Power Quality

(EE-465)

S7 - EE, 2020

by

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Overview

Module 1

- Power Quality
  - Sources
  - Effects
- Types of power quality disturbances
  - Voltage sag (dip)
  - Swell
  - Transients
  - Short duration voltage variation
  - Long duration voltage variation
  - Voltage imbalance
  - Waveform distortion
  - Voltage flicker

Module 2

- IEEE guide lines, standards and recommended practices
- Harmonics
  - Mechanism of harmonic generation
- Harmonic indices
  - Total Harmonic Distortion (THD)
  - Telephone Interference Factor (TIF)
  - Distortion Index (DIN)
  - C-message weights
- Power Quality Costs Evaluation
- Harmonic sources
  - Switching devices
  - Arcing devices
  - Saturable devices
- Effects of Power System harmonics

Module 3

- Harmonic Analysis
  - Fourier series and coefficients
  - Fourier transforms
  - Discrete Fourier transform
  - Fast Fourier transform
  - Window function
- Numerical problems

Module 4

- Power quality Monitoring
  - Power line disturbance analyzer
  - Power quality measurement equipment
  - Harmonic spectrum analyzer
  - Flicker meters
  - Disturbance analyzer

Module 5

- Harmonic elimination
  - Design and analysis of filters
  - Power conditioners
  - Passive filter
  - Active filter
    - Shunt filter
    - Series filter
    - Hybrid filter

Module 6

- Power Quality Management in Smart Grid
  - Power Quality issues
  - Power Quality Conditioners
- Electromagnetic Interference
  - Frequency Classification
  - Electrical fields & Magnetic Fields
  - EMI Terminology
  - Power frequency fields & High frequency fields

2. Expected Outcome

After the successful completion of this course, the students will be able to

1. Identify the power quality problems, causes and suggest suitable mitigating techniques

3. References

1. *"Electrical Power System Quality"* - *R. C. Dugan*
2. "*Power Quality*" - C. Sankaran
3. "*Power Quality*" - G. T. Heydt
4. "*Power System Harmonics*" - Jose Arillaga
5. "*Understanding Power Quality Problems*" - Math H. Bollen
6. "*Handbook of Power Quality*" - Angelo Baggini

Thank You

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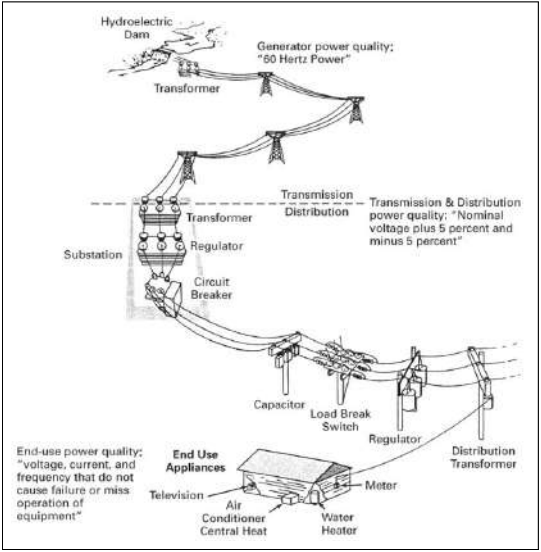
Module 1: Overview I

1. Power Quality
   - Reasons for the concern about power quality
   - Sources and effects of power quality problems
2. Power Quality Evaluation Procedure
3. General Classes of Power Quality Problems
4. Types of power quality disturbances
   - Transients
     - Impulsive Transient
     - Oscillatory Transient
   - Long-Duration Voltage Variations
     - Overvoltage
     - Undervoltage
     - Sustained interruptions
   - Short-Duration Voltage Variations
     - Interruption
     - Sags (dips)
     - Swell

Module 1: Overview II

- Voltage imbalance
- Waveform distortion
  - DC offset
  - Harmonics
  - Interharmonics
  - Notching
  - Noise
- Voltage Fluctuation
- Power Frequency Variations

1. Power Quality I



1. Power Quality II

- Electric utilities and end users of electrical power are concerned about the quality of electric power
- Power Quality Perspectives
  - **Supplier side** : Generators ability to generate power at 50 Hz with slight variations
  - **Consumer side** : Refers to steady voltage within $\pm 5\%$
- Power is the rate of energy delivered or consumed. Power is proportional to the product of the voltage and current
- Power supply system can generally control the **quality of voltage** $\rightarrow$ standards in the power quality area are devoted to maintaining the supply voltage within certain limits
- Any significant deviation in the **magnitude, frequency, or distortion** of sinusoidal voltage waveform is a power quality problem

1. Power Quality III

- **Definition**: Any power problem manifested in voltage, current, or frequency deviations that results in failure or mis-operation of customer equipment
- **IEEE definition**: Power quality is the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment
- Power quality is determined by the performance and productivity of end-user equipment $\rightarrow$ If the electric power is inadequate for the consumer needs, then power quality is lacking
- **Lightning** can be considered as a natural cause of power quality issues in the system

