

Various Power Quality Issues of Distribution Networks: An Introduction

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Power Quality

- ❖ It is the ability of electrical grid or network to supply a clean and stable power to the consumers.
- ❖ Electric power quality mainly involves voltage, frequency and waveform.
- ❖ Good power quality can be defined by:
 - ✓ Steady supply voltage within prescribed range
 - ✓ Steady AC frequency close to rated value
 - ✓ Smooth voltage waveform (resembles a sine wave)

Power quality problems

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

Different power quality terms

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

Power quality problems and their 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 transformer, single line-to-ground faults
	Swell	Magnitude, Duration	Ferroresonant transformer, single line-to-ground faults
	Interruption	Duration	Temporary (self-clearing) faults
Long duration voltage variation	Undervoltage	Magnitude, Duration	Switching on loads, capacitor deenergization
	Overvoltage	Magnitude, Duration	Switching off loads, capacitor energization
	Sustained Interruptions	Duration	Faults

Power quality problems and their causes

Broad Categories	Specific Categories	Methods of Characterization	Typical Causes
Voltage imbalance		Symmetrical Components	Single-phase loads, single phasing condition
Waveform distortion	Harmonics	THD, harmonic spectrum	Adjustable speed drives, and other non-linear loads
	Notching	THD, harmonic spectrum	Power electronic converters
	DC offset	Volts, Amps	Geo-magnetic disturbances, half-wave rectification
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnace, arc lamps

Ref. Arindam Ghosh and Gerard Ledwich, Power Quality Enhancement Using Custom Power Devices; Springer, 2009.

Power quality standards

Phenomena	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

IEEE: Institute of Electrical and Electronics Engineers

IEC: International Electrotechnical Commission

Ref. Arindam Ghosh and Gerard Ledwich, Power Quality Enhancement Using Custom Power Devices; Springer, 2009.

Transients

❖ A transient is short duration problem due to sudden change of state.

❖ Transient can be classified into two categories:

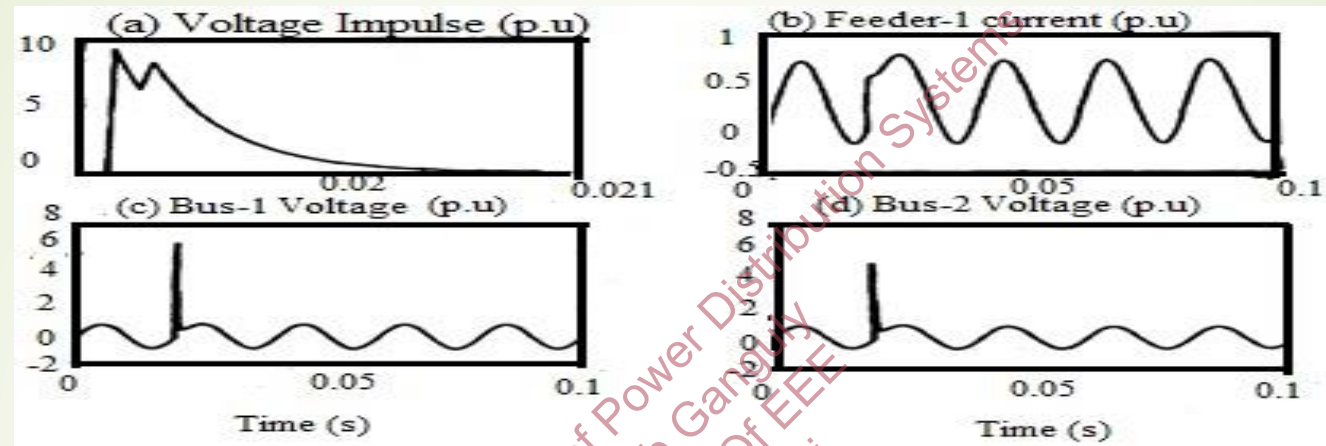
1. **Impulsive transient:**

- ✓ An impulsive transient is a sudden, non-power frequency change in voltage, current etc. It is unipolar in nature (either positive or negative).
- ✓ It has very fast rise time and decaying time.

