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Power System Dynamics & Quality of Supply

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Power Quality



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Dr Victor Levi

INTRODUCTION TO POWER QUALITY



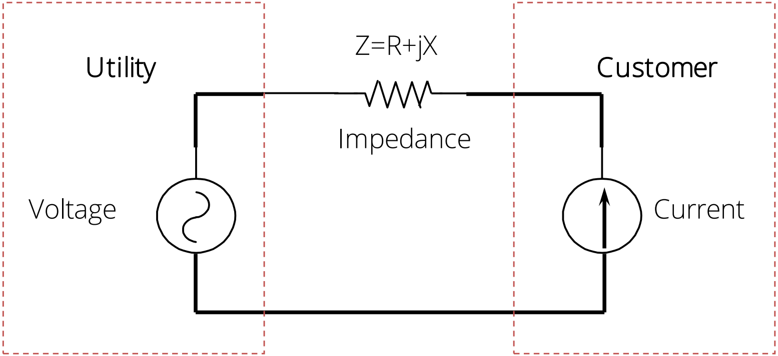
What is ‘Power Quality’ ?

- Power Quality is an issue driven by the end users.
- Power Quality is a collection of various subjects, for example:
  - Interruptions
  - Sags (Dips)
  - Lightning Surges
  - Undervoltages
  - Harmonics
  - Switching of capacitors
  - Flicker
  - Overvoltages

- Power Quality in broader sense encompasses reliability - interruptions; in narrower sense does not!
- We are doing Power Quality in *narrower sense*.

Power Quality = Voltage Quality!

- 'Power Quality' usually refers to the quality of the voltage supplied by the utility (frequency, magnitude, waveform and symmetry)
- Because the system has impedance, currents outside the direct control of the utility can adversely affect (voltage) power quality.

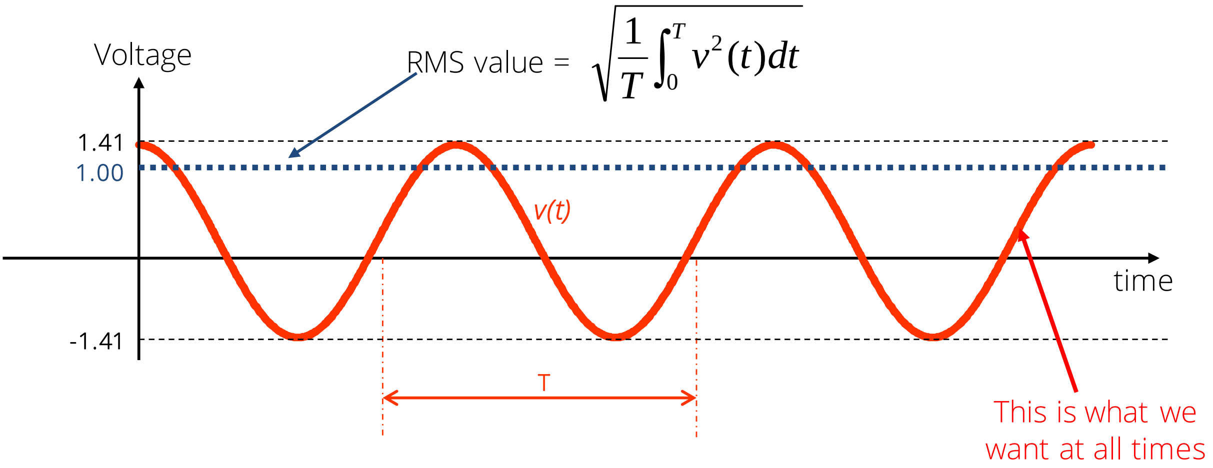


What is ‘Good’ Power Quality?

- If the voltage:
  - Has a constant sine wave shape with fundamental frequency only
  - Is supplied at constant frequency
  - Forms a symmetrical three-phase power system
  - Has a constant RMS value, unchanged over time
  - Is unaffected by load changes
  - Is reliable, i.e., energy available when required

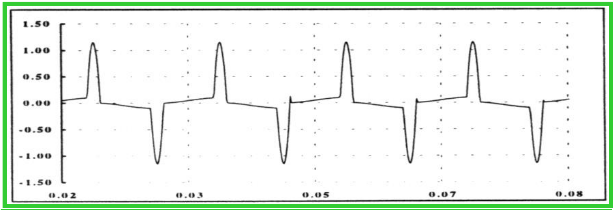
it is of “good” quality!

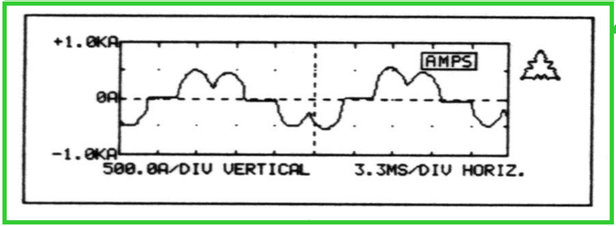
What we want…



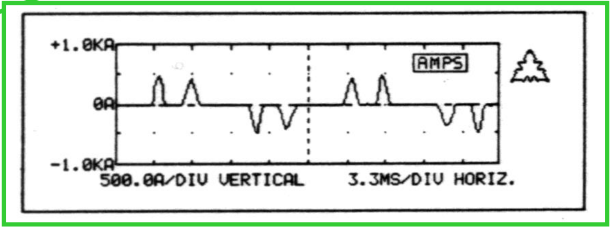
Voltage
RMS value = $\sqrt{\frac{1}{T}\int_0^T v^2(t)dt}$
1.41
1.00
-1.41
v(t)
time
T
This is what we want at all times

...what we get





This is what we sometimes get



Power Quality Categories – 1

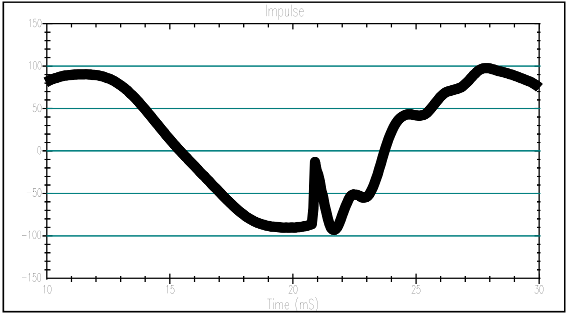
- There are two major categories of Power Quality variations:
  - Disturbances:
    - Transients
    - Voltage Sags (Dips) and Swells
    - Interruptions of supply
  - Steady State Variations:
    - Voltage Regulation
    - Voltage Unbalance
    - Harmonic Distortion
    - Voltage Flicker

Power Quality Categories – 2

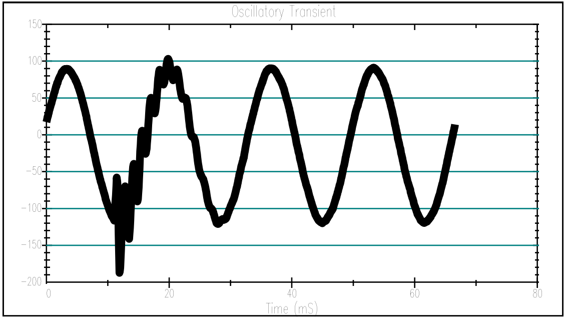
- Power Quality variations can be classified as:
  - Long Duration:
    - » Voltage Regulation (under- & over-voltages)
    - » Voltage Unbalance
    - » Harmonic Distortion
  - Short Duration:
    - » Instantaneous (0.5 cycles to 30 cycles)
    - » Momentary (30 cycles to 3 s)
    - » Temporary (3 s to 1 min)

Disturbances: Transients

Impulsive transients



Oscillatory transients



IEEE 1159

Disturbances: Voltage Sag & Interruption

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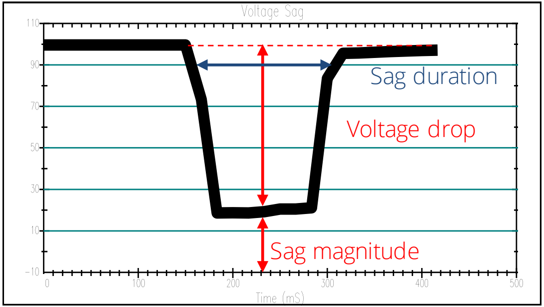
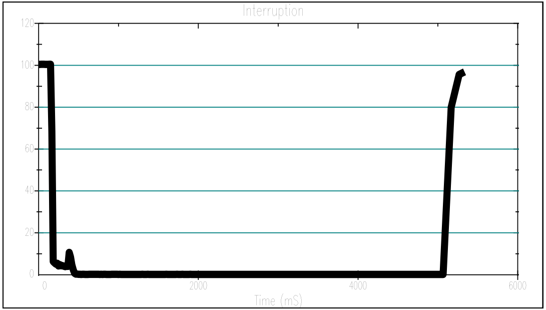
Voltage Sag:
0.1 p.u. - 0.9 p.u. *retained voltage*

Voltage Swell:
short duration overvoltage (less than 1 min) between 1.1 p.u. and 1.8 p.u.



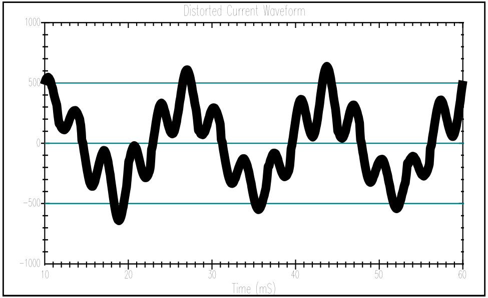
Interruption:
less than 0.01 p.u. *retained voltage*

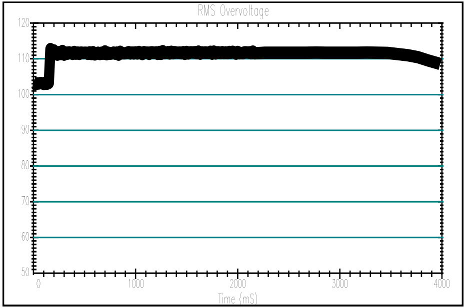


IEEE 1159

Steady-state: Harmonics & Over-voltages

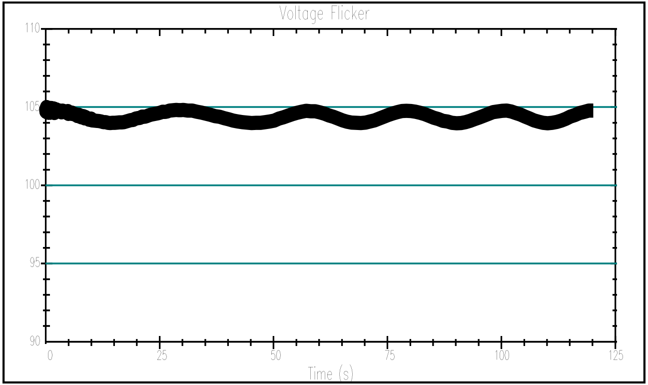
- Harmonics
- *Interharmonics*: frequencies are not an integer of the fundamental frequency
- Sub-harmonics: frequencies are below fundamental frequency
- Overvoltage





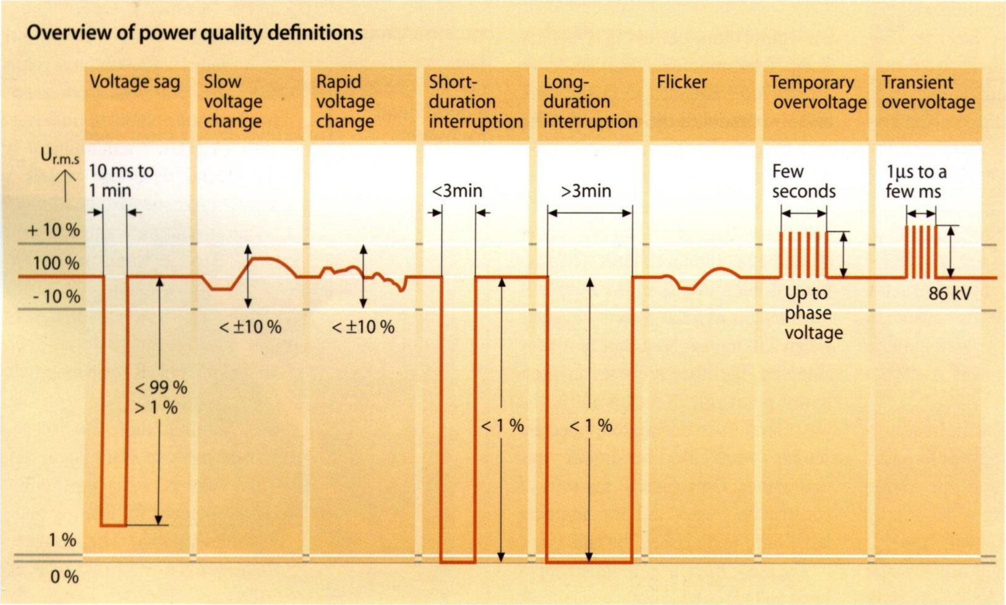
Steady-state: Voltage Flicker & Regulation

- Voltage Flicker:
  - The modulation in the RMS value of the fundamental frequency voltage (typically in the range 1-25(30)Hz).
  - Visible change in brightness of a lamp due to rapid fluctuations in the voltage of the power supply
  - Irritating visual sensation.



- Voltage Regulation:
  - (For example) Change of voltage RMS over distance
  - Can result in (long-term) under- and over-voltages

Illustration of Power Quality categories



Definitions: RMS

- Root-mean-square (RMS) value of voltage or current over one cycle or half-cycle of the fundamental power frequency.

$$X = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} x_i^2}$$

X – voltage (V) or current (I)

T – period

N – number of discrete values

Definitions: SCR

$$\boxed{SCR = \frac{I_{SC}}{I_{nom}}}$$

- *SCR* – Short Circuit Ratio
- *Inom* – Circuit nominal (or maximum) current measured and averaged in 15min intervals over one calendar year.
- *Isc* – Short-circuit current at a bus, i.e., three-phase (or single phase if applicable) current due to a bolted short-circuit to ground.
- Typical values of *SCR* are between 20 and 100 for residential circuits and much higher (to 1000 or more) for industrial circuits.
- It is often limited by the distribution transformer when the customer connection is at the transformer secondary (in such cases it is estimated as the inverse of the transformer per unit reactance).

Definitions: SCC

$$SCC = \frac{V_n^2}{X_{source}}$$

SCC	–	Short Circuit Capability (MVA or p.u.)
V_n	–	Nominal voltage at the ‘source’ node
X_{source}	–	‘Source’ impedance – reactance (i.e. impedance from the network ‘beginning’ to the ‘source’ node).

- Source impedance is used to model the (non-modelled) upstream part of the network

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VOLTAGE VARIATIONS



CLASSIFICATION OF VOLTAGE VARIATIONS

Voltage variations

- Steady State Variations
  - Voltage Regulation
  - Voltage Unbalance
  - Voltage Flicker
  - Harmonic Distortion (in-detail consideration)
- Disturbances
  - Voltage transients
  - Interruptions of supply and outages
  - Voltage Sags and Swells (in-detail consideration)

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VOLTAGE REGULATION



Definition of Voltage regulation

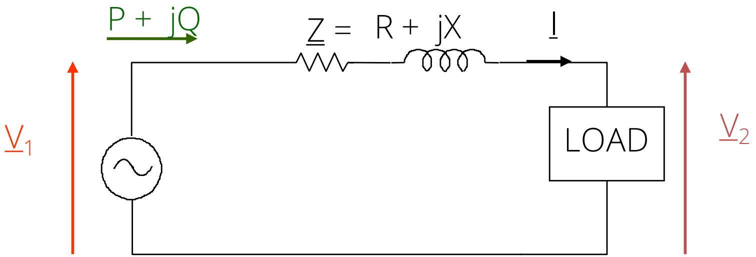
$$\boxed{V_R[\%] = 100\left(1 - \frac{V_{rated} - V}{V_{rated}}\right)}$$

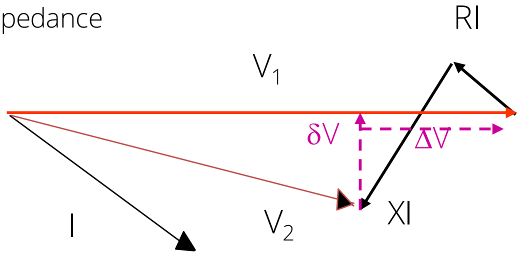
V_{rated} - rated circuit voltage
V - measured RMS voltage

- The regulation of voltage is closely related to the ‘strength’ of the bus, i.e. the ability of the bus to supply current without changing voltage amplitude.

