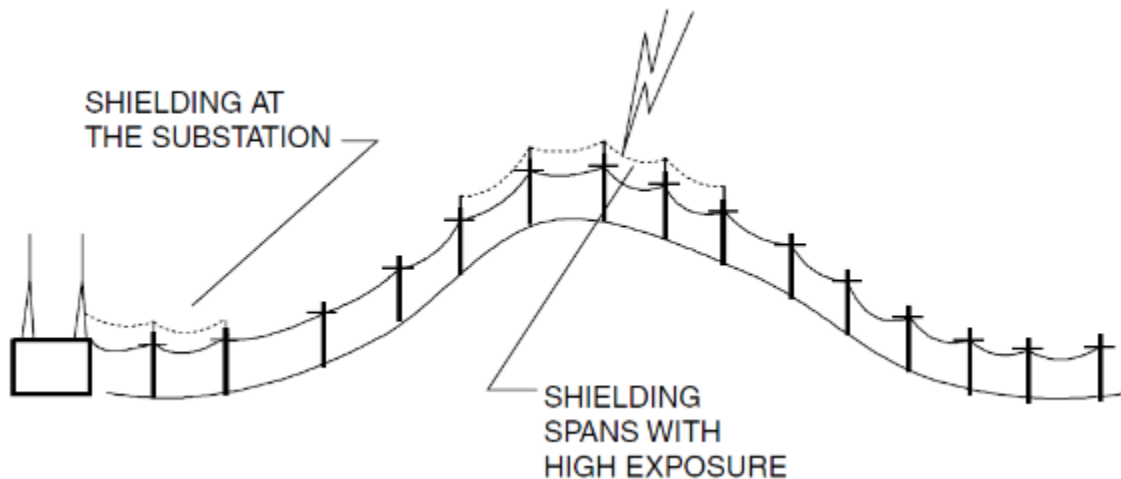
Protective devices used to prevent the system from lightning overvoltages are,

- Surge arresters
  - TVSS (Transient Voltage Surge Suppressor)
- 
- The arresters are diverting the surges to ground independently of the rest of the system.
  - It is important to place the arrester across the sensitive equipment or instruments to be protected.
  - The arresters are usually connected to the local ground. So the local ground may not remain at zero potential during transient events.
  - In Fig. the first arrester is connected from the line to the neutral- ground bond at the service entrance.
  - It limits the line voltage  $V_1$  from rising too high relative to the neutral and ground voltage at the panel.
  - When it performs its voltage-limiting action, it provides a low impedance path for the surge current to travel onto the ground lead.
  - Note that the ground lead and the ground connection itself have significant impedance.
  - Therefore, the potential of the whole power system is raised with respect to that of the remote ground by the voltage drop across the ground impedance.
  - For common values of surge currents and ground impedances, this can be several kilovolts.
  - One hopes, in this situation, that most of the surge energy will be discharged through the first arrester directly into ground. In that sense, the arrester becomes a surge “diverter.”
  - It can only be a diverter if there is a suitable path into which the current can be diverted.
  - That is not always easy to achieve, and the surge current is sometimes diverted toward another critical load where it is not wanted.
  - In this figure, there is another possible path for the surge current - the signal cable indicated by the dotted line and bonded to the safety ground.
  - If this is connected to another device that is referenced to ground elsewhere, there will be some amount of surge current flowing down the safety ground conductor.
  - Damaging voltages can be impressed across the load as a result.
  - The first arrester at the service entrance is electrically too remote to provide adequate load protection.
  - Therefore, a second arrester is applied at the load—again, directly across the insulation to be protected. It is connected “line to neutral” so that it only protects against normal mode transients.
  - This illustrates the principles without complicating the diagram but should be considered as the minimum protection one would apply to protect the load.
  - Frequently, surge suppressors will have suppression on all lines to ground, all lines to neutral, and neutral to ground.
  - Efforts to block the surge current are most effective for high-frequency surge currents such as those originating with lightning strokes and capacitor-switching events.
  - The amount of current flowing between the grounds may be reduced by improving all the intentional grounds at the service entrance and nearby on the utility system.
  - This will normally reduce, but not eliminate entirely, the incidence of equipment failure within the facility due to lightning.

- However, some structures also have significant lightning exposure, and the damaging surge currents can flow back into the utility grounds.
- It doesn't matter which direction the currents flow; they cause the same problems.
- Again, the same principle applies, which is to improve the grounds for the structure to minimize the amount of current that might seek another path to ground.
- When it is impractical to keep the currents from flowing between two grounds, both ends of any power or signal cables running between the two grounds must be protected with voltage-limiting devices to ensure adequate protection.
- This is common practice for both utility and end-user systems where a control cabinet is located quite some distance from the switch, or other device, being controlled.

### ➤ **Shielding**

- Shielding is the arrangement of installing grounded bare conductor over the live conductor of the power system to provide protection from the lightning strikes. This will intercept most lightning strokes before they strike the phase wires.

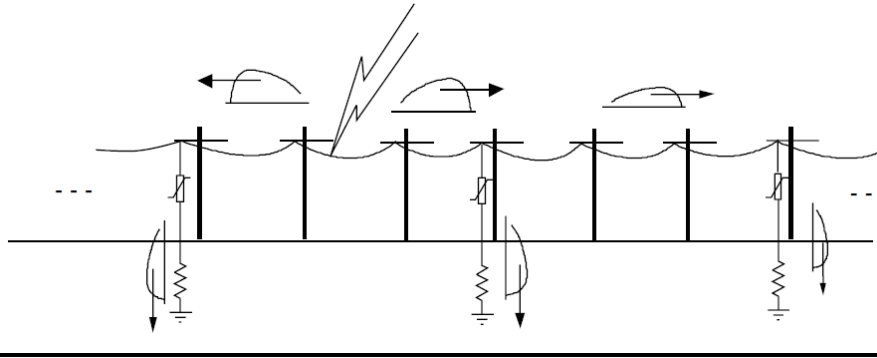


- Grounded neutral wire over the phase wires intercept lightning strokes before striking on the phase wires.
- But, they will not necessarily prevent back flashovers.
- This shielding is common in transmission lines and substations, but is not common on distribution lines because of its added cost.
- The back flashovers lead to temporary faults. In order to avoid back flashovers, the ground path must carefully be chosen to maintain adequate clearance with the phase conductors.
- Also the value of grounding resistance is important to maintain the voltage as low as possible.
- When a particular section of a feeder is being struck frequently, the section may be modified with a shield wire with justification to reduce the number of transient faults and to maintain good power quality.
- Figure shows a substation connected with a transmission line in which few spans nearby substation being shielded to prevent high current faults that can damage substation transformer and breaker.



- It is also common near substations for distribution lines to be underbuilt on transmission or sub-transmission structures.
- Hence the shielded transmission provides shielding for the distribution as well, provided adequate clearance can be maintained for the ground lead.
- If any other section of the feeder is experiencing more number of strikes, the area may be effectively shielded to reduce lightning induced faults.
- This increase the cost to extend poles to accommodate the shield wire.
- Opting line arresters would be more economical and effective for many applications.

### ➤ Line arresters



- Mounting line arresters in a periodic interval along the phase wires of a line exposed to frequent lightning is more effective.
- Normally, lines flashover first at the pole insulators. Therefore, preventing insulator flashover will reduce the interruption and sag rate significantly.
- It is observed that this strategy is more economical than shielding and results in fewer line flashovers.
- Neither shielding nor line arresters will prevent all flashovers from lightning. The aim is to reduce flashovers in particular trouble spots.
- Sometimes the arrester bleed off some of the stroke current as it passes along the line as shown in figure.
- The amount that an individual arrester bleeds off will depend on the grounding resistance.
- The spacing of the line arresters should ensure the voltage level at the poles in the span should not exceed BIL (Basic Impulse Level) of the line insulators.
- This usually requires an arrester at every second or third pole.
- It may be necessary to place arresters at every pole when the feeder supplies to highly critical load or the feeder with high ground resistance.
- Some systems may be provided with the line arresters only on the top phase when other lines are placed below.
- In other cases, the arresters put on all three phases to get consistent reduction in flashovers.

### ➤ Protection of transformers

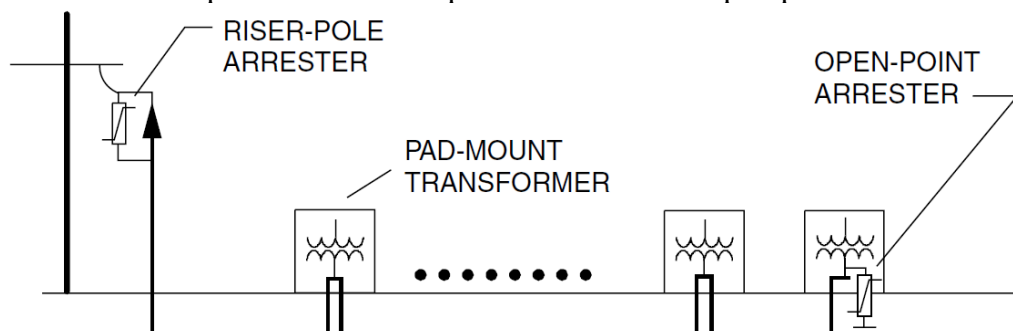
- Common ways for the utility to protect the transformer:
  - i. Use transformers with interlaced secondary windings. (Design Characteristics)

ii. Apply surge arresters at the X terminals.(Possible to place arresters at LV terminals)

- Note that arresters at the load service entrance will not protect the transformer. In fact, they will virtually guarantee that there will be a surge current path and thereby cause additional stress on the transformer.
- While interlaced transformers have a lower failure rate in lightning-prone areas than noninterlaced transformers, recent evidence suggests that low-voltage arresters have better success in preventing failures.
- The primary arrester is mounted directly on the tank with very short lead lengths. With the evidence mounting that lightning surges have steeper wavefronts than previously believed, this is an ever increasing requirement for good protection practice.
- It requires a special fuse in the cutout to prevent fuse damage on lightning current discharge.
- The transformer protection is completed by using a robust secondary arrester. This shows a heavy-duty, secondary arrester adapted for external mounting on transformers.
- Internally mounted arresters are also available. An arrester rating of 40-kA discharge current is recommended.
- The voltage discharge is not extremely critical in this application but is typically 3 to 5 kV.
- Transformer secondaries are generally assumed to have a BIL of 20 to 30 kV.
- Gap-type arresters also work in this application but cause voltage sags, which the MOV-type arresters avoid.

### ➤ **Protection of cables**

- Main source of outages in underground distribution is cable failures.
- As a cable ages, the insulation becomes progressively weaker and a moderate transient overvoltage causes breakdown and failure.
- The life of the cable may be increased for few years by arrester protection than cable replacement.
- Depending on voltage class, the cable may have been installed with only one arrester at the riser pole or both a riserpole arrester and an open-point arrester.



- To provide additional protection, utilities may choose from a number of options:
  1. Add an open-point arrester, if one does not exist.
  2. Add a third arrester on the next-to-last transformer.
  3. Add arresters at every transformer.