1.1 Reasons for the concern about power quality

- Today's **load equipments are more sensitive** to power quality variations than equipments used earlier. Many load devices contain **microprocessor based controls** and power electronic devices that are sensitive to many types of disturbances
- **Industries are now more automated** and have more modern equipment than the past. The electronically controlled, energy efficient equipment is **more sensitive to deviations** in the supply voltage than its electro-mechanical predecessors. Thus the quality of power can have a direct economic impact on many industrial consumers
- To increase overall efficiency of power systems, many **power electronic devices** are used. This results in increased harmonic levels
- **Increased awareness** of power quality issues by the end users challenges the utilities to improve the quality of power delivered
- Many things are **interconnected**. Failure of any one component leads to more important consequences

1.2 Sources and effects of power quality problems I

1. **Non-linear loads**
   - Mainly power electronics devices
   - For non-linear loads, current and voltage do not follow each other linearly $\rightarrow$ causes harmonic distortion $\rightarrow$ overheating of equipments and machines
2. **IT and office equipments**
   - Integrated circuit (IC) chips
   - ICs are very sensitive to changes in power supply
   - Computers, microprocessors, consumer electronic and telecommunication appliances have switched mode power supply (SMPS)
   - **SMPS** significantly increases level of 3rd, 5th and 7th harmonic orders in the voltage $\rightarrow$ causes distortions
3. **Arcing devices**
   - Electric arc furnaces, arc welders and electric discharge lamps
   - Highly non-linear loads
   - Causes harmonic distortion

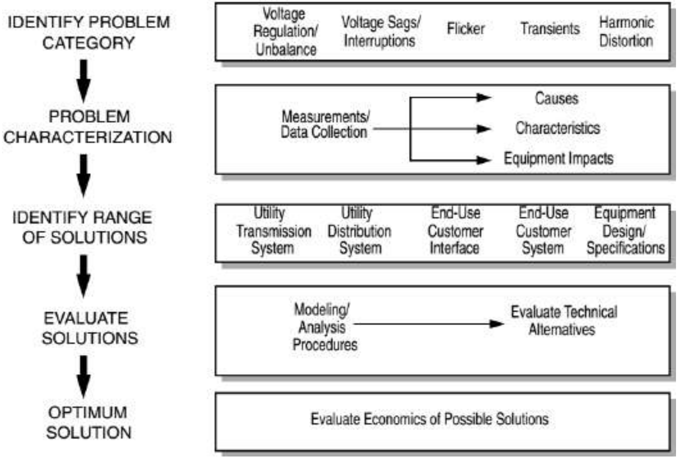
1.2 Sources and effects of power quality problems II

4. **Load switching**
   - Transients might occur as the result of switching in a heavy loads
5. **Large motor starting**
   - Dynamic nature of induction machines means that they draw current depending on the mode of operation. During starting, this current can be as high as six times the normal rated current. This increased loading on the local network that has the effect of causing a voltage dip
   - Modern motors employ a sophisticated power electronic converter drive, which control the motors starting current to a reasonable level
   - Lower cost types of motor use series capacitors or resistors to reduce the starting current. These components are then switched out once the motors rated speed has been reached
   - Autotransformers are used to start motors. These have a variable secondary winding that allows the motor stator voltage to be controlled and hence the current drawn from the supply

1.2 Sources and effects of power quality problems III

6. **Inter-connectedness of power system**
   - Power quality problem can propagate and difficult to isolate
   - Harmonics and icker are examples of power quality problems that can be transferred from a utility to another through interconnection
7. **Lightning strike and environmental disturbances**
   - Lightning strikes $\rightarrow$ transient over-voltages
   - Lightning strikes that hit overhead lines often cause ash-over to neighbouring conductors due to insulators break down $\rightarrow$ causes transient overvoltage as well as fault-clearing interruptions and dips

2. Power Quality Evaluation Procedure I



- General steps associated with investigating power quality problems

2. Power Quality Evaluation Procedure II

- Existing power quality problem or one that could result from a new design or from proposed changes to the system?
- **Measure** parameters and record impacts of the power quality variations at the same time so that problems can be correlated with possible causes
- **Solutions** need to be evaluated
  - System perspective: from utility supply to the end-use equipment being affected
  - Economics and technical limitations

3. General Classes of Power Quality Problems I

- IEEE Standards Coordinating Committee 22 (IEEE SCC22)
- American National Standards Institute (ANSI)
- IEEE Standard 519-1992, *Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems*
- Attributes to categorize electromagnetic phenomena
  - **Steady-state phenomena**
    - Amplitude
    - Frequency
    - Spectrum
    - Modulation
    - Source impedance
    - Notch depth
    - Notch area

3. General Classes of Power Quality Problems II

- **Non-steady-state phenomena**
  - Rate of rise
  - Amplitude
  - Duration
  - Spectrum
  - Frequency
  - Rate of occurrence
  - Energy potential
  - Source impedance

4. Types of power quality disturbances

- Types
  1. Transients
  2. Long-Duration Voltage Variations
  3. Short-Duration Voltage Variations

4.1 Transients

- Sudden changes / Surge
- Reflects the wave shape of a current or voltage transient
- Types
  - Impulsive Transients
  - Oscillatory Transients