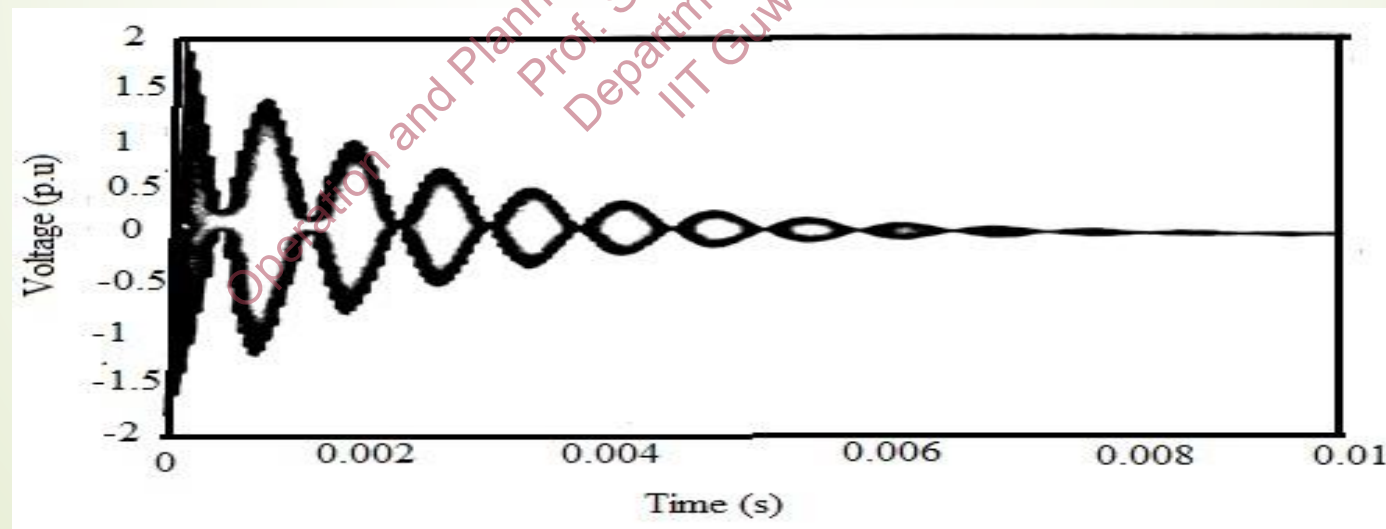
2. **Oscillatory transients:**

- ✓ It is usually bipolar in nature.
- ✓ It has one or more sinusoidal components that get multiplied by a decaying term.

Transients: Example



Voltage impulse



Typical oscillatory voltage transient

Short duration voltage variations

- ❖ Short duration voltage variations typically sustain for a few cycles up to ONE minute.
- ❖ Usually such variations are caused by faults, energization of large loads, and intermittent loose connection in wiring.
- ❖ Short duration variations are further classified as,
 - ✓ **Voltage sag:** It is defined as fundamental frequency decrease in supply voltage magnitude for a short duration (5 cycle to a minute).
 - ✓ **Voltage swell:** It is defined as increase of fundamental frequency voltage magnitude for a short duration.
 - ✓ **Interruptions:** It occurs when supply voltage (or load current) decreases to less than 0.1 per unit for a period of less than 1 minute.

Long duration voltage variations

- ❖ These are defined as the RMS variations in the supply voltage at fundamental frequency for periods more than 1 minute.
- ❖ These variations are classified as,
 - ✓ **Overvoltage:** An overvoltage is a 10% increase in RMS voltage for more than 1 minute.
 - ✓ **Undervoltage:** An undervoltage is a 10% decrease in RMS voltage for more than 1 minute.
 - ✓ **Sustained interruptions:** It happens when the supply voltage becomes zero for more than 1 minute.