4. Add special low-discharge voltage arresters.
5. Inject an insulation-restoring fluid into the cable.
6. Employ a scout arrester scheme on the primary
  - The cable life is an exponential function of the number of impulses of a certain magnitude that it receives. The damage to the cable is related by,

$$D = NV^c$$

where, D - Constant, representing damage to the cable

N - Number of impulses

V - Magnitude of impulses

c - Empirical constant ranging from 10 to 15

- Therefore, anything that will decrease the magnitude of the impulses only slightly has the potential to extend cable life a great deal.

### ➤ **An introduction to computer analysis tools for transients, PSCAD and EMTP.**

- The most widely used computer programs for transients analysis of power systems are the Electromagnetic Transients Program, commonly known as EMTP, and its derivatives such as the Alternate Transients Program (ATP).
- *EMTP* was originally developed by Hermann W. Dommel at the Bonneville Power Administration (BPA) in the late 1960s and has been continuously upgraded since.
- One of the reasons this program is popular is its low cost due to some versions being in the public domain.
- This program features a very sophisticated graphical user interface that enables the user to be very productive in this difficult analysis..
- Nearly all the tools for power systems solve the problem in the time domain, recreating the waveform point by point.
- A few programs solve in the frequency domain and use the Fourier transform to convert to the time domain. Unfortunately, this essentially restricts the addressable problems to linear circuits. Time-domain solution is required to model nonlinear elements such as surge arresters and transformer magnetizing characteristics. The penalty for this extra capability is longer solution times, which with modern computers becomes less of a problem each day.
- It takes considerably more modeling expertise to perform electro-magnetic transients studies than to perform more common power system analyses such as of the power flow or of a short circuit. Therefore, this task is usually relegated to a few specialists within the utility organization or to consultants.
- While transients programs for electronic circuit analysis may formulate the problem in any number of ways, power systems analysts almost uniformly favor some type of nodal admittance formulation.

- For one thing, the system admittance matrix is sparse allowing the use of very fast and efficient sparsity techniques for solving large problems. Also, the nodal admittance formulation reflects how most power engineers view the power system, with series and shunt elements connected to buses where the voltage is measured with respect to a single reference.
- To obtain conductances for elements described by differential equations, transients programs discretize the equations with an appropriate numerical integration formula. The simple trapezoidal rule method appears to be the most commonly used, but there are also a variety of Runge-Kutta and other formulations used.
- Nonlinearities are handled by iterative solution methods.
- Some programs include the nonlinearities in the general formulation, while others, such as those that follow the EMTP methodology, separate the linear and nonlinear portions of the circuit to achieve faster solutions.
- This impairs the ability of the program to solve some classes of nonlinear problems but is not usually a significant constraint for most power system problems.

## UNIT IV      HARMONICS

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

### ➤ **Harmonic sources from commercial and industrial loads**

Harmonics of different orders generated when connected power system network by different sources as below:

- i. The non linear loads such as inverter fed adjustable speed drive.
- ii. The use of powerfactor correction capacitor creates parallel or series resonance problems increasing the harmonic distortion.
- iii. Process control and solid state power conversion equipments.
- iv. Energy efficient compact fluorescent lamps.
- v. Use of AC and DC adjustable speed drives
- vi. Static VAR compensators.
- vii. Transformers produce very high levels of harmonics when they are initially energized, the so called inrush current will generate harmonics of several orders.
- viii. Cycloconverters, Lift control system, Traction, AC voltage regulators, UPS, Battery chargers.

### ➤ **Harmonic Sources Commercial Loads:**

#### **Commercial Places:**

- Office complexes
- Department stores
- Hospitals and
- Internet data centers

#### **Loads:**

- High-efficiency fluorescent lighting with electronic ballasts
- Adjustable-speed drives for the heating, ventilation, and air conditioning (HVAC) loads
- Elevator drives and
- Sensitive electronic equipment supplied by single-phase switch-mode power supplies.

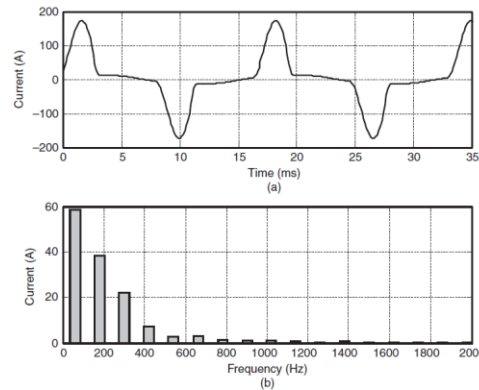
- ❖ Commercial loads are characterized by a large number of small harmonic-producing loads.
- ❖ Depending on the diversity of the different load types, these small harmonic currents may add in phase or cancel each other.
- ❖ Voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion.

#### **Single-phase power supplies:**

- ❖ Electronic power supplies are very important in commercial premises because of increased utilization of personal computers, adjustable speed drives, dc motor drives, battery charges etc.,
- ❖ The SMPS is now replacing the old transformer power supplies. The input diode bridge is directly connected to the AC main, eliminating transformer. The direct current is then

converted back to AC at very high frequency by the switches and subsequently rectified again. All computer peripherals now employ SMPS because of its light weight, compact size, efficient operation and lack of need for a transformer.

- ❖ SMPS causes very high 3rd Harmonics. These 3rd Harmonics causes overloading of neutral conductors, especially where undersized old neutral wires may have been installed.



Current and Frequency spectrum of SMPS

### Fluorescent Lighting:

- ❖ Commercial building loads consumes 40% - 60% of generated energy for lighting
- ❖ Lighting (1995) – 77% Fluorescent lighting, 14% Incandescent lighting.
- ❖ In discharge lamps, ballasts are used for generating high initial voltage. After establishing the electron flow from one electrode to another, arc current increases and the voltage decreases.
- ❖ Discharge is a short circuit. Ballast has to reduce the current within the limit to maintain the specified lumen output. i.e, Ballast is also a current limiting device.
- ❖ Types: 1. Magnetic Ballast and 2. Electronic Ballast.

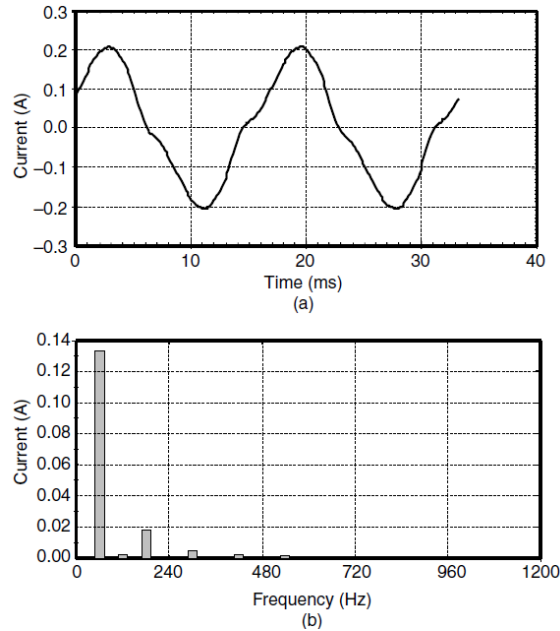
Magnetic Ballast: It is made with iron core and used with a capacitor. It produces heat loss.

Electronic Ballast: Switch mode power supply is used to convert the fundamental frequency voltage in to a much higher frequency (25-40 kHz) voltage.

### Advantages of High frequency:

- Small inductor is enough to limit the arc current.
- High Frequency eliminates 100 or 120 Hz flicker associated with iron core magnetic ballast.
- ❖ Magnetic Ballast can be used for 2 lamps. But electronic Ballast can be used for 4 lamps.
- ❖ Comparison: Electronic Ballast produces double or triple the standard magnetic ballast harmonic output.
- ❖ Other electronic ballasts have been specifically designed to minimize harmonics and may actually produce less harmonic distortion than the normal magnetic ballast-lamp combination.
- ❖ Typical THD allowed in electronic ballast is between 10-32%.
- ❖ THD greater than 32% is excessive according to ANSI C82.11-1993, *High frequency Fluorescent Lamp Ballasts*.
- ❖ In many cases, passive filtering used to reduce input current harmonic distortion to less than 20%.

- ❖ Harmonics in commercial buildings are usually distributed along the phases in a nearly balanced manner.



Current and Frequency spectrum of fluorescent lighting

#### Adjustable Speed Drives:

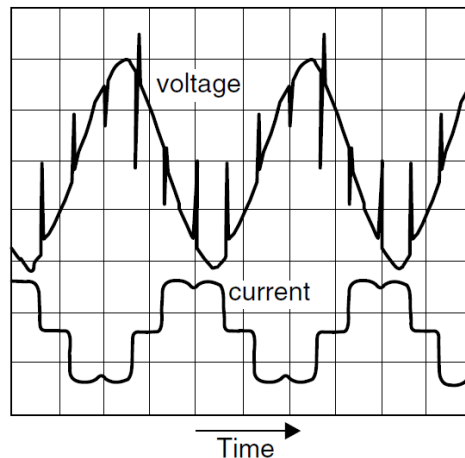
- ❖ Applications of ASDs:
  - Elevator Motors
  - Pumps and Fans of HVAC Systems
- ❖ ASD consists of electronic power converter that converts constant ac voltage and frequency into variable voltage and frequency.
- ❖ Variable voltage and frequency allows the ASD to control motor speed to match the application requirement such as slowing a pump or fan.
- ❖ ASDs also find many applications in industrial loads
- **Harmonic Sources – Industrial Loads:**
- ❖ In modern Industries, non linear loads are unavoidable today. They are injecting harmonics in to the system.
- ❖ Non linear Loads are operating at low power factor. Therefore, power factor correction strategies are applied to the system. Widely using power factor correction capacitors magnify the harmonics.
- ❖ High Voltage distortions are experienced at LV side (Capacitor side).
- ❖ At resonance condition, motor and transformer overheating, and misoperation of sensitive electronic equipment are occurred.
- ❖ Three categories of nonlinear industrial loads :
  - Three-phase power converters
  - Arcing devices and
  - Saturable devices.

#### Three-phase power converters:

- ❖ All equipment containing static converters, as variable speed controllers, UPS units and a.c./d.c. converters in general, are based on a three-phase bridge, also known as a six-pulse bridge because there are six voltage pulses per cycle (one per half cycle per phase)

on the d.c. output.

- ❖ This bridge produces in supply networks current harmonics of order  $6n \pm 1$ , which means one more and one less than each multiple of six.
- ❖ In theory, the magnitude of each harmonic should be equal to the reciprocal of the harmonic number, so there would be 20% of the 5th harmonic and 9% of the 11th harmonic, etc.
- ❖ Figure shows a waveform of a thyristor bridge current against the phase voltage.
- ❖ Commutation notches are clearly visible in the voltage waveform (the source of high-frequency distorting components).
- ❖ The magnitude of the harmonics is significantly reduced by the use of a 12-pulse converter.



