Day-3
Power Quality & Custom Power

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Power Quality (PQ)

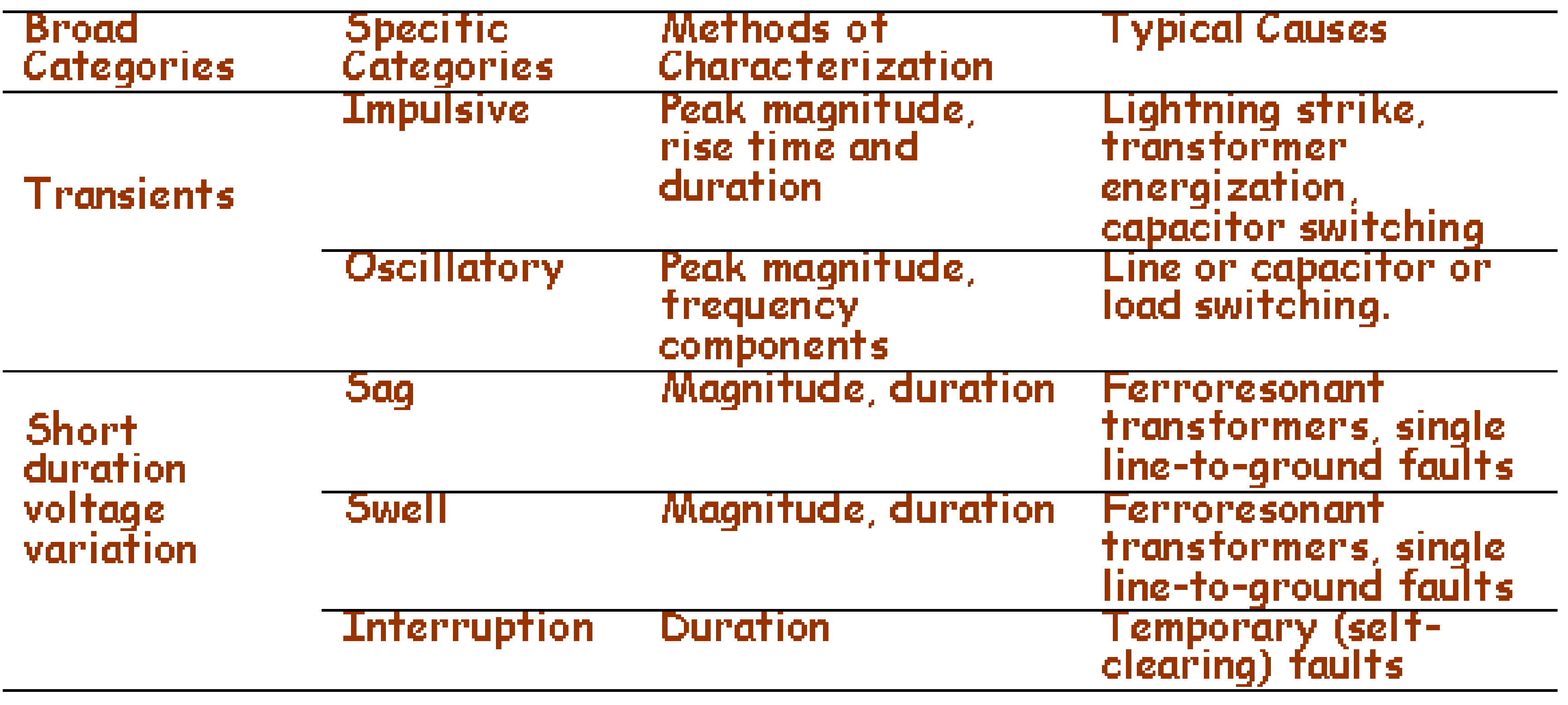
- The term *electric power quality* broadly refers to maintaining a near sinusoidal power distribution bus voltage at rated magnitude and frequency.
- In addition, the energy supplied to a customer must be uninterrupted from the reliability point of view.
- It is to be noted that even though power quality (PQ) is mainly a distribution system problem, power transmission systems may also have an impact on the quality of power.

Causes of PQ Deterioration

They can be divided into two categories.

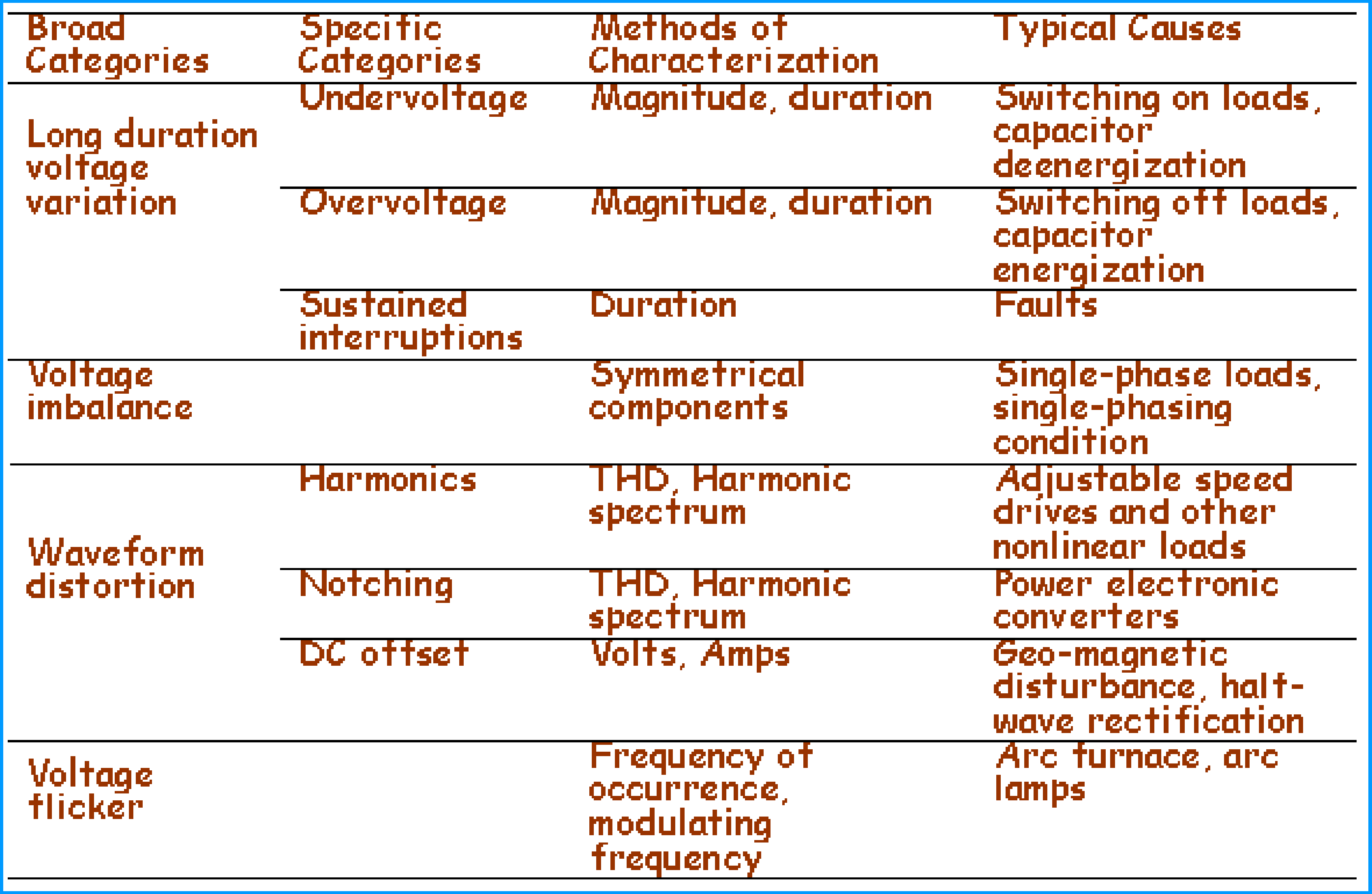
- **Natural Causes:** Faults or lighting strikes on transmission lines or distribution feeders, falling of trees or branches on distribution feeders during stormy conditions, equipment failure etc.
- **Due to Load or Transmission Line/Feeder Operation:** Transformer energization, capacitor or feeder switching, power electronic loads (UPS, ASD, converters etc.), arc furnaces and induction heating systems, switching on or off of large loads etc.

PQ Problems and Causes



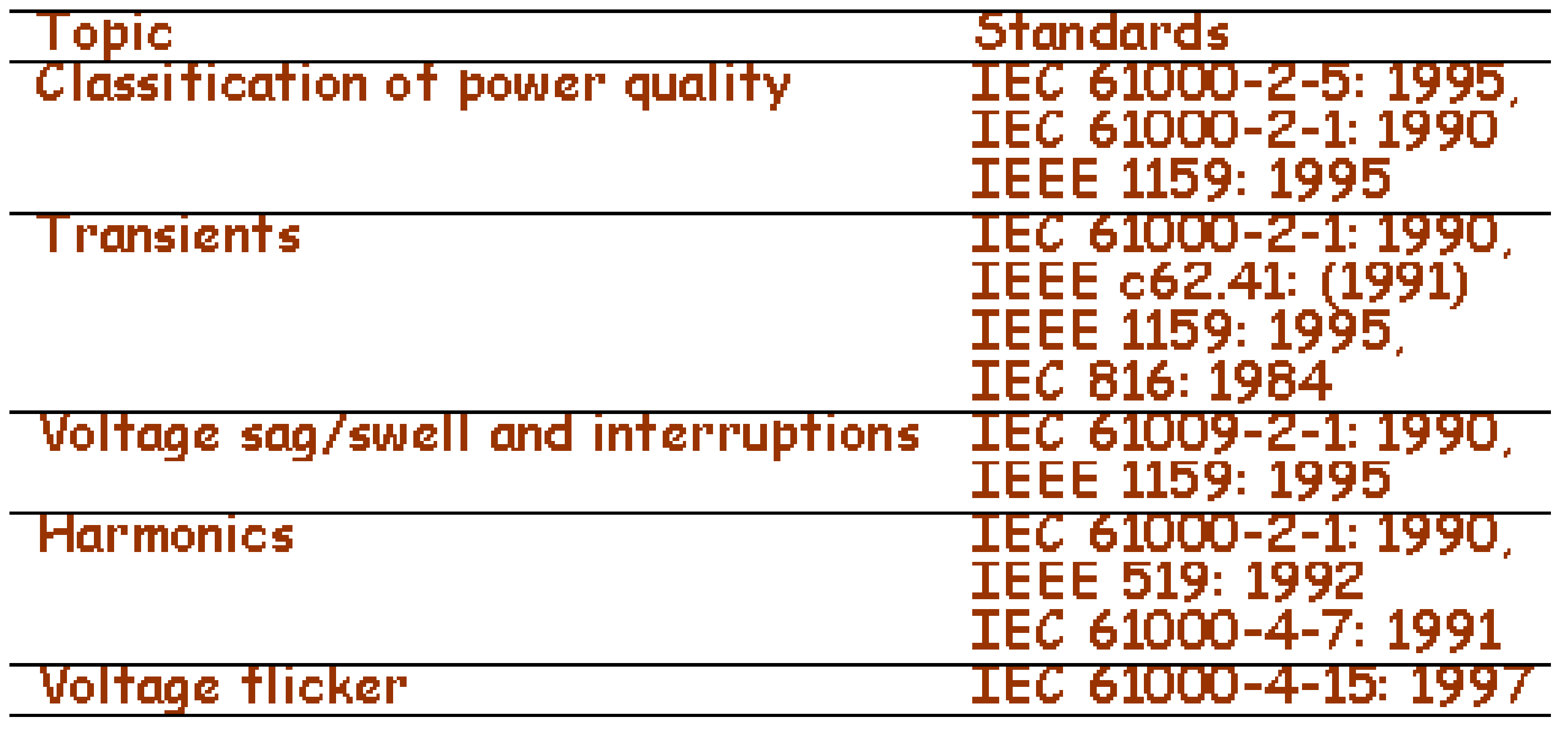
Broad Categories	Specific Categories	Methods of Characterization	Typical Causes
Transients	Impulsive	Peak magnitude, rise time and duration	Lightning strike, transformer energization, capacitor switching
	Oscillatory	Peak magnitude, frequency components	Line or capacitor or load switching.
Short duration voltage variation	Sag	Magnitude, duration	Ferroresonant transformers, single line-to-ground faults
	Swell	Magnitude, duration	Ferroresonant transformers, single line-to-ground faults
	Interruption	Duration	Temporary (self-clearing) faults

PQ Problems and Causes



Broad Categories	Specific Categories	Methods of Characterization	Typical Causes
Long duration voltage variation	Undervoltage	Magnitude, duration	Switching on loads, capacitor deenergization
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization
	Sustained interruptions	Duration	Faults
Voltage imbalance		Symmetrical components	Single-phase loads, single-phasing condition
Waveform distortion	Harmonics	THD, Harmonic spectrum	Adjustable speed drives and other nonlinear loads
	Notching	THD, Harmonic spectrum	Power electronic converters
	DC offset	Volts, Amps	Geo-magnetic disturbance, half-wave rectification
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnace, arc lamps

PQ Standards



Topic	Standards
Classification of power quality	IEC 61000-2-5: 1995, IEC 61000-2-1: 1990 IEEE 1159: 1995
Transients	IEC 61000-2-1: 1990, IEEE c62.41: (1991) IEEE 1159: 1995, IEC 816: 1984
Voltage sag/swell and interruptions	IEC 61009-2-1: 1990, IEEE 1159: 1995
Harmonics	IEC 61000-2-1: 1990, IEEE 519: 1992 IEC 61000-4-7: 1991
Voltage flicker	IEC 61000-4-15: 1997

PQ Monitoring

- Power quality variations are classified as either ***disturbances*** or ***steady state variations***.
- **Disturbances** pertain to abnormalities in the system voltages or currents due to fault or some abnormal operations.
- **Steady state variations** refer to rms deviations from the nominal quantities or harmonics.
- Power quality variations are monitored by disturbance analyzers, voltage recorders, harmonic analyzers etc.