4.1.1 Impulsive transient I

- **Sudden, non-power frequency** change in the steady-state condition of voltage, current, or both that is **unidirectional in polarity** (primarily either positive or negative)
- Characterized by rise and decay times
- $1.2 \times 50\mu s$ 2000 volt (V) impulsive transient
  - Rises from zero to it's peak value of 2000 V in $1.2\mu s$
  - then decays to half it's peak value in $50\mu s$
- **Lightning**: Most common cause of impulsive transients

4.1.1 Impulsive transient II

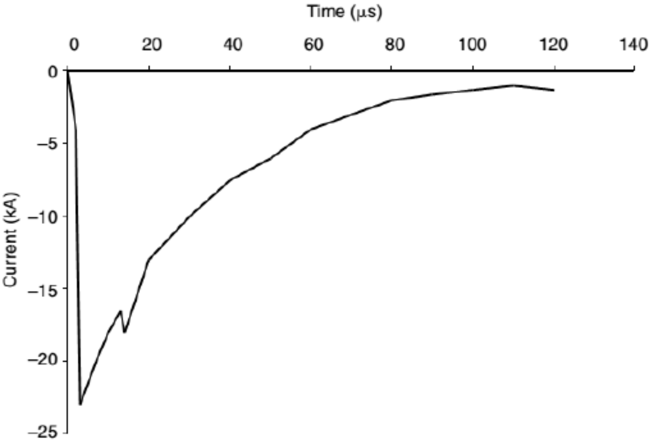


Figure 1 : Lightning stroke current impulsive transient

4.1.1 Impulsive transient III

- Shape of impulsive transients can be changed quickly by circuit component since high frequencies are involved
- Generally transients are not conducted far from the source of where they enter the power system
- Impulsive transients can excite the natural frequency of power system circuits and produce oscillatory transients
- Categories of Impulsive Transients
  - Nanosecond: 5 ns rise
  - Microsecond: 1 μs rise
  - Millisecond: 0.1 ms rise

4.1.2 Oscillatory transient I

- **Sudden, nonpower frequency change** in the steady-state condition of voltage, current, or both, that includes **both positive and negative polarity values**
- Oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly
- Oscillatory transient is described by it's spectral content (predominate frequency), duration, and magnitude

4.1.2 Oscillatory transient II

- Classification based on **frequencies**
  - **High-frequency transients**
    - Oscillatory transients with a primary frequency component greater than 500 kHz
    - Typical duration is measured in microseconds (or several cycles of the principal frequency)
    - Generally produced as a result of a local system response to an impulsive transient
  - **Medium-frequency transient**
    - Oscillatory transients with a primary frequency component between 5 and 500 kHz
    - Typical duration is measured in the tens of microseconds (or several cycles of the principal frequency)
    - Causes: Back-to-back capacitor energization, Cable switching, system response to an impulsive transient etc.

4.1.2 Oscillatory transient III

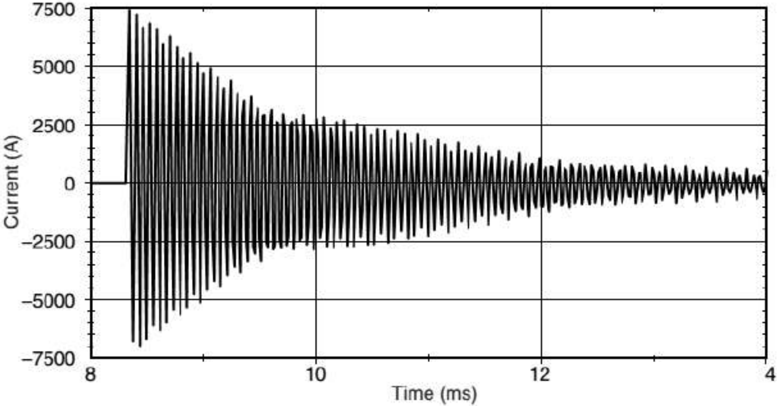


Figure 2 : Oscillatory transient current caused by back-to-back capacitor switching

4.1.2 Oscillatory transient IV

- **Low-frequency transient**
  - Oscillatory transient with a primary frequency component less than 5 kHz
  - Typical duration is from 0.3 to 50 ms
  - Common in utility sub-transmission and distribution systems
  - Causes: capacitor bank energization (voltage transient with a primary frequency between 300 and 900 Hz, peak magnitude can approach 2.0 pu with a duration of between 0.5 and 3 cycles)

4.1.2 Oscillatory transient V

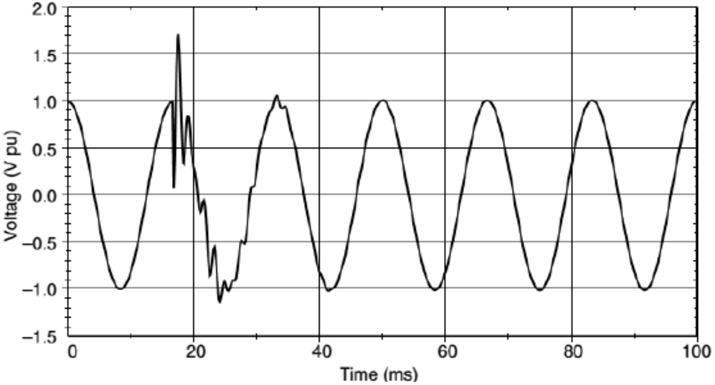


Figure 3 : Low-frequency oscillatory transient caused by capacitor bank energization (34.5 kV bus voltage)