Source of the problem (low voltage)

Voltage drop across system impedance





$$\underline{V}_2 = V_1 - \underbrace{\frac{PR+QX}{V_1}}_{\Delta V} - j\underbrace{\frac{PX-QR}{V_1}}_{\delta V} = V_1 - d\underline{V}$$

$$d\underline{V} = \underbrace{\frac{PR+QX}{V_1}}_{\Delta V} + j\underbrace{\frac{PX-QR}{V_1}}_{\delta V}$$

We often use: $d\underline{V} \approx \dfrac{Q\cdot X}{V_n}$

ΔV - change in voltage magnitude is influenced mostly by transmission of reactive power.
δV - change in voltage angle (phase shift between voltages) is influenced mostly by transmission of real (active) power.
Usually ΔV is much larger than δV => δV is neglected

Principles for improving voltage

- Add shunt capacitor to reduce current

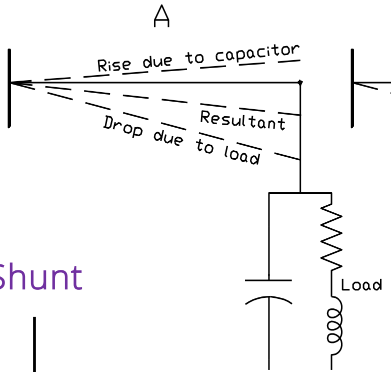
$$\Delta V - \Delta V_{sh} = \frac{X}{V_n}(Q_{load} - Q_{sh})$$

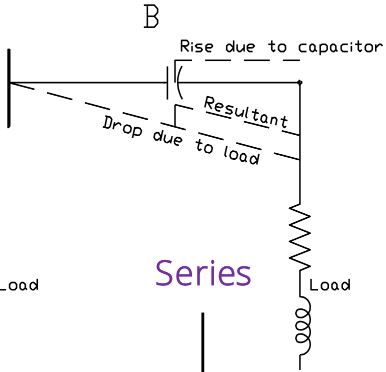
- Add series capacitor to counter voltage drop X*I

$$\Delta V - \Delta V_{se} = \frac{Q_{load}}{V_n}(X_{line} - X_c)$$

- Add voltage regulators to boost voltage (11kV, 0.4kV)
- Use tap-changing transformer
- Add static VAR system

Addition of Capacitors





Shunt

Series

Voltage change: $\Delta V \approx \frac{X_{tx} \cdot Q_{cap}}{V_n}$

$$\Delta V\% = \frac{X_{tx} \cdot kVAr_{cap}}{V_n^2} 100 = \frac{z_{tx} \cdot V_n^2}{100 \cdot S_n} \frac{kVAr_{cap}}{V_n^2} 100 = \frac{kVAr_{cap} * z_{tx}(\%)}{kVA_{tx}}$$

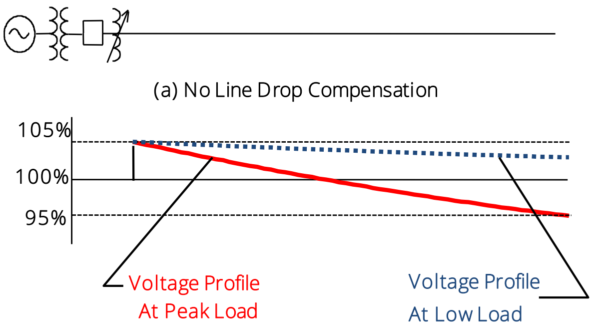
Capacitor size (both cases):

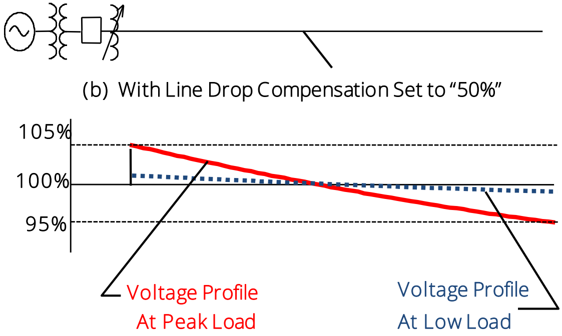
$$kVAr = kW\left(\tan\phi_{orig} - \tan\phi_{new}\right)$$

$$= kW\left(\sqrt{\frac{1}{PF_{orig}^{\ 2}} - 1} - \sqrt{\frac{1}{PF_{new}^{\ 2}} - 1}\right)$$

Distribution network tap changers

- Tap-changer at the beginning of *radial* networks
- On-load tap-changer (OLTC): automatic voltage relay (AVR) gives input to the motor that changes primary taps up and down
- AVR set-point:
  - (a) Voltage – 'no line drop compensation' (say, 105%)
  - (b) Voltage plus 'impedance' times (measured) current – 'with line drop compensation' (say, 101% + 0.5$\cdot Z_{line} \cdot I_{feeder}$)





Example PQ1: Power factor correction (Ref. 3)

- An industrial 300/22kV, 80 MVA transformer with *X=12%* is supplying a 50 MVA load whose power factor is 0.9. A shunt capacitor bank should be used to increase the power factor to 0.95. Find the size of the capacitor and the voltage rise knowing that the short-circuit capacity (level) at the 300 kV bus is 2000 MVA.

Upstream system (based power is 100 MVA)

$$SCC = 2000\ MVA = 20PU => X_S = \frac{\left(V_n^2\ \right)}{SNN} = \frac{1^2}{20} = 0.05\ pu$$

Transformer and total reactance up to 22 kV node:

$$X_T = 0.12\frac{100}{80} = 0.15\ pu \quad X_{22} = X_S + X_T = 0.05 + 0.15 = 0.2\ pu$$

Load:

$$P_L = S \cdot \cos\varphi = 0.45\ pu$$

Example PQ1: Power factor correction (Ref. 3)

- The size of the capacitor bank:

$$Q_C = P_L \cdot (\tan\varphi_1 - \tan\varphi_2) = 0.45(0.48432 - 0.32868)$$
$$= 0.07\ pu\ (7\ MVAr)$$
$$=> X_C = 14.278\ pu\ (69.1\ ohm)$$

- Voltage improvement (rise)

$$\Delta V = \frac{X_{22} \cdot Q_C}{V_n^2} = \frac{0.2 \cdot 0.07}{1^2} = 0.014\ pu\ (1.4\%)$$

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VOLTAGE UNBALANCE

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Voltage unbalance (imbalance)

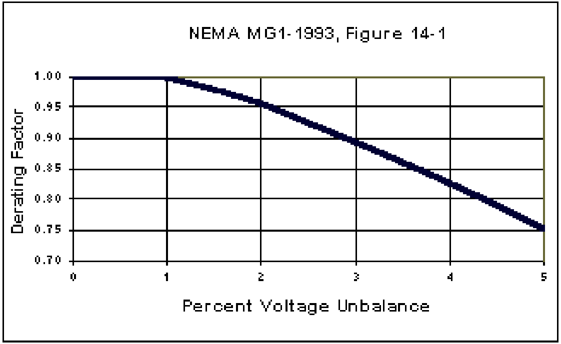
- **Voltage unbalance:** A condition in which the three phase voltages differ in magnitude, are displaced from their normal 120° phase relationship, or both.
- **Magnitude unbalance:** The maximum deviation among the three phases from the average three phase voltage divided by the average of the three phase voltage.
- **Phase-angle unbalance:** The maximum deviation of the angular difference between the three phases divided by 120°.
- **Negative (zero) sequence unbalance ratio:** The ratio of the negative (zero) sequence component to the positive sequence component. (Usually expressed as a percentage)

Voltage unbalance - causes

- Single phase loads on a three-phase circuits (usually less than 2%).
- Blown fuses in one phase of a three-phase capacitor bank.
- Single phase faults (usually greater than 5%).
- Single phase generation (e.g. PVs)

Motor heating and unbalance

- Unbalance = negative sequence/positive sequence =V2/V1
- EN 50160 Limit = 2%



Some studies showed that for:
THD ≤ 15%
and
V2/V1 ≤ 3%
there is no problem with overheating of motors

Energy efficient motors – Warning:

- Energy efficient motors have lower locked rotor impedances (negative sequence) which results in higher currents when the voltage is unbalanced.
- These currents could cause nuisance tripping if the motor protection is set very sensitive.

OVERVOLTAGES AND UNDERVOLTAGES

Definitions

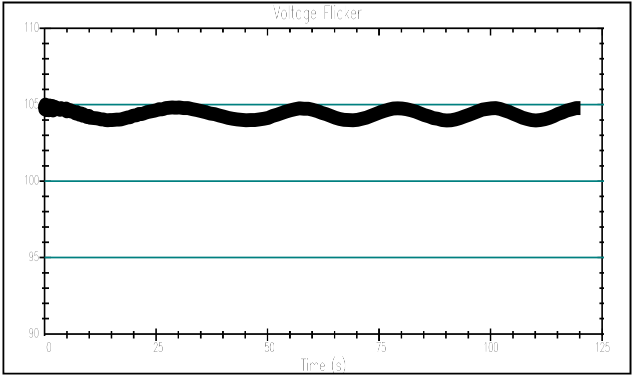
- **Overvoltage:** An increase in the RMS value of voltage above 110% for more than 1 min.
  - Main causes:
    - Load switching (switching off large load, energizing capacitor bank)
    - Incorrect tap settings on transformers (e.g. new DG w/o tap changer)
    - The system is to weak for the desired voltage regulation or voltage controls are inadequate.
- **Undervoltage:** A decrease in the RMS value of voltage below 90% for more than 1 min.
  - Main causes:
    - Load switching (switching on large load, de-energizing capacitor bank)
    - Incorrect tap settings on transformers (e.g. rural areas)
    - Overloaded systems.

VOLTAGE FLICKER



Voltage Flicker

- **Voltage Flicker:** The modulation in the RMS value of the fundamental frequency voltage component (typically in the range 1-25(30)Hz ; most sensitive 8-10Hz).
- Impression of unsteadiness of visual sensation induced by a light stimulus whose spectral distribution fluctuates with time.
- The magnitude of voltage is usually within the voltage range of 0.9 p.u. - 1.1 p.u.
- The main causes are the loads with continuous, rapid variations in the load current magnitude (Arc-furnaces, Embedded generation plant - (Wind mills), Welding)



Who can cause flicker?

Fluctuations per Unit Time	Typical Equipment
1-30 fluctuations per hour	House pumps, sump pumps, air conditioning, theatrical lighting, refrigerators, oil burners
0.5-10 fluctuations per minute	Single elevators, hoists, cranes, x-ray equipment, wye-delta changes on elevator motor generators sets
10-60 per minute	Arc furnaces, flashing signs, arc-welders, saws group elevators, drop hammers, spot welders
1-15 per second	Reciprocating pumps, compressors, automatic spot welders

- More: 175Hz inter-harmonics may also cause flicker
  - Induction furnace output frequency coupled back to input frequency results in interharmonics (good isolation is necessary by DC link.)
  - Wind generators can produce interharmonics

Flicker severity measurement

- IEC has published design specification for **flickermeter**
- Flickermeter has two main parts:
  - Electrical model of the lamp-eye-brain chain giving flicker sensation-irritation through the *instantaneous flicker level* (IFL)
  - On-line statistical processing of the IFL giving *short-term flicker perceptibility-severity index (P_{ST})* in 10 minute intervals
- P_{ST} is a p.u. quantity where 1 p.u. represents a flicker severity that corresponds to perceptible flicker in 60 Watt incandescent lights.
- Long term flicker severity index P_{LT} is calculated from 12 successive P_{ST} values over a 2 hour period using the formula (limiting value for P_{ST} is 0.65):

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum_{j=1}^{12} {P_{st_j}}^3}$$

Flicker summary

- Caused by variable loads (mainly) or generation
- Be aware of loads that generate inter-harmonics.
- Standardized monitoring approach (IEC 1000-4-15).
- Most annoying frequencies 8-10 Hz.
- Mitigation: *Flicker compensator*

INTERRUPTIONS AND OUTAGES

Interruptions and Outages

- Supply interruptions were studied in the Reliability Analysis
- Classification of interruptions:
  - **Long Interruption:** A decrease in the RMS voltage to less than 0.1 p.u. for a duration in excess of 1 min. (The total loss of supply followed by ‘manual’ restoration of supply.)
  - **Short Interruption:** A decrease in the RMS voltage to less than 0.1 p.u. for a duration not exceeding 1 min. (The total loss of supply followed by automatic restoration of supply.)

Types of outages & interruptions

Outages

- Permanent
  - Associated with damaged faults that require repair or replacement.
- Temporary
  - Associated with undamaged faults that are restored by manual switching or fuse replacement.
- Transient
  - Associated with undamaged faults but are restored automatically.

Interruptions

- Momentary (short) interruptions
  - Last less than 1 min
  - Not recorded in fault statistics
  - Due to transient faults and switching
- Sustained (long) interruptions
  - Last longer than 1 min
  - Generally recorded in fault statistics
  - Due to permanent and temporary faults

System reliability indices

- Defined in the “Reliability Analysis “ section at three levels:
  - Load-Generation systems
  - Composite Generation-Transmission systems
  - Distribution systems

VOLTAGE TRANSIENTS



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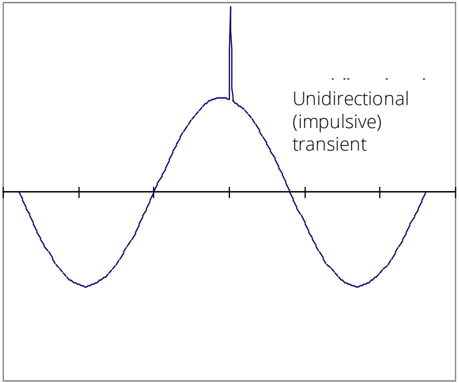
Voltage transients - definitions

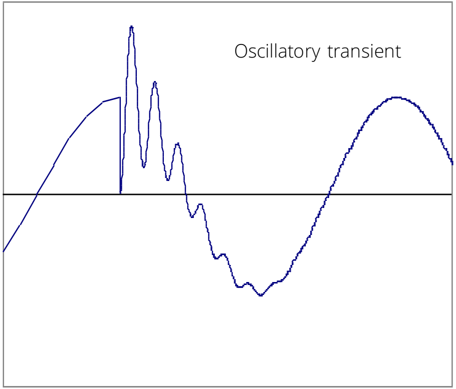
Transients

Impulsive Oscillatory

- Impulsive transient
  - A sudden, non-power frequency change in the steady state condition of the waveform of voltage, current or both that is unidirectional in polarity (primarily either positive or negative).
  - *Sub-cycle overvoltage (undervoltage):* duration less than 0.5 cycle
- Oscillatory transient
  - A sudden, non-power frequency change in the steady state condition of the waveform of voltage, current or both that includes both positive and negative polarity values.
  - *Sub-cycle voltage oscillation:* oscillation frequency >> fundamental frequency

Typical transients





Characterized by: peak voltage, duration, rates-of rise, energy content, frequency (if oscillatory).

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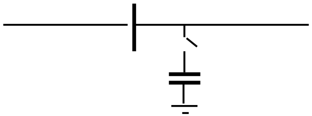
Causes of voltage transients

- Capacitor bank energizing
- Capacitor and DG interaction
- Back-to back capacitor energizing
- Adjustable Speed Drives (ASDs) and electronic loads
- Lightning
- Cable switching (5kHz - 500kHz)
- Ferroresonance (less than 300Hz, >2p.u. - >4p.u.)

  (Magnetizing reactance of transformer in series with cable (capacitance) or PF capacitor; Manual switching of unloaded/ lightly loaded cable-fed transformer with one/two open phases)

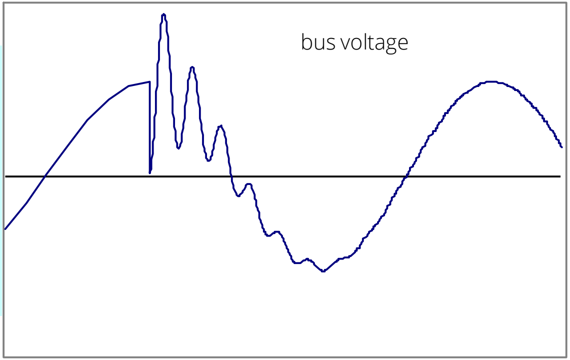
Switching-in a capacitor



Resonant frequency ($X_L = X_C$):

$$\boxed{f_0 = \frac{1}{2\pi\sqrt{LC}}}$$

- Frequency is usually less than 1kHz (300Hz - 900Hz), lasts 0.5-3 cycles
- Maximum possible peak is twice system peak voltage (i.e., 2 p.u.), in practice maximum peak is about 1.4 p.u.
- Will generally pass through distribution transformer by nearly the amount related to transformer turns ratio
- Voltage rise of about 2-3% is common when typical capacitor bank is energised

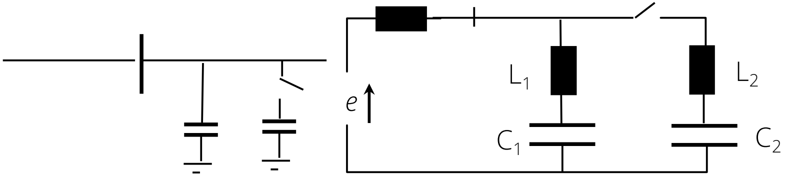


Capacitor and DG Interaction

- Utility capacitor switching can kick DGs off
- Varying DG production can cause excessive capacitor switching (to regulate the voltage)
- Self excitation (Induction generator suddenly isolated on a capacitor bank can continue to generate for some time resulting in unregulated voltage.)
- Switching ‘local’ capacitor to regulate voltage/reactive power may yield resonance(s) with frequency(ies) that coincide with harmonics produced in the same facility.

- Solutions:
  - Block utility capacitors while DG is operating
  - Change tap on DG service transformer
  - Increase capacitor control band or switch to a different type of control

Back-to-back capacitor switching



Resonant frequency ($X_L = X_C$):

$$f_0 = \frac{1}{2\pi\sqrt{L_{eq}C_{eq}}}$$

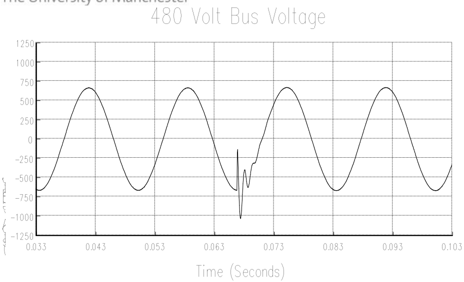
where $L_{eq} = L_1 + L_2$

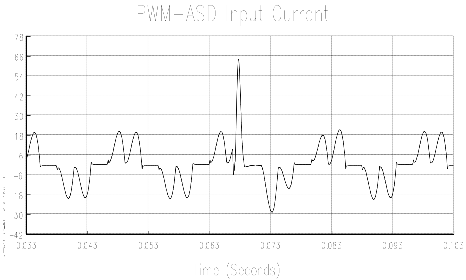
and $C_{eq} = C_1C_2 / (C_1 + C_2)$

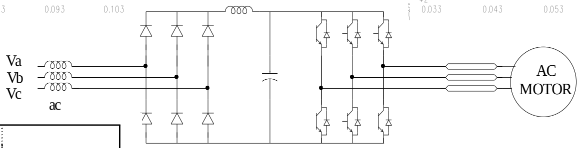
- Frequency is usually below 10kHz
- Maximum possible peak can reach 2.p.u.

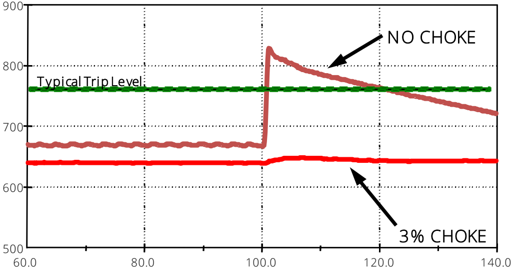
The major consequence of these transient overvoltages is that they can cause misoperation of electronic power conversion devices which typically have withstand capability of 1.75 p.u. voltage.

Impact of capacitor energizing on ASDs









Solutions:
-Add reactance (A.K.A. “choke”) on the front end of the drive or built it into the DC link (3% of drive rating);
-Drive motor with first few turns with better insulation.

Transient overvoltages

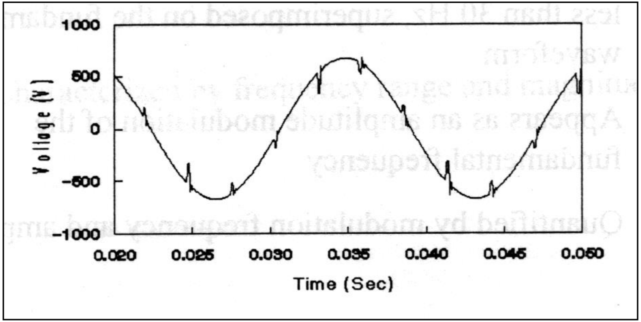
- Lightning (rise time 1.2 μs, decay time to half peak value 50 μs)
  - Direct stroke to phase conductor
  - Stroke to overhead shielding wire or tower
  - Indirect coupling
    - via grounding system
    - inductive coupling
    - capacitive coupling
  - \- Flashover of external clearances in the air
- Switching on transmission and distribution networks
  - Inductive / capacitive circuits

VOLTAGE NOTCHING



Voltage notching

- **Definition**: A disturbance of the normal power voltage waveform, lasting less than a half-cycle, which is initially of *opposite polarity* than the waveform, and is thus subtractive from the normal waveform in terms of the peak value of the disturbance voltage. (Dependent on firing angle and amount of commutating inductance).
- **Solution:** Addition of a reactance or isolation transformer on the input to the drive.