PQ Monitoring

- The input data for any power quality monitoring device is obtained through transducers like CT, PT, Hall-effect transducers etc.
- Disturbance analyzers and disturbance monitors are instruments that are specifically designed for power quality measurements.
- There are two categories of these devices – conventional analyzers and graphics-based analyzers.

PQ Monitoring

- Conventional analyzers provide information like magnitude and duration of sag/swells, under/overvoltages etc.
- Graphic-based analyzers are equipped with memory such that the real-time data can be saved.
- The advantage of this device is that the saved data can be analyzed later to determine the source and cause of the power quality problems.
- These analyzers can also graphically present the real-time data.

PQ Monitoring

- Harmonic data are analyzed with the help of DSP-based harmonic or spectrum analyzers. They can perform fast Fourier transform (FFT) by sampling real-time data.
- These analyzers can simultaneously measure the voltage and currents such that harmonic power can be computed.
- They can also sample the signals at a very high rate such that harmonics up to about 50th order can be determined.

PQ Monitoring

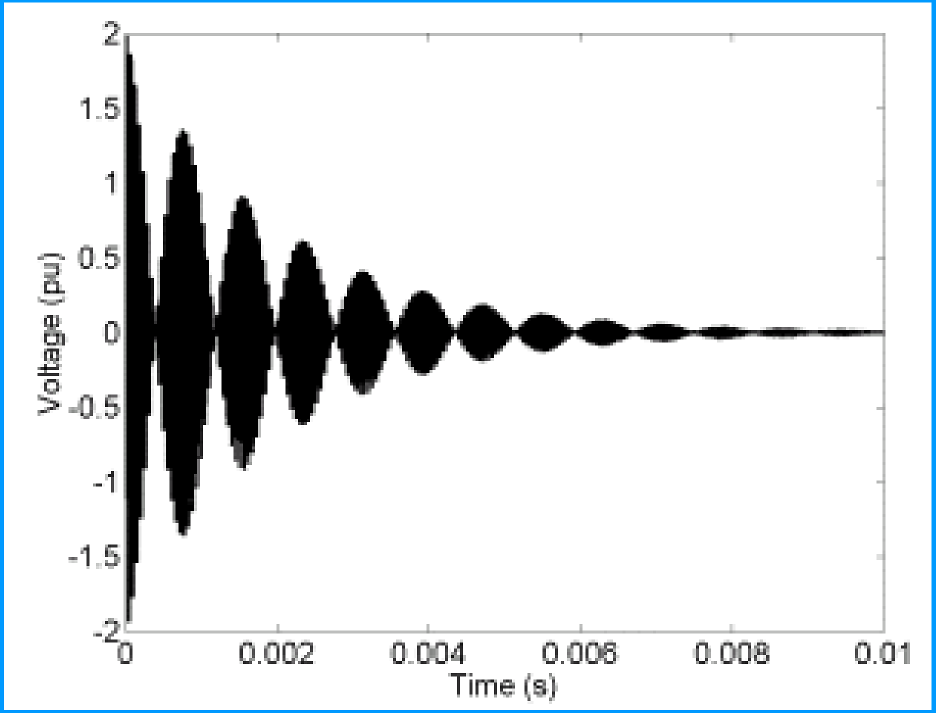
- Flicker monitoring is done through IEC flickermeter.
- These meters measure the instantaneous flickering voltage. This is called the instantaneous flicker level (IFL).
- The recorded IFL is then stored and statistical operations on these data are performed to determine short term (10 min) flicker severity index and long term flicker severity index.

PQ Terms and Definitions

- Transients
- Short duration voltage variations
- Long duration voltage variations
- Voltage imbalance
- Waveform distortions
- Voltage fluctuations
- Power frequency variations

Transients

- Transients are of two types – impulsive and oscillatory transients.

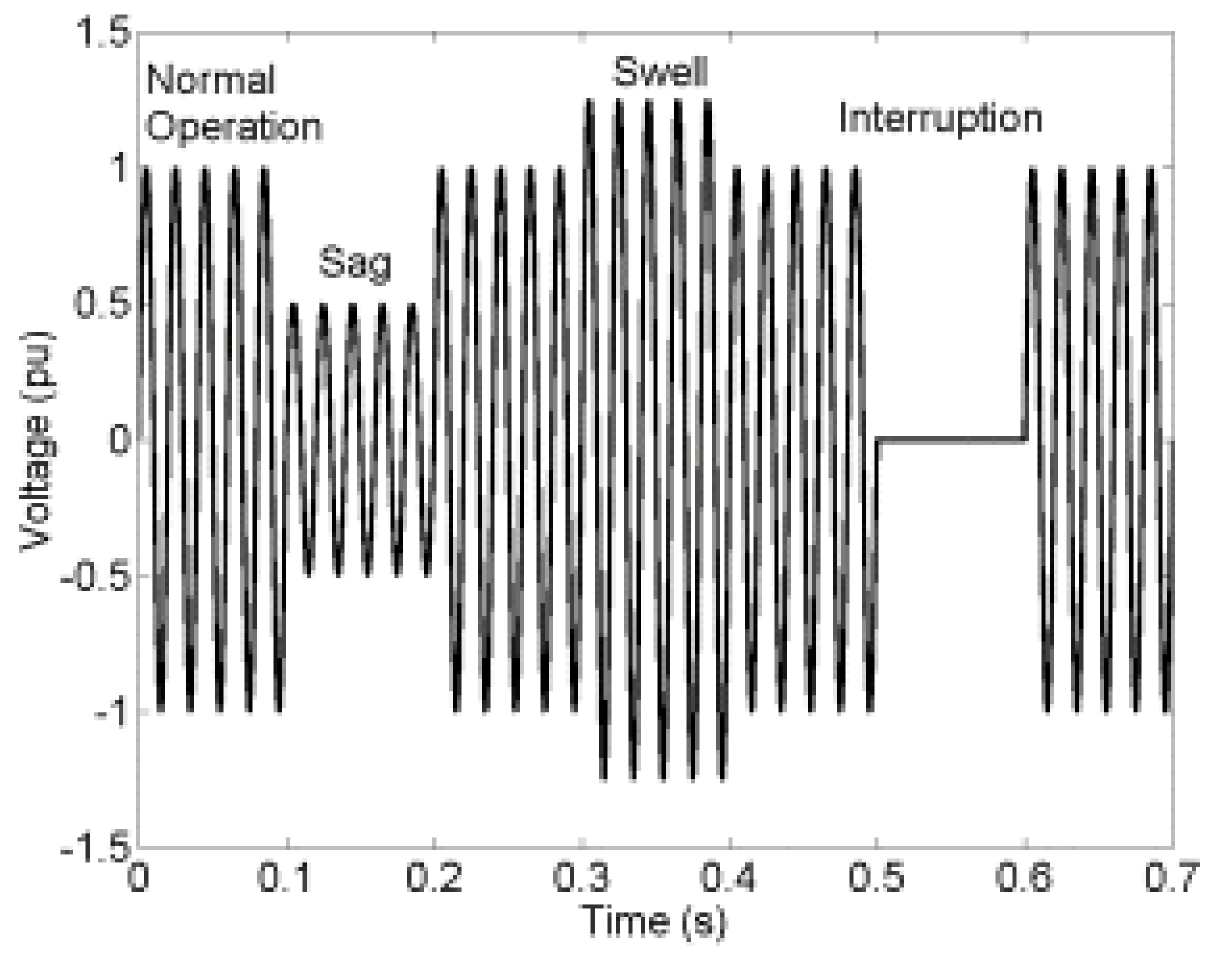


- Impulsive transients like lightning are unipolar in nature.
- Oscillatory transients are bipolar and are caused by transformer energization, capacitor or converter switching etc.

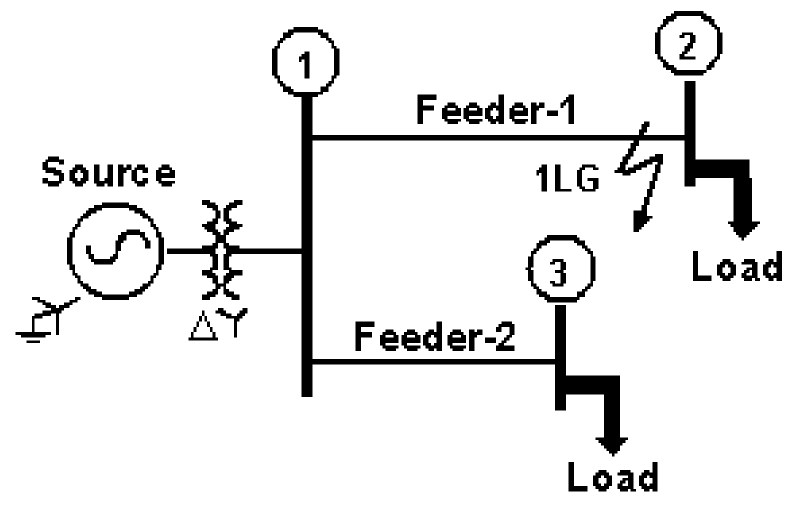
Short Duration Voltage Variations

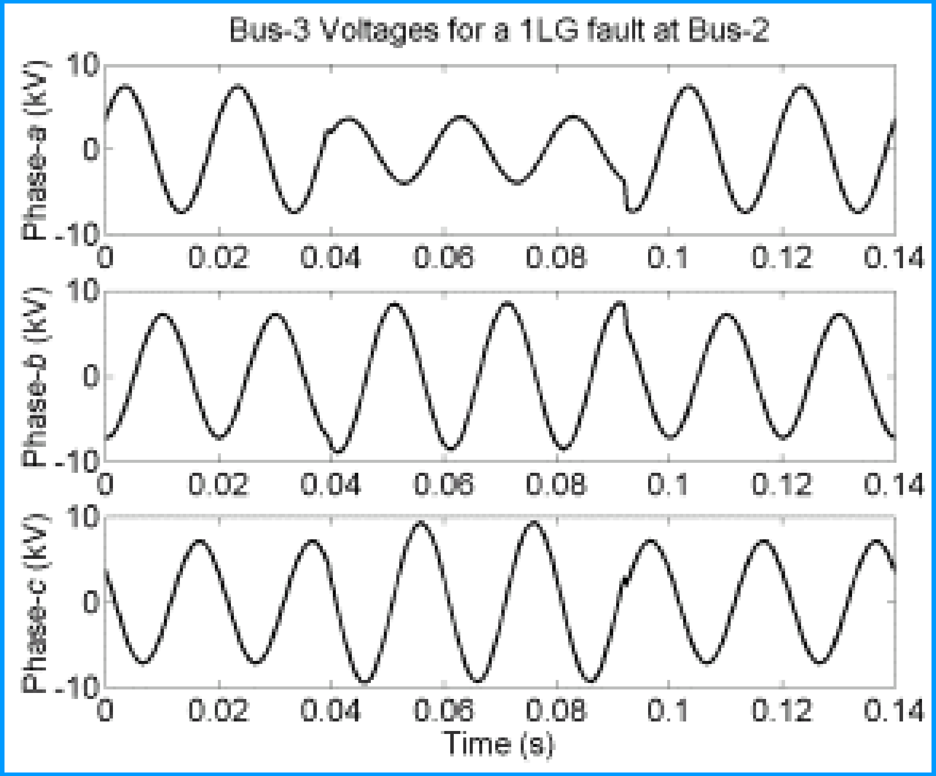
- **Voltage sag** is a fundamental frequency decrease in the supply voltage for a short duration (5 cycles to one minute).
- **Voltage swell** is defined as the increase of fundamental frequency voltage for a short duration.
- An **interruption** occurs when the supply voltage (or load current) decreases to less than 0.1 per unit for a period of time not exceeding 1 minute.