Example waveforms of the supply voltage and current of a six-pulse thyristor bridge with d.c. side reactor

### **Arcing Devices:**

- ❖ The following are the arcing devices:
  - Arc furnaces,
  - Arc welders, and discharge-type
  - Lighting (fluorescent, sodium vapor, mercury vapor) with magnetic ballasts.
- ❖ The voltage-current characteristics of electric arcs are nonlinear. Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system.
- ❖ In electric arc furnace applications, the limiting impedance is primarily the furnace cable and leads with some contribution from the power system and furnace transformer. Currents in excess of 60,000 A are common.
- ❖ The electric arc itself is actually best represented as a source of voltage harmonics. Its magnitude is largely a function of the length of the arc.
- ❖ The arcing load thus appears to be a relatively stable harmonic current source, which is adequate for most analyses.
- ❖ The exception occurs when the system is near resonance and a Thevenin equivalent model using the arc voltage waveform gives more realistic answers.
- ❖ Three phase arcing devices can be arranged to cancel the triplen harmonics through the transformer connection.
- ❖ However, this cancellation may not work in three-phase arc furnaces because of the

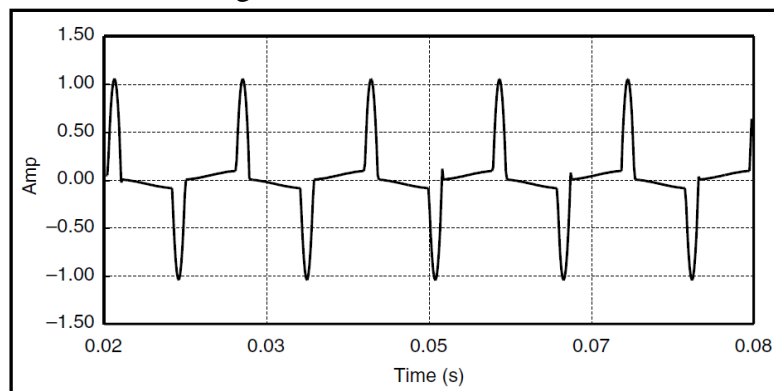


frequent unbalanced operation during the melting phase.

- ❖ During the refining stage when the arc is more constant, the cancellation is better.

#### **Saturable Devices:**

- ❖ Equipment in this category includes transformers and other electromagnetic devices with a steel core, including motors.
- ❖ Harmonics are generated due to the nonlinear magnetizing characteristics of the steel.
- ❖ Power transformers are designed to operate below the 'knee point' of the magnetic saturation characteristics.
- ❖ Selection of the operating point depends on,
  - Steel cost
  - No-load losses
  - Noise and
  - Other factors
- ❖ Some transformers are purposefully operated in the saturated region. One example is a triplen transformer used to generate 180 Hz for induction furnaces.
- ❖ Motors also exhibit some distortion in the current when overexcited, although it is generally of little consequence.
- ❖ There are, however, some fractional horsepower, single-phase motors that have a nearly triangular waveform with significant third-harmonic currents.



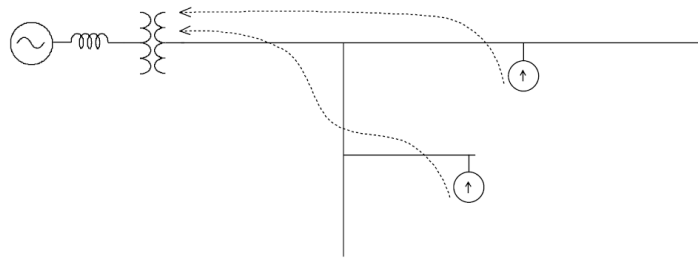
Transformer magnetizing current and harmonic spectrum.

- ❖ The waveform shown in Fig. is for single-phase or wye-grounded three-phase transformers.
- ❖ The current obviously contains a large amount of third harmonic.
- ❖ Delta connections and ungrounded-wye connections prevent the flow of zero-sequence harmonic, which triplens tend to be.
- ❖ Thus, the line current will be void of these harmonics unless there is an imbalance in the system

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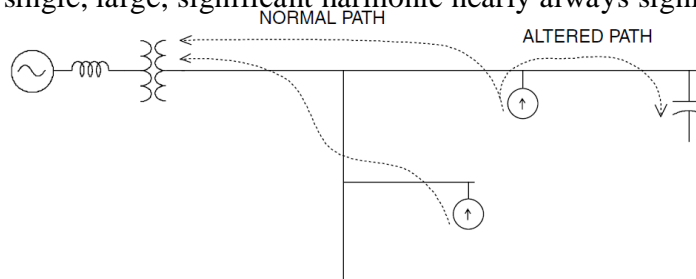
#### ➤ **Locating harmonic sources**

- ❖ On radial utility distribution feeders and industrial plant power systems, the main tendency is for the harmonic currents to flow from the harmonic-producing load to the power system source.
- ❖ The impedance of the power system is normally the lowest impedance seen by the harmonic currents. Thus, the bulk of the current flows into the source



General flow of harmonic current in radial system

- ❖ This general tendency of harmonic current flows can be used to locate sources of harmonics.
- ❖ Using a power quality monitor capable of reporting the harmonic content of the current, simply measure the harmonic currents in each branch starting at the beginning of the circuit and trace the harmonics to the source.
- ❖ Power factor correction capacitors can alter this flow pattern for at least one of the harmonics.
- ❖ Adding a capacitor to the circuit may draw a large amount of harmonic current into that portion of the circuit. In such a situation, following the path of the harmonic current will lead to a capacitor bank instead of the actual harmonic source.
- ❖ Thus, it is generally necessary to temporarily disconnect all capacitors to reliably locate the sources of harmonics.
- ❖ It is usually straightforward to differentiate harmonic currents due to actual sources from harmonic currents that are strictly due to resonance involving a capacitor bank.
- ❖ A resonance current typically has only one dominant harmonic riding on top of the fundamental sine wave.
- ❖ None of the harmonic sources presented earlier in this chapter produce a single harmonic frequency in addition to the fundamental.
- ❖ They all produce more than one single harmonic frequency.
- ❖ Waveforms of these harmonic sources have somewhat arbitrary waveshapes depending on the distorting phenomena, but they contain several harmonics in significant quantities. A single, large, significant harmonic nearly always signifies resonance.



Power factor capacitors can alter the direction of flow of one of the harmonic components of the current.

- ❖ This fact can be exploited to determine if harmonic resonance problems are likely to exist in a system with capacitors. Simply measure the current in the capacitors.
- ❖ If it contains a very large amount of one harmonic other than the fundamental, it is likely that the capacitor is participating in a resonant circuit within the power system.
- ❖ Always check the capacitor currents first in any installations where harmonic problems are suspected.

## ➤ **Power system response characteristics**

- ❖ In power systems, the response of the system is equally as important as the sources of harmonics.
- ❖ Power systems are quite tolerant of the currents injected by harmonic-producing loads unless there is some adverse interaction with the impedance of the system.
- ❖ Identifying the sources is only half the job of harmonic analysis. The response of the power system at each harmonic frequency determines the true impact of the nonlinear load on harmonic voltage distortion.
- ❖ There are three primary variables affecting the system response characteristics, i.e.,
  - the system impedance,
  - the presence of a capacitor bank, and
  - the amount of resistive loads in the system

### **System impedance**

- ❖ At the fundamental frequency, power systems are primarily inductive, and the equivalent impedance is sometimes called simply the short-circuit reactance.
- ❖ Capacitive effects are frequently neglected on utility distribution systems and industrial power systems.
- ❖ One of the most frequently used quantities in the analysis of harmonics on power systems is the short-circuit impedance to the point on a network at which a capacitor is located.
- ❖ If not directly available, it can be computed from short-circuit study results that give either the short-circuit mega-voltampere (MVA) or the short-circuit current

### **Capacitor impedance**

- ❖ Shunt capacitors, either at the customer location for power factor correction or on the distribution system for voltage control, dramatically alter the system impedance variation with frequency.
- ❖ Capacitors do not create harmonics, but severe harmonic distortion can sometimes be attributed to their presence.
- ❖ While the reactance of inductive components increases proportionately to frequency, capacitive reactance  $X_C$  decreases proportionately
- ❖ For three-phase banks, use phase-to-phase voltage and the three-phase reactive power rating.
- ❖ For single-phase units, use the capacitor voltage rating and the reactive power rating.

### **Parallel resonance**

- ❖ All circuits containing both capacitances and inductances have one or more natural frequencies.
- ❖ When one of those frequencies lines up with a frequency that is being produced on the power system, a resonance may develop in which the voltage and current at that frequency continue to persist at very high values.
- ❖ From the perspective of harmonic sources the shunt capacitor appears in parallel with the equivalent system inductance (source and transformer inductances) at harmonic frequencies
- ❖ Furthermore, since the power system is assumed to have an equivalent voltage source of fundamental frequency only,
- ❖ Parallel resonance occurs when the reactance of  $X_C$  and the distribution system cancel each other out.

- ❖ The frequency at which this phenomenon occurs is called the parallel resonant frequency

### **Series resonance**

- ❖ There are certain instances when a shunt capacitor and the inductance of a transformer or distribution line may appear as a series LC circuit to a source of harmonic currents.
- ❖ If the resonant frequency corresponds to a characteristic harmonic frequency of the nonlinear load, the LC circuit will attract a large portion of the harmonic current that is generated in the distribution system.
- ❖ A customer having no nonlinear load, but utilizing power factor correction capacitors, may in this way experience high harmonic voltage distortion due to neighboring harmonic sources
- ❖ During resonance, the power factor correction capacitor forms a series circuit with the transformer and harmonic sources.
- ❖ The inductance in series with the capacitor is that of the service entrance transformer.
- ❖ The series combination of the transformer inductance and the capacitor bank is very small (theoretically zero) and only limited by its resistance.
- ❖ The harmonic current corresponding to the resonant frequency will flow freely in this circuit.
- ❖ The voltage at the power factor correction capacitor is magnified and highly distorted

### **Effects of resistance and resistive load**

- ❖ Loads and line resistances are the reasons why catastrophic harmonic problems from capacitors on utility distribution feeders are seldom seen.
- ❖ That is not to say that there will not be any harmonic problems due to resonance, but the problems will generally not cause physical damage to the electrical system components.
- ❖ The most troublesome resonant conditions occur when capacitors are installed on substation buses, either utility substations or in industrial facilities.
- ❖ In these cases, where the transformer dominates the system impedance and has a high X/R ratio, the relative resistance is low and the corresponding parallel resonant impedance peak is very sharp and high.
- ❖ This is a common cause of capacitor, transformer, or load equipment failure.

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### **➤ Effect of harmonics**

The duration presence of long duration harmonic cause more serious effects on the various equipments connected to the power system.

- ❖ ***Amplitude of harmonics:*** Large amplitude harmonics of short duration under resonance condition cause dielectric breakdown due to over voltages.
- ❖ Now a day various devices and equipment being measured applications are more sensitive compared to the past.
- ❖ The capacitor used for power factor correction and in different filters decreases resulting in increasing in current drawn by capacitor beyond permissible limits.
- ❖ The capacitor acts as sink for harmonic currents resultant effect of harmonics is overloading, hence over heating increases dielectric stress and increase the power lost.
- ❖ The thermal failure of capacitor may take place because of higher temperature.
- ❖ Non sinusoidal power supplies results in reduction of torque of induction motor.
- ❖ It will increase interference with telephone, communication and logic circuits.
- ❖ Error in reading of induction type energy meters which are calibrated for pure sinusoidal

A.C power.