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Power Quality



Dr Victor Levi

VOLTAGE SAGS

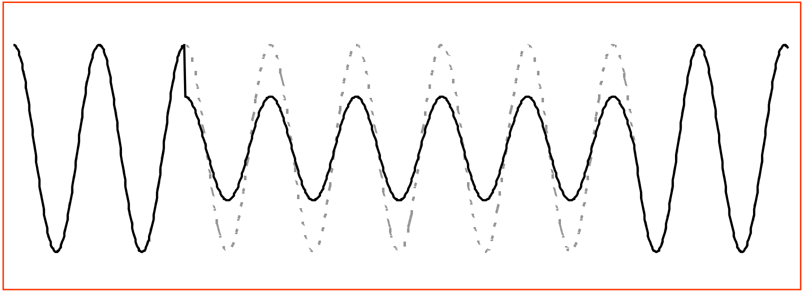


DEFINITIONS AND CHARACTERISTICS OF VOLTAGE SAGS



Voltage sag (Dip)

- Voltage sag is a decrease in the RMS ac voltage, at the power frequency, of duration from 0.5 cycles (10ms for 50Hz systems) to 2-3 seconds.



RMS Voltage Disturbances

IEEE Std. 1159 Definitions

Short Duration Variations	Duration	Voltage Magnitude
Instantaneous		
Sag	0.5 to 30 cycles	0.1 to 0.9 pu
Swell	0.5 to 30 cycles	1.1 to 1.8 pu
Momentary		
Interruption	30 cycles to 3 s	<0.1 pu
Sag	30 cycles to 3 s	0.1 to 0.9 pu
Swell	30 cycles to 3 s	1.1 to 1.4 pu
Temporary		
Interruption	3s to 1 min	<0.1 pu
Sag	3s to 1 min	0.1 to 0.9 pu
Swell	3s to 1 min	1.1 to 1.2 pu
Long Duration Variations		
Sustained Interruption	>1 min	0.0 pu
Undervoltage	>1 min	0.8 to 0.9 pu
Overvoltage	>1 min	1.1 to 1.2 pu

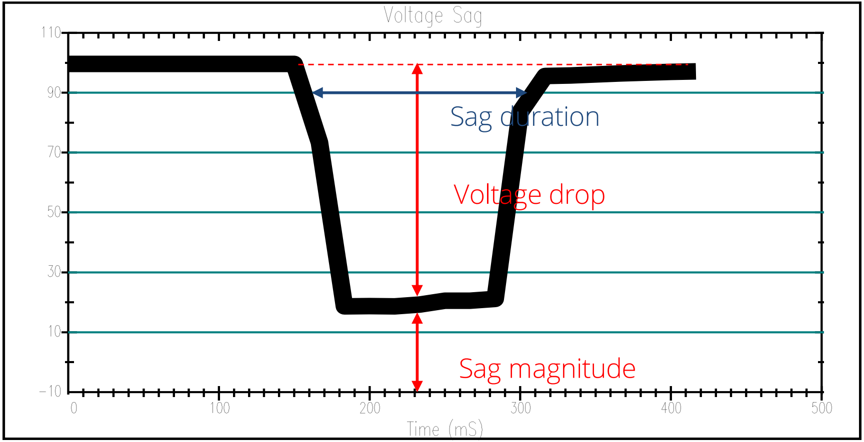
Voltage sags characteristics

- Following voltage sag characteristics are studied:
  - Sag Magnitude
  - Sag Duration
  - Phase angle jump (phase-shift)
  - Point on the wave of voltage reduction and restoration
  - Asymmetry of voltage reduction in three phases

Sag Characteristics: Definitions - 1

- **Voltage sag magnitude:** The remaining RMS voltage in percent or per-unit (p.u.) of the pre-fault voltage during the 'event'. (In the case of the non-rectangular sag, the sag magnitude is a function of time.)
- **Voltage drop:** The difference between the pre-'event' RMS voltage and the RMS voltage during the 'event'.
- **Voltage sag duration:** The duration of the RMS reduction of the voltage sag. (The persistent time that the voltage of the phase with the lowest magnitude is lower than 0.9 p.u. of the nominal voltage.)

Voltage Sag – RMS illustration

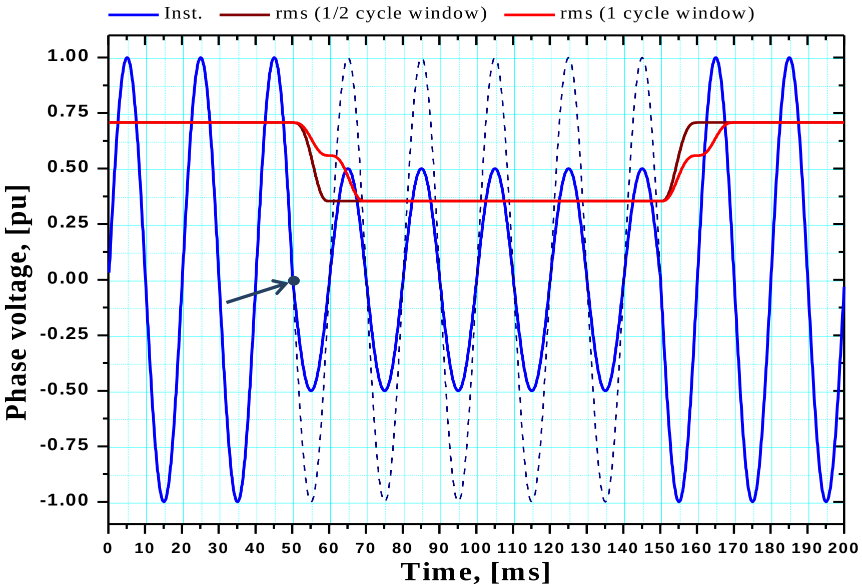


Voltage Sag (0.1 p.u. - 0.9 p.u. *retained voltage*)

Voltage Swell - short duration overvoltage (less than 1 min) between 1.1 p.u. and 1.8 p.u.

IEEE 1159

Voltage Sag – Time Domain



1-ph sag to 50%,

100ms,

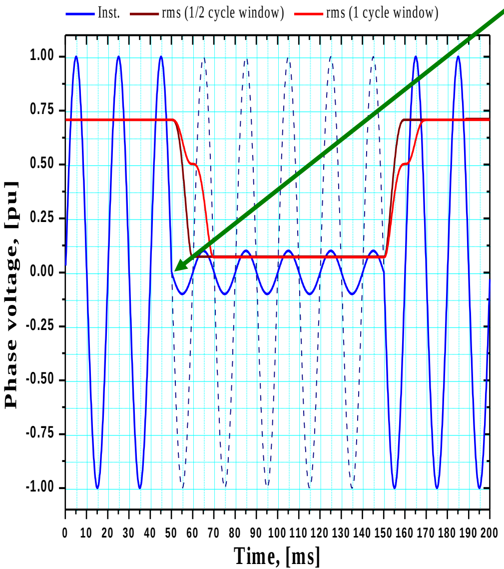
180^{o} point on wave

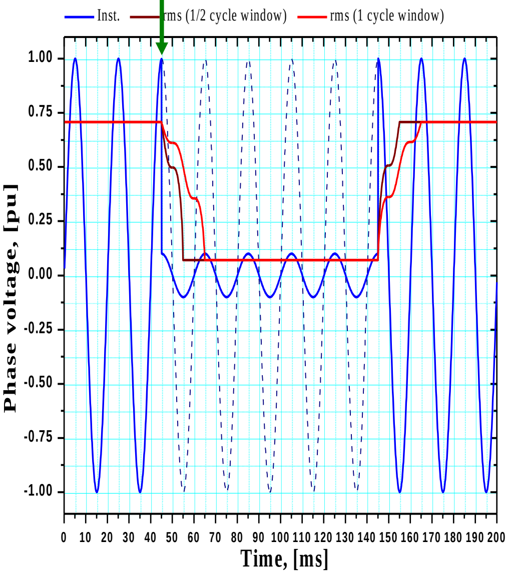
Sag Characteristics: Definitions - 2

- **Point-on-wave of sag initiation:** The phase angle of the voltage at the moment the voltage waveform shows a significant drop compared to its normal waveform. (The phase angle is measured with respect to the last upward zero-crossing of the voltage waveform.)
- **Point-on-wave of sag recovery:** The phase angle of the voltage at the moment the voltage waveform shows a significant recovery.
- **Non-rectangular sag:** A voltage sag where the sag magnitude vs. time is not constant.

Voltage Sag – Time Domain

1-ph sag to 10%, 100ms, 180° and 90 ° point on wave



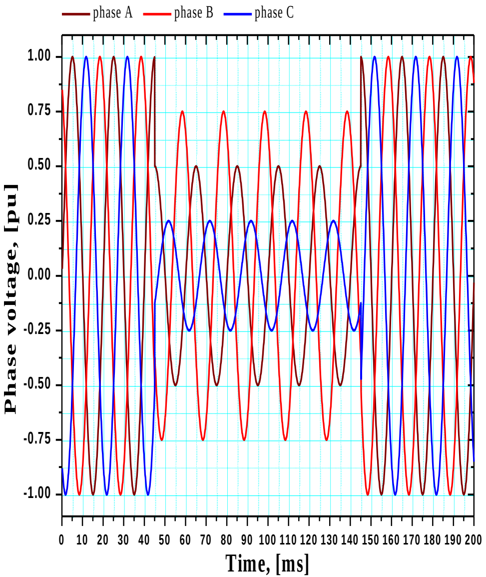


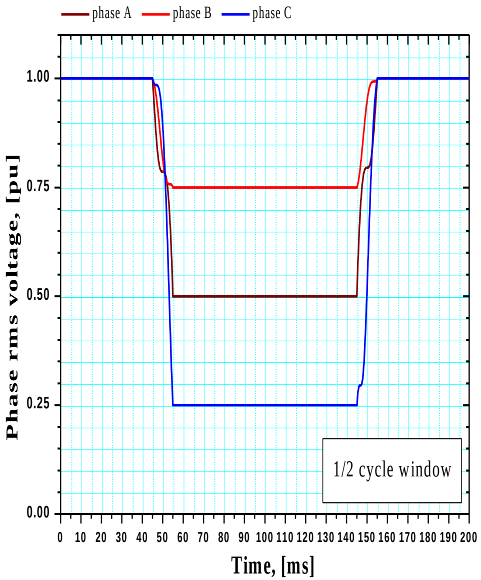
Sag Characteristics: Definitions - 3

- **Voltage unbalance**: A condition in which the three phase voltages differ in magnitude, are displaced from their normal 120° phase relationship, or both.
- **Magnitude unbalance**: The maximum deviation among the three phases from the average three phase voltage divided by the average of the three phase voltages.
- **Phase-angle unbalance**: The maximum deviation of the angular difference between the three phases divided by 120°.

Voltage Sag – Time Domain & RMS

3-ph sag to 75%, 50%, 25%, 100ms



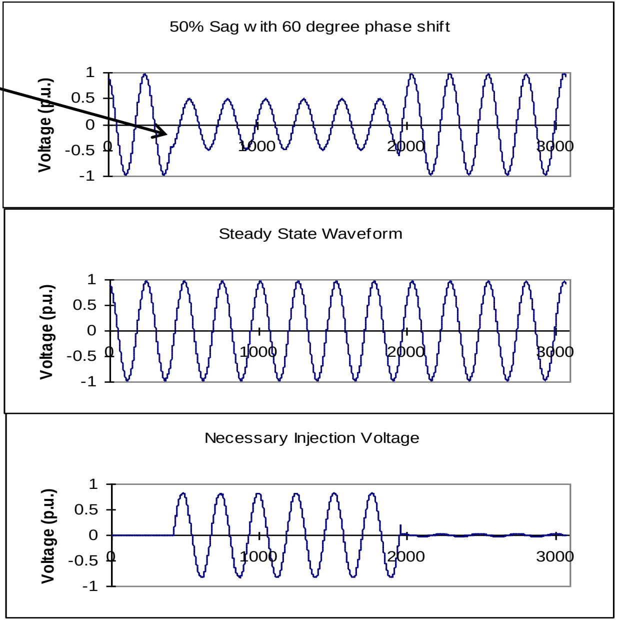


Sag Characteristics: Definitions - 4

- **Negative (zero) sequence unbalance ratio**: The ratio of the negative (zero) sequence component to the positive sequence component. (Usually expressed as a percentage.)
- **Missing voltage:** The difference between the actual voltage during the "event" and the voltage as it would have been if the "event" had not taken place.
- **Complex missing voltage:** A complex number which represents the missing voltage of a voltage sag in one phase. Difference in the complex plane between the pre-'event' voltage and the voltage during the sag.

Missing voltage

-60 degree



Source: IEEE P1409

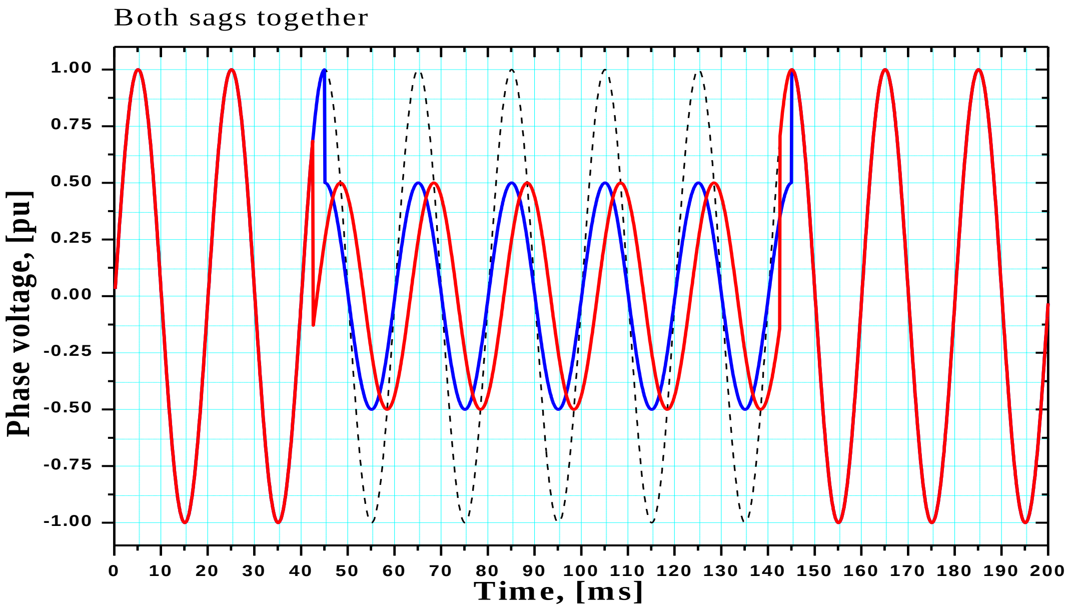
Sag Characteristics: Definitions - 5

- **Phase-angle jump (shift):** The difference in voltage phase-angle between the pre-“event” voltage and the voltage during the sag.

  (The displacement in time of the during- “event” voltage waveform relative to the pre-“event” waveform. A positive phase-angle shift indicates that the phase-angle of the during-“event” voltage waveform leads the pre-“event” waveform.)

  (Measured as the shift of zero crossing.)

Two 1-ph sags to 50%, 100ms: with 90° point on wave, no phase shift; and with 45° point on wave and phase shift of - 60°



CAUSES OF VOLTAGE SAGS, EQUIPMENT SENSITIVITY AND STANDARDS



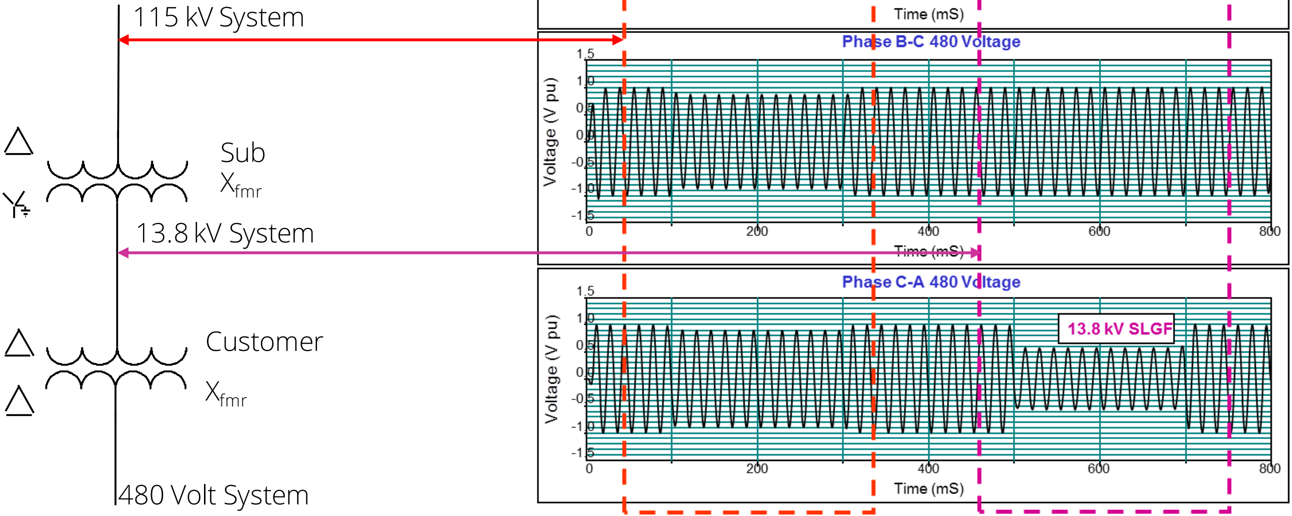
Causes of voltage sags

- Power system faults (lightning, wind, ice, contamination of insulators, animal contact, transportation/construction incidents)
  - The most common L-G fault
  - The most severe L-L-L fault
- Starting of large Induction Motors
- Transformer energizing (asymmetrical sags - different inrush currents in the three phases associated with large 2nd and 4th harmonic distortion.)
- Load changes

Voltage sags are influenced by

- System grounding
- Fault impedance and location (the magnitude reduces with the increase of the distance from the fault in radial systems).
- Configuration of the power system
- Transformer connections
- System protection practices (reclosing may result in several successive sags).
- Load connection (single phase, “two phase”, three phase)

1. Fault at 115 kV phase A
2. Fault at 13.8 kV phase A



Equipment susceptible to voltage sags

- Low power
  - Computers
  - Programmable logic controllers (PLCs)
  - Variable speed drive (VSD) control
  - Tension control
  - IT
  - Robotic controls
- High power
  - Variable speed drives (VSDs)
  - Motors
  - Tension actuators
  - Lighting
  - Robotic equipment
  - Contactors

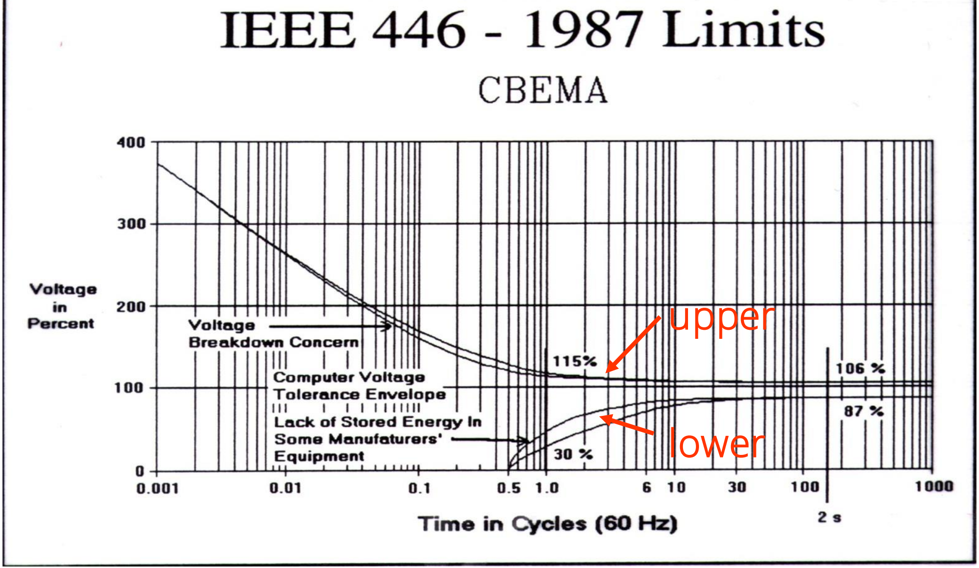
Example: Equipment sensitivity to voltage sags

Rectangular voltage tolerance curve is assumed.