Voltage Sag, Swell & Interruption



Example of Sag and Swell





- A 1LG fault is created at 0.04 s in Feeder-1.
- While phase-a voltage sags, the other two phases swells.

Long Duration Voltage Variations

- These are the rms variations in the supply voltage at fundamental frequency for periods exceeding 1 minute.
- Classifications:
  - *overvoltages*
  - *undervoltages*
  - *sustained interruptions*
- An **overvoltage** (or **undervoltage**) is a 10% or more increase (or decrease) in rms voltage for more than 1 minute.

Long Duration Voltage Variations

- In a weak system the switching off of a large load or the energization of a large capacitor bank may result in an overvoltage.
- An undervoltage is the result of an event, which is a reverse of the event that causes overvoltage.
- The term *brownout* is often referred as sustained periods of undervoltage due to utility strategy to reduce power demand.

Long Duration Voltage Variations

- When the supply voltage is zero for a period of time in excess of 1 minute, the long duration voltage variation is called **sustained interruption**.
- Typical causes of sustained interruptions vary from place to place.
- Human intervention is required during sustained interruptions for repair and restoration.

Voltage Imbalance

- This is the condition in which the voltages of the three phases of the supply are not equal in magnitude or equally displaced in time.
- The primary cause is the single-phase loads in three-phase circuits. These are however restricted to within 5%.
- Severe imbalance (greater than 5%) can result during single phasing conditions when the protection circuit opens up one phase of a three-phase supply.

Waveform Distortion

- Classifications:
  - Dc offset
  - harmonics
  - notching
- The major causes of *dc offsets* are geomagnetic disturbance and half-wave rectification.
- The offsets due to geomagnetic disturbances are especially severe in higher latitudes.
- Poor grounding can also result in dc offsets.
- Effects: Transformer saturation and heating.

Harmonics

- Classifications:
    - Integer harmonics
    - Subharmonics
    - Interharmonics
- For a fundamental frequency of f_0, **integer harmonics** have frequency components that are integer multiples of f_0, i.e., nf_0, where n is a positive integer.
- Causes of integer harmonics are power electronic equipment and loads, like ASD, UPS etc.

Harmonics

- **Subharmonics** are those components that are below the fundamental component, i.e., mf_0 for $0 < m < 1$.
- **Interharmonics** are those components that are above fundamental component but are not integer multiple of the fundamental frequency, i.e., mf_0 for non-integer $m > 1$.
- Cycloconverters mainly cause interharmonics.
- Interharmonics are rather difficult to detect.
- Harmonics can cause damages to power apparatus and appliances.

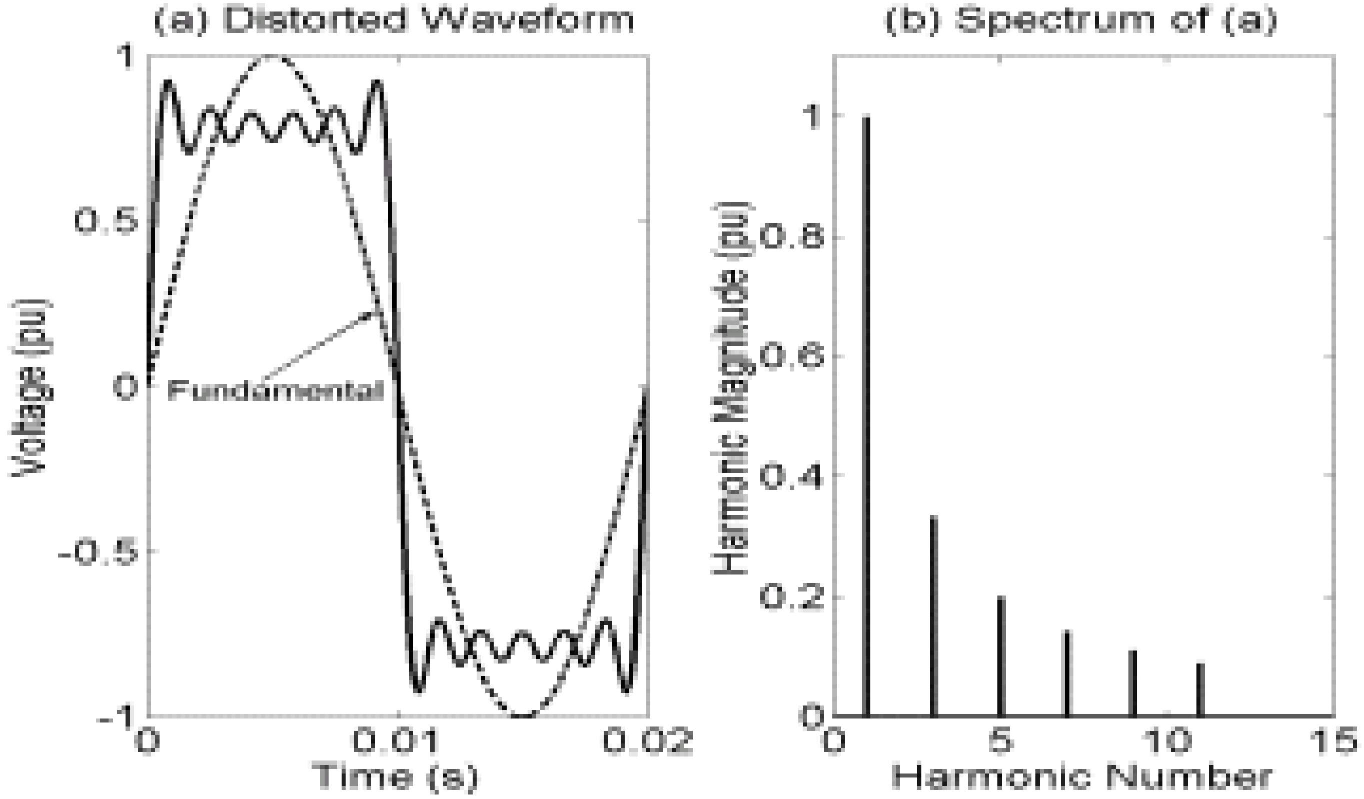
Harmonics (THD)

A measure of harmonic content in a signal is the ***total harmonic distortion*** (***THD***). The percentage *THD* in a voltage is given by

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1}$$

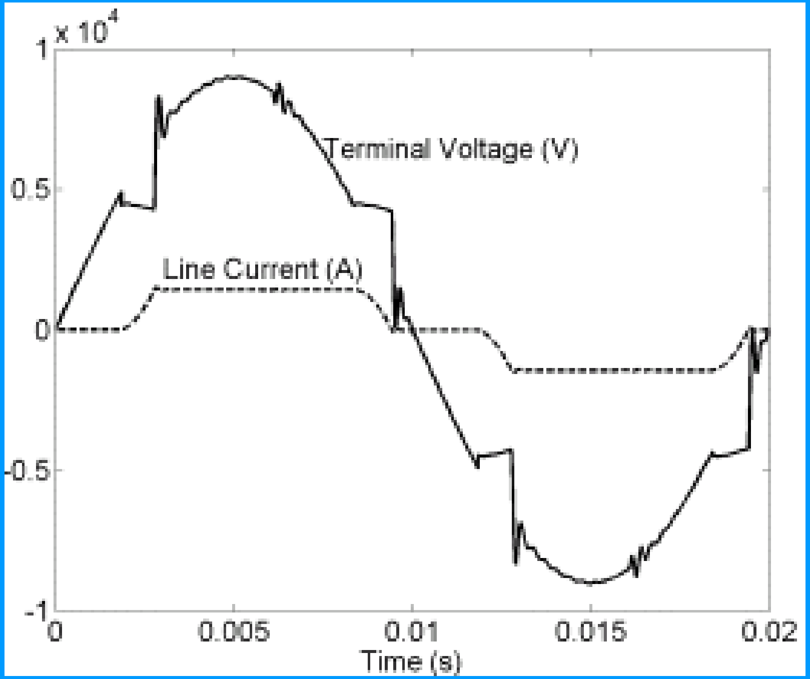
where V_n denotes the magnitude of the n^{th} harmonic voltage and V_1 is the magnitude of the fundamental voltage

Harmonics Spectrum



$$THD = 43.83\%$$

Notching



- Cause: operation of power electronic converters.
- Occurs when current commutates from one phase to other causing a momentary short circuit between the two phases.
- The frequency components that are associated with notches are usually very high.
- The maximum voltage during notches depends on the system impedance.

Voltage Fluctuations

- These are systematic random variations in supply voltages.
- A very rapid change in the supply voltage is called ***voltage flicker***.
- This is caused by rapid variations in current magnitude of loads such as arc furnaces in which a large inrush current flows when the arc strikes first causing a dip in the bus voltage.
- Other customers that are connected to the same bus face regular severe voltage drops.

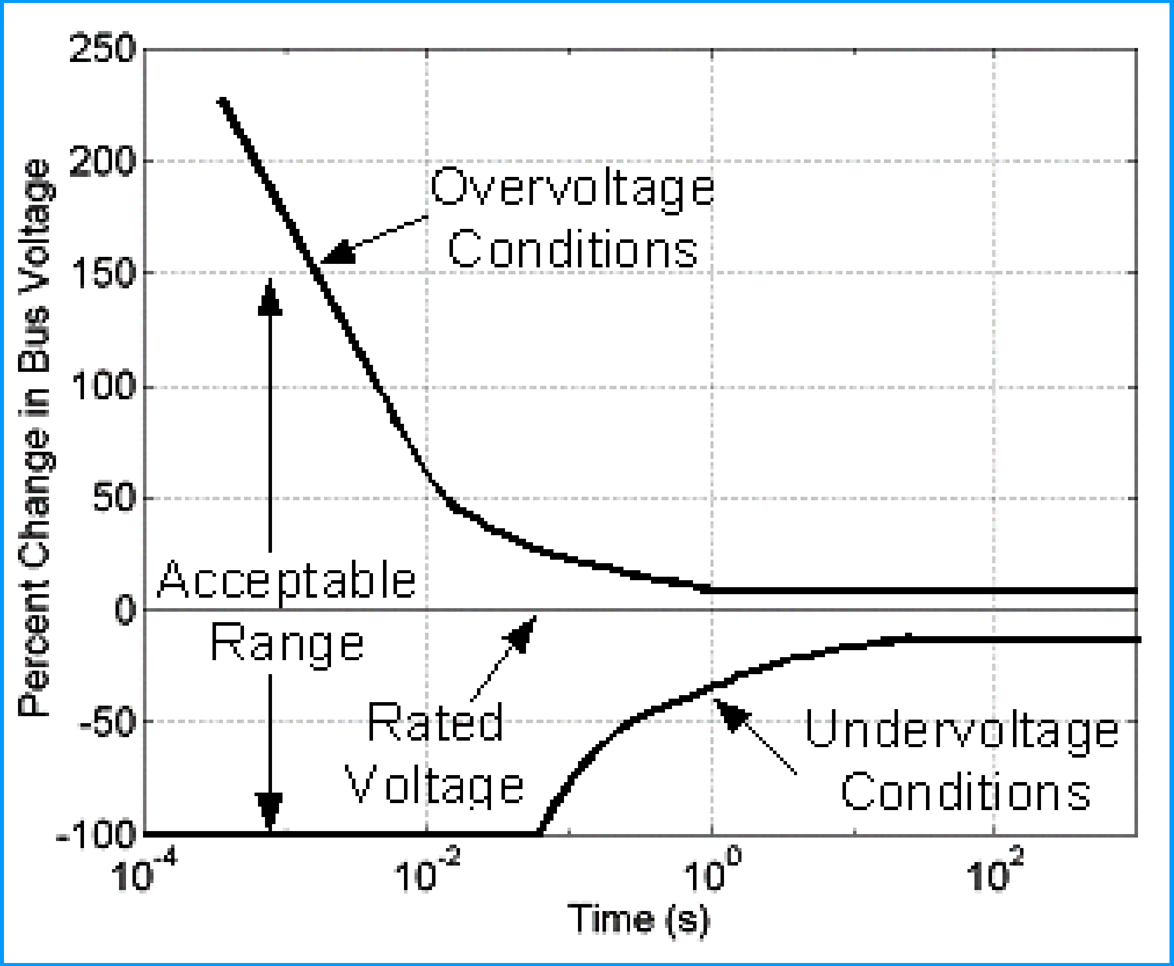
Frequency variations

- These variations are usually caused by rapid changes in the load connected to the system.
- The maximum tolerable variation in supply frequency is often limited within ± 0.5 Hz. From the nominal frequency of 50 or 60 Hz.
- The frequency is directly related to the rotational speed of the generators.
- Thus a sustained operation outside the tolerable frequency range may reduce the life span of turbine blades on the shaft.