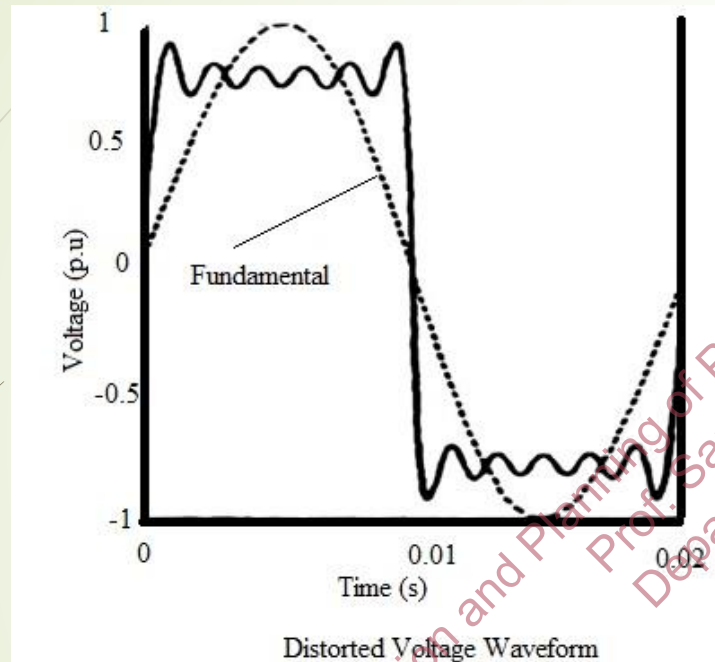
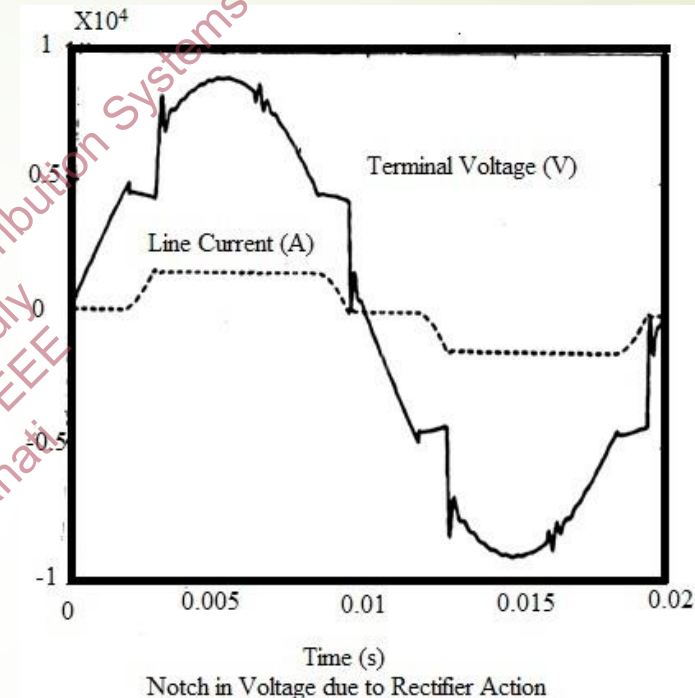
Voltage imbalance

- ❖ In the case of voltage imbalance, the voltages of the three phases of the supply are not equal in magnitude.
- ❖ Voltages of three phases may not even be equally displaced.
- ❖ The primary cause of voltage unbalance is the single phase loads in three phase circuits and unequal line parameters.
- ❖ These are restricted to within 5%.

Waveform distortions

- ❖ This is the steady state deviation in voltage or current waveform from an ideal sine wave.
- ❖ These distortions are classified as:
 - ✓ **DC offset:** The major causes of dc offsets in power systems are geomagnetic disturbance and half wave rectification.
 - ✓ **Harmonics:** Power electronic loads like UPS, adjustable speed drives etc., usually cause harmonics. A measure of harmonic content in a signal is the total harmonic distortion (THD).
 - ✓ **Notching:** It is a periodic voltage distortion due to the operation of power electronic converters when current commutates from one phase to other. During this period there is momentary short circuit between the two phases that distorts voltages.