4.1.2 Oscillatory transient VI

- Ferroresonance and transformer energization can result in oscillatory transients with principal frequencies less than 300 Hz in distribution system

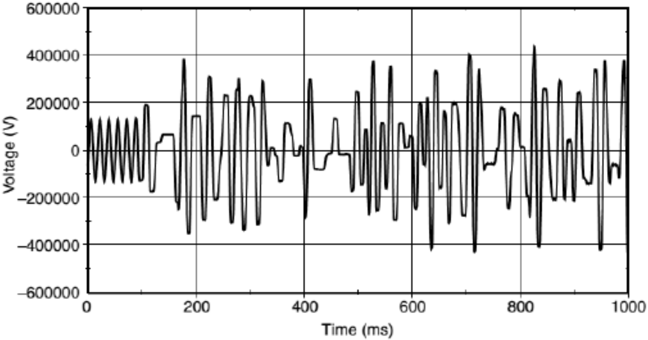


Figure 4 : Low-frequency oscillatory transient caused by ferroresonance of an unloaded transformer

4.1.2 Oscillatory transient VII

- Classification based on **mode** in a three-phase system with a separate neutral conductor
  - **Common mode transient**: appears between line or neutral and ground
  - **Normal mode transients**: appears between line and neutral

4.2 Long-Duration Voltage Variations

- Long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min
- **ANSI C84.1** specifies the steady-state voltage tolerances expected on a power system
- A voltage variation is considered to be long duration when the ANSI limits are **exceeded for greater than 1 min**
- Generally caused by load variations on the system and system switching operations
- Long-Duration Voltage Variations are typically displayed as plots of rms voltage versus time
- Types
  1. Overvoltage
  2. Undervoltage

4.2.1 Overvoltage

- **Increase in the rms ac voltage greater than 110 % at the power frequency for a duration longer than 1 min**
- Overvoltages result because either the **system is too weak** for the desired voltage regulation or **voltage controls are inadequate**
- Causes
  - Load switching (e.g., switching off a large load or energizing a capacitor bank)
  - Incorrect tap settings on transformers

4.2.2 Undervoltage

- **Decrease in the rms ac voltage to less than 90 percent at the power frequency for a duration longer than 1 min**
- Causes
  - Load switching ON
  - Capacitor bank switching OFF
  - Overloaded circuits
- Voltage regulation equipment on the system can bring the voltage back to within tolerances
- **Brownout**: sustained periods of under-voltage initiated as a specific utility dispatch strategy to reduce power demand

4.2.3 Sustained interruptions

- **Supply voltage has been zero for a period of time in excess of 1min**
- Often permanent and **require human intervention** to repair the system for restoration
- **Sustained interruptions**: more specific regarding the absence of voltage for long periods
- **Outage**: state of a component in a system that has failed to function as expected

4.3 Short-Duration Voltage Variations

- **Voltage dips and short interruptions**
- Depending on duration
  - **Instantaneous**: (0.5 - 30 cycles)
  - **Momentary**: (30 cycles - 3 s)
  - **Temporary**: (3s - 1 min)
- Causes
  - Fault conditions
  - Energization of large loads which require high starting currents
  - Intermittent loose connections in power wiring

4.3.1 Interruption I

- Interruption occurs when the supply voltage or load current **decreases to less than 0.1 pu** for a period of time **not exceeding 1 min**
- Causes
  - Power system faults
  - Equipment failures
  - Control malfunctions
- Instantaneous reclosing of protective devices will limit the interruption caused by a non-permanent fault to less than 30 cycles
- Interruptions may be preceded by a voltage sag when these interruptions are due to faults on the source system

4.3.1 Interruption II

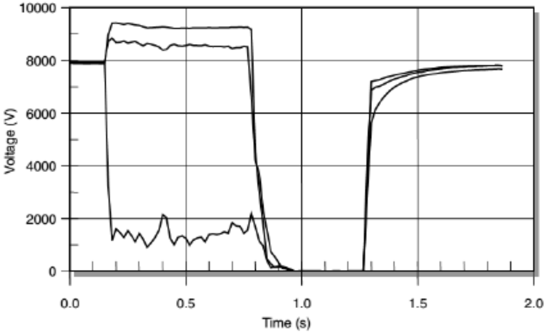


Figure 5 : Three-phase rms voltages for a momentary interruption due to a fault and subsequent recloser operation

- In figure, voltage on one phase sags to about 20% for about 3 cycles and then drops to zero for about 1.8s until the recloser closes back in

4.3.2 Sags (dips) I

- **Decrease** to between **0.1 and 0.9 pu** in rms voltage or current at the **power frequency** for durations from **0.5 cycle to 1 min**
- A "20 percent sag" will be considered an event during which the rms voltage decreased by 20 percent to 0.8 pu
- **Causes**
  - System faults
  - Energization of heavy loads
  - Starting of large motors
- Typical fault clearing times range from 3 to 30 cycles, depending on the fault current magnitude and the type of over-current protection