- ❖ Higher order harmonics causes voltage stress and corona.
- ❖ Presence of harmonics in power system network can cause additional losses in power system network, overheating of transmission lines, transformers and generators etc.
- ❖ Malfunction or even failure of electronic or computer controls.
- ❖ Hence it is clear that day by day the increase in harmonic contents will impose new problems on operations of electronic equipment.
- ❖ The energy efficient electronic equipment that will be produced in future trends result in poor performance due to the voltage distortion.
- ❖ Hence it is essential to have the proper coordination between the supply authorities and consumers regarding the power quality problem, their causes and results and solutions available to eliminate them.

### ➤ **Harmonic indices**

The two most commonly used indices for measuring the harmonic content of a waveform are the total harmonic distortion and the total demand distortion. Both are measures of the effective value of a waveform and may be applied to either voltage or current.

#### **Total harmonic distortion(THD)**

The THD is a measure of the effective value of the harmonic components of a distorted waveform. That is, it is the potential heating value of the harmonics relative to the fundamental. This index can be calculated for either voltage or current:

*The ratio of the root mean square of the harmonic content to the rms value of the fundamental quantity, expressed as a per- cent of the fundamental*

$$\text{THD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} M_h^2}}{M_1}$$

where  $M_h$  is the rms value of harmonic component  $h$  of the quantity  $M$ .

The rms value of a distorted waveform is the square root of the sum of the squares

#### **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 fundamental current, expressed as a percent.*

$$\text{TDD} = \frac{\sqrt{\sum_{h=2}^{h_{\max}} I_h^2}}{I_L}$$

### ➤ **Harmonic Distortion**

- ❖ Harmonic distortion is caused by nonlinear devices in the power system. A nonlinear device is one in which the current is not proportional to the applied voltage.
- ❖ While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a

different waveshape.

- ❖ When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave. This multiple is called a harmonic of the fundamental.
- ❖ The sum of sinusoids is referred to as a Fourier series, When both the positive and negative half cycles of a waveform have identical shapes, the Fourier series contains only odd harmonics.
- ❖ The presence of even harmonics is often a clue that there is something wrong—either with the load equipment or with the transducer used to make the measurement.

### ➤ **Harmonics Vs transients**

- ❖ Harmonics represent distortion of sinusoidal voltage or current signals. They are caused by nonlinear elements in the system like saturating cores or switching elements like thyristors.
- ❖ The Fourier series analysis of a distorted waveform shows presence of harmonics. They are present in every cycle of the signal.
- ❖ On the contrary, transients, which are also distortions, are present only for a limited period of time. They are caused by abrupt switching on or switching off of a load or occurrence of a fault.
- ❖ We normally use time domain methods to analyse transients and frequency domain methods to analyse harmonics.

### ➤ **Voltage versus Current Distortion**

1. The harmonic voltages are too great (the voltage too distorted) for the control to properly determine firing angles.
  2. The harmonic currents are too great for the capacity of some device in the power supply system such as a transformer, and the machine must be operated at a lower than rated power.
  3. The harmonic voltages are too great because the harmonic currents produced by the device are too great for the given system condition.
- ❖ Nonlinear loads appear to be sources of harmonic current in shunt with and injecting harmonic currents into the power system.
  - ❖ For nearly all analyses, it is sufficient to treat these harmonic-producing loads simply as current sources. voltage distortion is the result of distorted currents passing through the linear, series impedance of the power delivery system, although, assuming that the source bus is ultimately a pure sinusoid, there is a nonlinear load that draws a distorted current.
  - ❖ The harmonic currents passing through the impedance of the system cause a voltage drop for each harmonic.
  - ❖ This results in voltage harmonics appearing at the load bus. While the load current harmonics ultimately cause the voltage distortion, it should be noted that load has no control over the voltage distortion.
  - ❖ The same load put in two different locations on the power system will result in two different voltage distortion values.
  - ❖ IEEE Standard 519-1992, Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems:
    1. The control over the amount of harmonic current injected into the system takes place at the end-use application.

2. Assuming the harmonic current injection is within reasonable limits, the control over the voltage distortion is exercised by the entity having control over the system impedance, which is often the utility.

### ➤ **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. They can appear as discrete frequencies or as a wideband spectrum. Interharmonics can be found in networks of all voltage classes.

Causes: Static frequency converters, cycloconverters, induction furnaces, and arcing devices.

- ❖ Power line carrier signals can also be considered as interharmonics.
- ❖ Interharmonic currents can excite quite severe resonances on the power system as the varying interharmonic frequency becomes coincident with natural frequencies of the system. They have been shown to affect power-line-carrier signaling and induce visual flicker in fluorescent and other arc lighting as well as in computer display devices.
- ❖ Since interharmonics can assume any values between harmonic frequencies, the interharmonic spectrum must have sufficient frequency resolution.
- ❖ Thus, a single-cycle waveform sample is no longer adequate to compute the interharmonic spectrum since it only provides a frequency resolution of 50 or 60 Hz.
- ❖ Any frequency in between harmonic frequencies is lost. The one-cycle waveform though is commonly used to compute the harmonic spectrum since there is no frequency between harmonic frequencies.

### ➤ **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.

#### **Parallel resonance**

- ❖ All circuits containing both capacitances and inductances have one or more natural frequencies.
- ❖ When one of those frequencies lines up with a frequency that is being produced on the power system, a resonance may develop in which the voltage and current at that frequency continue to persist at very high values.
- ❖ This is the root of most problems with harmonic distortion on power systems.
- ❖ From the perspective of harmonic sources the shunt capacitor appears in parallel with the equivalent system inductance (source and transformer inductances) at harmonic frequencies
- ❖ Furthermore, since the power system is assumed to have an equivalent voltage source of fundamental frequency only,
- ❖ Parallel resonance occurs when the reactance of XC and the distribution system cancel each other out.
- ❖ The frequency at which this phenomenon occurs is called the parallel resonant frequency

### Series resonance

- ❖ There are certain instances when a shunt capacitor and the inductance of a transformer or distribution line may appear as a series LC circuit to a source of harmonic currents.
- ❖ If the resonant frequency corresponds to a characteristic harmonic frequency of the nonlinear load, the LC circuit will attract a large portion of the harmonic current that is generated in the distribution system.
- ❖ A customer having no nonlinear load, but utilizing power factor correction capacitors, may in this way experience high harmonic voltage distortion due to neighboring harmonic sources
- ❖ During resonance, the power factor correction capacitor forms a series circuit with the transformer and harmonic sources.
- ❖ The inductance in series with the capacitor is that of the service entrance transformer.
- ❖ The series combination of the transformer inductance and the capacitor bank is very small (theoretically zero) and only limited by its resistance.
- ❖ The harmonic current corresponding to the resonant frequency will flow freely in this circuit.
- ❖ The voltage at the power factor correction capacitor is magnified and highly distorted

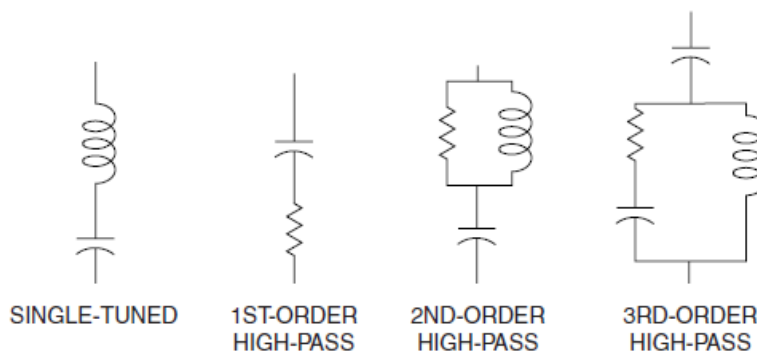
### ➤ Devices for controlling harmonic distortion

- ❖ Three different solutions can be adopted in the reduction of the harmonic distortion:
  - i. Reduction of harmonic emission from non-linear loads, by modifications to their structure;
  - ii. High harmonic filters (passive and active); and
  - iii. Isolation and harmonic reduction transformers.
- ❖ The devices used to control harmonic distortion are,
  - i. Reinforce distribution system
  - ii. Passive Filters
  - iii. Active Filters
  - iv. Isolation transformers
  - v. Harmonic mitigation transformer
  - vi. Multi-pulse converters

### ➤ Passive and active filters

#### Passive Filters:

- ❖ They include devices that provide low impedance paths to divert harmonics to ground and devices that create a high impedance path to discourage the flow of harmonics.



Common passive filter configurations.

❖ Both of these devices, by necessity, change the impedance characteristics of the circuits into which they are inserted.

❖ Another weakness of the passive harmonic technologies is that they cannot adapt to changes in electrical systems in which they operate.

❖ Notch filters can



provide power factor correction in addition to harmonic suppression. In fact, power factor correction capacitors may be used to make notch filters.

Advantages of Passive filters:

1. Simple in construction, less costly and efficient
2. Serves dual purpose: harmonic filtration and power factor correction of load.

Disadvantages of Passive filters:

1. Cannot function under saturated condition.
2. Number of passive filters installed must be equal to the number of harmonic levels to be compensated.
3. Connection of passive filters necessitates a specific analysis of each installation.
4. Non adaptability to system variations.
5. Bulky in size.
6. Tendency to resonate with the other load.

Active filters:

- ❖ When the number of harmonics to be filtered, large no of branches of passive filters will be required .
- ❖ The large no of branches of passive filters will be required.
- ❖ The actual number of branches will depend upon no of harmonic level of branches will depend upon no of harmonic level to be compensated.
- ❖ Hence, because of passive filter use for filtration of large no of harmonics results in large size & more cost.
- ❖ Introduction of self commutated devices e.g. MOSFETS, IGBT etc, accelerated the research in design of active filter & resulted low cost, high performance active filter suitable to eliminate the harmonics of different orders to overcome the drawbacks of passive filters.
- ❖ Active filters compensate voltage of current harmonic signal measured.
- ❖ The injected voltage or current harmonic signal measured.
- ❖ The injected voltage or current harmonic signals in to the power system network is of same magnitude and opposite in phase of the measured harmonic signal.
- ❖ It comprises power converter and control loop which controls the harmonics injection of the filter as the function of harmonic signal measure.