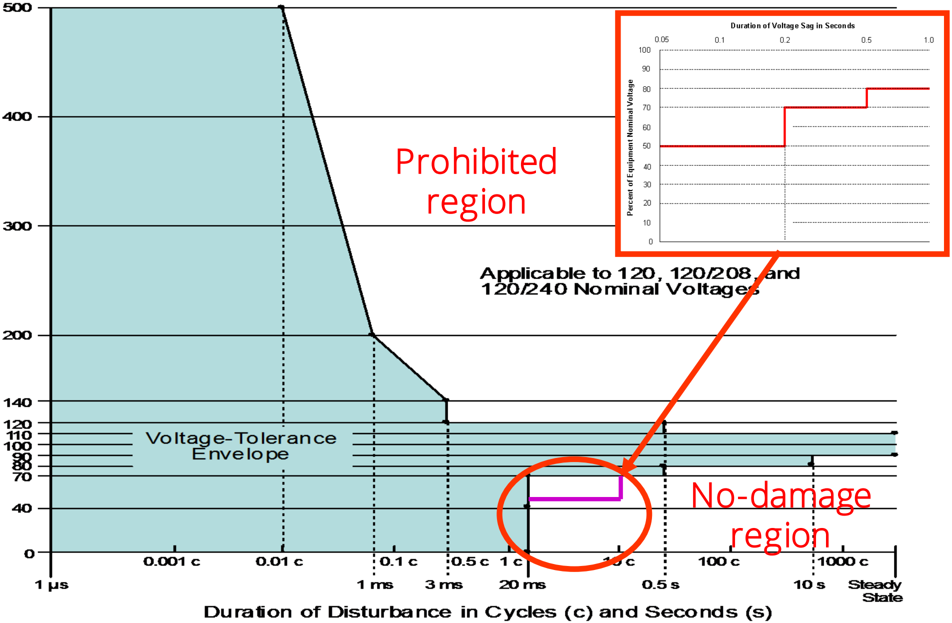
Equipment						
HP sodium lamp	<79% >10ms					<85-45% >1 cycles
PC power supply	<65-35% >80-450ms				<80-50% >30-70ms	<70-50% >30-170ms
VCR	<60-40% >50-220ms					
Air compressor		<55% >55ms				
Digital controller (PLC)		<35% >200ms			<75-45% >20-620ms	<85-35% >1-3cycles
ASD		<80% >120ms			<80-60% >30-80ms	<85-75% >1-30cycles
Relay without hold-in device			<80% >1 cycle	<75-80% >10-30ms	<75-60% >10-30ms	<75-80% >10-30ms
Relay with hold-in device			<15% 2cycles			
Motor starter without hold-in			<50-60% >1-2cycls		<60-40% >20-80ms	
Motor starter with hold-in device			<25% >5-15cycl			

Voltage tolerance envelopes-1987 CBEMA Curve

Computer **B**usiness **E**quipment **M**anufacturers **A**ssociation

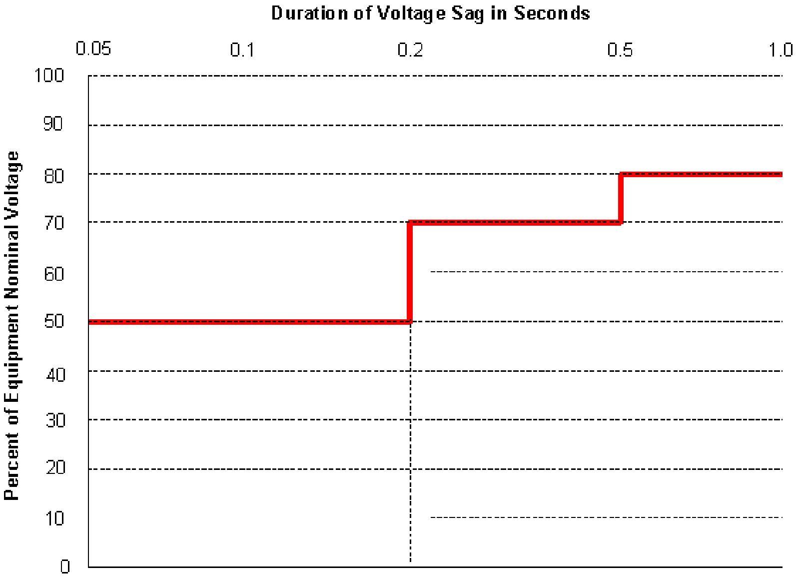


Voltage tolerance envelopes - 1996 ITIC Curve

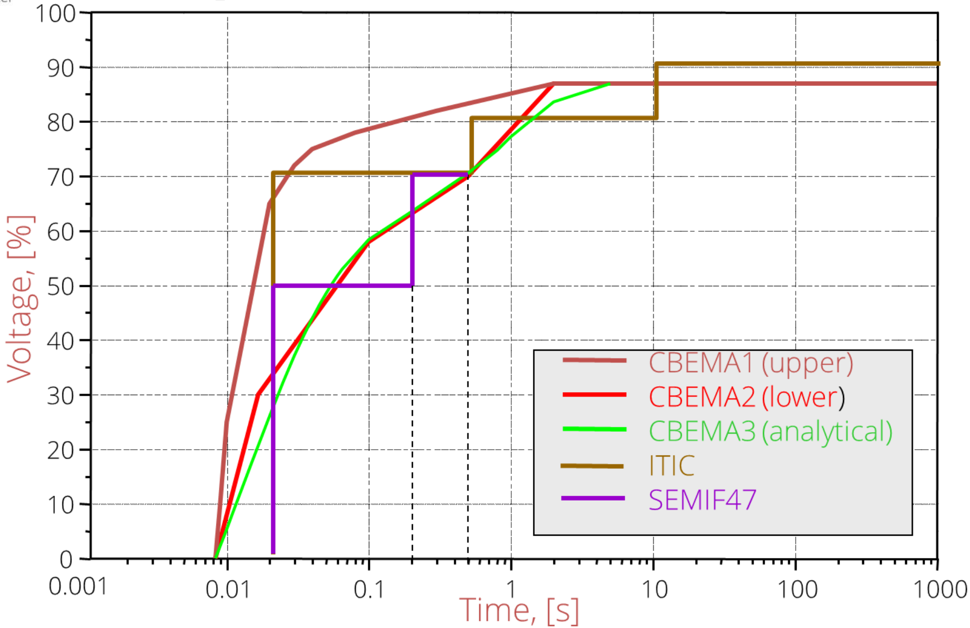


Voltage tolerance envelopes - 1999 SEMI Curve

Semiconductor **E**quipment and **M**aterials **I**nternational



Comparison of Standards



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ASSESSMENT OF VOLTAGE SAGS AND VOLTAGE SAG PROPAGATION



Assessment of Voltage Sags

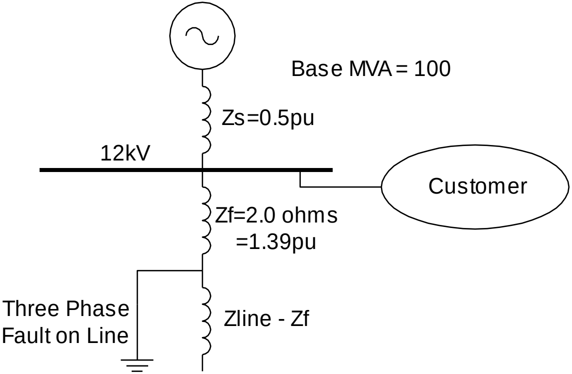
- Measurements,
- Analytical Techniques,
- Combination of Measurements and Analytical Techniques

Example PQ2: Post-fault regime

A customer is connected at a 12 kV busbar that feeds several radial feeders; its pre-fault voltage is 1.0 p.u. A 3-phase fault occurs on one of the radial feeders at the location whose electrical distance to the 12 kV busbar is 1.39 p.u. Find the post-fault voltage at the 12 kV busbar given that the system reactance is 0.5 p.u. on a 100 MVA base.

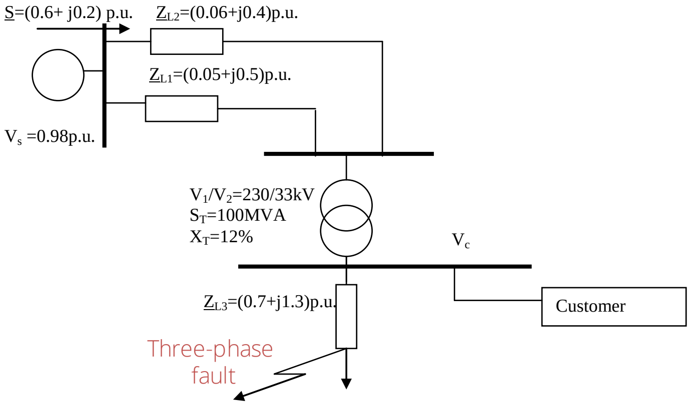
Regimes with a 3-phase fault can be calculated from the ***positive sequence*** network. A simple positive sequence network shows the customer voltage can be found using the "voltage divider":

$$V_{customer} = V \frac{Z_f}{Z_f + Z_S} = 1.0 \frac{1.39}{1.39 + 0.5} = 0.735\,pu$$

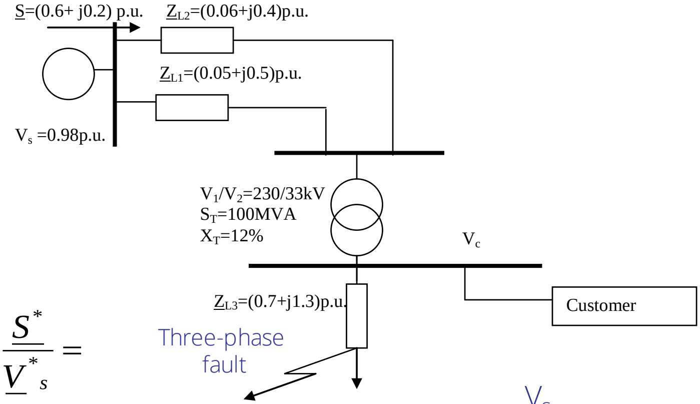


Example PQ3: Simple sag calculation/1

A customer is connected at a the transformer secondary side (see figure). A 3-phase fault occurs at an outgoing circuit whose electrical distance to the busbar is (0.7+j1.3) p.u. Find the post-fault voltage sag magnitude and phase shift at the customer busbar. Repeat the calculations when the electrical distance is (0.8 + j0.4) p.u.



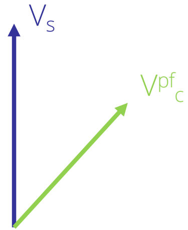
Example PQ3: Simple sag calculation/2



Assuming the source voltage V_S is along the real axis, the pre-fault voltage at customer busbar is found by calculating the voltage drop:

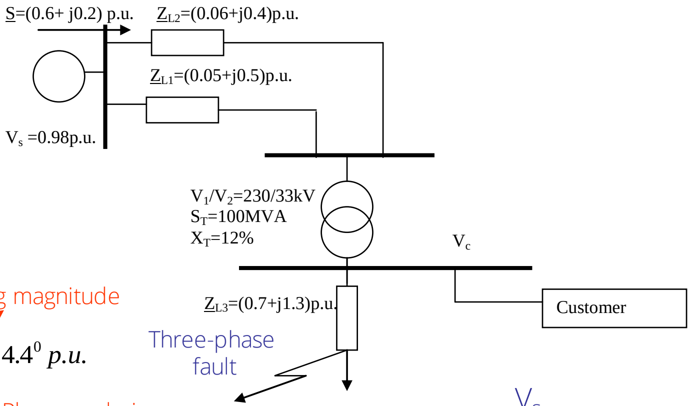
$$\underline{V}_c^{pre-fualt} = \underline{V}_s - \underline{Z}_S \underline{I} = \underline{V}_s - (\underline{Z}_T + \underline{Z}_{L1} \parallel \underline{Z}_{L2}) \frac{\underline{S}^*}{\underline{V}^*_s} =$$

$$= 0.98\angle 0^0 - (0.0284 + j0.3424)\frac{0.6 - j0.2}{0.98} = 0.92\angle -12.12^0 \; p.u.$$



Customer pre-fault voltage is lagging which is shown by two vectors on the right-hand side

Example PQ3: Simple sag calculation/3



Post-fault voltage is found from the expression for voltage divider:

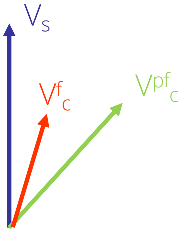
Sag magnitude

$$\underline{V}_c^{\,fault} = \underline{V}_s \frac{\underline{Z}_{L3}}{\underline{Z}_{L3} + \underline{Z}_S} = 0.98\angle 0^0 \frac{0.7 + j1.3}{0.7284 + j1.6424} = 0.8\angle -4.4^0 \; p.u.$$

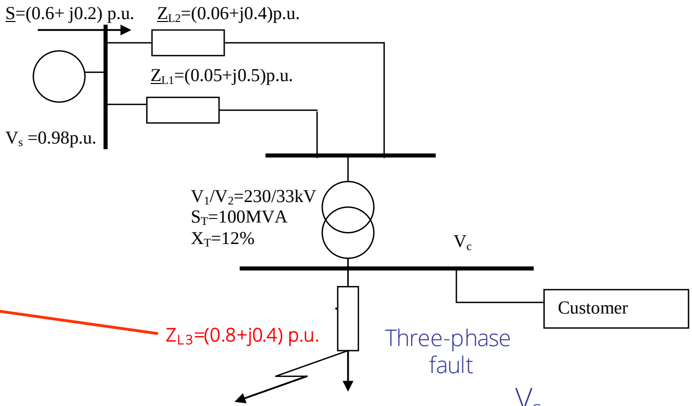
$$\Delta\theta = \theta_c^{fault} - \theta_c^{pre-fault} = -4.4^0 + 12.12^0 = 7.72^0$$

Phase angle jump

Voltage phasors are shown on the right-hand side:



Example PQ3: Simple sag calculation/4



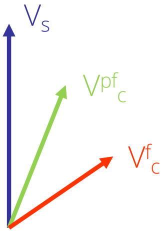
For : $Z_{L3} = (0.8+j0.4)\ p.u.$

$V_c^{fault} = 0.79\ \angle -15.3^0\ p.u.$

$\Delta\vartheta = -15.3^0 + 12.12^0 + = -3.2^0$

Phase angle shift is negative

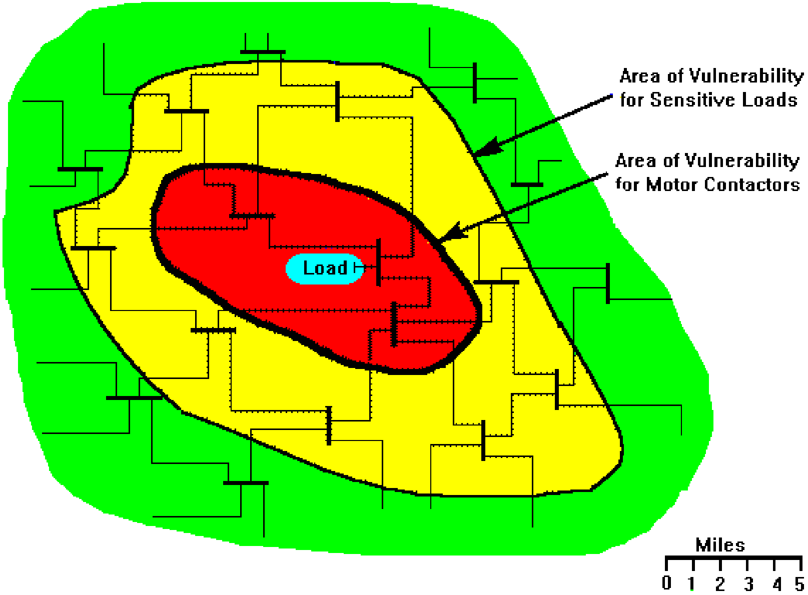
Voltage phasors are shown on the right-hand side:



Voltage sag prediction

- Lightning is one of the most frequent causes of faults and it is weather related:
  - Utilising geometry of the transmission lines, parameters of the insulators and ground flash density the expected number of 'lightning' faults per km of line per year can be predicted.
- The effects of fault on plant equipment depend on the sag characteristics (magnitude and duration, phase angle jump) which are influenced by fault clearing time, fault impedance and location, configuration of the network and the system protection design.
- The area of vulnerability can be defined for a particular customer and the likelihood of a fault within this area can then be calculated.

Example: Area of vulnerability



Sag propagation

- The sag is propagated in approximately inverse to the fault levels at the buses on the direct path.
- If a bus on a direct path has a fault level 10 times that at the point of fault then, the sag at that bus will be approximately 10%.