Waveform distortion



IEEE 519: Voltage Distortion limits

Bus Voltage	p.u. voltage for n-th harmonics	Voltage THD (percent)
Less than 69 kV	3.0	5.0
Between 69 kV and 161 kV	1.5	2.5
Above 161 kV	1.0	1.5

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 load current due to application of non-linear loads.

Power 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.
- ❖ The frequency is directly related to the rotational speed of the generators.

Analysis of unbalance

- ❖ Unbalance in a three-phase ac system has always been treated through symmetrical components. A set of three unbalanced phasors can be resolved into three sets of balanced phasors i.e. by positive sequence, negative sequence and zero sequence.
- ✓ **Positive sequence:** These are set of equal magnitudes three phase vectors that are displaced from each other by 120 degree and have same phase sequence as the original phasor;
- ✓ **Negative sequence:** These are set of equal magnitudes three phase vectors that are displaced from each other by 120 degree and have opposite phase sequence to the original.
- ✓ **Zero sequence:** These are set of equal magnitudes three phase phasors that are exactly in the phase with each other.

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Analysis of unbalance

- ❖ Symmetrical components are defined in terms of operator 'a' that is given as, $a = e^{j120^\circ}$.
- ❖ Let us define the vectors, $V_{abc}^T = [V_a \ V_b \ V_c]$ and $V_{a012}^T = [V_{a0} \ V_{a1} \ V_{a2}]$
- ❖ **Voltage and current transformation from abc to 012-plane is given by,**

$$V_{a(012)} = \begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \frac{1}{K} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = P V_{abc}$$

$$I_{a(012)} = \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \frac{1}{K} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = P I_{abc}$$

where, $K = 1/3$ or $1/\sqrt{3}$

- ❖ Three phase power for original unbalanced system is given by,
- $$P_{abc} + jQ_{abc} = [V_a I_a^* + V_b I_b^* + V_c I_c^*]$$

Analysis of unbalance

- ❖ Relation between abc and 012- plane Complex power is as,

$$V_{a0}I_{a0}^* + V_{a1}I_{a1}^* + V_{a2}I_{a2}^* = \frac{3}{K^2} [V_a I_a^* + V_b I_b^* + V_c I_c^*]$$

- ❖ There are two ways of choosing the value of 'K',

- ✓ K must be equal to '3', if

$$P_{abc} + jQ_{abc} = \sum_{i=a,b,c} (V_{i0}I_{i0}^* + V_{i1}I_{i1}^* + V_{i2}I_{i2}^*)$$

and in this case P and P^{-1} are,

$$P = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}, P^{-1} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

- ✓ K must be equal ' $\sqrt{3}$ ', if

$$P_{abc} + jQ_{abc} = V_{a0}I_{a0}^* + V_{a1}I_{a1}^* + V_{a2}I_{a2}^* = V_{a012}^T I_{a012}^*$$

and in this case P and P^{-1} are

$$P = 1/\sqrt{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}, P^{-1} = 1/\sqrt{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

Instantaneous real and reactive power

- ❖ Let the instantaneous voltage and current vectors for three phase instantaneous quantities are as

$$v_{abc}^T = [v_a \ v_b \ v_c] \quad \text{and} \quad i_{abc}^T = [i_a \ i_b \ i_c]$$

- ❖ The instantaneous real power is defined as the dot product of voltage and current vectors,

$$p = v_{abc} i_{abc} = v_a i_a + v_b i_b + v_c i_c$$

- ❖ The instantaneous reactive power is defined as the cross product of voltage and current vectors,

$$q = v_{abc} \times i_{abc}$$

- ❖ The scalar representation of instantaneous reactive power is given by,

$$\|q\| = \sqrt{q_a^2 + q_b^2 + q_c^2} \quad \text{and} \quad q_{sum} = \frac{q_a + q_b + q_c}{\sqrt{3}}$$