4.3.2 Sags (dips) II

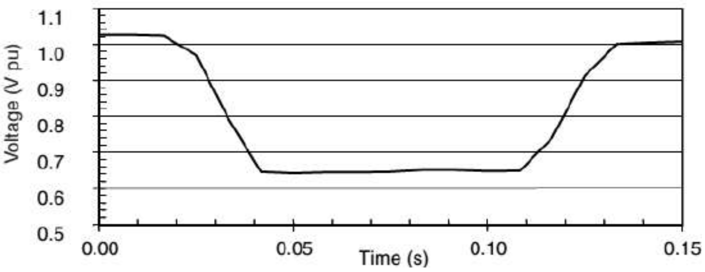


Figure 6 : RMS waveform of voltage sag caused by an SLG fault

- 80% sag exists for about 3 cycles until the substation breaker is able to interrupt the fault current

4.3.2 Sags (dips) III

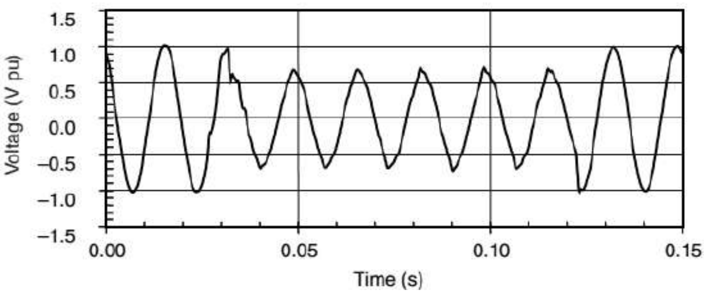


Figure 7 : Voltage sag waveform caused by an SLG fault

4.3.2 Sags (dips) IV

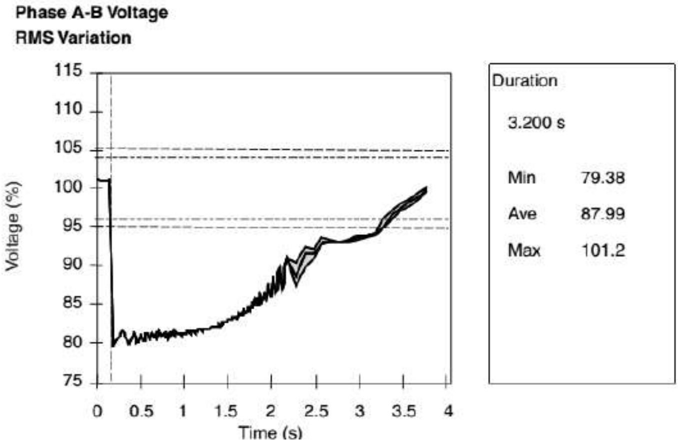


Figure 8 : Temporary voltage sag caused by motor starting

4.3.2 Sags (dips) V

- Large motor starting
  - Induction motor will draw 6 to 10 times its full load current during start-up
  - If the current magnitude is large relative to the available fault current in the system at that point, the resulting voltage sag can be significant
  - In figure, voltage sags immediately to 80 percent and then gradually returns to normal in about 3s

4.3.3 Swell I

- **Increase** to between **1.1 and 1.8 pu** in rms voltage or current at the **power frequency** for durations from **0.5 cycle to 1 min**
- Swells are characterized by their magnitude (rms value) and duration
- Severity of a voltage swell during a fault condition depends on **fault location, system impedance, and grounding**
- **Causes**
  - System fault: on unfaulted phase during an SLG fault
  - Switching OFF a large load
  - Energizing a large capacitor bank

4.3.3 Swell II

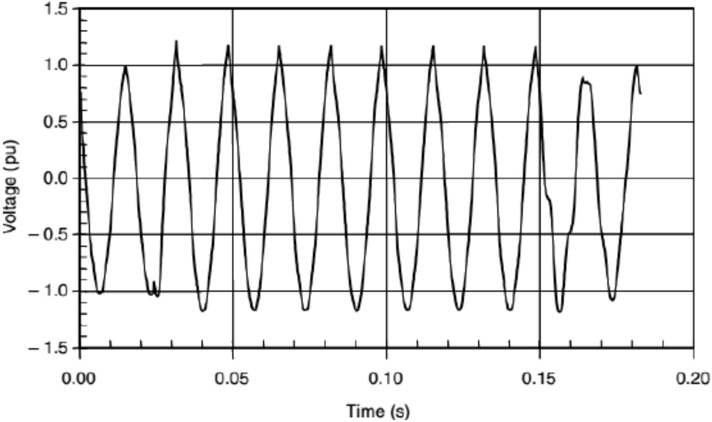


Figure 9 : Instantaneous voltage swell caused by an SLG fault

4.4 Voltage imbalance I

- **Voltage unbalance**
- **Maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percent**
- Symmetrical components
- **Ratio of either the negative or zero sequence component to the positive sequence component** can be used to specify the percent unbalance
- Causes of voltage unbalance of less than 2%
  - Single-phase loads on a three-phase circuit
  - Blown fuses in one phase of a three-phase capacitor bank
- Cause of severe voltage unbalance (greater than 5%): single-phasing conditions