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MITIGATION MEASURES FOR VOLTAGE SAGS



Mitigation Measures

- Reduction in number of faults
- Voltage profile improvement

Reduction in number of faults

- Transmission network
  - Adjusting transmission tower footing resistance
  - Installing line arresters
  - Regular insulator washing
  - Fast switches with instantaneous protection
  - Arc-suppression coil earthing with time grading protection (used extensively in Europe, typical reduction in faults 10%)

Example: "Duke Power" (North & South Caroline) reduced footing resistance at their 100kV transmission below 10Ω (typical 50Ω, 60Ω) and installed arresters to reduce back-flash and so helped their customers (mainly small textile industry).

Reduction in number of faults

- Distribution networks
  - Network automation (11kV, LV)
  - Regular tree trimming
  - Installing animal guards
  - Installing arresters
  - Network loop schemes (instead of radial),
  - Modified feeder designs (covered OH conductor)

Improving voltage profile - 1

- Utility level
  - Faster protection
  - More meshes – loops in the network (where possible)
  - Installation of FACTS devices:
    - (Distribution) Static Compensator – (D)STATCOM
    - Dynamic Voltage Restorer (DVR)
    - (Distribution) Unified Power Flow Controller – (D)UPFC
    - Solid State Transfer Switch (SSTS)
    - Fault limiting reactors

Improving voltage profile - 2

- Selected distribution feeders / Customer interface
  - DSTATCOM
  - DVR
  - DUPFC
  - SSTS
  - Electronic tap-changer
  - Private generation
  - Motor – generator sets
  - Uninterruptible power supply (UPS)
  - Constant voltage transformers

Improving voltage profile - 3

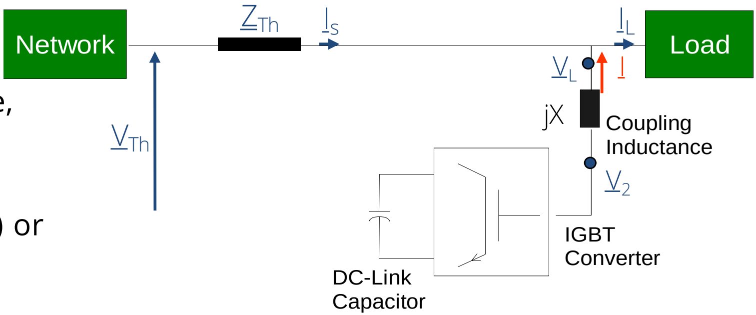
- End use equipment and systems
  - "Advanced" capacitors for fault ride through
  - Improved Variable Speed Drives (VSDs)
  - Improved motor starters
    - DC supplies
    - Lower drop-out
  - Customer systems designed for sag tolerance

Devices for improving voltage profile – 1

- Distribution Static Compensators (DSTATCOMs)
- Dynamic Voltage Restorers (DVRs)
- Unified Power Flow Controllers (UPFCs)
- Solid-State Breakers at dual feeders capable of switching load from one feeder to the other in extremely short period of time.
- Solid State Series Compensators (SSSCs)

DSTATCOM: Parallel – shunt conditioner

- Shunt reactive power source connected “close” to the load
- Components: coupling inductance, IGBT converter, DC capacitor
- DSTATCOM is a Current Source
- Good for fluctuating loads (flicker) or harmonics



Injected current driven by converter voltage V_2

$$\underline{I} = \frac{\underline{V}_2 - \underline{V}_L}{jX}$$

Assuming V_L is known, V_2 can be found from the 2 equations

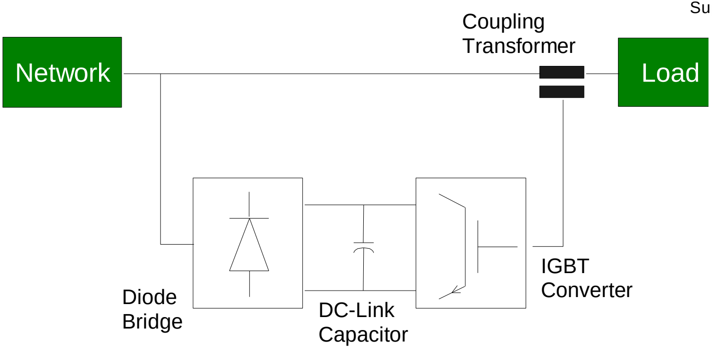
$$\underline{I} = \underline{I}_L - \underline{I}_s = \underline{I}_L - \frac{\underline{V}_{th} - \underline{V}_L}{\underline{Z}_{th}}$$

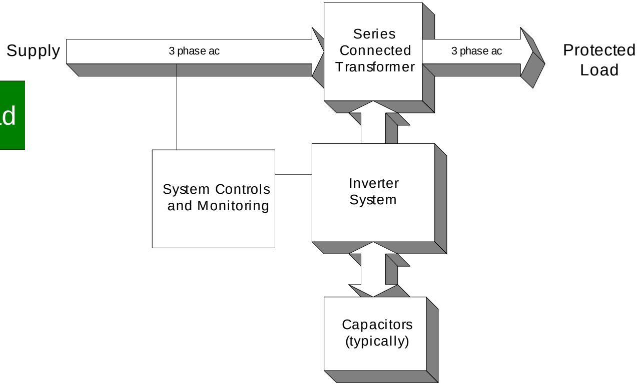
Limitations of DSTATCOM

- Shunt device with effect dependent on network source impedance.
- Provides support to load busbar and nearby network.
- Reactive power support only.
- Robust control system required.

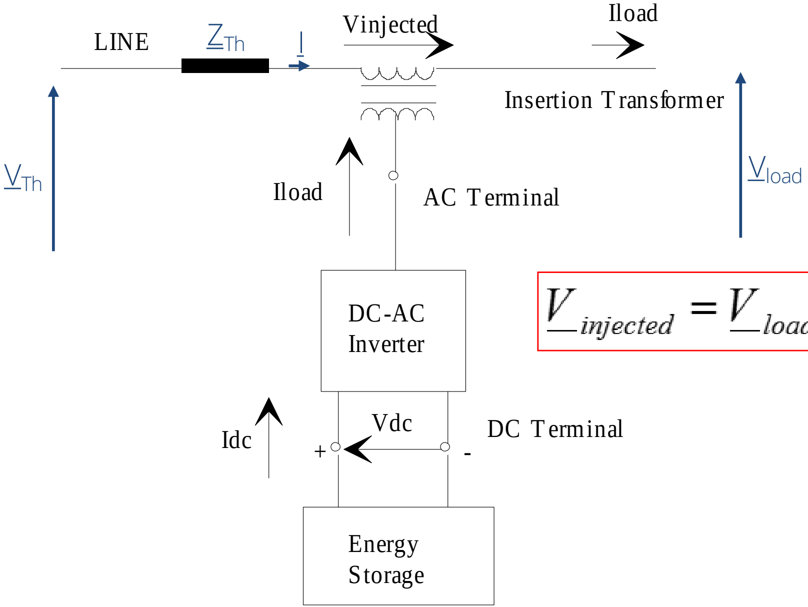
DVR: Series power conditioner

- Voltage source inserted in series with the load
- Components: rectifier, DC capacitor, inverter, coupling transformer
- DVR is a voltage source
- DVR supplies “missing” voltage during voltage sags, or corrects for harmonic distortion.





DVR with energy storage



$$\underline{V}_{injected} = \underline{V}_{load} + \underline{Z}_{th}\underline{I} - \underline{V}_{th}$$

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Dynamic Voltage Restorer (DVR)

- Voltage vector added in series with supply to control load voltage.
- Reactive support possible on all phases.
- Real power from energy storage or from un-faulted phases.
- Implemented on a number of semiconductor fabrication plants and paper mills (about 14 so far).

Features of DVRs

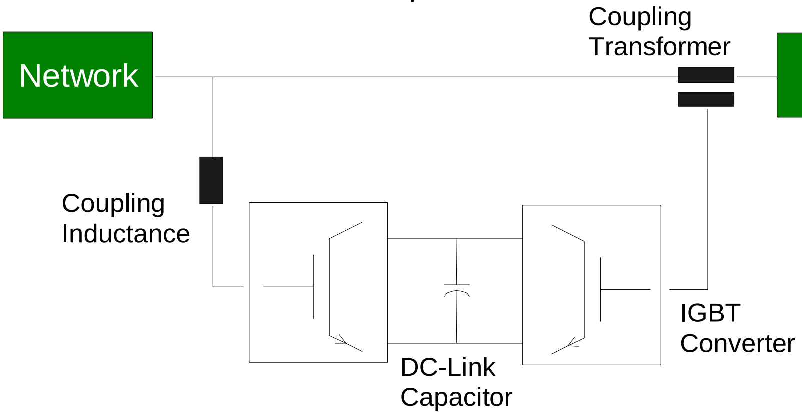
- Lower rated device may be used.
- Series transformers must be rated for full load current but the magnitude of the injected voltage can be reduced.
- $MVA_{DVR} = MVA_{LOAD}$ x Injected Voltage (p.u.)

  (5MW = 10MW x 0.5 p.u.)

(In UK paper mill application, the DVR rated at 50% of sensitive load can restore the voltage to 90% of nominal for 98% of sags.)

Distribution UPFC

- Voltage inserted via coupling transformer (right-hand side) or current injected via coupling inductance (left-hand side)
- Components: coupling inductance and transformer, two fully controllable converters, DC capacitor



Operation of Distribution UPFC

- Concept based on Unified Power Flow Controller of FACTS.
- Combination of STATCOM and DVR.
- Independent operation of bridges possible with fast switching of converters.
- Order of bridges may be reversed to give Unified Power Quality Controller.

Devices for Improving voltage profile – 2

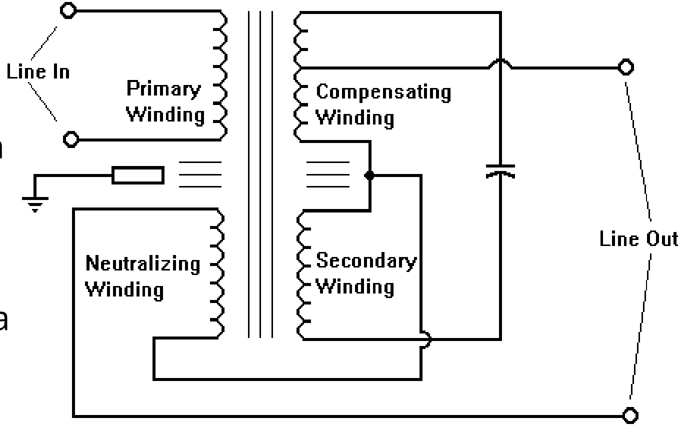
- Constant voltage transformers (CVT) and ferroresonant transformers
- Motor-generator sets (several seconds)
- Superconducting storage devices
- Uninterruptable Power Supply (UPS) systems

Constant Voltage Transformer (CVT)

- It should be oversized to at least 200% - 250% of load because in-rush current of load(s) MUST be considered in sizing
- Acts as an isolation transformer and protects against voltage sags.
- Very good for protection of computers, controls, relays
- Typically 0-3 kVA loads

Ferroresonant transformers (CVTs)

- Transformer with a 1:1 turns ratio and with a core that is highly magnetised (close to saturation) during normal operation.
- Secondary resonant winding with a capacitor to produce nearly constant voltage output with varying load
- Variation of primary voltage has a much reduced effect on the secondary voltage.
- For constant, low-power loads



Static tap switching voltage regulator

- Traditional tap-changer realized via power electronics
- Similar to series connected active conditioner except voltage boost is provided by tap switching transformer with fast static tap switching.
- Cannot be configured to control harmonics and transients as the active conditioner can.

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Power System Dynamics & Quality of Supply

Power Quality



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Dr Victor Levi

HARMONICS CAUSES, SOURCES AND CONSEQUENCES

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HARMONIC – FOURIER ANALYSIS

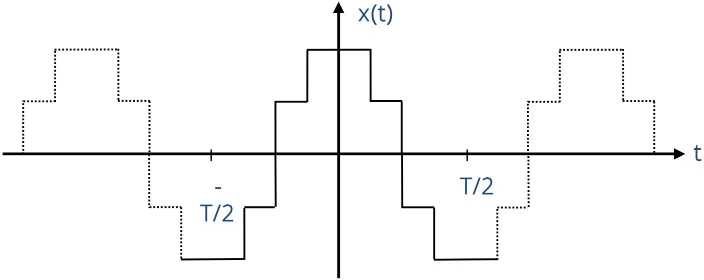


Fourier Series

- Any continuous function repetitive in an interval *T* can be represented by the sum of a fundamental sinusoidal component and a series of higher order harmonic components at frequencies which are *integral multiples* of the fundamental frequency; this is *Fourier series*

Definition of a periodic function:

$$x(t+T) = x(t) \text{ for all } t.$$



Fourier Series and Coefficients

- Fourier series:

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left(a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right)\right)$$

Time domain signal converted into Frequency domain representation, where a_n and b_n are the coefficients of the Fourier series

- Fourier series in vector form:

$$x(t) = a_0 + \sum_{n=1}^{\infty}\left(c_n sin\left(\frac{2\pi nt}{T} + \Phi_n\right)\right)$$

where amplitude and phase are:

$$c_n = \sqrt{a_n^2 + b_n^2}\ ;\ \ \Phi_n = tan^{-1}\left(\frac{a_n}{b_n}\right)$$

Fourier Series and Coefficients

- Zero-th order term, a_0, can be calculated as follows ($\omega=2\pi/T$):

$$a_0 = \frac{1}{T}\int_{-T/2}^{T/2} x(t)dt$$

or:

$$a_0 = \frac{1}{2\pi}\int_{-\pi}^{\pi} x(\omega t)d(\omega t)$$

- Coefficients a_n, $n\neq 0$, can be determined in the following way:

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} x(t)\cos\left(\frac{2\pi nt}{T}\right)dt \quad \text{for} \quad n = 1 \to \infty$$

or:

$$a_n = \frac{1}{\pi}\int_{-\pi}^{\pi} x(\omega t)\cos(n\omega t)d(\omega t)$$

- Coefficients b_n, $n\neq 0$, can be found as follows:

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} x(t)\sin\left(\frac{2\pi nt}{T}\right)dt \quad \text{for} \quad \text{n} = 1 \to \infty$$

or:

$$b_n = \frac{1}{\pi}\int_{-\pi}^{\pi} x(\omega t)\sin(n\omega t)d(\omega t)$$

Harmonic Sequences

In a balanced 3-phase system, individual harmonics are of either positive or negative or zero sequence:

	1st harmonic	2nd harmonic	3rd harmonic	4th harmonic	5th harmonic
Phase a	$V_1\cos(\omega t)$	$V_2\cos(2\omega t)$	$V_3\cos(3\omega t)$	$V_4\cos(4\omega t)$	$V_5\cos(5\omega t)$
Phase b	$V_1\cos(\omega t\text{-}120)$	$V_2\cos[2(\omega t\text{-}120)]$	$V_3\cos[3(\omega t\text{-}120)]$	$V_4\cos[4(\omega t\text{-}120)]$	$V_5\cos[5(\omega t\text{-}120)]$
Phase c	$V_1\cos(\omega t+120)$	$V_2\cos[2(\omega t+120)]$	$V_3\cos[3(\omega t+120)]$	$V_4\cos[4(\omega t+120)]$	$V_3\cos[5(\omega t+120)]$

Harmonic order	f[Hz]	Sequence
Fundamental (1st)	50 (60)	+
2nd	100 (120)	-
3rd	150 (180)	0
4th	200 (240)	+
5th	250 (300)	-
6th	300 (360)	0
7th	350 (420)	+
8th	400 (480)	-
9th	450 (540)	0
10th	500 (600)	+
11th	550 (660)	-
12th	600 (720)	0
13th	650 (780)	+

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CAUSES OF HARMONICS

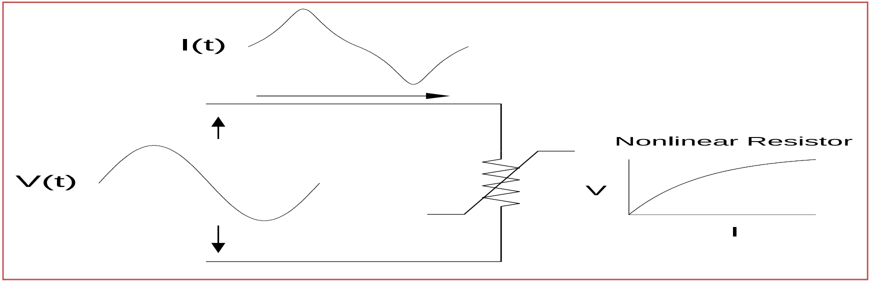


Causes of harmonics

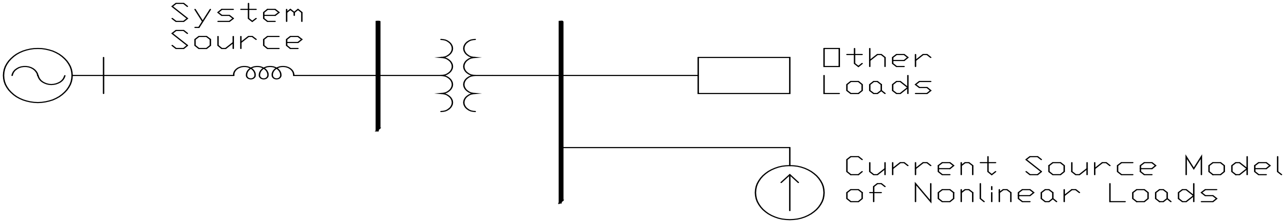
- Harmonics are sinusoidal components of a *periodic* waveform having a frequency that is an integer multiple of a fundamental frequency (50Hz or 60Hz).
- Some load equipment does not draw a sinusoidal current from a perfectly sinusoidal voltage source!
- The relationship between voltage and current at every instant of time is not constant, i.e., the load is *non-linear*.
- Harmonic currents flowing through the system impedance results in *harmonic voltages* at the load.

The effect of nonlinear loads

- Harmonic distortion comes from nonlinear devices, principally loads.