Instantaneous real and reactive power

- ❖ The instantaneous real and reactive current vectors are as,

$$i_p = \begin{bmatrix} i_{ap} \\ i_{bp} \\ i_{cp} \end{bmatrix} = \frac{p}{v_{abc} \cdot v_{abc}} v_{abc} \quad i_q = \begin{bmatrix} i_{aq} \\ i_{bq} \\ i_{cq} \end{bmatrix} = \frac{q \times v_{abc}}{v_{abc} \cdot v_{abc}}$$

- ❖ The total current vector $i_{abc} = i_p + i_q$

- ❖ The scalar instantaneous apparent power is given by,

$$s = \|v_{abc}\| \|i_{abc}\|$$

- ❖ Let us now define a vector containing the instantaneous symmetrical component vectors as

$$v_{a012}^T = [v_{a0} \quad v_{a1} \quad v_{a2}] \quad \text{and} \quad i_{a012}^T = [i_{a0} \quad i_{a1} \quad i_{a2}]$$

- ❖ The instantaneous voltage and current vectors can be written as

$$v_{abc} = P^{-1} v_{a012} \quad \text{and} \quad i_{abc} = P^{-1} i_{a012}$$

Instantaneous real and reactive power

- ❖ The instantaneous active power in terms of symmetrical components is given by,

$$p = v_{a012}^T P^{-T} P^{-1} i_{a012} = v_{a012}^T \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} i_{a012} = v_{a0} i_{a0} + v_{a2} i_{a1} + v_{a1} i_{a2}$$

- ❖ The instantaneous reactive power in terms of symmetrical components is given by,

$$q = \begin{bmatrix} q_a \\ q_b \\ q_c \end{bmatrix} = -\frac{2}{\sqrt{3}} \text{Im} \begin{bmatrix} v_{a1} i_{a1}^* \\ v_{a1} i_{a1}^* \\ v_{a1} i_{a1}^* \end{bmatrix} - \frac{2v_{a0}}{\sqrt{3}} \text{Im} \begin{bmatrix} i_{a1} \\ i_{a1} e^{-\frac{j2\pi}{3}} \\ i_{a1} e^{+\frac{j2\pi}{3}} \end{bmatrix} + \frac{2i_{a0}}{\sqrt{3}} \text{Im} \begin{bmatrix} v_{a1} \\ v_{a1} e^{-\frac{j2\pi}{3}} \\ v_{a1} e^{+\frac{j2\pi}{3}} \end{bmatrix}$$

Analysis of distortion

- ❖ The main cause of voltage and current waveform distortions are harmonics, notching, and inter harmonics.
- ❖ The main impacts due to distortions are as,
 - ✓ Increased losses
 - ✓ Reduced equipment life
 - ✓ Interference with protection and communication circuits
 - ✓ Interference with customer equipment

Interpretations of various harmonic terms

Term	A frequency component
Harmonics	$f = n \times f_0$ for an integer $n > 0$
DC Offset	$f = n \times f_0$ for $n = 0$
Interharmonics	$f = n \times f_0$ for a non-integer $n > 0$
Sub-harmonics	$0 < f < f_0$

f_0 is the fundamental frequency

Harmonic indices

- ❖ The amplitude of harmonic contents in a current or voltage signal is measured by the total harmonic distortion (THD).