4.4 Voltage imbalance II

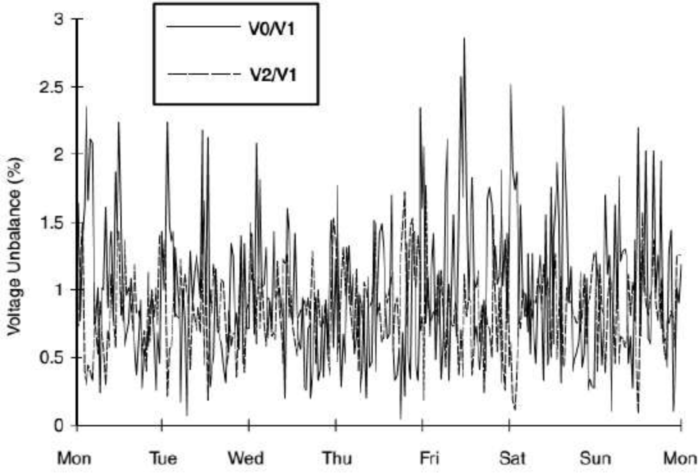


Figure 10 : Voltage unbalance trend for a residential feeder

4.5 Waveform distortion

- **Steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation**
- Types
  1. DC offset
  2. Harmonics
  3. Interharmonics
  4. Notching
  5. Noise

4.5.1 DC offset

- **Presence of a dc voltage or current in an ac power system**
- **Causes**
  - Geomagnetic disturbance
  - Asymmetry of electronic power converters
- **Effects**
  - Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation $\rightarrow$ additional heating and loss of transformer life
  - Electrolytic erosion of grounding electrodes and other connectors

4.5.2 Harmonics I

- Sinusoidal voltages or currents having frequencies that are **integer multiples of the frequency** at which the supply system is designed to operate (termed as fundamental frequency)
- Harmonic distortion originates in the **non-linear characteristics** of devices and loads on the power system
- Periodically distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics $\rightarrow$ Fourier Analysis
- **Harmonic spectrum**: magnitudes and phase angles of each individual harmonic component
- **Total harmonic distortion (THD)**: measure of the effective value of harmonic distortion

4.5.2 Harmonics II

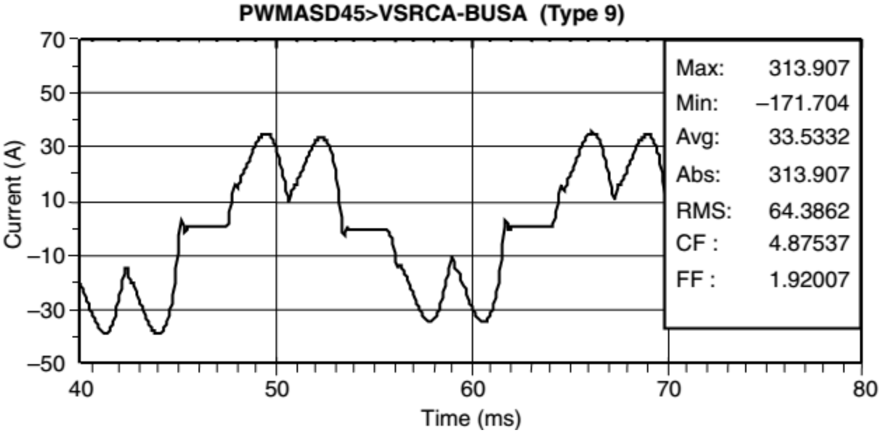


Figure 11 : Current waveform for an ASD input current

4.5.2 Harmonics III

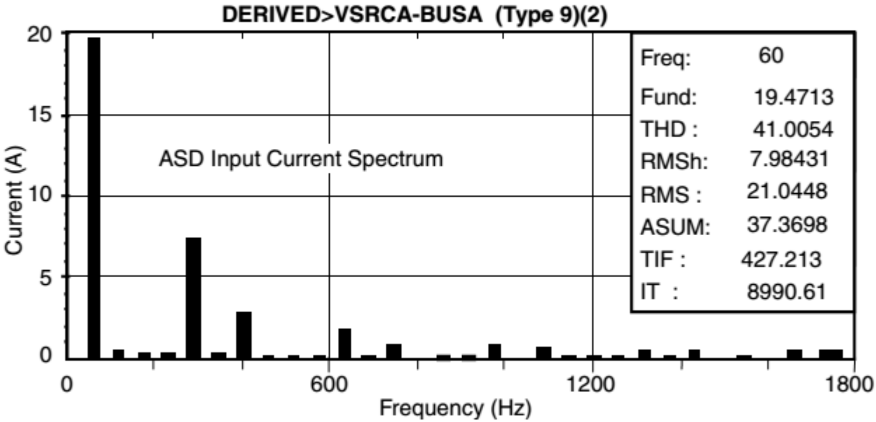


Figure 12 : Harmonic spectrum for an ASD input current

4.5.2 Harmonics IV

- **Total Harmonic Distortion (THD)**:
  - Ratio of the root-sum-square value of the harmonic content of the current to the root-mean-square value of the fundamental current

$$I_{THD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}}{I_1} \times 100\%$$