- A nonlinear load can be represented as a source of harmonic currents:



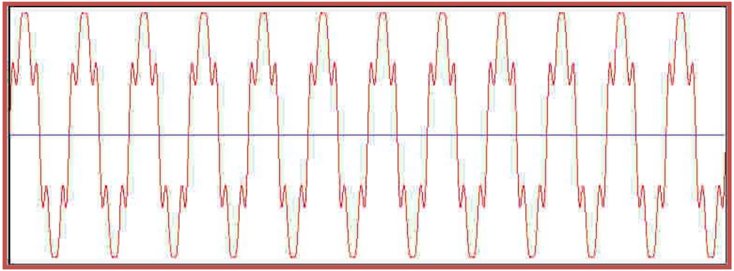
Voltage distortion

- Voltage distortion is the result of the interaction between harmonic currents drawn by the non-linear load and the impedance of the power system itself.
- Voltage distortion can be calculated as the product of the corresponding **harmonic current injection** and system (i.e. Thevenin) impedance at that frequency.

$$V_n(f = f_n) = Z_n(f = f_n) I_n$$

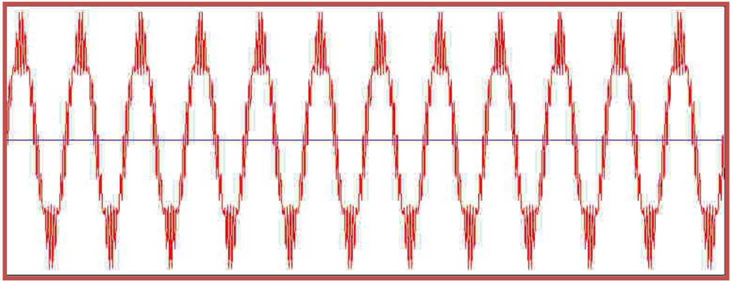
- Because of low system impedance, the power system can normally absorb a significant amount of harmonic currents without serious voltage distortion. (High short-circuit capacity systems will be able to absorb more harmonic current than weak, low-capacity systems!)

Harmonic distortion



Low order harmonics

I_1=100%
I_5=20% (α=0^0)
I_7=14% (α=0^0)
THD=24.41%



High order harmonics

I_1=100%
I_{19}=20% (α=0^0)
I_{23}=14% (α=0^0)
THD=24.41%

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MEASURES OF HARMONIC DISTORTION

Active, Reactive, Apparent & Distortion Power

- Distorted ***periodic*** voltage and current waveforms are:

$$v(t) = \sum_{n=1}^{\infty} V_n cos(n\omega t + \theta_n) \qquad i(t) = \sum_{n=1}^{\infty} I_n cos(n\omega t + \Phi_n)$$

- ***Active power*** is the average of *p(t)=v(t)·i(t)*:

$$P = \frac{1}{T}\int_0^T v(t) \cdot i(t) = \frac{1}{2}\sum_{n=1}^{\infty} V_n I_n \cos\left(\theta_n - \Phi_n\right) = \sum_{n=1}^{\infty} V_n^{rms} I_n^{rms} \cos\left(\theta_n - \Phi_n\right)$$

- ***Reactive power*** is:

$$Q = \frac{1}{2}\sum_{n=1}^{\infty} V_n I_n \sin\left(\theta_n - \Phi_n\right) = \sum_{n=1}^{\infty} V_n^{rms} I_n^{rms} \sin\left(\theta_n - \Phi_n\right)$$

Active, Reactive, Apparent & Distortion Power

- *RMS values* of voltage and current are:

$$V^{rms} = \sqrt{\sum_{n=1}^{\infty} (V_n^{rms})^2} \qquad I^{rms} = \sqrt{\sum_{n=1}^{\infty} (I_n^{rms})^2}$$

- *Apparent power* is:

$$S = V^{rms} \cdot I^{rms} = \sqrt{\sum_{n=1}^{\infty} (V_n^{rms})^2 \cdot (I_n^{rms})^2}$$

- 'Traditional' relation $S=(P^2+Q^2)^{0.5}$ does bot hold!
- We need to define *Distortion Power* (voltamperes):

$$D = \sqrt{S^2 - (P^2+Q^2)}$$

or:

$$S = \sqrt{(P^2+Q^2 + D^2)}$$

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Powers

- P = Active Power
  - Represents energy consumption
- S = Apparent Power
  - Represents required system capacity
- Q = Reactive Power
  - Reactive component is not a conservative quantity
- D = Distortion Power
  - This component is not a conservative quantity

Example PQ4: Powers of signals with harmonics

Harmonic content of a non-linear load is shown in the table below. Find real, reactive, apparent and distortion power for that customer.

RMS Value	50 Hz	150 Hz	350 Hz
	$1 \angle 0^0$	$0.2 \angle 20^0$	$0.05 \angle 10^0$
	$1 \angle -30^0$	$0.2 \angle 80^0$	$0.15 \angle -20^0$

- Real power: P=(1)(1)cos(0+30) + (0.2)(0.2)cos(20-80) + (0.05)(0.15)cos(10+20) = 0.892
- Reactive power: Q =(1)(1)sin(0+30) + (0.2)(0.2)sin(20-80) + (0.05)(0.15)sin(10+20) = 0.469
- RMS values: $(V^{rms})^2 = 1^2+0.2^2+0.05^2 = 1.021$

  $(I^{rms})^2 = 1^2+0.2^2+0.15^2 = 1.031$
- Apparent power: $S=V^{rms} \cdot I^{rms} = 1.052 \neq (P^2+Q^2)^{0.5} = 1.00778$
- Distortion power: $D= (1.052^2 - 1.00778^2)^{0.5} = 0.3018$

Power Factor

- (True) power factor is the ratio of the active power to the apparent power *P/S*.
- When harmonics are present, power factor *P/S* is different from the "standard" power factor characterizing the fundamental frequency
- "Standard" power factor is now called "*Displacement Power Factor*":

$$\boxed{PF_{displacement} = \frac{P}{S_1}}$$

- "*Distortion Power Factor*" is defined as:

$$\boxed{PF_{distortion} = \frac{S_1}{S}}$$

- *True Power Factor* is:

$$\boxed{PF = \frac{P}{S} = PF_{disp} * PF_{dist}}$$

Total Harmonic Distortion (THD)

- THD- Measure of the effective (rms) value of harmonic distortion (this may show high relative distortion even though the magnitude of the current may be low)

$$THD = \frac{\sqrt{\sum_{n>1}^{n_{\max}} M_n^2}}{M_1}$$

n - order of harmonic
M_n - rms of *n*-th harmonic

Voltage and Current THD Factors

- Voltage THD gives increase of voltage RMS with respect to the fundamental harmonic:

$$THD_V = \frac{1}{V_1^{rms}} \sqrt{\sum_{n=2}^{\infty} V_n^2} = \sqrt{\left(\frac{V^{rms}}{V_1^{rms}}\right)^2 - 1}$$

$$V^{rms} = V_1^{rms} \sqrt{1 + THD_V^2}$$

- Current THD gives increase of current RMS with respect to the fundamental harmonic:

$$THD_I = \frac{1}{I_1^{rms}} \sqrt{\sum_{n=2}^{\infty} I_n^2} = \sqrt{\left(\frac{I^{rms}}{I_1^{rms}}\right)^2 - 1}$$

$$I^{rms} = I_1^{rms} \sqrt{1 + THD_I^2}$$

Example PQ5: Total harmonic distortion

Voltage and current harmonic content is given in the table below. Find the voltage and current THD.

Frequency (Hz)	|V|	|I|
50	1.00	1.00
150	0.01	0.31
250	0.04	0.15
350	0.03	0.07
400	0.02	0.03
550	0.01	0.02

$THDV^2 = (0.01^2+0.04^2+0.03^2+0.02^2+0.01^2)/1^2 = 0.0031$

$THDV = 5.57\%$

$THDI^2 = (0.31^2+0.15^2+0.07^2+0.03^2+0.02^2)/1^2 = 0.1248$

$THDI = 35.33\%$

Total Demand Distortion (TDD)

$$TDD = \frac{\sqrt{\sum_{n>1}^{n_{\max}} I_n^2}}{I_L}$$

I_n - magnitude of the individual harmonic components

I_L – maximum demand load current (rms amps) at the fundamental frequency at the Point of Connection (annual average) – fundamental harmonic of the sample may change over time

Note: I_L is sometimes total load RMS value.

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Current and Voltage Crest Factor

Peak and *not RMS* values are considered:

$$CCF = \frac{\sum_{n=2} I_n}{I_1}$$

Current Crest Factor

$$VCF = \frac{\sum_{n=2} V_n}{V_1}$$

Voltage Crest Factor

Ignoring the phase angles, the total peak *I* or *V* would be:

$$I_{peak} = \sum_{n=1} I_n = I_1(1 + CCF) \quad \text{and it is} \neq \sqrt{2} I_{rms}$$

$$V_{peak} = \sum_{n=1} V_n = V_1(1 + VCF) \quad \text{and it is} \neq \sqrt{2} V_{rms}$$

Corresponding *p.u.* increase (wrt first harmonic) in ***total peak*** *I* or *V* is:

$$\Delta I_{peak_{pu}} = CCF \qquad \Delta V_{peak_{pu}} = VCF$$

Telephone Interference

- Harmonics produce telephone interference through electromagnetic coupling.
- Telephone interference factor:

$$TIF = \frac{\sqrt{\sum_{n=1}^{\infty} \omega_n^2 \cdot I_n^2}}{I^{rms}}$$

- *I·T* product:

$$I \cdot T = TIF \cdot I^{rms} = \sqrt{\sum_{n=1}^{\infty} \omega_n^2 \cdot I_n^2}$$

where ω_n is the telephone interference weighting factor at the *n-th* harmonic

Example PQ6: Telephone Interference

A harmonic source has the following harmonic content and telephone interference weighting factors. Calculate the IT product.

N	1	5	7	11	13	17	19	23
I_n (%)	100	17.5	11.1	4.5	2.4	1.5	1.0	0.9
ω_n	0.5	225	650	2260	3360	5100	5630	6370

$$= 189.5 \qquad I \cdot T = \sqrt{\Sigma}$$

Harmonic Content

- "Three-phase group" of harmonic currents
  - Result from 6 pulse conversion apparatus
  - With 12 pulse conversion equipment the lowest harmonic is 11th

Harmonic order	f[Hz]	Sequence
Fundamental (1st)	50 (60)	+
5th	250 (300)	-
7th	350 (420)	+
11th	550 (660)	-
13th	650 (780)	+

100%/n

Harmonic order	Theoretical $(I_h \backslash I_1)100\%$	Typical $(I_h \backslash I_1)100\%$
5th	20	37
7th	14	7
11th	9	9
13th	8	1
17th	6	-
19th	5	-

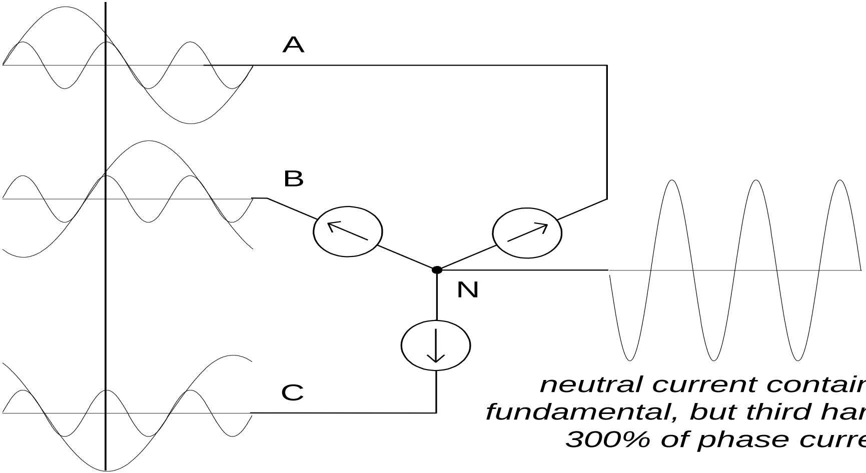
- 'Single-phase group' of harmonic currents
  - They may add (not cancel) in a common wire and result in high neutral currents!

Harmonic order	f[Hz]	Sequence
Fundamental (1st)	50 (60)	+
3rd	150 (180)	0
9th	450 (540)	0
15th	750 (900)	0

Triplen Harmonics

Third, sixth, ninth, etc. harmonics -> ‘zero sequence’

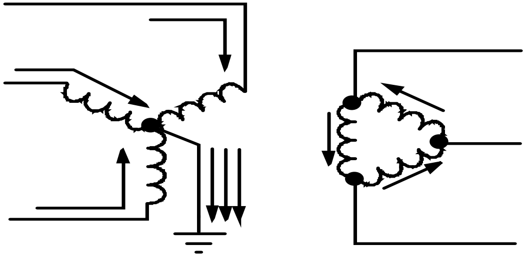
balanced fundamental currents sum to 0,
but balanced third harmonic currents coincide



neutral current contains no fundamental, but third harmonic is 300% of phase current

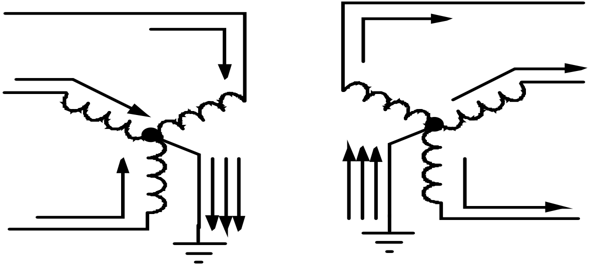
Flow of Triplens in Transformers

Grounded Y- Δ



No triplens on the secondary side

Grounded Y-
Grounded Y



HARMONIC SOURCES

Harmonic sources

- **Saturable devices**: transformers, rotating machines, non-linear reactors.
- **Arcing devices**: arc furnaces, arc welders, fluorescent lighting; (They can produce harmonic currents $\geq$ 20% of their rating).
- **Power electronics**: VSD, DC motor drives, electronic power supplies, rectifiers, inverters, SVCs, HVDC transmission; (They can produce harmonic currents $\geq$ 20% of their rating).
- **Example – Commercial buildings**:
  - Electronic Loads (switch mode power supplies)
  - Fluorescent Lighting
  - Variable Speed Drives (HVAC Applications)

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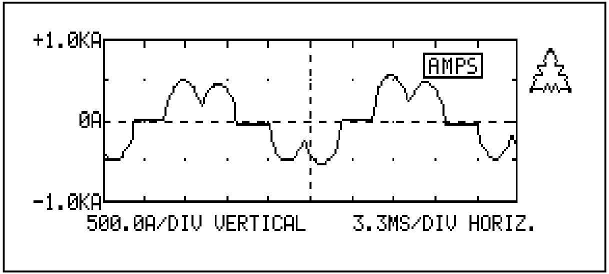
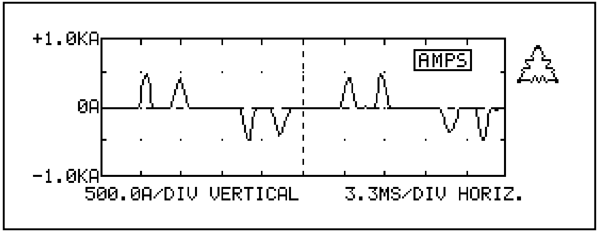
Example: DC drive



PHASE A CURRENT SPECTRUM 11:20:42 AM
Fundamental amps: 319.6 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-75°	2nd	4.8%	-64°
3rd	1.2%	28°	4th	1.5%	164°
5th	33.6%	156°	6th		
7th	1.6%	29°	8th	1.7%	-170°
9th	0.4%	-91°	10th	0.3%	96°
11th	8.7%	49°	12th		
13th	1.2%	54°	14th	1.3%	86°
15th	0.3%	148°	16th	0.2%	51°
17th	4.5%	-57°	18th		
19th	1.3%	-46°	20th	1.1%	-18°
21st	0.3%	34°	22nd	0.3%	-31°
23rd	2.8%	-163°	24th		
25th	1.2%	-149°	26th	0.9%	-123°
27th	0.3%	-75°	28th	0.3%	-128°
29th	2.0%	90°	30th		
31st	1.0%	107°	32nd	0.8%	133°
33rd	0.3%	173°	34th	0.3%	135°
35th	1.4%	-17°	36th		
37th	1.0%	2°	38th	0.8%	28°
39th	0.3%	63°	40th	0.3%	31°
41st	1.1%	-123°	42nd		
43rd	0.9%	-104°	44th	0.8%	-75°
45th	0.3%	-47°	46th	0.3%	-70°
47th	1.0%	128°	48th	0.2%	102°
49th	0.9%	152°	50th	0.7%	-179°
ODD	35.4%		EVEN	5.9%	
THD:	35.9%				

Example: PWM drive, no choke-reactance

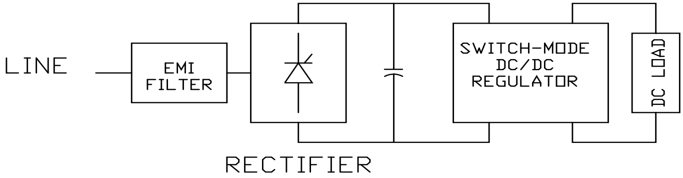


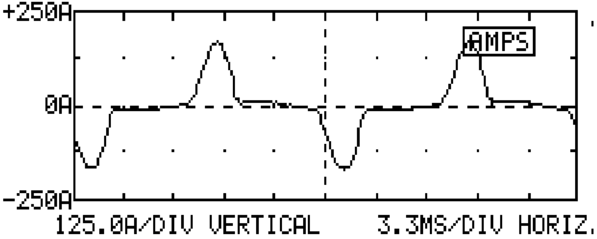
PHASE A CURRENT SPECTRUM 11:49:06 AM
Fundamental amps: 103.8 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	10°	2nd	1.1%	78°
3rd	3.9%	−122°	4th	0.5%	167°
5th	82.8%	−125°	6th	1.7%	−56°
7th	77.5%	79°	8th	1.2%	131°
9th	7.6%	−80°	10th	0.7%	112°
11th	46.3%	−52°	12th	1.0%	−48°
13th	41.2%	149°	14th		
15th	5.7%	−26°	16th	0.3%	172°
17th	14.2%	19°	18th	0.4%	78°
19th	9.7%	−145°	20th	0.4%	−138°
21st	2.3%	19°	22nd	0.5%	−14°
23rd	1.5%	−148°	24th	0.5%	89°
25th	2.5%	108°	26th	0.7%	−135°
27th	0.9%	−29°	28th	0.3%	9°
29th	2.0%	−29°	30th	0.2%	55°
31st	2.0%	169°	32nd	0.3%	149°
33rd	0.5%	−19°	34th	0.4%	−61°
35th	0.3%	−147°	36th	0.1%	25°
37th	0.8%	75°	38th	0.3%	148°
39th	0.5%	−58°	40th		
41st	0.6%	−100°	42nd		
43rd	0.7%	114°	44th	0.1%	113°
45th	0.4%	−59°	46th	0.1%	−32°
47th	0.2%	165°	48th		
49th	0.4%	44°	50th	0.3%	144°
ODD	130.9%		EVEN	3.0%	
THD:	130.9%				

Example: Switch-mode power supplies

Waveform and spectrum for a circuit supplying electronic loads.