Power Acceptability Curves

- These curves quantify the acceptability of supply power as a function of duration versus magnitude of bus voltage disturbances.
- Most popular curve was originally developed by Computer Business Equipment Manufacturers Association (CBEMA) to set limits to the withstanding capabilities of computers.
- The CBEMA curve has however become a de facto standard for measuring the performance of all types of equipment and power systems.

CBEMA Curve



250
200
150
100
50
0
-50
-100
Percent Change in Bus Voltage
Overvoltage Conditions
Acceptable Range
Rated Voltage
Undervoltage Conditions
10^{-4}
10^{-2}
10^{0}
10^{2}
Time (s)

CBEMA Curve

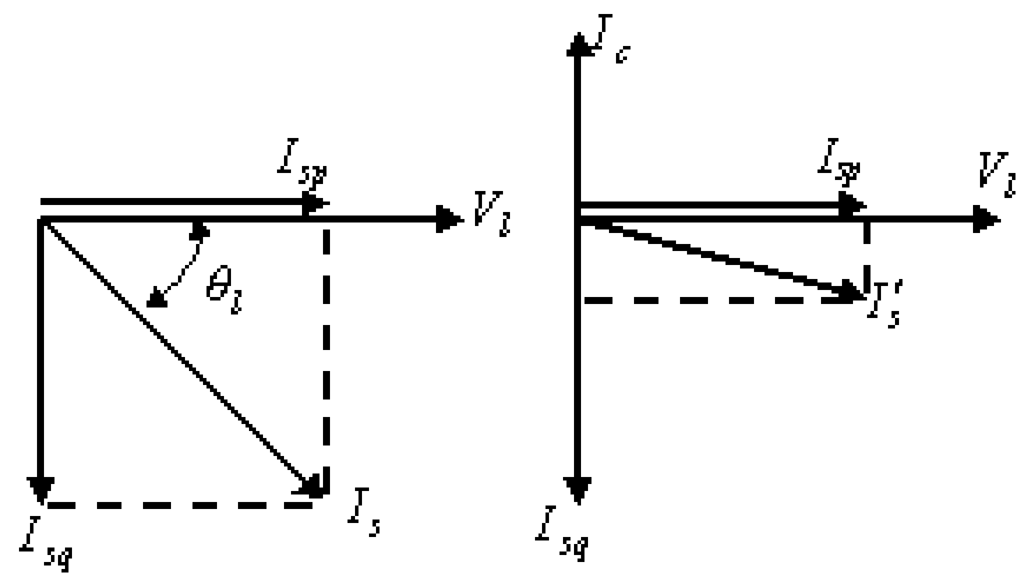
- In the CBEMA curve there are two traces – one for overvoltage and the other for undervoltage.
- These show the percent bus voltage deviation from the rated voltage against time.
- The region below the upper trace and above the lower trace is the acceptable range. This region defines the tolerance level.
- Example an overvoltage of very short duration can be tolerable if it is in the acceptable region.

PQ Problems

Some of the major concerns of both customers and utility are

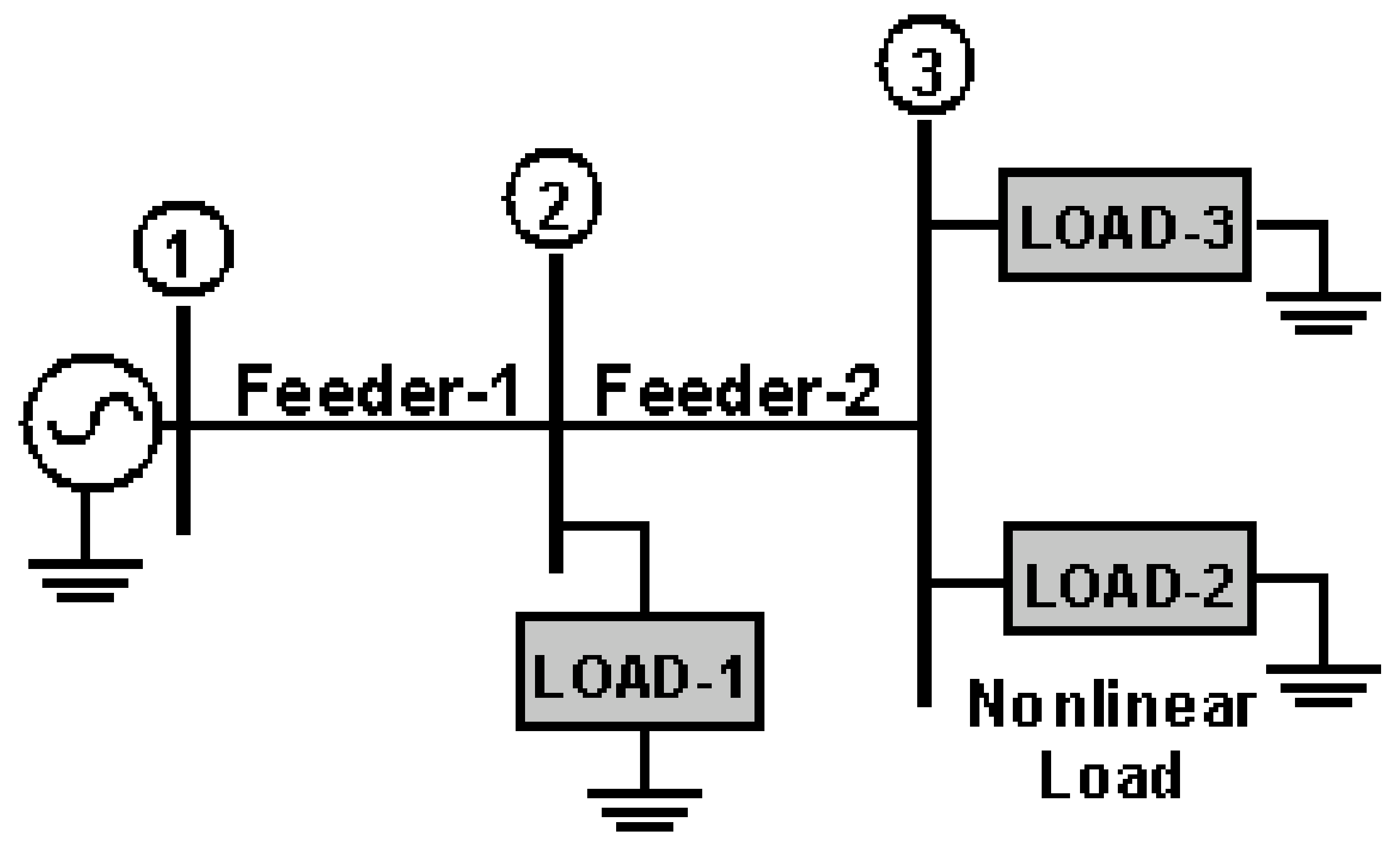
- Poor load power factor
- Harmonic contents in loads
- Notching in load voltages
- Dc offset in load voltages
- Unbalanced loads
- Supply voltage distortion
- Voltage sag/swell
- Voltage flicker

Load Power Factor



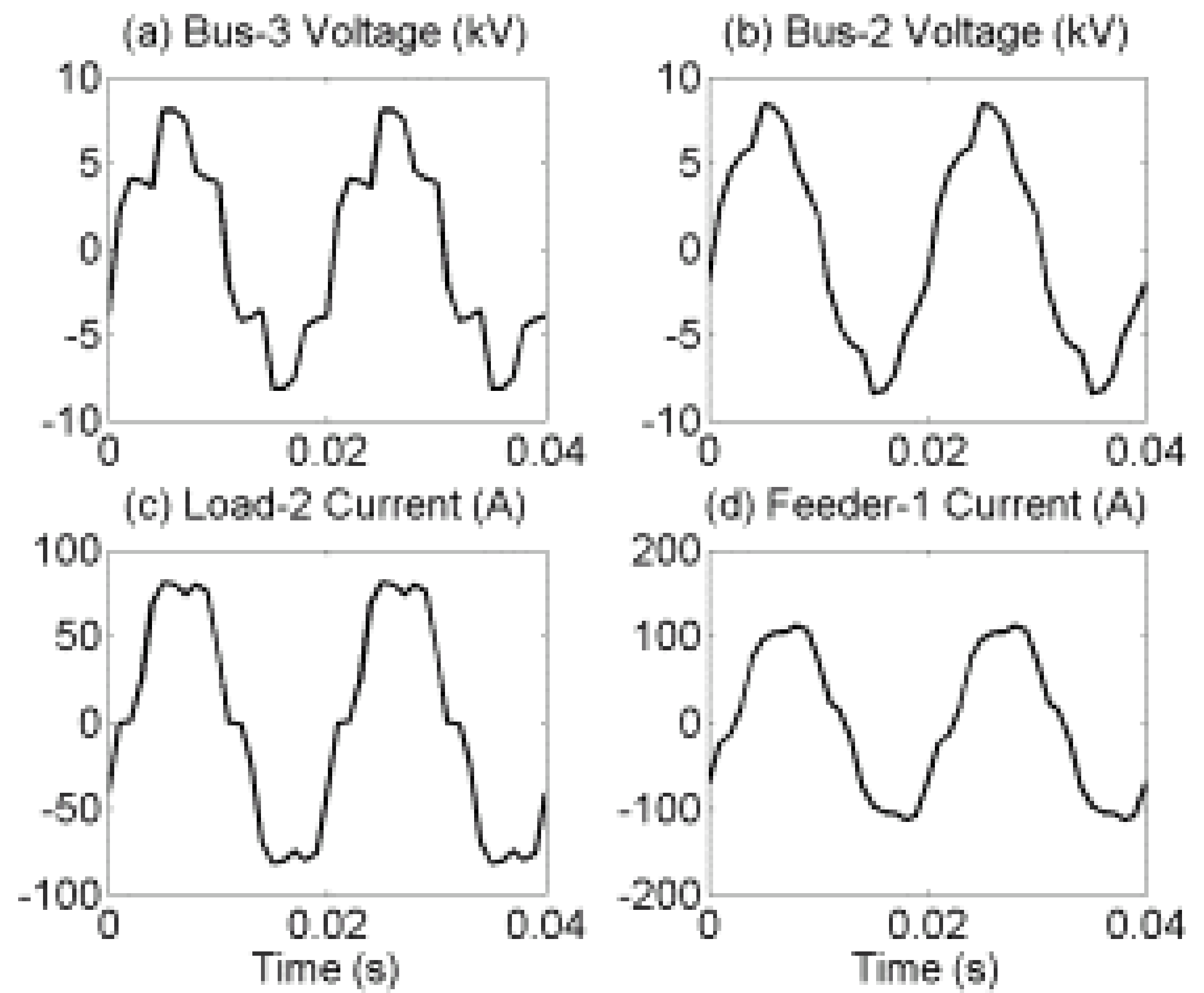
- A significant drop in the feeder voltage is caused when the magnitude of the load current $|I_s|$ is large.
- There will also be a large amount of $|I_s|^2 R_s$ loss associated with high heat dissipation in the feeder.

Nonlinear Loads



In the distribution system shown, the nonlinear load (Load-2) will cause distortion in voltages of buses 2 and 3 and all the currents.