- **Total demand distortion (TDD)**
  - This term is same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude at the instant of measurement
  - **Ratio of the root-sum-square value of the harmonic current to the maximum demand load current**

$$I_{TDD} = \frac{\sqrt{I_2^2 + I_3^2 + I_4^2 + ... + I_n^2}}{I_L} \times 100\%$$

4.5.2 Harmonics V

- IEEE Standard 519-1992 provides guidelines for harmonic current and voltage distortion levels on distribution and transmission circuits

4.5.3 Interharmonics

- Voltages or currents having frequency components that are **not integer multiples** of the frequency at which the supply system is designed to operate are called **interharmonics**
- Appear as discrete frequencies or as a wideband spectrum
- Power line carrier signals are considered as interharmonics
- Interharmonics can excite quite **severe resonances** on the power system when the varying interharmonic frequency becomes coincident with natural frequencies of the system
- **Sources**
  - Static frequency converters
  - Cycloconverters
  - Induction furnaces
  - Arcing devices
- **Effects**
  - Affects power-line-carrier signalling
  - Induce visual flicker in fluorescent and other arc lighting as well as in computer display devices

4.5.4 Notching I

- **Periodic voltage disturbance** caused by the normal operation of power electronic devices **when current is commutated from one phase to another**
- Characterized through the harmonic spectrum of the affected voltage
- Frequency components associated with notching are quite high

4.5.4 Notching II

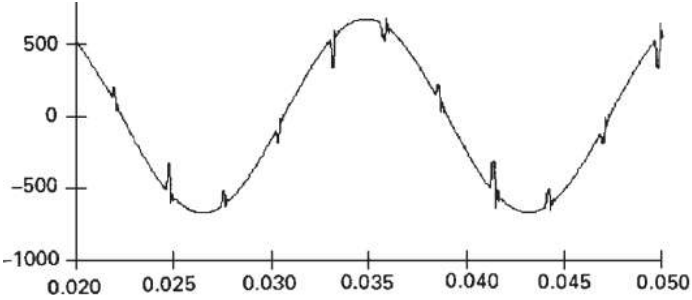


Figure 13 : Voltage notching caused by a three-phase converter

- During notching period, there is a **momentary short circuit** between two phases, pulling the voltage as close to zero as permitted by system impedances

4.5.5 Noise I

- **Unwanted electrical signals** with broadband spectral content **lower than 200kHz** superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines
- Noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients
- Causes
    - Power electronic devices
    - Control circuits
    - Arcing equipment
    - Loads with solid-state rectifiers
    - Switching power supplies

4.5.5 Noise II

- Noises are often worsened b improper grounding that fails to conduct noise away from the power system
- Effects
  - Disturbs electronic devices such as microcomputer and programmable controllers
- Mitigated by using **filters, isolation transformers, and line conditioners**

4.6 Voltage Fluctuation I

- **Systematic variations** of the voltage envelope or a **series of random voltage changes**, the magnitude of which **does not normally exceed** the voltage ranges specified by ANSI C84.1 of **0.9 to 1.1 pu**
- **IEC 61000-2-1 Type (d) voltage fluctuations**: characterized as a series of random or continuous voltage fluctuations
- Loads that can exhibit continuous, rapid variations in the load current magnitude can cause voltage variations that are often referred to as **flicker**
- Flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker
- **Voltage fluctuation is an electromagnetic phenomenon while flicker is an undesirable result of the voltage fluctuation in some loads**. However, the two terms are often linked together in standards

4.6 Voltage Fluctuation II

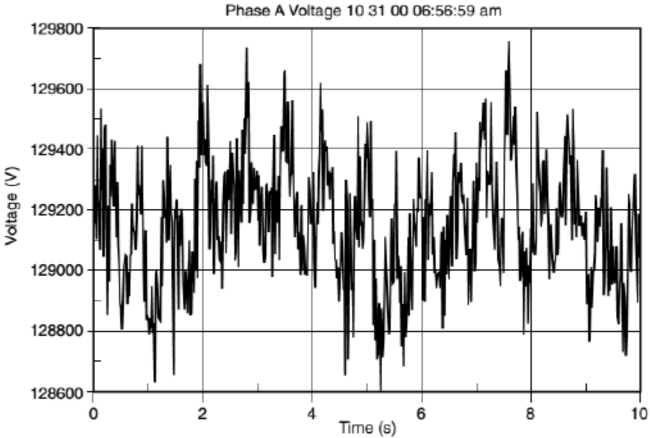


Figure 14 : Voltage fluctuations caused by arc furnace operation

4.6 Voltage Fluctuation III

- **Short-term flicker sensation (Pst)**
  - This measurement method simulates the lamp/eye/brain transfer function and produces a fundamental metric called short-term flicker sensation (Pst)
  - This value is normalized to 1.0 to represent the level of voltage fluctuations sufficient to cause noticeable flicker to 50 percent of a sample observing group
  - Normally reported at 10 min intervals
- **Long-term flicker sensation (Plt)**
  - Used for the purpose of verifying compliance with compatibility levels established by standards bodies and used in utility power contracts
  - This value is a longer-term average of Pst samples
  - Plt value is produced every 2 h from the Pst values