Advantages of Active filters:

1. Superior filtering performance
2. Smaller physical size
3. Flexibility

➤ **Harmonic Distortion Evaluations**

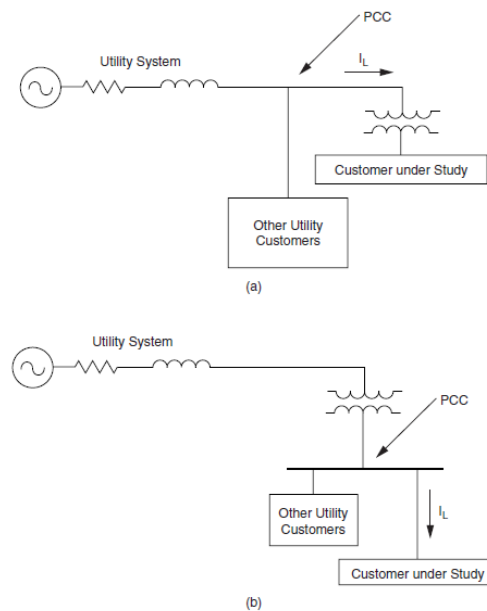
1. End users

- ❖ For individual end users, IEEE Standard 519-1992 limits the level of harmonic current injection at the point of common coupling (PCC). This is the quantity end users have control over.
- ❖ Recommended limits are provided for both individual harmonic components and the total demand distortion.
- ❖ These limits are expressed in terms of a percentage of the end user's maximum demand current level, rather than as a percentage of the fundamental. This is intended to provide a common basis for evaluation over time.

## **2. The utility.**

- ❖ Since the harmonic voltage distortion on the utility system arises from the interaction between distorted load currents and the utility system impedance, the utility is mainly responsible for limiting the voltage distortion at the PCC.
- ❖ The limits are given for the maximum individual harmonic components and for the total harmonic distortion (THD).
- ❖ These values are expressed as the percentage of the fundamental voltage.
- ❖ For systems below 69 kV, the THD should be less than 5 percent. Sometimes the utility system impedance at harmonic frequencies is determined by the resonance of power factor correction capacitor banks. This results in a very high impedance and high harmonic voltages.
- ❖ Therefore, compliance with IEEE Standard 519-1992 often means that the utility must ensure that system resonances do not coincide with harmonic frequencies present in the load currents

## **3. Point of common coupling**



❖ Evaluations of harmonic distortion are usually performed at a point between the end user or customer and the utility system where another customer can be served. This point is known as the point of common coupling.

❖ The PCC can be located at either the primary side or the secondary side of the service transformer depending on whether or not multiple customers are supplied from the transformer.

❖ In other words, if multiple customers are served from the primary of the transformer, the PCC is then located at the primary.

❖ On the other hand, if multiple customers are served from the secondary of the transformer, the PCC is located at the secondary.

## **➤ IEEE and IEC standards**

### **IEEE Standards:**

IEEE power quality standards: Institute Of Electrical and Electronics Engineer.

IEEE power quality standards: International Electro Technical Commission.

IEEE power quality standards: Semiconductor Equipment and Material International.

IEEE power quality standards: The International Union for Electricity Applications

IEEE Std 519-1992: IEEE Recommended practices and requirements for Harmonic control in Electric power systems.

IEEE Std 1159-1995: IEEE Recommended practices for monitoring electrical power

IEEE std 141-1993, IEEE Recommended practice for electric power distribution for industrial plants.

IEEE std 1159-1995, IEEE recommended practice for Monitoring electrical power quality.

#### **IEC Standards:**

##### **Part 1: General.**

These standards deal with general considerations such as introduction, fundamental principles, rationale, definitions, and terminologies. They can also describe the application and interpretation of fundamental definitions and terms.

Their designation number is **IEC 61000-1-x**.

##### **Part 2: Environment.**

These standards define characteristics of the environment where equipment will be applied, the classification of such environment, and its compatibility levels.

Their designation number is **IEC 61000-2-x**.

##### **Part 3: Limits.**

These standards define the permissible levels of emissions that can be generated by equipment connected to the environment. They set numerical emission limits and also immunity limits.

Their designation number is **IEC 61000-3-x**.

##### **Part 4: Testing and measurement techniques.**

These standards provide detailed guidelines for measurement equipment and test procedures to ensure compliance with the other parts of the standards.

Their designation number is **IEC 61000-4-x**.

##### **Part 5: Installation and mitigation guidelines.**

These standards provide guidelines in application of equipment such as earthing and cabling of electrical and electronic systems for ensuring electromagnetic compatibility among electrical and electronic apparatus or systems. They also describe protection concepts for civil facilities against the high-altitude electromagnetic pulse (HEMP) due to high altitude nuclear explosions.

They are designated with **IEC 61000-5-x**.

##### **Part 6: Miscellaneous.**

These standards are generic standards defining immunity and emission levels required for equipment in general categories or for specific types of equipment.

Their designation number is **IEC 61000-6-x**.

IEC standards relating to harmonics generally fall in parts 2 and 3. Unlike the IEEE standards on harmonics where there is only a single publication covering all issues related to harmonics, IEC standards on harmonics are separated into several publications. There are standards dealing with environments and limits which are further broken down based on the voltage and current levels.

## **UNIT V      POWER QUALITY MONITORING**

Monitoring considerations - monitoring and diagnostic techniques for various power quality problems - modeling of power quality (harmonics and voltage sag) problems by mathematical simulation tools - power line disturbance analyzer – quality measurement equipment - harmonic / spectrum analyzer - flicker meters - disturbance analyzer. Applications of expert systems for power quality monitoring

### ➤ **Monitoring considerations**

- ❖ Power quality monitoring is the process of gathering, analyzing, and interpreting raw measurement data into useful information. The process of gathering data is usually carried out by continuous measurement of voltage and current over an extended period.
- ❖ The monitoring objectives often determine the choice of monitoring equipment, triggering thresholds, methods for data acquisition and storage, and analysis and interpretation requirements.
- ❖ Several common objectives of power quality monitoring are summarized here.
  - Monitoring to characterize system performance.
  - Monitoring to characterize specific problems.
  - Monitoring as part of an enhanced power quality service.
  - Monitoring as part of predictive or just-in-time maintenance.
- ❖ **Objectives of power quality measurements (Needs for power quality measurement)**
  - Preventive and predictive maintenance.
  - Determining the need for mitigation equipment.
  - Ensuring equipment performance.
  - Sensitivity assessment of process equipment to disturbances.

### ➤ **Monitoring and diagnostic techniques for various power quality problems**

#### **Monitoring as part of a facility site survey**

- ❖ Site surveys are performed to evaluate concerns for power quality and equipment performance throughout a facility.
- ❖ The survey will include inspection of wiring and grounding concerns, equipment connections, and the voltage and current characteristics throughout the facility.
- ❖ Power quality monitoring, along with infrared scans and visual inspections, is an important part of the overall survey.
- ❖ The initial site survey should be designed to obtain as much information as possible about the customer facility.
- ❖ This information is especially important when the monitoring objective is intended to address specific power quality problems.
- ❖ This information is summarized here.
  1. Nature of the problems (data loss, nuisance trips, component failures, control system malfunctions, etc.)
  2. Characteristics of the sensitive equipment experiencing problems (equipment design information or at least application guide information)
  3. The times at which problems occur
  4. Coincident problems or known operations (e.g., capacitor switching) that occur at the same time
  5. Possible sources of power quality variations within the facility (motor starting, capacitor

- switching, power electronic equipment operation, arcing equipment, etc.)
6. Existing power conditioning equipment being used
  7. Electrical system data (one-line diagrams, transformer sizes and impedances, load information, capacitor information, cable data, etc.)

### **Determining what to monitor**

- ❖ Power quality encompasses a wide variety of conditions on the power system.
- ❖ Important disturbances can range from very high frequency impulses caused by lightning strokes or current chopping during circuit interruptions to long-term overvoltages caused by a regulator tap switching problem.
- ❖ The range of conditions that must be characterized creates challenges both in terms of the monitoring equipment performance specifications and in the data-collection requirements

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### **Choosing monitoring locations**

- ❖ The monitoring experience gained from the EPRI DPQ project<sup>1</sup> provides an excellent example of how to choose monitoring locations.
- ❖ The primary objective of the DPQ project was to characterize power quality on the U.S. electric utility distribution feeders.
- ❖ Actual feeder monitoring began in June 1992 and was completed in September 1995. Twenty four different utilities participated in the data-collection effort with almost 300 measurement sites.
- ❖ Monitoring for the project was designed to provide a statistically valid set of data of the various phenomena related to power quality.

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### **Options for permanent power quality monitoring equipment**

Permanent power quality monitoring systems should take advantage of the wide variety of equipment that may have the capability to record power quality information. Some of the categories of equipment that can be

1. *Digital fault recorders (DFRs)*
2. *Smart relays and other IEDs.*
3. *Voltage recorders.*
4. *In-plant power monitors.*
5. *Special-purpose power quality monitors.*
6. *Revenue meters.*

#### **Computer Tools for Transients Analysis**

- ❖ There are two fundamental issues that need to be considered in developing a system model for harmonic simulation studies.
- ❖ The first issue is the extent of the system model to be included in the simulation.
- ❖ Secondly, one must decide whether the model should be represented as a single-phase equivalent or a full three-phase model
- ❖ The most widely used computer programs for transients analysis of power systems are the Electromagnetic Transients Program, commonly known as EMTP, and its derivatives such as the Alternate Transients Program (ATP).
- ❖ EMTP was originally developed by Hermann W. Dommel at the Bonneville Power Administration (BPA) in the late 1960s and has been continuously upgraded since.
- ❖ One of the reasons this program is popular is its low cost due to some versions being in the public domain. Some power system analysts use computer programs developed more for the analysis of electronic circuits, such as the wellknown SPICE program and its

derivatives.

- ❖ Although the programs just discussed continue to be used extensively, there are now many other capable programs available.
- ❖ Nearly all the tools for power systems solve the problem in the time domain, re-creating the waveform point by point.
- ❖ A few programs solve in the frequency domain and use the Fourier transform to convert to the time domain.
- ❖ Unfortunately, this essentially restricts the addressable problems to linear circuits.
- ❖ Time-domain solution is required to model nonlinear elements such as surge arresters and transformer magnetizing characteristics.
- ❖ The penalty for this extra capability is longer solution times, which with modern computers becomes less of a problem each day.
- ❖ It takes considerably more modeling expertise to perform electromagnetic transients studies than to perform more common power system analyses such as of the power flow or of a short circuit.
- ❖ Therefore, this task is usually relegated to a few specialists within the utility organization or to consultants.
- ❖ While transients programs for electronic circuit analysis may formulate the problem in any number of ways, power systems analysts almost uniformly favor some type of nodal admittance formulation.
- ❖ For one thing, the system admittance matrix is sparse allowing the use of very fast and efficient sparsity techniques for solving large problems.
- ❖ Also, the nodal admittance formulation reflects how most power engineers view the power system, with series and shunt elements connected to buses where the voltage is measured with respect to a single reference.
- ❖ To obtain conductances for elements described by differential equations, transients programs discretize the equations with an appropriate numerical integration formula.
- ❖ The simple trapezoidal rule method appears to be the most commonly used, but there are also a variety of Runge-Kutta and other formulations used.
- ❖ Nonlinearities are handled by iterative solution methods.
- ❖ Some programs include the nonlinearities in the general formulation, while others, such as those that follow the EMTP methodology, separate the linear and nonlinear portions of the circuit to achieve faster solutions. This impairs the ability of the program to solve some classes of nonlinear problems but is not usually a significant constraint for most power system problems.