Nonlinear Loads



Effects of Harmonics

- The presence of harmonics can cause additional losses in induction motors, especially when they are operating close to their rated values, resulting in increased heating.
- the supply voltage is used for timing purposes in many cases like digital clocks. Power electronic equipment like phase controlled thyristor circuits use the zero crossing of the supply voltage to generate trigger pulses. A distorted voltage waveform can create false triggering of the timing circuits.

Supply Voltage Disturbance

The disturbances in the supply voltage can have an adverse impact on the customers. Examples:

- Even a small duration voltage interruption can cause relay tripping and stopping a process line resulting in many hours of production loss.
- Even a short duration outage can cause defects in semiconductor processing.
- A sustained overvoltage can cause domestic lights to burn out faster and can put stress on capacitors.

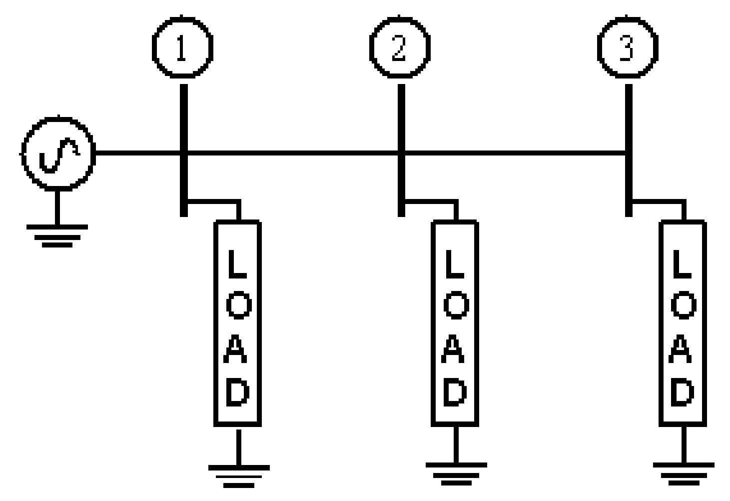
Supply Voltage Disturbance

- Voltage spikes or transient overvoltage can cause permanent damage on capacitors thereby burning power supply or other semiconductor components of computers, TVs, VCRs and household appliances.
- Sustained undervoltage or even a few cycle voltage sag can cause motors to stall.
- Voltage flicker can be very annoying to the human eyes as it causes incandescent lamps to flicker. This can cause headaches, nausea or migraine.

Custom Power

- The term Custom Power (CP) pertains to the use of power electronic controllers for power distribution systems.
- Just as the FACTS controllers improve the reliability and quality of power transmission systems, the custom power enhances the quality and reliability of power that is delivered to customers.
- Since the custom power devices improve the power quality, they can also be called power quality enhancing devices as well.

Utility-Customer Interface



Let the load connected to Bus-3 be unbalanced and nonlinear. Then

- The feeder current will be unbalanced and distorted.
- Voltages of Bus-2 will also be unbalanced and distorted affecting the loads connected to these buses. (Assumption Bus-1 is a stiff bus).

Utility-Customer Interface - Solutions

- Customer at Bus-3 installs a shunt device to compensate for the unbalance and distortion.
- Instead the customer pays penalty for not complying.
- However unbalance and distortion will persist.
- Alternative: Utility connects a shunt device.
- Bus-1 is a stiff bus, not affected by unbalance or distortion.
- Therefore place a shunt controller at Bus-2 for voltage control.
- This will correct for upstream current as well.

Custom Power Devices

- Custom power devices are of two types – those used for isolation & protection and those used for compensation.
- **Network reconfiguring type**
  - Static Current Limiter (SCL)
  - Static Circuit Breaker (SCB)
  - Static Transfer Switch (STS)
- **Compensating type**
  - Distribution STATCOM (DSTATCOM)
  - Dynamic Voltage Restorer (DVR)
  - Unified Power Quality Conditioner (UPQC)

Custom Power Devices

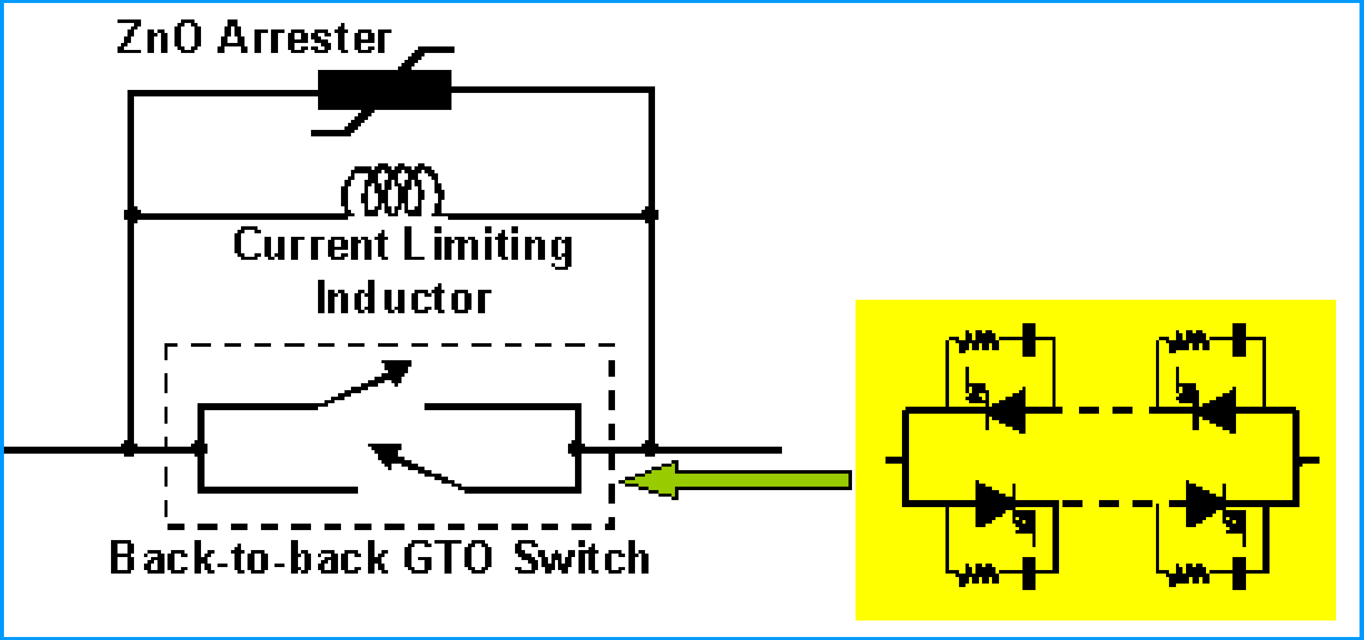
- **Static Current Limiter (SCL)** limits a fault current by quickly inserting a series inductance in the fault path.
- **Static Circuit Breaker (SCB)** breaks a faulted circuit much faster than a mechanical circuit breaker.
- **Static Transfer Switch (STS)** is connected in the bus tie position when a sensitive load is supplied by two feeders. It protects the load by quickly transferring it from the faulty feeder to the healthy feeder.

- **Distribution STATCOM (DSTATCOM)** this is shunt connected device that can operate in two modes:
  - **Current Control**: In this mode the DSTATCOM acts as an active filter, power factor corrector, load balancer etc. These functions are called the load compensation.
  - **Voltage Control**: In this mode the DSTATCOM can regulate a bus voltage against any distortion, sag/swell, unbalance and even short duration interruptions.

Custom Power Devices

- **Dynamic Voltage Restorer (DVR)** is a series compensating device. It is used for protecting a sensitive load that is connected downstream from sag/swell etc. It can also regulate the bus voltage at the load terminal.
- **Unified Power Quality Conditioner (UPQC)** this device, like the UPFC, consists of two voltage source inverters. The capabilities of this device are still unexplored. However it can simultaneously perform the tasks of DSTATCOM and DVR.

Static Current Limiter (SCL)



An SCL is a parallel connection of

- an anti-parallel gate turn-off thyristor (GTO) switch with snubbers
- a current limting inductor
- a zinc oxide (ZnO) arrester

SCL - Operation

- A GTO can be switched off at any time by applying a negative gate pulse.
- Therefore it can interrupt a current instantaneously.
- A thyristor switches off only when the current through it changes polarity.
- An anti-parallel thyristor switch is in a current limiter will keep on conducting till the next zero crossing irrespective of the instant of occurrence of the fault.
- This will defeat the purpose for which a current limiter is installed.

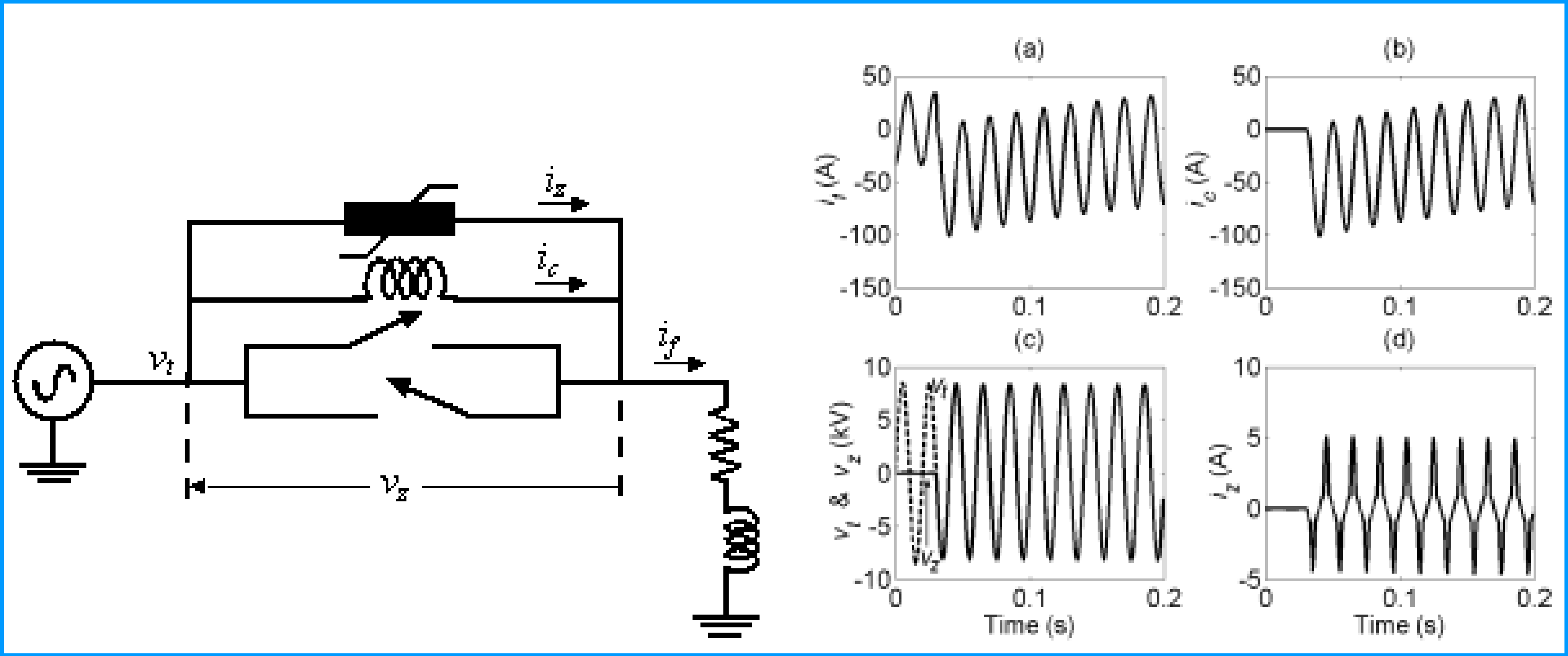
SCL - Operation

- Under normal (unfaulted) operating conditions, the GTOs are gated for full conduction.
- Once a fault occurs, the GTOs are turned off as soon as the fault is detected.
- A GTO can respond within a few microseconds.
- Once the GTOs are turned off, the fault current is diverted to the snubber capacitor that limits the rate of rise in voltage across the GTOs.
- The voltage across the anti-parallel GTO switch rises until it reaches the clamping level established by the ZnO arrester.

SCL - Operation

- The same voltage also appears across the current limiting reactor.
- Once the clamping level of the voltage is reached, the current across the reactor will rise linearly.
- This linear rise will continue till it becomes equal to the instantaneous level of current flowing in the line.
- Thus the current will be limited by total effective series impedance, i.e., by a combination of the impedance of the limiting reactor and the faulted feeder impedance.