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \quad \text{or} \quad THD = \frac{\sqrt{V_{rms}^2 - V_1^2}}{V_1}$$

V_n is RMS harmonic contents for $n=2, \dots, \infty$
and V_1 is fundamental RMS value

- ❖ When no fundamental component is present then THD become infinity. To avoid it an alternate index is used. This index is called distortion index (DIN).

$$DIN = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{\sqrt{\sum_{n=1}^{\infty} V_n^2}}$$

- ❖ THD and DIN is interrelated by,

$$DIN = \frac{THD}{\sqrt{1 + THD^2}}$$

- ❑ IEEE prefers THD and
- ❑ IEC prefers DIN

Power factor and displacement factor

- ❖ Power factor (PF) is defined as

$$PF = \frac{P}{V_{rms} I_{rms}}$$

- ❖ The above PF calculation is not applicable when voltage and current waveforms are not sinusoidal. In such case displacement factor (DF) is of interest.

$$DF = \cos \phi_1 = \frac{P_1}{|V_1| |I_1|}$$

- ❖ In case of current distortions,

$$❖ PF = \frac{V_1 I_1 DF}{V_1 \sqrt{I_1^2 + I_{dis}^2}} = \frac{DF}{\sqrt{1 + \frac{I_{dis}^2}{I_1^2}}} = \frac{DF}{\sqrt{1 + THD^2}}$$

- ❖ Only fundamental components present then $PF = DF$ otherwise $PF \leq DF$.

Analysis of voltage sag

- ❖ Voltage dips are experienced when customers share a common supply impedance with an over current event on the supply system or in customer premises.
- ❖ Indices used for the calculation of a composite voltage sag,
- ✓ **Detroit Edison sag score (SS)**, $SS = \frac{V_A + V_B + V_C}{3}$
 V_A, V_B and V_C are the RMS value of phase voltages in per unit
- ✓ **Voltage sag energy (E_{VS})**, $E_{VS} = \int_0^T \left\{ 1 - \frac{V(t)}{V_{nom}} \right\}^2 dt$
 V is magnitude of voltage, V_{nom} is nominal voltage and T is duration of sag
- ✓ **Voltage sag lost energy index (VSLEI)**, $\left\{ 1 - \frac{V}{V_{nom}} \right\}^{3.14} T$
 V is phase voltage (pu), T is sag duration (msec)
- ✓ For 3-phase and unequal duration sag VSLEI is,

$$W = \left\{ 1 - \frac{V_a}{V_{nom}} \right\}^{3.14} T_a + \left\{ 1 - \frac{V_b}{V_{nom}} \right\}^{3.14} T_b + \left\{ 1 - \frac{V_c}{V_{nom}} \right\}^{3.14} T_c$$

Custom power devices

- ❖ In distribution systems, power electronic based controllers are used to improve the reliability and quality of custom power (power delivered to customers) are called custom power devices.
- ❖ These devices are used to provide following specifications:
 - ✓ Frequency of rare power interruptions
 - ✓ Magnitude and duration of over and undervoltage within specified limits
 - ✓ Low harmonic distortion in the supply voltage
 - ✓ Low phase unbalance
 - ✓ Low flicker in supply voltage
 - ✓ Frequency of supply voltage within specified limits

Devices used for power quality improvement

- ❖ The power electronic controllers are used either for reconfiguration purpose or for compensation.
- ❖ Based on its functioning custom power devices are either of reconfiguration type or compensation type.
- ✓ **Reconfiguration type:** The network reconfiguration devices are usually called switchgear and they include current limiting, current breaking and current transferring devices.
 - The solid state or static version of devices are called
 - Solid state current limiter (SSCL)
 - Solid state breaker (SSB)
 - Solid state transfer switch (SSTS)

Devices used for power quality improvement

- ✓ **Compensation type:** These type of devices either compensate a load, (i.e. correct its power factor, unbalance etc.) or improve the quality of supplied voltage.
- These devices are either connected in shunt or in series or a combination of both. The devices are as:
 - Distribution STATCOM (DSTATCOM): usually it is connected in shunt.
 - Dynamic voltage restorer (DVR): usually it is connected in series.
 - Unified power quality conditioner (UPQC): it is combination of DSTATCOM and DVR.

References

- ❖ Arindam Ghosh and Gerard Ledwich, *Power Quality Enhancement Using Custom Power Devices*; Springer, 2009.
- ❖ T. Gonen. *Electric Power Distribution System Engineering*; CRC Press, 3rd Edition, 2014.

Thank You...

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