#### **Disturbance analyzers / power line disturbance analyzer**

Disturbance analyzers and disturbance monitors form a category of instruments that have been developed specifically for power quality measurements. They typically can measure a wide variety of system disturbances from very short duration transient voltages to long-duration outages or undervoltages. Thresholds can be set and the instruments left unattended to record disturbances over a period of time. The information is most commonly recorded on a paper tape, but many devices have attachments so that it can be recorded on disk as well. There are basically two categories of these devices:

1. **Conventional analyzers** that summarize events with specific information such as overvoltage and undervoltage magnitudes, sags and surge magnitude and duration, transient magnitude and duration, etc.
2. **Graphics-based analyzers** that save and print the actual waveform along with the descriptive

information which would be generated by one of the conventional analyzers. It is often difficult to determine the characteristics of a disturbance or a transient from the summary information available from conventional disturbance analyzers. For instance, an oscillatory transient cannot be effectively described by a peak and a duration. Therefore, it is almost imperative to have the waveform capture capability of a graphics-based disturbance analyzer for detailed analysis of a power quality problem. However, a simple conventional disturbance monitor can be valuable for initial checks at a problem location.

#### **Smart power quality monitors / quality measurement equipment**

All power quality measurement instruments previously described are designed to collect power quality data. Some instruments can send the data over a telecommunication line to a central processing location for analysis and interpretation. However, one common feature among these instruments is that they do not possess the capability to locally analyze, interpret, and determine what is happening in the power system. They simply record and transmit data for post processing. Since the conclusion of the EPRI DPQ project in Fall 1995, it was realized that these monitors, along with the monitoring practice previously described, were inadequate. An emerging trend in power quality monitoring practice is to collect the data, turn them into useful information, and disseminate it to users. All these processes take place within the instrument itself. Thus, a new breed of power quality monitor was developed with integrated intelligent systems to meet this new challenge. This type of power quality monitor is an intelligent power quality monitor where information is directly created within the instrument and immediately available to the users. A smart power quality monitor allows engineers to take necessary or appropriate actions in a timely manner. Thus, instead of acting in a reactive fashion, engineers will act in a proactive fashion.

One such smart power quality monitor was developed by Electrotek Concepts, Dranetz-BMI, EPRI, and the Tennessee Valley Authority (TVA). The system features on-the-spot data analysis with rapid information dissemination via Internet technology, e-mails, pagers, and faxes. The system consists of data acquisition, data aggregation, communication, Web-based visualization, and enterprise management components.

The data acquisition component (DataNode) is designed to measure the actual power system voltages, currents, and other quantities. The data aggregation, communication, Web-based visualization, and enterprise management components are performed by a mission-specific computer system called the InfoNode. The communication between the data acquisition device and the InfoNode is accomplished through serial RS-232/485/422 or Ethernet communications using industry standard protocols (UCA MMS and Modbus). One or more data acquisition devices, or DataNodes, can be connected to an InfoNode. The InfoNode has its own firmware that governs the overall functionality of the monitoring system. It acts as a special-purpose database manager and Web server. Various special-purpose intelligent systems are implemented within this computer system. Since it is a Web server, any user with Internet connectivity can access the data and its analysis results stored in its memory system. The monitoring system supports the standard file transfer protocol (FTP). Therefore, a database can be manually archived via FTP by simply copying the database to any personal computer with connectivity to the mission-specific computer system via network or modem. Proprietary software can be used to archive data from a group of InfoNodes.

#### **Power Quality Measurement Equipment**

Although instruments have been developed that measure a wide variety of disturbances, a number of different instruments may be used, depending on the phenomena being

investigated. Basic categories of instruments that may be applicable include

- Wiring and grounding test devices
- Multimeters
- Oscilloscopes
- Disturbance analyzers
- Harmonic analyzers and spectrum analyzers
- Combination disturbance and harmonic analyzers
- Flicker meters
- Energy monitors

Besides these instruments, which measure steady-state signals or disturbances on the power system directly, there are other instruments that can be used to help solve power quality problems by measuring ambient conditions:

■ Infrared meters can be very valuable in detecting loose connections and overheating conductors. An annual procedure of checking the system in this manner can help prevent power quality problems due to arcing, bad connections, and overloaded conductors.

■ Noise problems related to electromagnetic radiation may require measurement of field strengths in the vicinity of affected equipment. Magnetic gauss meters are used to measure magnetic field strengths for inductive coupling concerns. Electric field meters can measure the strength of electric fields for electrostatic coupling concerns.

■ Static electricity meters are special-purpose devices used to measure static electricity in the vicinity of sensitive equipment. Electrostatic discharge (ESD) can be an important cause of power quality problems in some types of electronic equipment.

Regardless of the type of instrumentation needed for a particular test, there are a number of important factors that should be considered when selecting the instrument. Some of the more important factors include

- Number of channels (voltage and/or current)
- Temperature specifications of the instrument
- Ruggedness of the instrument
- Input voltage range (e.g., 0 to 600 V)
- Power requirements
- Ability to measure three-phase voltages
- Input isolation (isolation between input channels and from each input to ground)
- Ability to measure currents
- Housing of the instrument (portable, rack-mount, etc.)
- Ease of use (user interface, graphics capability, etc.)



- Documentation
- Communication capability (modem, network interface)
- Analysis software

The flexibility (comprehensiveness) of the instrument is also important. The more functions that can be performed with a single instrument, the fewer the number of instruments required

### **Spectrum analyzers and harmonic Analyzers**

Instruments in the disturbance analyzer category have very limited harmonic analysis capabilities. Some of the more powerful analyzers have add-on modules that can be used for computing fast Fourier transform (FFT) calculations to determine the lower-order harmonics.

However, any significant harmonic measurement requirements will demand an instrument that is designed for spectral analysis or harmonic analysis. Important capabilities for useful harmonic measurements include

- Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained.
- Capability to measure both magnitude and phase angle of individual harmonic components (also needed for power flow calculations).
- Synchronization and a sampling rate fast enough to obtain accurate measurement of harmonic components up to at least the 37th harmonic (this requirement is a combination of a high sampling rate and a sampling interval based on the 60-Hz fundamental).
- Capability to characterize the statistical nature of harmonic distortion levels (harmonics levels change with changing load conditions and changing system conditions).

There are basically three categories of instruments to consider for harmonic analysis:

**1. Simple meters.** It may sometimes be necessary to make a quick check of harmonic levels at a problem location. A simple, portable meter for this purpose is ideal. There are now several hand-held instruments of this type on the market. Each instrument has advantages and disadvantages in its operation and design. These devices generally use microprocessor-based circuitry to perform the necessary calculations to determine individual harmonics up to the 50th harmonic, as well as the rms, the THD, and the telephone influence factor (TIF). Some of these devices can calculate harmonic powers (magnitudes and angles) and can upload stored waveforms and calculated data to a personal computer.

**2. General-purpose spectrum analyzers.** Instruments in this category are designed to perform spectrum analysis on waveforms for a wide variety of applications. They are general signal analysis instruments. The advantage of these instruments is that they have very powerful capabilities for a reasonable price since they are designed for a broader market than just power system applications. The disadvantage is that they are not designed specifically for sampling power frequency waveforms and, therefore, must be used carefully to assure accurate harmonic analysis. There are a wide variety of instruments in this category.

**3. Special-purpose power system harmonic analyzers.** Besides the general-purpose spectrum analyzers just described, there are also a number of instruments and devices that have been designed specifically for power system harmonic analysis. These are based on the FFT with sampling rates specifically designed for determining harmonic components in power

signals. They can generally be left in the field and include communications capability for remote monitoring.

**Combination disturbance and harmonic analyzers:** The most recent instruments combine harmonic sampling and energy monitoring functions with complete disturbance monitoring functions as well. The output is graphically based, and the data are remotely gathered over phone lines into a central database. Statistical analysis can then be performed on the data. The data are also available for input and manipulation into other programs such as spreadsheets and other graphical output processors.

One example of such an instrument: This instrument is designed for both utility and end-user applications, being mounted in a suitable enclosure for installation outdoors on utility poles. It monitors three-phase voltages and currents (plus neutrals) simultaneously, which is very important for diagnosing power quality problems. The instrument captures the raw data and saves the data in internal storage for remote downloading. Off-line analysis is performed with powerful software that can produce a variety of outputs. The top chart shows a typical result for a voltage sag. Both the rms variation for the first 0.8 s and the actual waveform for the first 175 ms are shown. The middle chart shows a typical wave fault capture from a capacitor-switching operation. The bottom chart demonstrates the capability to report harmonics of a distorted waveform. Both the actual waveform and the harmonic spectrum can be obtained.

Another device is shown in Fig. 11.15. This is a power quality monitoring system designed for key utility accounts. It monitors three-phase voltages and has the capability to capture disturbances and page power quality engineers. The engineers can then call in and hear a voice message describing the event. It has memory for more than 30 events. Thus, while only a few short years ago power quality monitoring was a rare feature to be found in instruments, it is becoming much more commonplace in commercially available equipment.

#### **Flicker meters\***

Over the years, many different methods for measuring flicker have been developed. These methods range from using very simple rms meters with flicker curves to elaborate flicker meters that use exactly tuned filters and statistical analysis to evaluate the level of voltage flicker. This section discusses various methods available for measuring flicker.

**Flicker standards.** Although the United States does not currently have a standard for flicker measurement, there are IEEE standards that address flicker. IEEE Standards 141-19936 and 519-19927 both contain flicker curves that have been used as guides for utilities to evaluate the severity of flicker within their system. Both flicker curves, from Standards 141 and 519, are shown in Fig. 11.16. In other countries, a standard methodology for measuring flicker has been established. The IEC flicker meter is the standard for measuring flicker in Europe and other countries currently adopting IEC standards.

The IEC method for flicker measurement, defined in IEC Standard 61000-4-158 (formerly IEC 868), is a very comprehensive approach to flicker measurement and is further described in "Flicker Measurement Techniques" below. More recently, the IEEE has been working toward adoption of the IEC flicker monitoring standards with an additional curve to account for the differences between 230-V and 120-V systems.

**Flicker measurement techniques RMS strip charts.** Historically, flicker has been measured using rms meters, load duty cycle, and a flicker curve. If sudden rms voltage deviations occurred with specified frequencies exceeding values found in flicker curves, such as one

shown in Fig. 11.16, the system was said to have experienced flicker. A sample graph of rms voltage variations is shown in Fig. 11.17 where large voltage deviations up to 9.0 V rms ( $\frac{\Delta V}{V} \times 100$  percent on a 120-V base) are found. Upon comparing this to the flicker curve in Fig. 11.16, the feeder would be experiencing flicker, regardless of the duty cycle of the load producing the flicker, because any sudden total change in voltage greater than 7.0 V rms results in objectionable flicker, regardless of the frequency. The advantage to such a method is that it is quite simple in nature and the rms data required are rather easy to acquire. The apparent disadvantage to such a method would be the lack of accuracy and inability to obtain the exact frequency content of the flicker.