SCL - Operation

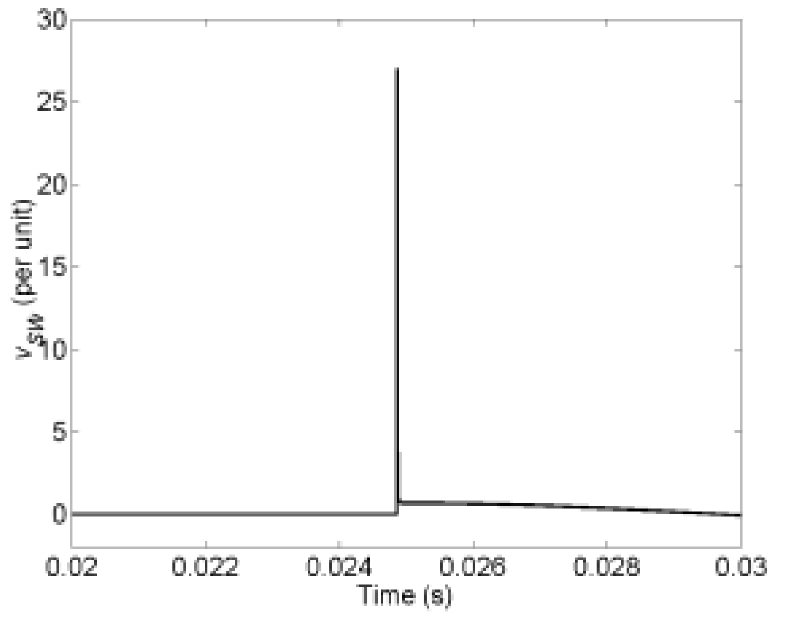


- The peak of the fault current is limited to about 100 A.
- The peak of fault current can go up to 1000 A.

SCL – Function of Snubbers

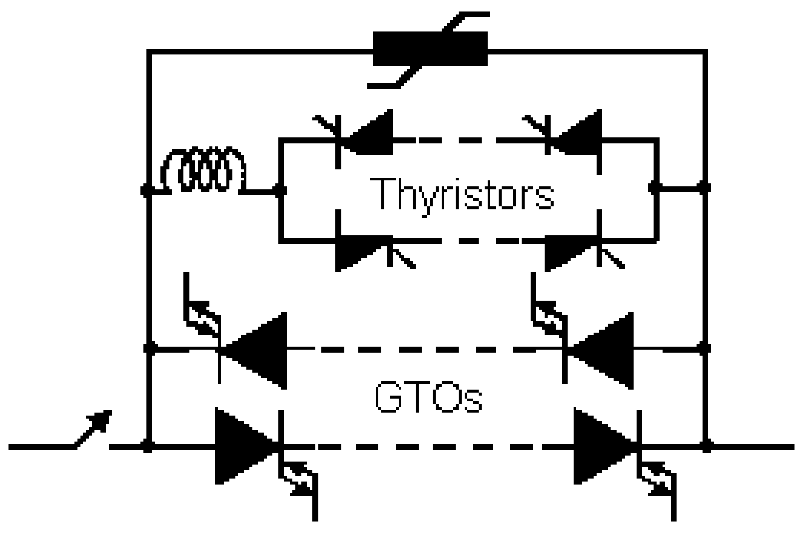
- Without the snubber circuit, the limiting inductor comes in series with the feeder inductance once the GTO switch is turned off.
- The initial condition of the limiting inductor current is zero, while the feeder current flows through the feeder reactance.
- However when these two inductance come in series, the current through these two inductances must be same.
- Therefore the limiting inductor must be forced to instantaneously carry the feeder current.

SCL – Function of Snubbers



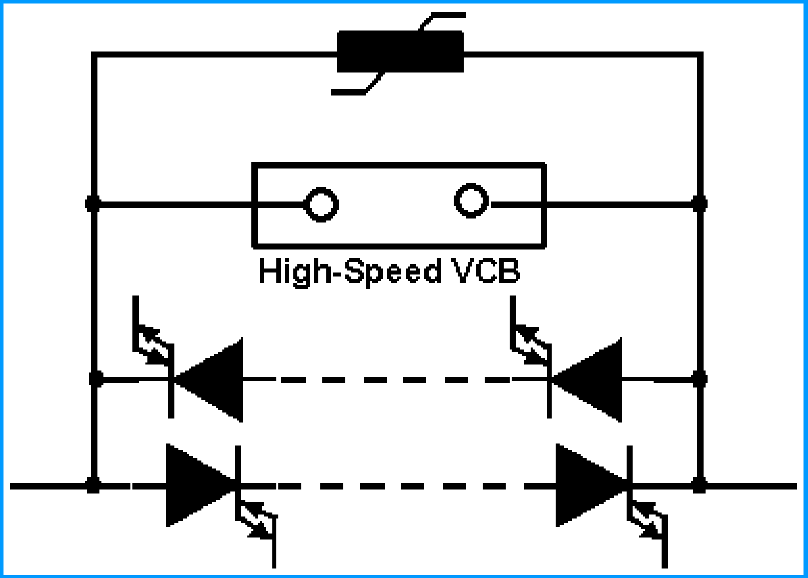
- To achieve this, a large *L*(*di/dt*) must be applied across the switch thereby causing a damaging voltage spike.
- In the presence of the snubber circuit, the fault current is diverted to the snubber capacitor once the GTO switch is switched off.
- The current through the limiting inductor is allowed build up slowly as discussed before.

Static Circuit Breaker (SCB)



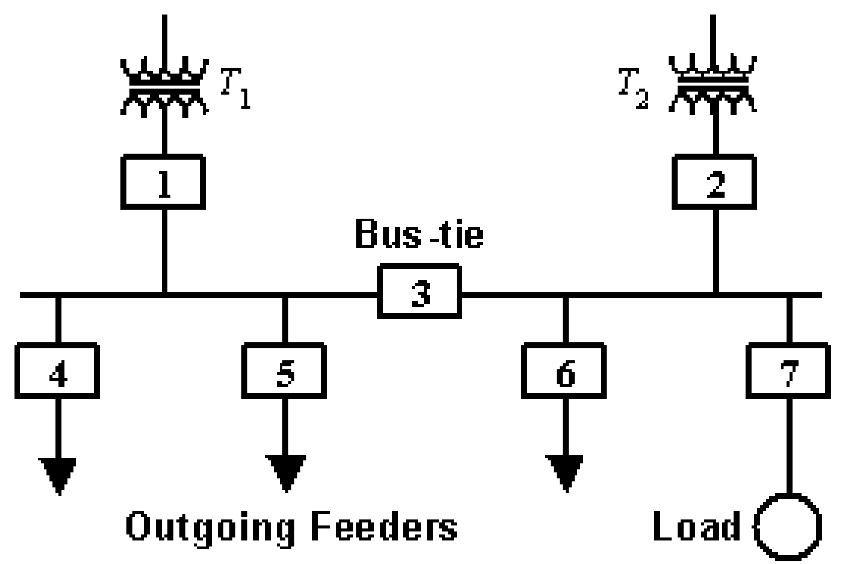
- The GTOs are the normal current carrying elements.
- With the detection of a fault, they go through a number of sub-cycle auto reclose operations.
- For a persistent fault, the GTOs are turned off and the thyristors are turned on.
- The fault current now starts flowing through the current limiting inductor.
- The fault current is eventually cut off by blocking the thyristors.

SCB – Alternate Topology



- The current in the normal (unfaulted) state flows through the VCB.
- With the detection of a fault, simultaneously the GTOs are turned on and an open signal is given to the VCB.
- For high speed contact parting the VCB uses electromagnetic repulsion.
- The fault current starts flowing through the GTO switch and when the current is completely commutated, it is interrupted by turning the GTO switch off.

Coordination Issues with Static Limiting and Transferring



- Let 1 is an SCB while 4 is a conventional breaker.
- For a fault downstream from 4, breaker 1 will operate before breaker 4.
- This will disconnect both faulty and healthy feeders supplied by T_1.
- A potential installation point of an SSB is the bus-tie location 3.
- This will require no coordination with any other protection device.

Coordination Issues with Static Limiting and Transferring

- Example, for a fault in the transformer T_1 side of the system, the SSB will open the bus tie thereby preventing transformer T_2 from feeding the fault.
- An SCB can be connected at location 7.
- A fault on the load side can be quickly isolated by the SCB without affecting the other protective devices.
- The best position for the placement of a current limiter is at the output of the main incoming transformers, i.e., locations 1 and 2.

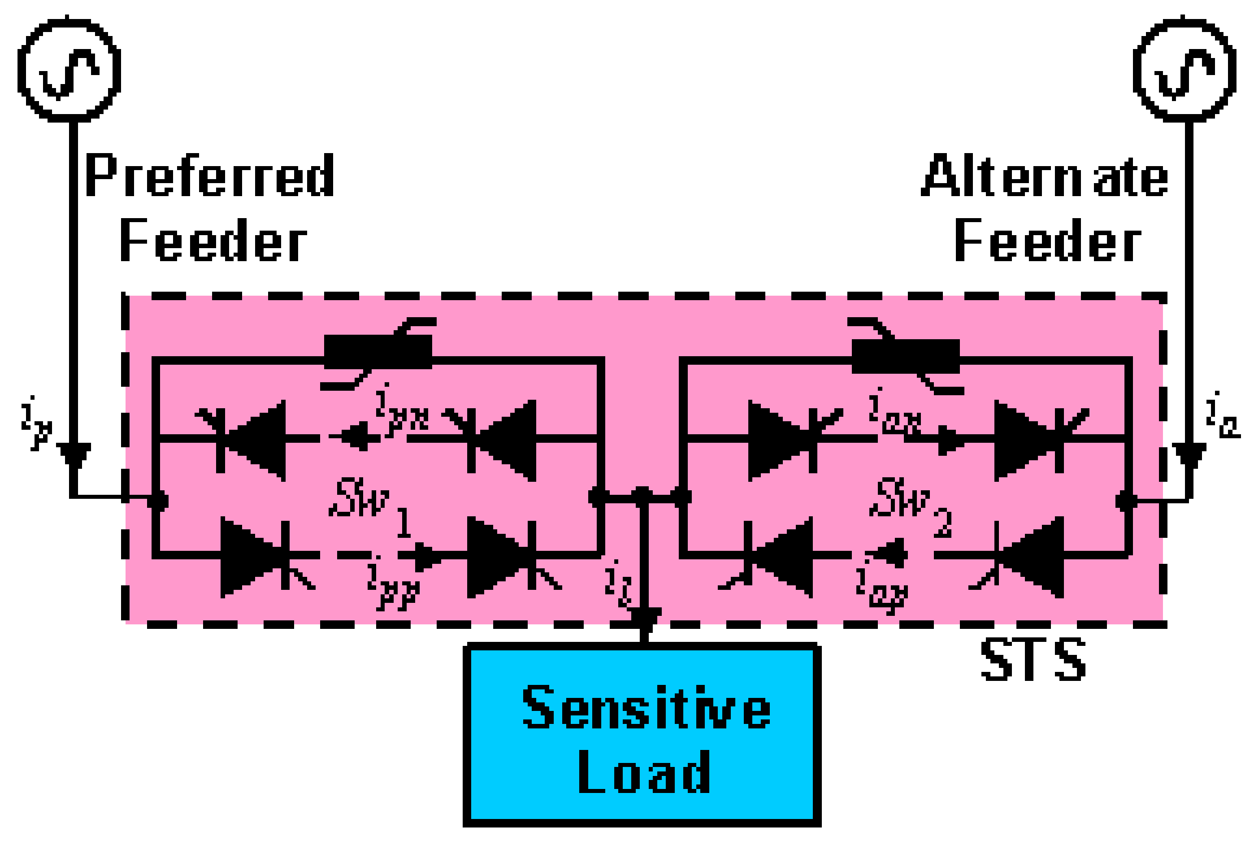
Coordination Issues with Static Limiting and Transferring

- The fault at any part of the network will be limited without causing any coordination problem.
- The current tap settings of the downstream overcurrent relays can then be set at lower values.
- A limiter at the bus tie location 3 can be most beneficial as it will have lower losses under normal operating conditions.
- Since the current flowing through this position for a fault at any part of the circuit is maximum, the rating of the device at this location must be very high.