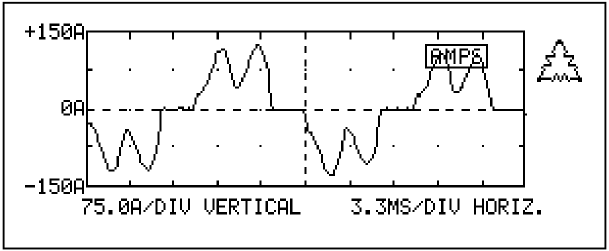


Fundamental amps: 58.5 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	PHASE	HARM	PCT	PHASE
FUND	100.0%	-37°	2nd	0.2%	65°
3rd	65.7%	-97°	4th	0.4%	-72°
5th	37.7%	-166°	6th	0.4%	-154°
7th	12.7%	113°	8th	0.3%	112°
9th	4.4%	-46°	10th		
11th	5.3%	-158°	12th	0.1%	142°
13th	2.5%	92°	14th	0.1%	65°
15th	1.9%	-51°	16th		
17th	1.8%	-151°	18th		
19th	1.1%	84°	20th		
21st	0.6%	-41°	22nd		
23rd	0.8%	-148°	24th		
25th	0.4%	64°	26th		
27th	0.2%	-25°	28th		
29th	0.2%	-122°	30th		
31st	0.2%	102°	32nd		
33rd	0.2%	56°	34th		

Example: VSDs (HVAC Systems)

PWM Type ASD
with 3% input choke



PHASE B CURRENT SPECTRUM 2:23:40 PM
Fundamental amps: 61.2 A rms
Fundamental freq: 60.0 Hz

HARM	PCT	SINE PHASE	HARM	PCT	SINE PHASE
FUND	100.0%	-128°	2nd	1.0%	145°
3rd	3.9%	-149°	4th	0.4%	-57°
5th	39.7%	-122°	6th	0.8%	175°
7th	18.9%	122°	8th	0.2%	10°
9th	0.8%	47°	10th	0.2%	159°
11th	6.8%	67°	12th	0.4%	-27°
13th	3.8%	-118°	14th	0.3%	111°
15th	0.4%	-140°	16th	0.4%	6°
17th	3.2%	-144°	18th	0.4%	109°
19th	2.3%	10°	20th	0.3%	2°
21st	0.3%	29°	22nd	0.2%	141°
23rd	1.8%	11°	24th	0.2%	-79°
25th	1.7%	145°	26th	0.2%	124°
27th	0.2%	-165°	28th	0.1%	-81°
29th	1.1%	160°	30th	0.1%	68°
31st	1.3%	-74°	32nd	0.1%	-112°
33rd	0.2%	-32°	34th	0.1%	81°
35th	0.7%	-49°	36th	0.1%	-114°
37th	1.0%	67°	38th		
39th	0.2%	153°	40th		
41st	0.5%	96°	42nd	0.1%	-1°
43rd	0.8%	-147°	44th	0.1%	134°
45th	0.2%	-59°	46th		
47th	0.4%	-112°	48th		
49th	0.7%	-5°	50th		
ODD	45.1%		EVEN	1.6%	
THD:	45.1%				

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CONSEQUENCES OF HARMONICS



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Effects of Voltage Harmonic Distortion

- Increased thermal stress (I^2R heating)
- Increased transformer magnetic losses (hysteresis and eddy-current losses)
- Increased dielectric losses
- Increased motor losses
- Increased insulation stress – though the increase of peak voltage, i.e. voltage crest factor
- Load disruption

Major Concerns

- Power factor correction capacitors can cause a parallel or series resonance.
- Motor overheating
- Transformer overheating and derating requirements
- Various problems at electronic devices
- High neutral currents
- Impact on communication circuits.
- Breaker and fuse nuisance tripping
- Flickering incandescent lighting
- Failure of ground fault relaying (due to excessive third harmonic currents)

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Power System Dynamics & Quality of Supply

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Power Quality

Harmonic Resonance

HARMONIC RESONANCE AND FILTERS



Resonance

- If the *natural – network frequency* corresponds to one of the characteristic *harmonic frequencies of a nonlinear load*, high distortion can occur => this is called *Resonance*
- The natural – network frequency is determined from the condition that the capacitive and inductive reactances are equal:

$$X_c = X_L \Rightarrow \frac{1}{\omega C} = \omega L \Rightarrow (2\pi f_r)^2 = \frac{1}{LC}$$

$$\boxed{f_r = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}}$$

- Natural, or simply *resonant frequency* f_r can be expressed as:

$$f_r = \frac{1}{2\pi\sqrt{LC}} = \frac{f_0}{\omega_0\sqrt{LC}} = f_0\sqrt{\frac{X_c}{X_L}}$$

- Harmonic order/number at resonance can be defined as: $h_r = \frac{f_r}{f_0} = \sqrt{\frac{X_c}{X_L}}$
- Typical utility wiring natural frequency: 400Hz - 2kHz
- Typical commercial wiring natural frequency: 20kHz - 500kHz

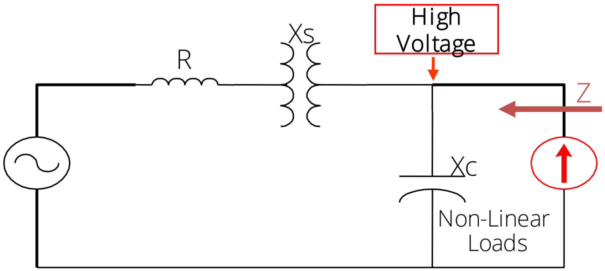
Parallel resonance - 1

- Capacitor is connected in parallel with the non-linear load
- Equivalent impedance at the load node is:

$$Z = \frac{X_c}{R^2 + (X_s - X_c)^2} \sqrt{(RX_c)^2 + [R^2 + (X_s - X_c)X_s]^2}$$

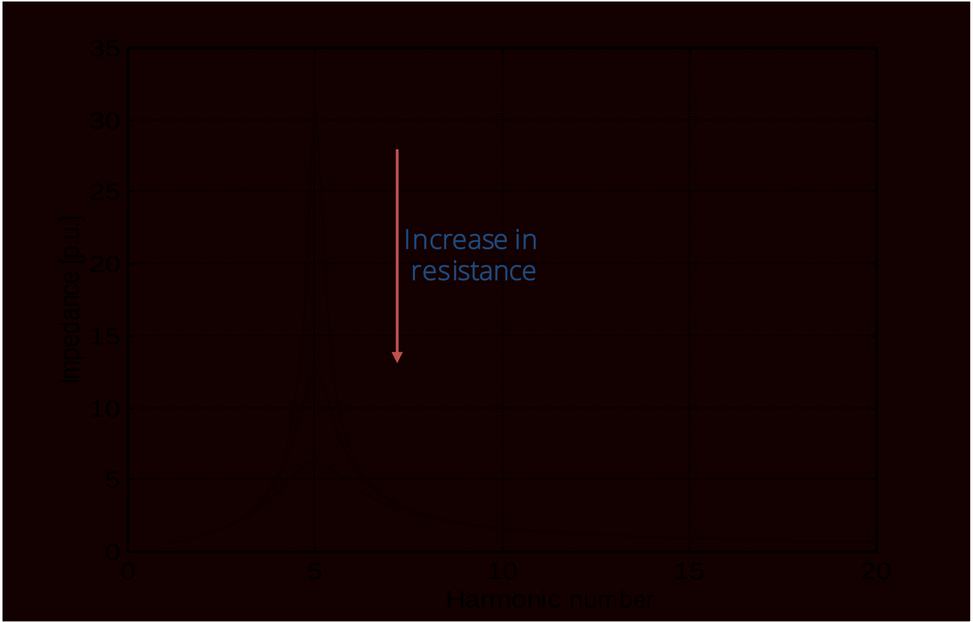
- For *Xc* = *Xs*:
  - High impedance: $Z \approx \frac{X_C^2}{R}$ $(\boldsymbol{Z} -> \infty)$
  - Magnified voltage: $\boldsymbol{V} = \boldsymbol{Z} \cdot \boldsymbol{I}$

  (at resonant frequency)



- Quality factor is defined as: $Q \approx \frac{R}{X_r}$
- Critical damping is for $Q = 0.5$ or $R = 0.5 \cdot X_r$

Parallel resonance - 2



Calculating the resonant frequency

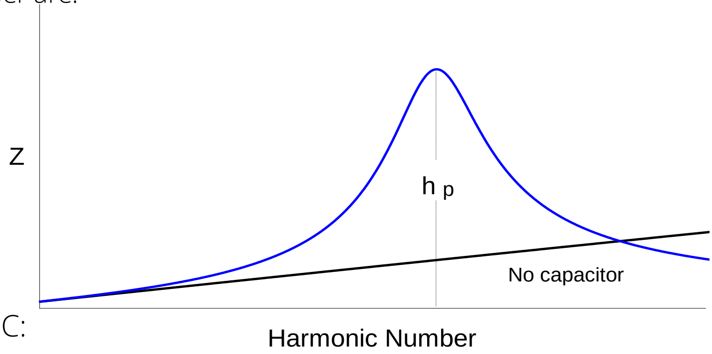
- The (parallel) resonant frequency and number are:

$$f_p = f_0\sqrt{\frac{X_c}{X_S}} = f_0\sqrt{\frac{\frac{V_n^2}{Q_{CAP}}}{\frac{V_n^2}{S_{SC}}}} = f_0\sqrt{\frac{S_{SC}}{Q_{CAP}}}$$

$$h_p = f_p/f_0 = \sqrt{\frac{S_{SC}}{Q_{CAP}}}$$

← Bus short circuit capacity

← Capacitor rating

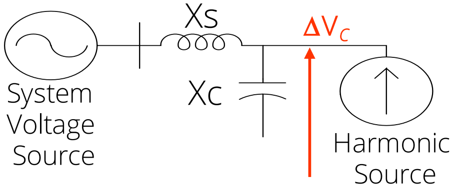


- Voltage change due to connection of C:

$$V_C^{post} = V_C^{pre} \cdot [\frac{X_C}{X_S + X_C}]$$

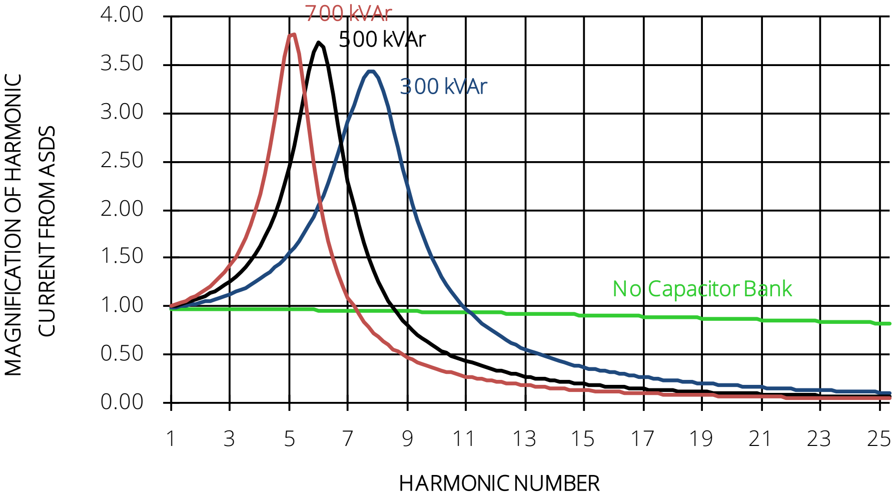
$$\Delta V_C = V_C^{pre} \cdot \left[\frac{-X_S}{X_S + X_C}\right] \quad =>$$

$$\Delta V_C^{p.u.} = \left[\frac{-X_S}{X_S + X_C}\right] = \frac{-1}{1 + h_p^2}$$

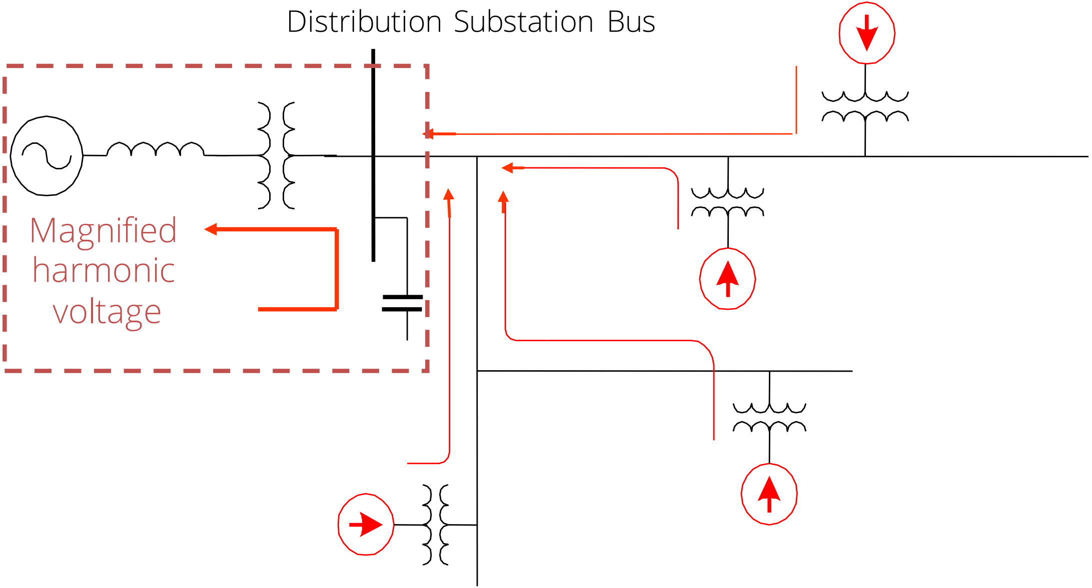


Example: Resonance frequency

Resonance vs. capacitor size for a typical customer supplied with a 1500 kVA, 6% transformer.



Parallel resonance in real life



Example PQ7: Parallel Resonance

Investigate parallel resonance in a network with X_C=60 Ω and X_S=0.497 Ω.

- Harmonic number is:

$$h_p = \sqrt{\frac{X_c}{X_S}} = \sqrt{\frac{60}{0.497}} = 10.987$$

and the circuit exhibits parallel resonance at the 11th harmonic.

- The circuit reactance at resonance is:

$$\frac{X_c}{h_p} = X_S \cdot h_p = X_r => \quad X_r = \sqrt{X_S \cdot X_c} = \sqrt{60 \cdot 0.497} = 5.46$$

- Resistance R is calculated as $R = Q \cdot X_r$ and shown in table below.

Q	0.5	1	2	3	4	5
R (Ω)	2.73	5.46	10.92	16.38	21.84	27.3

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Series resonance - 1

- In a series RLC circuit harmonic impedance is: $Z(n) = \sqrt{R^2 + (nX_S - \frac{X_c}{n})^2}$

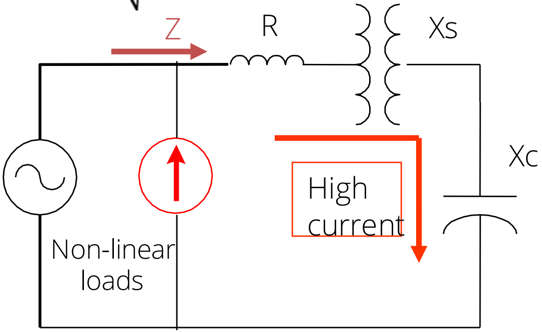
- Resonance occurs for $n = h_s$ and resonant reactance X_s:

$$\frac{X_c}{h_s} = X_S \cdot h_s = X_r \quad => \quad X_r^2 = X_S \cdot X_c \quad => \quad X_r = \sqrt{X_S \cdot X_c} = \sqrt{\frac{L}{C}}$$

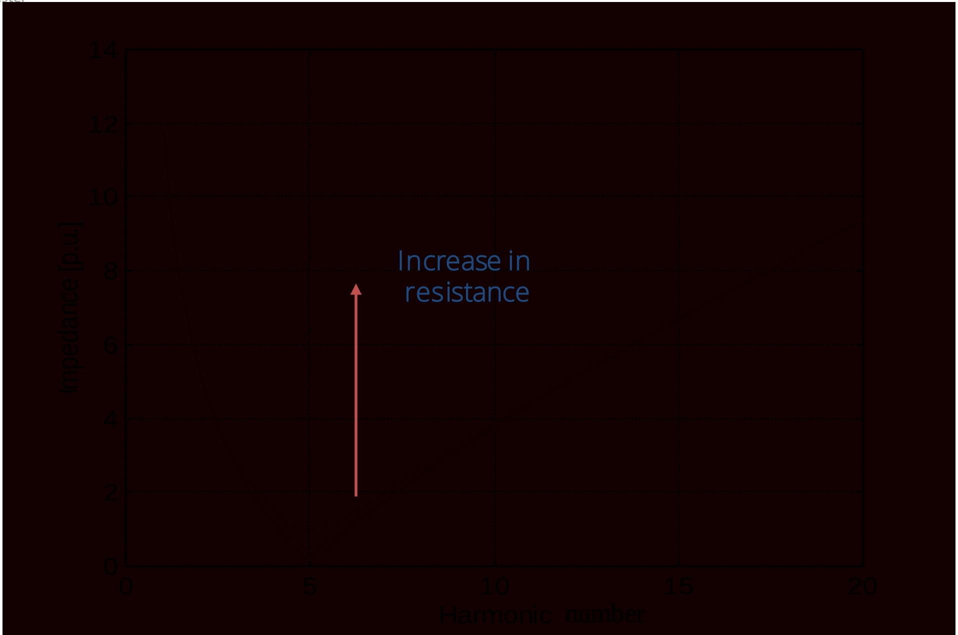
- At resonance frequency:
  - Impedance is very small: $[Z(h_s) = R]$
  - Current is magnified :

$$\underline{I} = \frac{\underline{V}}{\underline{Z} \to 0} \to \infty$$

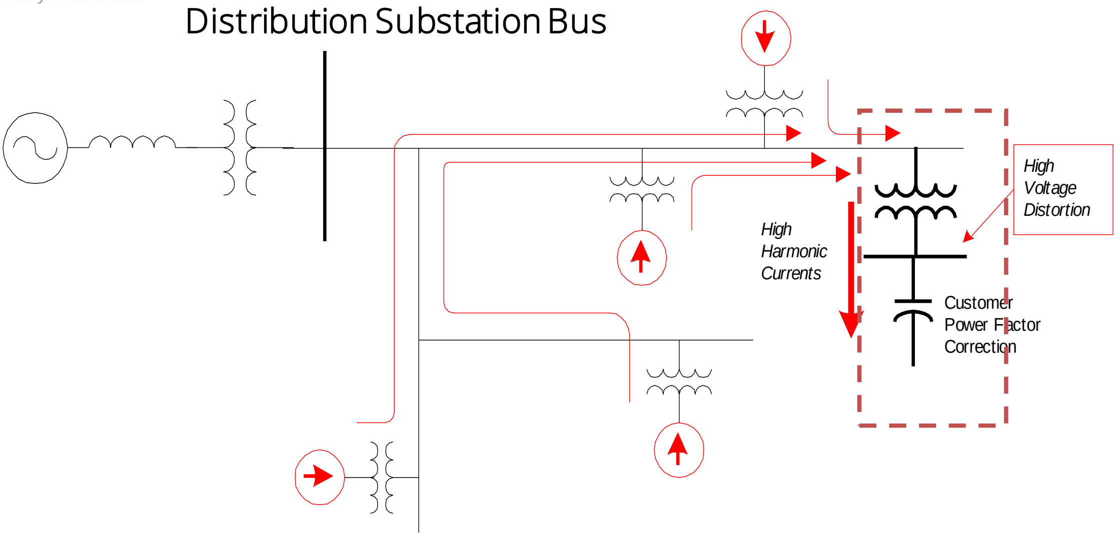
- Quality factor is : $Q \approx \frac{X_r}{R}$



Series resonance - 2



Series resonance in real life



- Series resonance can be intentional (harmonic filter), or unintentional (customer capacitor drawing harmonic currents through service transformer).