**Fast Fourier transform.** Another method that has been used to measure flicker is to take raw samples of the actual voltage waveforms and implement a fast Fourier transform on the demodulated signal (flicker signal only) to extract the various frequencies and magnitudes found in the data. These data would then be compared to a flicker curve. Although similar to using the rms strip charts, this method more accurately quantifies the data measured due to the magnitude and frequency of the flicker being known. The downside to implementing this method is associated with quantifying flicker levels when the flicker-producing load contains multiple flicker signals. Some instruments compensate for this by reporting only the dominant frequency and discarding the rest.

**Flicker meters.** Because of the complexity of quantifying flicker levels that are based upon human perception, the most comprehensive approach to measuring flicker is to use flicker meters. A flicker meter is essentially a device that demodulates the flicker signal, weights it according to established "flicker curves," and performs statistical analysis on the processed data. Generally, these meters can be divided up into three sections. In the first section the input waveform is demodulated, thus removing the carrier signal. As a result of the demodulator, a dc offset and higher-frequency terms (sidebands) are produced. The second section removes these unwanted terms using filters, thus leaving only the modulating (flicker) signal remaining. The second section also consists of filters that weight the modulating signal according to the particular meter specifications. The last section usually consists of a statistical analysis of the measured flicker. The most established method for doing this is described in IEC Standard 61000-4-15.8 The IEC flicker meter consists of five blocks, which are shown in Fig. 11.18. Block 1 is an input voltage adapter that scales the input half-cycle rms value to an internal reference level. This allows flicker measurements to be made based upon a percent ratio rather than be dependent upon the input carrier voltage level. Block 2 is simply a squaring demodulator that squares the input to separate the voltage fluctuation (modulating signal) from the main voltage signal (carrier signal), thus simulating the behavior of the incandescent lamp. Block 3 consists of multiple filters that serve to filter out unwanted frequencies produced from the demodulator and also to weight the input signal according to the incandescent lamp eye-brain response.

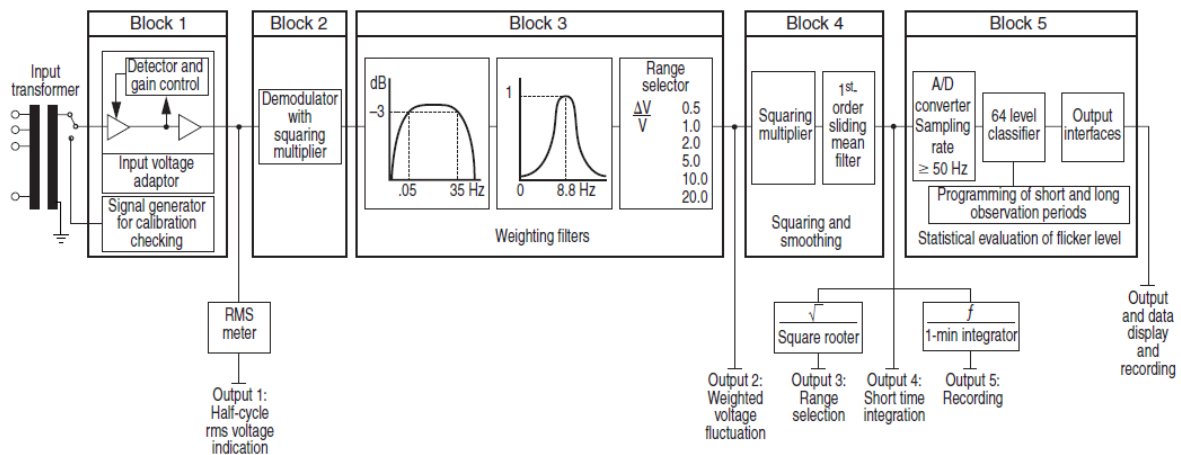


Figure 11.18 Diagram of the IEC flicker meter.

Block 4 consists of a squaring multiplier and sliding mean filter. The voltage signal is squared to simulate the nonlinear eye-brain response, while the sliding mean filter averages the signal to simulate the short term storage effect of the brain. The output of this block is considered to be the instantaneous flicker level. A level of 1 on the output of this block corresponds to perceptible flicker. Block 5 consists of a statistical analysis of the instantaneous flicker level. The output of block 4 is divided into suitable classes, thus creating a histogram. A probability density function is created based upon each class, and from this a cumulative distribution function can be formed.

### **Applications of expert systems for power quality monitoring**

Many advanced power quality monitoring systems are equipped with either off-line or on-line intelligent systems to evaluate disturbances and system conditions so as to make conclusions about the cause of the problem or even predict problems before they occur. The applications of intelligent systems or autonomous expert systems in monitoring instruments help engineers determine the system condition rapidly. This is especially important when restoring service following major disturbances. The implementation of intelligent systems within a monitoring instrument can significantly increase the value of a monitoring application since it can generate information rather than just collect data. The intelligent systems are packaged as individual autonomous expert system modules, where each module performs specific functions. Examples include an expert system module that analyzes capacitor switching transients and determines the relative location of the capacitor bank, and an expert system module to determine the relative location of the fault causing a voltage sag. Sections 11.5.1 and 11.5.2 describe the approach in designing an autonomous expert system for power quality data assessment, and give application examples.

### **Basic design of an expert system for monitoring applications**

The development of an autonomous expert system calls for many approaches such as signal processing and rule-based techniques along with the knowledge-discovery approach commonly known as data mining. Before the expert system module is designed, the functionalities or objectives of the module must be clearly defined. In other words, the designers or developers of the expert system module must have a clear understanding about what knowledge they are trying to discover from volumes of raw measurement data. This is very important since they will ultimately determine the overall design of the expert system module. The process of turning raw measurement data into knowledge involves data

selection and preparation, information extraction from selected data, information assimilation, and report presentation. These steps (illustrated in Fig. 11.30) are commonly known as knowledge discovery or data mining.

The first step in the knowledge discovery is to select appropriate measurement quantities and disregard other types of measurements that do not provide relevant information. In addition, during the data selection process preliminary analyses are usually carried out to ensure the quality of the measurement. For example, an expert system module is developed to retrieve a specific answer, and it requires measurements of instantaneous three-phase voltage and current waveforms to be available. The data-selection task is responsible for ensuring that all required phase voltage and current waveform data are available before proceeding to the next step. In some instances, it might be necessary to interpolate or extrapolate data in this step. Other preliminary examinations include checking any outlier magnitudes, missing data sequences, corrupted data, etc. Examination on data quality is important as the accuracy of the knowledge discovered is determined by the quality of data.

The second step attempts to represent the data and project them onto domains in which a solution is more favorable to discover. Signal-processing techniques and power system analysis are applied. An example of this step is to transform data into another domain where the information might be located. The Fourier transform is performed to uncover frequency information for steady-state signals, the wavelet transform is performed to find the temporal and frequency information for transient signals, and other transforms may be performed as well. Now that the data are already projected onto other spaces or domains, we are ready to extract the desired information. Techniques to extract the information vary from sophisticated ones, such as pattern recognition, neural networks, and machine learning, to simple ones, such as finding the maximum value in the transformed signal or counting the number of points in which the magnitude of a voltage waveform is above a predetermined threshold value. One example is looking for harmonic frequencies of a distorted waveform. In the second step the waveform is transformed using the Fourier transform, resulting in a frequency domain signal. A simple harmonic frequency extraction process might be accomplished by first computing the noise level in the frequency domain signal, and subsequently setting a threshold number to several fold that of the noise level. Any magnitude higher than the threshold number may indicate the presence of harmonic frequencies. The data mining step usually results in scattered pieces of information. These pieces of information are assimilated to form knowledge. In some instances assimilation of information is not readily possible since some pieces of information conflict with each other. If the conflicting information cannot be resolved, the quality of the answer provided might have limited use. The last step in the chain is interpretation of knowledge and report presentation.

#### **Example applications of expert systems**

One or more autonomous expert system modules can be implemented within an advanced power quality monitoring system. When a power quality event is captured, all modules will be invoked. Each module will attempt to discover the unique knowledge it is designed to look for. Once the unique knowledge is discovered, the knowledge will be available for users to inspect. The knowledge can be viewed on a standard browser, or sent as an e-mail, pager, or fax message. We present a few examples of autonomous expert systems.

**Voltage sag direction module.** Voltage sags are some of the most important disturbances on

utility systems. They are usually caused by a remote fault somewhere on the power system; however, they can also be caused by a fault inside end-user facilities. Determining the location of the fault causing the voltage sag can be an important step toward preventing voltage sags in the future and assigning responsibility for addressing the problem. For instance, understanding the fault location is necessary for implementing contracts that include voltage sag performance specifications. The supplier would not be responsible for sags that are caused by faults within the customer facility. This is also important when trying to assess performance of the distribution system in comparison to the transmission system as the cause of voltage sag events that can impact customer operations. The fault locations can help identify future problems or locations where maintenance or system changes are required. An expert system to identify the fault location (at least upstream or downstream from the monitoring location) can help in all these cases. An autonomous expert system module called the voltage sag direction module is designed just for that purpose, i.e., to detect and identify a voltage sag event and subsequently determine the origin (upstream or downstream from the monitoring location) of the voltage sag event.

If a data acquisition node is installed at a customer PCC, the source of the voltage sag will be either on the utility or the customer side of the meter. If the monitoring point is at a distribution substation transformer, the source of the voltage sag will be either the distribution system or the transmission system.

The voltage sag direction module works by comparing current and voltage rms magnitudes both before and after the sag event. It tracks phase angle changes from prefault to postfault. By assembling information from the rms magnitude comparison and the phase angle behavior, the origin of the voltage sag event can be accurately determined.

In addition, the voltage sag direction module is equipped with algorithms to assess the quality of the knowledge or answer discovered. If the answer is deemed accurate, it will be sent as an output; otherwise, it will be neglected and no answer will be provided. In this way, inaccurate or false knowledge can be minimized. Inaccurate knowledge can be due to a number of factors, primarily to missing data and unresolved conflicting characteristics. Outputs of the voltage sag direction module can be displayed on a computer screen using Web browser software, displayed in printed paper format, sent to a pager, or sent as an e-mail. Figure 11.31 shows an output of a voltage sag direction expert system module. The first column indicates the event time, the second column indicates the monitor identification, the third column indicates event types, the fourth column indicates the triggered channel, and finally the fifth column indicates the characteristics of the event and outputs of the answer module.

**Radial fault locator module.** Radial distribution feeders are susceptible to various short-circuit events such as symmetrical faults (three-phase) and unsymmetrical faults, including single-line-to-ground, double line-to-ground, and line-to-line faults. These system faults arise from various conditions ranging from natural causes such as severe weather conditions and animal contacts to human intervention and errors, including equipment failure. Quickly identifying the source and location of faults is the key to cost-efficient system restoration. The current practice to locate the faults is to send a lineperson to patrol the suspected feeders. While this is a proven method, it is certainly not a cost effective way to restore power. An expert system module called the radial fault locator is developed to estimate the distance to a fault location from the location where the measurements were made. The unique feature of this module is that it only requires a set of three-phase voltages and

currents from a single measurement location with the sequence impedance data of the primary distribution feeder. The module works by first identifying a permanent fault event based on the ground fault and phase fault pickup current threshold. Users can enter these values in the answer module setup window shown in Fig. 11.33. Once a permanent fault event is identified, the distance to fault estimation is carried out based on the apparent impedance approach.<sup>13</sup> Estimates of the distance to the fault are then displayed in a computer screen with the Web browser illustrated in Fig. 11.34 or sent to a lineperson via a pager. The lineperson can quickly pinpoint the fault location. This example illustrates the emerging trend in smart power quality monitoring, i.e., collect power quality data and extract and formulate information for users to perform necessary actions.