Requirements of SCL

- It must limit a short circuit current such that the current does not exceed the interrupting rating of any downstream protecting device.
- It must maintain a fault current within a specified limit till a downstream device clears the fault.
- It must allow sufficient fault current to flow such that downstream overcurrent protection devices can isolate the fault.
- The limiter must reset automatically after a fault clearance.

Static Transfer Switch (STS)

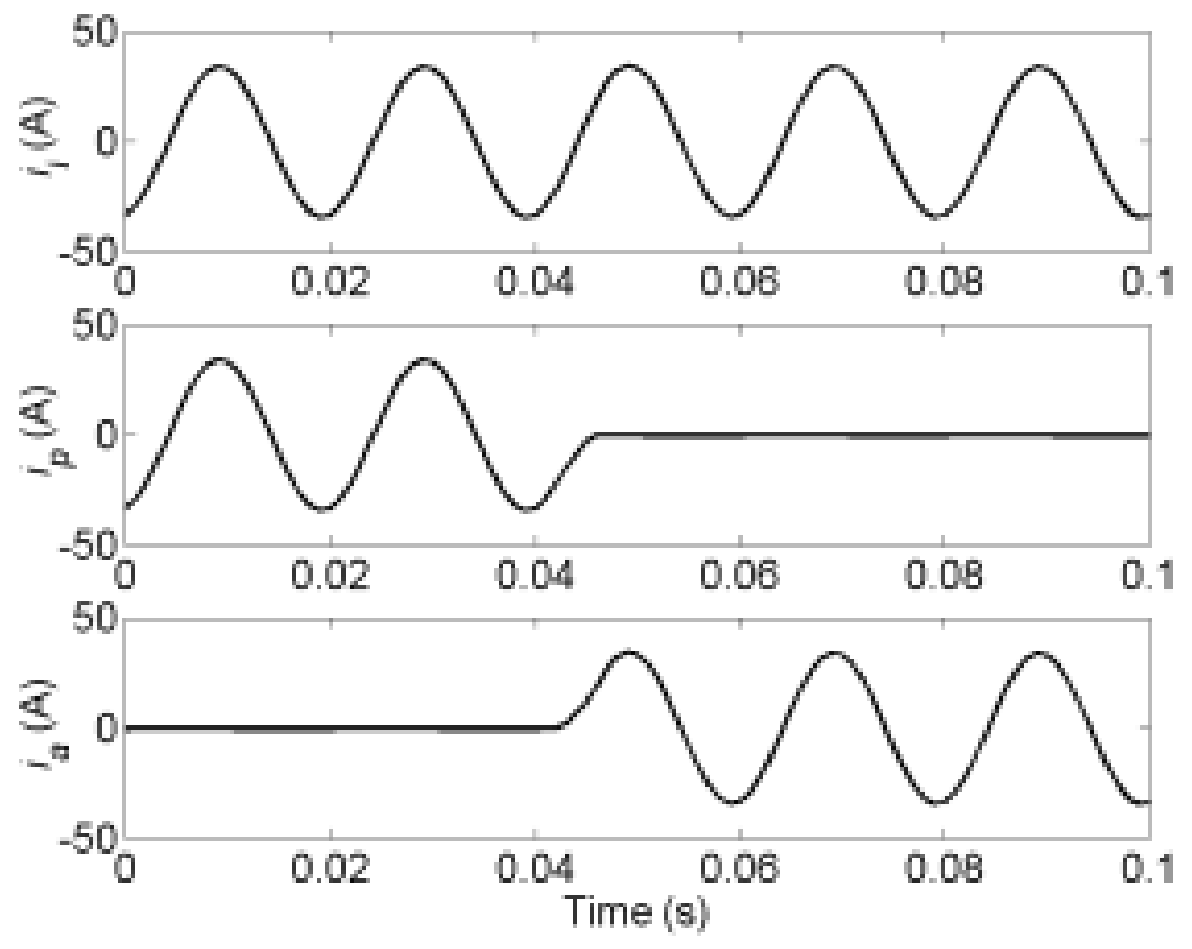


An STS is used for protecting a sensitive load from sag/swell, fault in the preferred feeder.

STS – Functioning

- Usually the load is supplied by the preferred feeder and the load current flows through the switch Sw_1.
- When a deep voltage sag or interruption is detected in this feeder, the switch Sw_2 is turned on.
- Once the load current starts flowing through the switch Sw_2 the switch Sw_1 is turned off.
- This switching action is called **make-before-break (MBB)**.

STS – Make-Before-Break (MBB) Operation

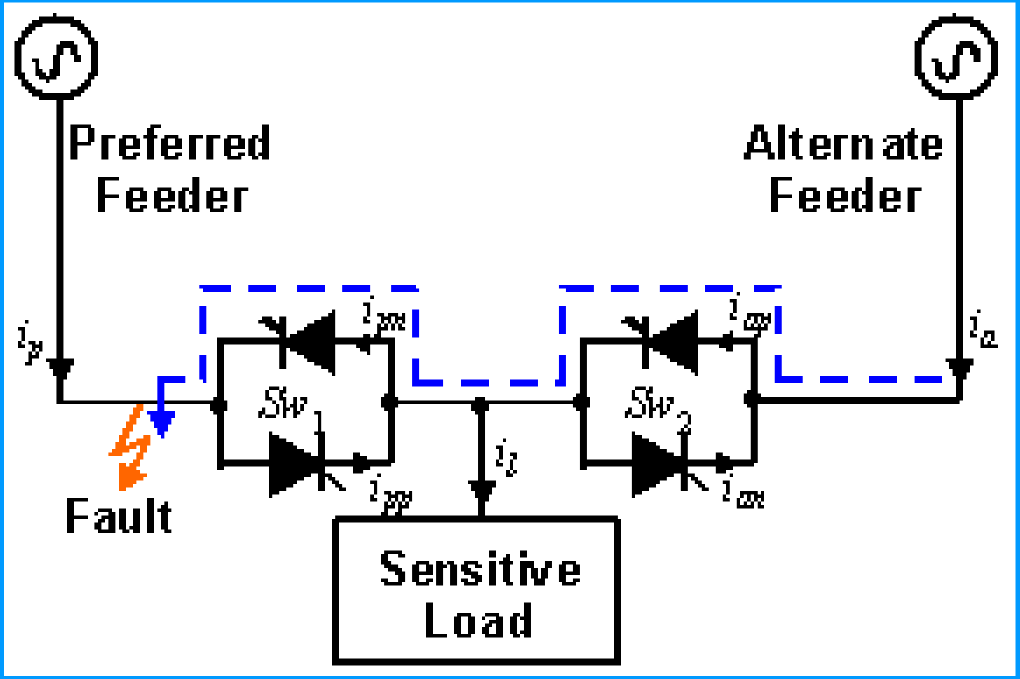


Load Current

Preferred feeder current

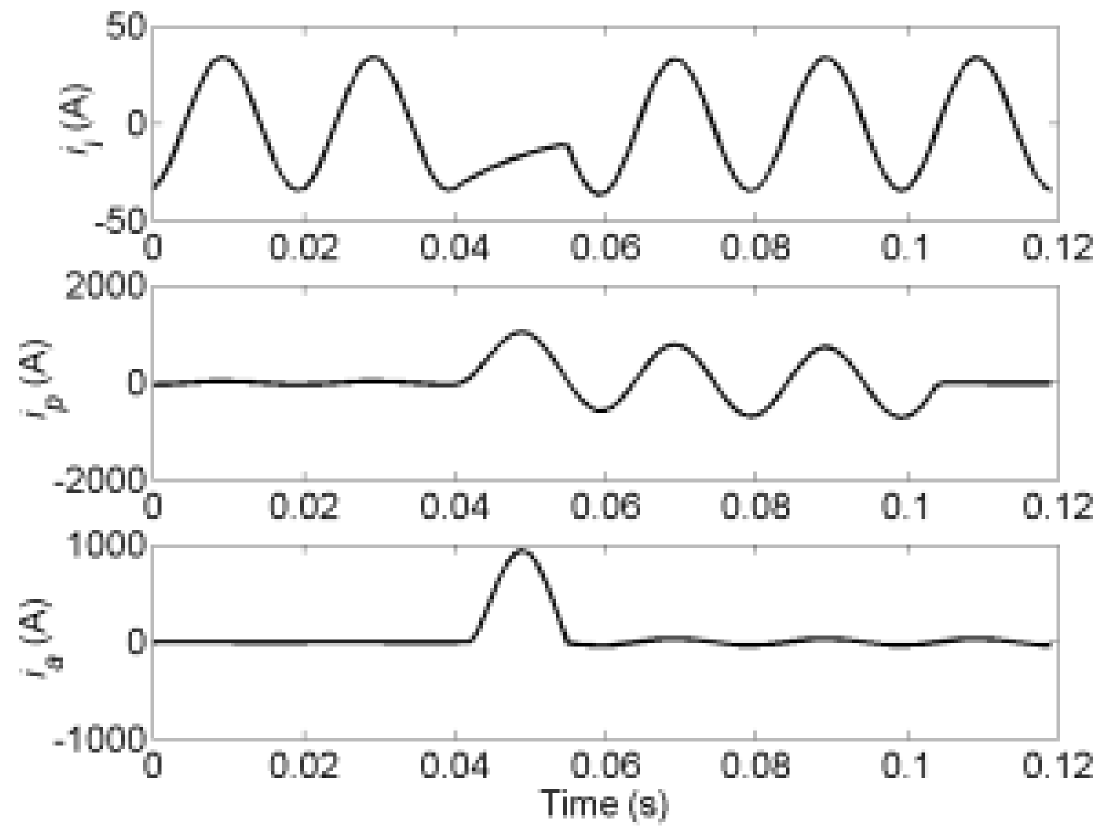
Alternate feeder current

STS – MBB Operation During Fault



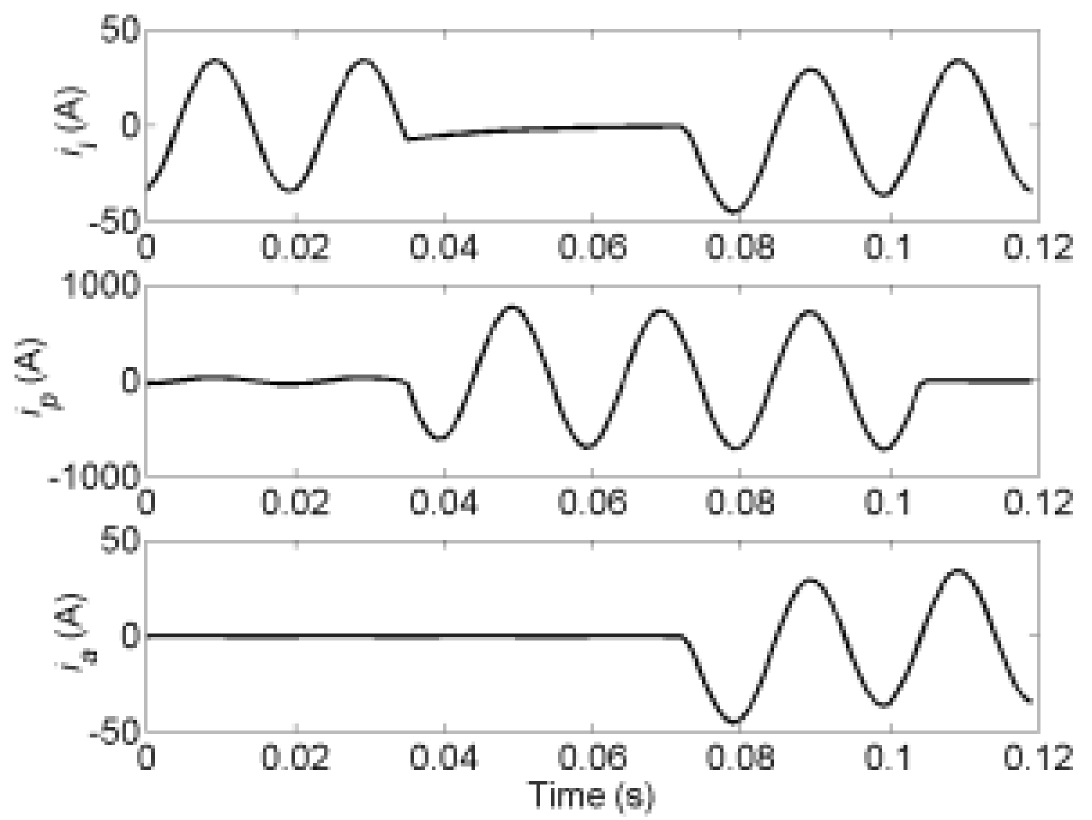
- The MBB operation of the STS will cause a fault current to be supplied by the alternate feeder before the switch Sw_1 is cut off.
- The path for this current is indicated by the dotted line.