Example PQ8: Series Resonance

Investigate series resonance in a network with $X_C = 1.6\ \Omega$ and $X_S = 0.064\ \Omega$.

- Harmonic number is:

$$h_p = \sqrt{\frac{X_C}{X_S}} = \sqrt{\frac{1.6}{0.064}} = 5$$

and the circuit exhibits series resonance at the 5th harmonic.

- The circuit reactance at resonance is:

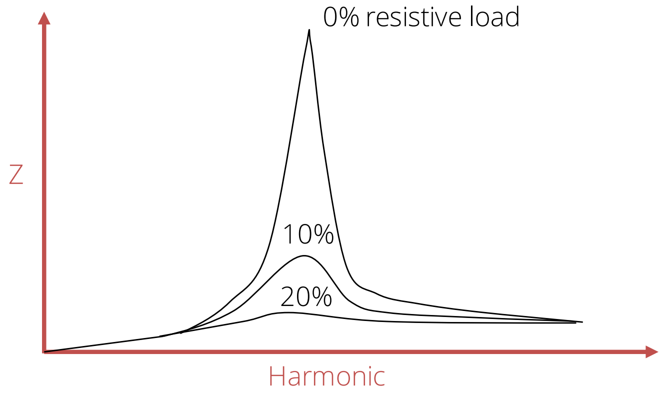
$$X_r = \sqrt{X_S \cdot X_C} = \sqrt{1.6 \cdot 0.064} = 0.32\Omega$$

- Resistance R is calculated as $R = X_r/Q$ and shown in table below.

Q	**50**	**100**	**200**	**300**
R (Ω)	0.0064	0.0032	0.0016	0.00107

Influence on system damping

- Resistive loads are very effective.
- Motor loads have very little influence. (They may even increase distortion, by shifting resonance towards a frequency excited by a harmonic source).



Consequences of harmonic resonance

- Capacitor failures
- Fuse blowing
- High voltage distortion can impact other loads - e.g. motor heating
- High currents in supply transformer - overheating concerns.

Solutions for resonance problems

- Do not use power factor correction capacitors!?
- Apply power factor correction capacitors as tuned banks (harmonic filters).
- Keep parallel resonance frequency above the 8th harmonic. (Still could have problems at the 11th or 13th but less likely).

HARMONIC FILTERS



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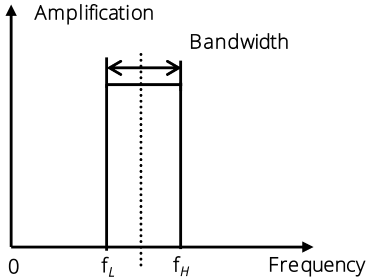
Purpose of Harmonic Filters

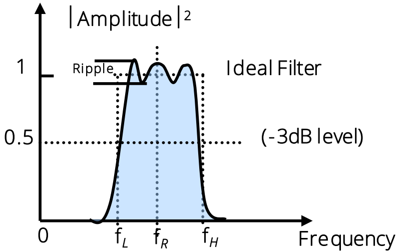
- To reduce (i.e. attenuate) the amplitude of one or more fixed frequency currents or voltages
- Shunt filters:
  - The harmonic currents are prevented from entering the rest of the system by providing a shunt path of low impedance to the harmonic frequencies.
  - Consists of an inductor and capacitor connected in series
- Series filters:
  - Prevent a particular frequency from entering the system
  - Consists of a parallel inductor and capacitor which is a large impedance to the relevant frequency.

Band-Pass Filters

- Bandpass describes a type of filter; it is to be distinguished from passband, which is the actual portion of the affected frequency spectrum.
- An ideal bandpass filter has completely flat passband and would completely attenuate all frequencies outside the passband
- The bandwidth of ideal filter is difference between the upper and lower cut-off frequencies B=fh – fl
- 'Effective bandwidth' can be obtained by dividing the area under the practical filter characteristic of by the |amplitude|2
- Effective bandwidth B=fh – fl is determined at 0.5 level (-3dB)



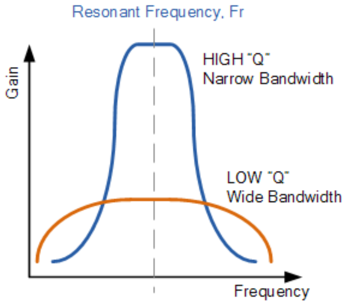
Ideal bandpass filter

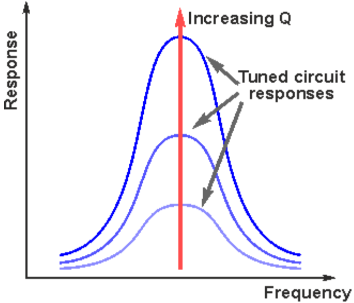


Practical filter characteristic:: Noise bandwidth equals bandwidth of ideal filter

Quality of Bandpass Filters

- A band-pass filter can be characterized by its quality factor or Q factor. The Q-factor is the reciprocal of the *fractional bandwidth*.
- High-Q filter has narrow passband; Low-Q filter has wide passband
- Filter quality Q determines the sharpness of tuning:
  - The high Q filter is sharply tuned to one of the lower harmonic frequencies (e.g. the fifth) and a typical value is between 30 and 60.
  - The low Q filter, typically in the region of 0.5-5, has a low impedance over a wide range of frequencies. When used to eliminate the higher order harmonics (e.g. 17th up), it is also called a high-pass filter.





Quality of Bandpass Filters

- Quality of ***high Q filter*** is $Q=X_r/R$, where X_r is resonant reactance (inductive or the capacitive reactance at the resonant frequency)
- Quality of ***low Q filter*** is $Q=R/X_r$
- The Q factor determines the qualitative behaviour of damped oscillations; there are 3 main regimes relating damping and Q factor

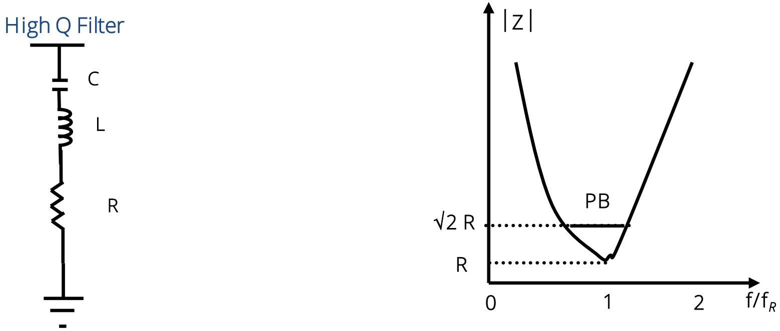
  – ***Overdamped (Q < 1/2):*** The system response will exponentially decay, approaching the steady state value asymptotically. As the quality factor is reduced, so the systems responds more slowly.

  – ***Underdamped (Q > 1/2):*** As the quality factor increases, the damping falls and oscillations will be sustained for longer. In a theoretical system where the Q factor is infinite, the oscillation would be maintained indefinitely without the need for adding any further stimulus.

  – ***Critically damped (Q = 1/2) :*** Like an over-damped system, the output does not oscillate, and does not overshoot its steady-state output. The system will approach the steady-state asymptote in the fastest time.

Filter Types: Series-Tuned Filters

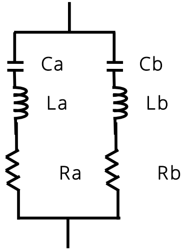
- Consists of a capacitor and a reactor connected in series and tuned to low harmonic frequency
- The filter impedance is:
  - Purely resistive at the tuned frequency – harmonic
  - Capacitive for lower harmonics than the tuned
  - Inductive for higher harmonics than the tuned

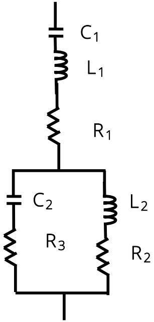


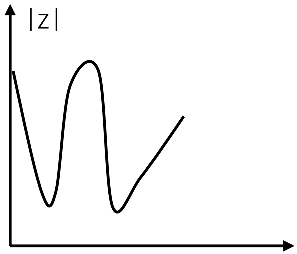
(a) *Single-tuned* shunt filter; and (b) Single-tuned shunt filter impedance versus frequency

Filter Types: Double Tuned Filter

- The impedance of the filter is low at two tuned frequencies
- The equivalent impedances of two single tuned filters near their resonance frequencies are practically the same as those of a double tuned filter configuration if impedance equivalencing is done
- The main advantage is in high voltage applications, because of the reduction in the number of inductors to be subjected to full line impulse voltages



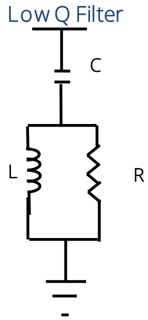


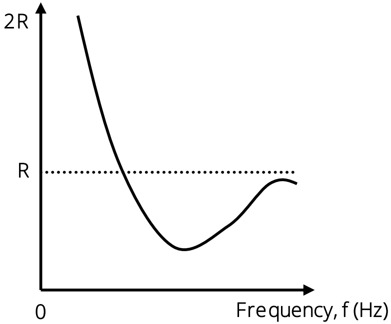


(a) Two single-tuned filters; (b) Double-tuned filter; (c) Double-tuned filter: impedance versus frequency characteristic

Filter Types: Damped Filters

- 1st, 2nd and 3rd order damped filters; most commonly used 2nd order
- A 2nd order damped filter provides low impedance for wide range of frequencies
- When used to eliminate high order harmonics (e.g. 17th and above), referred to as a *high-pass filter*





(a) *Second-order damped* shunt filter; and (b) Second-order damped shunt filter impedance versus frequency

Damped Filters

- **Advantages**:
  i. Its frequency and loading is less sensitive to temperature variation, frequency deviation, loss of capacitor elements.
  ii. It provides a low impedance for a wide spectrum of harmonics without the need for subdivision of parallel branches with increased switching and maintenance problems.
  iii. The use of tuned filters often results in parallel resonance between the filter and system admittances at a harmonic order ***below the lower tuned filter frequency, or in between tuned filter frequencies***. In such cases the use of one or more damped filters is more acceptable.
- **Disadvantages**:
  i. To achieve similar level of filtering performance the damped filter needs to be designed for higher fundamental VA ratings; good performance can often be met within the limits required for power factor correction.
  ii. The losses in the resistor and reactor are generally higher.

Automatically Tuned Filters

- Goal: to reduce maximum frequency deviation from the resonant

- Filters are tuned by either varying the inductance or automatically switching the capacitance. A range of ±5% is usually adequate.

- A control system, which measures the harmonic frequency reactive power in the filter, controls the *L* and the *C* based on the sign and the magnitude of this reactive power.

- Advantages of automatically tuned filters over fixed filters:
    i. The capacitor rating is lower
    ii. The capacitor can combine a high temperature coefficient of capacitance and a high reactive power rating per unit of volume and per unit of cost
    iii. The power loss is smaller because of higher Q factor.

- Advantages (i) and (ii) reduce the cost of the capacitor which is the most expensive component of the filter. Advantage (iii) reduces the cost of the resistor and the cost of system losses.

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DESIGN OF HARMONIC FILTERS

Harmonic Filter Design

- At the tuned harmonic, inductance is equal to capacitance:

$$X_{Ln} = h_n \cdot X_{L1} = X_{Cn} = \frac{X_{C1}}{h_n} = X_n \quad => \quad X_{L1} = \frac{X_{C1}}{(h_n)^2} \quad => X_n = \sqrt{X_{L1} \cdot X_{C1}} = \sqrt{L_1/C_1}$$

- The tuned frequency and order are:

$$f_n = h_n \cdot f_0 \; = f_0 \sqrt{\frac{X_{C1}}{X_{L1}}} \quad => \quad h_n = f_n/f_0 \; = \sqrt{\frac{X_{C1}}{X_{L1}}}$$

Harmonic Filter Design

- Capacitor voltage rating should be a sum of harmonics:

$$V_C^{L-L} = \sum_{n=1} V_{Cn}^{L-L} = \sum_{n=1} \sqrt{3}\frac{X_C}{n} I_{Cn}$$

- Reactive power absorber by reactor and delivered by capacitor are:

$$Q_L = \sum_{n=1} V_{Ln} I_{Ln} = \sum_{n=1} n X_L (I_{Ln})^2 = \sum_{n=1} \frac{(V_{Ln})^2}{n X_L}$$

$$Q_C = \sum_{n=1} V_{Cn} I_{Cn} = \sum_{n=1} \frac{X_C}{n} (I_{Cn})^2 = \sum_{n=1} \frac{n}{X_C} (V_{Cn})^2$$

Design of Series-Tuned Filters

- Series-tuned filter is tuned to the h_n harmonic
- Design steps:
  - Determine capacitor size: Q_C in MVAr
  - Capacitor's reactance is: $X_C = kV^2/Q_C$
  - Reactor reactance is: $X_L = X_C/(h_n)^2$
  - The resistance is: $R = X_n/$Q, where $30 < Q < 100$
  - Filter MVAr size is: $Q_{filter} = (kV^2)/(X_C - X_L) = Q_c \cdot \{(h_n)^2/[(h_n)^2 - 1]\}$
  - Capacitor fundamental voltage: $V_{C1}/V_{bus1} = -X_{C1}/(X_{L1} - X_{C1})$= $(h_n)^2$/[$(h_n)^2$-1]
  - Capacitor voltage at harmonic 'n': $V_{Cn}/V_{bus,n} = -\frac{jX_{Cn}}{R} = -jQ$

Example PQ9: Design of Series-Tuned Filter

A 33kV series-tuned filter has parameters $X_C = 544.5\ \Omega$, $X_L = 4.5\Omega$ and $\mathrm{R} = 0.825\ \Omega$. What is the tuning order, quality factor, capacitor reactive power and filter MVA size?

- The tuning order is: $h_n = \sqrt{X_C/X_L} = 11$
- The quality factor is: $Q = X_n/R$=60
- The reactive power produced by capacitor is: $Q_c = 33^2/545.5 = 2$ MVAr
- The filter's MVA size is: $Q_{filter} = kV^2/(X_C - X_L) = Q_c \cdot \{(h_n)^2/[(h_n)^2 - 1]\}$ $= 2 \cdot [11^2/(11^2 - 1) = 2.017$MVAr

Design of 2nd Order Damped Filters

- Second-order damped filter tuned to the h_n harmonic
- Design steps:
  - Determine capacitor size: Q_C in MVAr
  - Capacitor's reactance is: $X_C = kV^2/Q_C$
  - Reactor reactance is: $X_L = X_C/(h_n)^2$
  - Resistor bank has size of: $R = X_C \cdot \mathrm{Q}$, where $0.5 < Q < 5$
  - Filter MVAr size is: $Q_{filter} = Q_c \cdot \{(h_n)^2/[(h_n)^2 - 1]\}$
  - Current in the reactor can be found from the ***filter current*** (current divider)
  - Current in the resistor can be found from the ***filter current*** (current divider)

Example PQ10: Design of 2nd Order Damped Filter

- A 33 kV, 6.8 MVAr capacitor bank is used as a second-order damped filter tuned to $h_n \geq 4$. Find the elements of the filter.

- $X_C = 33^2/6.8$=160Ω
- $X_L = X_C(h_n)^2$=160/16=10Ω
- $X_n = \sqrt{X_L \cdot X_C}$=40 Ω
- $R = X_n \cdot Q$=20 Ω; 80 Ω; 120 Ω; 200 Ω for Q =0.5; 2; 3; 5
- $Q_{filter} = kV^2/(X_C - X_C)$=7.25 MVAr

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POWER SYSTEM HARMONIC STUDIES



Harmonic Power Flow Analysis

- Harmonic power flow analysis is usually done using a software tool
- The main steps of the methodology for harmonic power flow analysis are:

1. Input resistances, inductances and capacitances of all network elements; input harmonic current injections $\boldsymbol{I_{node}}\,(\boldsymbol{n})$ at all nodes for each harmonic $\boldsymbol{n}$
2. Build the bus admittance matrix $\boldsymbol{Y_{bus}}(\boldsymbol{n})$ for each harmonic $\boldsymbol{n}$
3. Get the impedance matrix $\boldsymbol{Z_{bus}}(\boldsymbol{n}) = \boldsymbol{Y_{bus}}^{-1}(\boldsymbol{n})$ for each harmonic $\boldsymbol{n}$ (triangular factorisation of admittance matrix)
4. Find the nodal voltages as $\boldsymbol{V_{node}}(\boldsymbol{n}) = \boldsymbol{Z_{bus}}(\boldsymbol{n}) \cdot \boldsymbol{I_{node}}(\boldsymbol{n})$ for each harmonic $\boldsymbol{n}$
5. Calculate branch current as $\boldsymbol{I_{br}}(\boldsymbol{n}) = \Delta\boldsymbol{V_{node}}(\boldsymbol{n})/\boldsymbol{diag}[\boldsymbol{Z_{br}}(\boldsymbol{n})]$ for each harmonic $\boldsymbol{n}$
6. Calculate voltage and current distortion factors

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Connection Studies

- When a generation or demand customer is to be connected to a network, it has to comply with Power Quality (PQ) standards (UK national standards '*Engineering Recommendations P28*').
- The customer has to provide harmonic current injections *I(n)* at the point of connection to the utility.
- The utility performs harmonics analysis and reports back to the customer whether the PQ standards are met or not.
- In case the PQ standards are exceeded, the customer has to provide technical details of the (shunt) filter that is going to be installed on customer premises; these studies are usually done by a third party.
- The utility performs harmonics analysis with either 'old' harmonic current injections *I(n)* and the proposed filter, or with new 'filtered' harmonic current injections $I_{fil}(n)$ at the point of connection.

Connection Studies: PQ Studies in Utility

- Existing voltage harmonics at the point of connection $\boldsymbol{V_{PoC}^{ex}(n)}$ are measured; they are often called 'background harmonics'
- Impedance scan (a.k.a. frequency scan) is done using a dedicated software to find the equivalent impedance of the network at the point of connection $\boldsymbol{Z_{Thev}(n)}$ for each harmonic $\boldsymbol{n}$
- Voltage harmonics caused by the new customer $\boldsymbol{V_{PoC}(n)}$ are calculated for each harmonic $\boldsymbol{n}$ (without and with filter)
- Existing $\boldsymbol{V_{PoC}^{ex}(n)}$ and new voltage harmonics $\boldsymbol{V_{PoC}(n)}$ are 'added' using the rules from ER P28