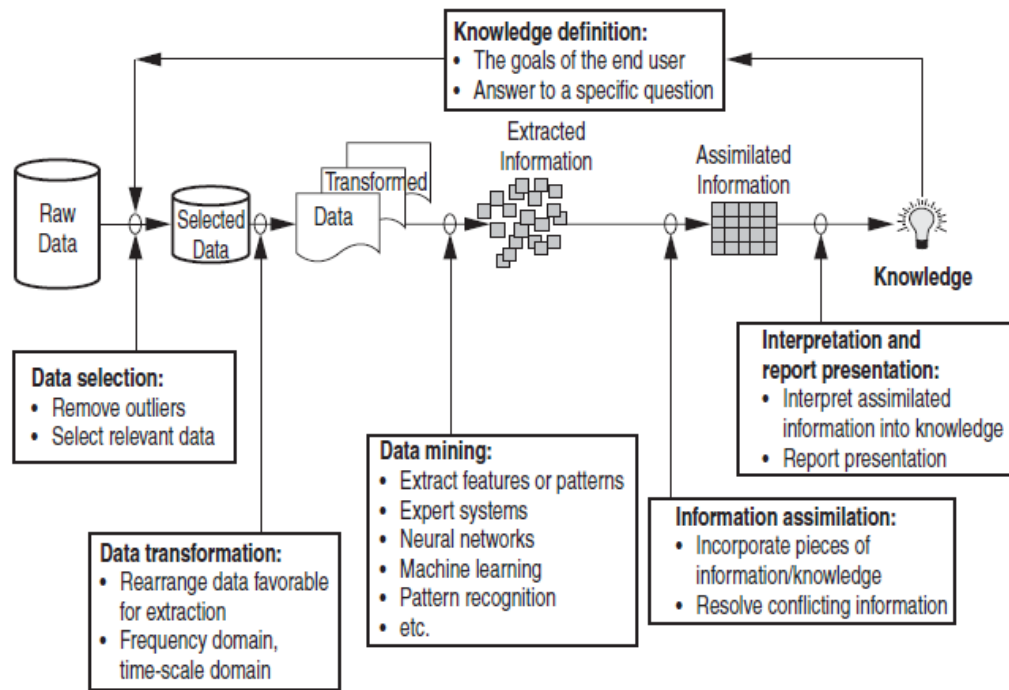
**Capacitor-switching direction module.** Capacitor-switching operations are the most common cause of transient events on the power system. When a capacitor bank is energized, it interacts with the system inductance, yielding oscillatory transients. The transient overvoltage in an uncontrolled switching is between 1.0 to 2.0 pu with typical overvoltages of 1.3 to 1.4 pu and frequencies of 250 to 1000 Hz. Transients due to energizing utility capacitor banks can propagate into customer facilities. Common problems associated with the switching transients include tripping off sensitive equipment such adjustable-speed drives and other electronically controlled loads. Some larger end-user facilities may also have capacitor banks to provide reactive power and voltage support as well.

When a sensitive load trips off due to capacitor-switching transients, it is important to know where the capacitor bank is, whether it is on the utility side or in the customer facility. A capacitor-switching direction expert system module is designed to detect and identify a capacitor switching event and determine the relative location of the capacitor bank from the point where measurements were collected. It only requires a set of three-phase voltages and currents to perform the tasks mentioned. This module is useful to determine the responsible parties, i.e., the utility or customer, and help engineers pinpoint the problematic capacitor bank.

The capacitor-switching transient direction module works as follows. When an event is captured, the module will extract the information and represent it in domains where detection and identification are more favorable. The domains where the information is represented are in the time-, frequency-, and time-scale (wavelet) domains. If the root cause of the event is due to a capacitor bank energization, the answer module will proceed to determine the most probable location of the capacitor bank.

There are only two possible locations with respect to the monitoring location, i.e., upstream or downstream. The expert system module works well with grounded, ungrounded, delta-configured, and wye- (or star-) configured capacitor banks. It also works well for back-to-back capacitor banks. The capacitor-switching transient direction module is equipped with algorithms to determine the quality of the information it discovers. Thus, the module may provide an undetermined answer. This answer is certainly better than an incorrect one. An example application of the answer module to analyze data capture from a data acquisition node installed at an office complex service entrance is shown in Fig. 11.35. The analysis results are shown in Fig. 11.36, which is a screen capture from a standard Web browser. Since the office complex has no capacitor banks, any capacitor-switching transients must originate from the utility side located upstream from the data acquisition node. The module correctly determines the relative location of the capacitor bank. Note that there are some instances where the expert system was not able to determine the relative location of the

capacitor bank. From the time stamp of the events, it is clear that capacitor bank energizations occur at about 5:00 A.M. and 7:00 P.M. each day.



**Capacitor-switching operation inspection module.** As described, capacitor-switching transients are the most common cause of transient events on the power system and are results of capacitor bank energization operation. One common thing that can go wrong with a capacitor bank is for a fuse to blow. Some capacitor banks may not be operating properly for months before utility personnel notice the problem. Routine maintenance is usually performed by driving along the line and visually inspecting the capacitor bank. An autonomous expert system was developed for substation applications to analyze downstream transient data and determine if a capacitor-switching operation is performed successfully and display a warning message if the operation was not successful. With the large number of capacitor banks on most power systems, this expert system module can be a significant benefit to power systems engineers in identifying problems and correlating them with capacitor-switching events. Successful capacitor bank energization is characterized by a uniform increase of kvar on each phase whose total corresponds to the capacitor kvar size. For example, when a 1200-kvar capacitor bank is energized, reactive power of approximately 400 kvar should appear on each phase. The total kvar increase can be determined by computing kvar changes in individual phases from the current and voltage waveforms before and after the switching operation. This total computed kvar change is then compared to the actual or physical capacitor bank kvar supplied by a user. If the expected kvar was not realized, the capacitor bank or its switching device may be having some problems.

Figure 11.37 shows the application of the capacitor-switching operation inspector expert system in a commercial monitoring system. The monitoring location is at the substation;



thus, all capacitor banks along the feeders are downstream from the monitoring location. The first capacitor-switching event indicates that two phases of the capacitor are out of service. Either the fuses have blown or the switch is malfunctioning. The second event shows a successful capacitor-switching operation.

**Lightning correlation module.** The majority of voltage sags and outages in the United States are attributed to weather-related conditions such as thunderstorms. For example, TVA has approximately 17,000 mi of transmission lines where lightning accounts for as much as 45 percent of the faults on their system. The lightning correlation expert system module is designed to correlate lightning strikes with measured power quality events and make that information available in real time directly at the point of measurement. Armed with the correlation results, engineers can evaluate the cause and impact of voltage sags for a specific customer at a specific monitoring point as well as evaluate the impact on all customers for a given event. When the lightning correlation module detects a voltage sag or transient event, it queries a lightning database via the Internet. The lightning data are provided by the U.S. National Lightning Detection Network operated by Global Atmospheric, Inc. If the query returns a result set, the lightning correlation module will store this information in the monitoring system database along with the disturbance data for information dissemination. The lightning data include the event time of the strike, the latitude and longitude of strike location, the current magnitude, and number of strokes.

#### **Future applications Industrial power quality monitoring applications**

- Energy and demand profiling with identification of opportunities for energy savings and demand reduction

- Harmonics evaluations to identify transformer loading concerns, sources of harmonics, problems indicating misoperation of equipment (such as converters), and resonance concerns associated with power factor correction

- Voltage sag impacts evaluation to identify sensitive equipment and possible opportunities for process ride-through improvement

- Power factor correction evaluation to identify proper operation of capacitor banks, switching concerns, resonance concerns, and optimizing performance to minimize electric bills

- Motor starting evaluation to identify switching problems, inrush current concerns, and protection device operation

- Short-circuit protection evaluation to evaluate proper operation of protective devices based on short-circuit current characteristics, time-current curves, etc.

#### **Power system performance assessment and benchmarking**

- Trending and analysis of steady-state power quality parameters (voltage regulation, unbalance, flicker, harmonics) for performance trends, correlation with system conditions (capacitor banks, generation, loading, etc.), and identification of conditions that need attention

- Voltage sag characterizing and assessment to identify the cause of the voltage sags (transmission or distribution) and to characterize the events for classification and analysis (including aggregation of multiple events and identification of subevents for analysis with respect to protective device operations)

- Capacitor-switching characterization to identify the source of the transient (upline or downline), locate the capacitor bank, and characterize the events for database management and analysis

- Performance index calculations and reporting for system benchmarking purposes and for prioritizing of system maintenance and improvement investments

**Applications for system maintenance, operations, and reliability**

- Locating faults. This is one of the most important benefits of the monitoring systems. It can improve response time for repairing circuits dramatically and also identify problem conditions related to multiple faults over time in the same location.

- Capacitor bank performance assessment. Smart applications can identify fuse blowing, can failures, switch problems (restrikes, reignitions), and resonance concerns.

- Voltage regulator performance assessment to identify unusual operations, arcing problems, regulation problems, etc.

- Distributed generator performance assessment. Smart systems should identify interconnection issues, such as protective device coordination problems, harmonic injection concerns, islanding problems, etc.

- Incipient fault identifier. Research has shown that cable faults and arrester faults are often preceded by current discharges that occur weeks before the actual failure. This is an ideal expert system application for the monitoring system.

- Transformer loading assessment can evaluate transformer loss of life issues related to loading and can also include harmonic loading impacts in the calculations.

- Feeder breaker performance assessment can identify coordination problems, proper operation for short-circuit conditions, nuisance tripping, etc.

**Power quality monitoring and the Internet**

Many utilities have adopted power quality monitoring systems to continuously assess system performance and provide faster response to system problems. It is clear that intranet and Internet access to the information has been key to the success of these systems. An example of a completely Web based power quality monitoring system is the result of research initiated by TVA and EPRI (Fig. 11.40). Specifications for the system were developed with the help of all the members of the EPRI Power Quality Target group to support the variety of applications which must be supported by such a system. The result was a modular system with a completely open architecture so that it can be interfaced with a wide variety of platforms. After helping with the development of the system, TVA is deploying the Web-based monitoring systems at important customers and substations throughout their system. TVA distributors are also taking advantage of the system. It already had an extensive power quality monitoring system in place, and the new system is integrated with the existing monitoring system infrastructure at the central data management level (enterprise level), as illustrated in Fig. 11.41. This provides the capability to provide systemwide analysis of the power quality information.

The future of these systems involves integration with other data-collection devices in the substation and the facility. Standard interfaces like the Power Quality Data Interchange Format (PQDIF) and COMTRADE are used to share the information, and standard protocols like UCA are used for the communications. The intelligent applications described

will be applied at both the substation level and at the enterprise level, as appropriate