STS – Incorrect Transfer During Fault



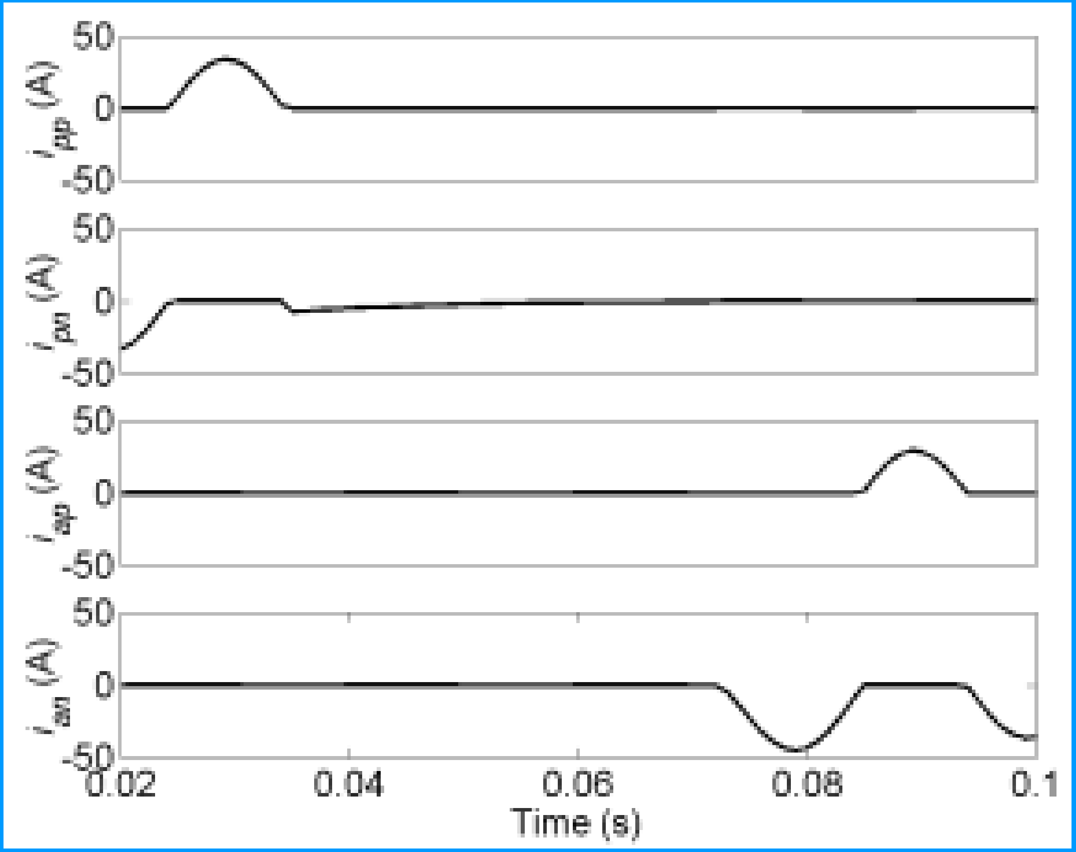
- The alternate feeder feeds the fault through switches *Sw*$_1$ and *Sw*$_2$.

STS – Correct Transfer During Fault



- The thyristors of the switch *Sw*$_1$ are blocked as soon as the fault is detected.
- The current through switch *Sw*$_1$ goes to zero at the next available zero crossing.

STS – Correct Transfer During Fault



- The thyristors of the switch Sw_2 are gated after the fault current becomes zero.
- The load current stabilizes within about one cycle.

Sag/Swell Detection

- For subcycle transfer, ideally it is desirable to detect any voltage sag/swell almost instantaneously.
- This however can only be achieved in the case of balanced sags and cannot be achieved for sag in one or two phases.
- The next best option is to detect this with as little delay as possible.
- An algorithm is discussed next in which it only takes only two consecutive samples for sag/swell detection.

Sag/Swell Detection

- Let three unbalanced voltage waveforms be denoted by v_a, v_b and v_c.
- Their corresponding phasor values are denoted by V_a, V_b and V_c.
- The phasor symmetrical components are (subscripts 0, 1 and 2 respectively represent zero, positive and negative sequences)

$$\begin{bmatrix} \tilde{V}_{a0} \\ \tilde{V}_{a1} \\ \tilde{V}_{a2} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} \tilde{V}_a \\ \tilde{V}_b \\ \tilde{V}_c \end{bmatrix}, \quad a = e^{j120^\circ}$$

Sag/Swell Detection

- Let us define the following instantaneous symmetrical components

$$\begin{bmatrix} v_{a0} \\ v_{a1} \\ v_{a2} \end{bmatrix} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

- All the three quantities on the left hand side are time varying.
- The vector v_{a2} is complex conjugate of the vector v_{a1}.

Sag/Swell Detection

- The instantaneous vectors can be decomposed as

$$v_{a0} = \frac{-j}{2\sqrt{3}}\left[\tilde{H}e^{j\omega t} - \left(\tilde{H}e^{j\omega t}\right)^*\right]$$

$$v_{a1} = \frac{-j}{2\sqrt{3}}\left[\tilde{F}e^{j\omega t} - \left(\tilde{B}e^{j\omega t}\right)^*\right]$$

- Then it can be shown that

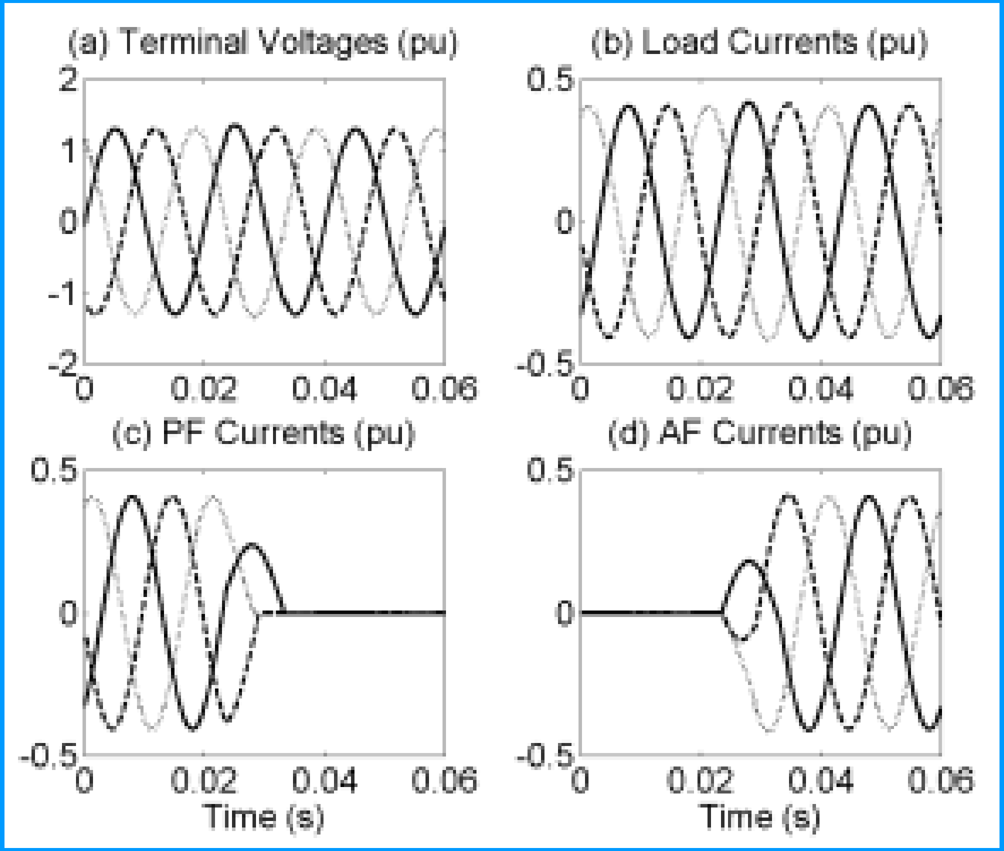
$$\tilde{V}_{\mathbf{a}0} = \frac{\tilde{H}}{\sqrt{6}}, \quad \tilde{V}_{a1} = \frac{\tilde{F}}{\sqrt{6}} \text{ and } \tilde{V}_{a2} = \frac{\tilde{B}}{\sqrt{6}}$$

Sag/Swell Detection

- The vectors H, F and B can be computed from two consecutive values of the instantaneous vectors v_{a0} and v_{a1}.
- These vectors are computed from the instantaneous values of the measured voltages v_a, v_b and v_c.
- From the vectors H, F and B, the phasor zero, positive and negative sequence components can be calculated.
- From the phasor sequence components the health of the system can be determined.

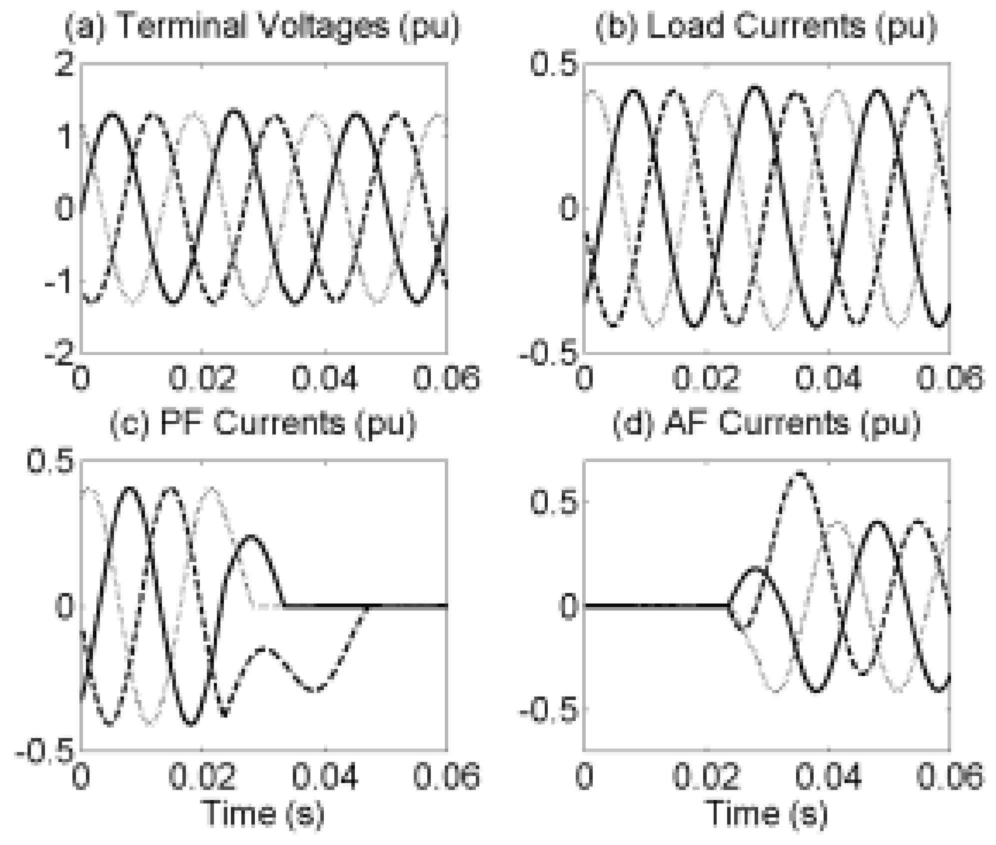
Sag/Swell Detection

- The plot shows the transfer operation for an angle unbalance of 3^0 in preferred feeder voltage.



Sag/Swell Detection

- The plot shows the transfer operation for an 11% sag in the magnitude of phase-b preferred feeder voltage.



STS – Total Transfer Time

- The total transfer time is the duration from the inception of voltage sag/swell or fault in the preferred feeder to the load being completely transferred to the alternate feeder.
- The load circuit parameters also influence the total transfer time.
- Also the phase difference between the two supplying source and feeder impedance will affect the transfer time.
- The gating strategy of the switches in both preferred and alternate feeders can play an important role.