4.6 Voltage Fluctuation IV

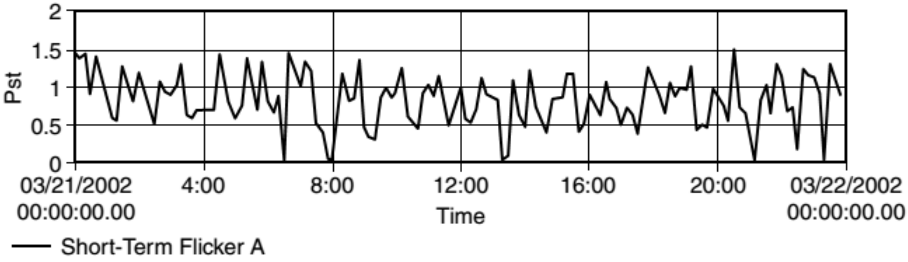


Figure 15 : Flicker (Pst) at 161 kV substation bus measured according to IEC Standard 61000-4-15

4.7 Power Frequency Variations I

- **Deviation of the power system fundamental frequency from it specified nominal value**
- Power system frequency is directly related to the rotational speed of the generators supplying the system
- There are slight variations in frequency as the dynamic balance between load and generation changes
- The size of the frequency shift and its duration depend on the load characteristics and the response of the generation control system to load changes

4.7 Power Frequency Variations II

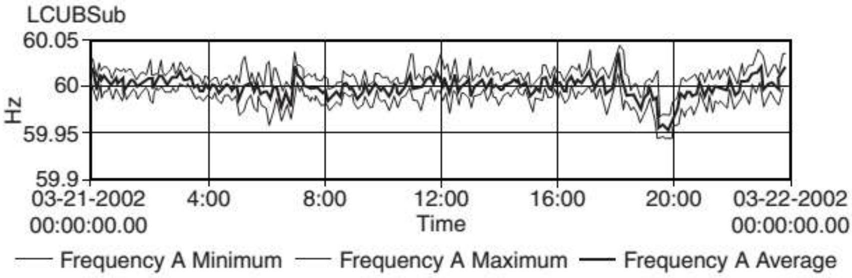


Figure 16 : Power frequency trend at 13 kV substation bus

4.7 Power Frequency Variations III

- **Causes**
  - Mismatch between power generation and demand
  - Faults on the bulk power transmission system
  - Large block of load being disconnected
  - Large source of generation going off-line

References

1. *"Electrical Power System Quality"* - *R. C. Dugan*
2. "*Power Quality*" - C. Sankaran
3. "*Power Quality*" - G. T. Heydt
4. "*Power System Harmonics*" - Jose Arillaga
5. "*Understanding Power Quality Problems*" - Math H. Bollen
6. "*Handbook of Power Quality*" - Angelo Baggini

Thank You

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Power Quality

(EE-465)

S7 - EE, 2020

by

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1. IEEE Guidelines, Standards and Recommended Practices
   - Harmonic Standards
     - IEC 61000 Series
     - IEEE 519 - 1992
   - Voltage Sag (Dip) Standards
   - Transients or Surges Standards
   - Harmonic Standards
   - IEEE 1250
   - IEEE 1453
   - IEEE 1159
   - Grounding and Wiring Standards
   - CBEMA and ITI Curves
   - Information Technology Industry Council (ITI)
   - Power Quality Standards in India
     - System Average Interruption Duration Index (SAIDI)
     - System Average Interruption Frequency Index (SAIFI)

- Average Interruption Duration Index (CAIDI)
- Electricity Supply Monitoring Initiative (ESMI)

2. Harmonics
   - Triplen Harmonics
   - Harmonics Vs Transients
   - Mechanism of Harmonic Generation
3. Harmonic Indices
   - Total Harmonic Distortion (THD)
   - Total Demand Distortion (TDD)
   - Telephone Interference Factor (TIF)
   - Distortion Index (DIN)
   - C-Message Weighted Index
4. Power Quality Costs Evaluation
   - Economic Impacts of Power Quality
     - Direct Economic Impacts
     - Indirect Economic Impacts

Module 2: Overview III

- Social Economic Impacts
- PQ Cost Categories
  - Staff Cost
  - Work in Progress
  - Equipment Malfunctioning
  - Equipment Damage
  - Other Costs
  - Specific Costs
  - Savings

5 Harmonic Sources

- Harmonic Sources from Commercial Loads
  - Single-phase Power Supplies
  - Fluorescent Lighting
  - Adjustable Speed Drives
- Harmonic Sources from Industrial Loads
  - Three-phase Power Converters
  - Arcing Devices

Module 2: Overview IV

- Saturable Devices

6. Effects of Power System Harmonics

1. IEEE Guidelines, Standards & Recommended Practices I

- Organizations responsible for developing power quality standards
  - Institute of Electrical and Electronics Engineers (IEEE)
  - American National Standards Institute (ANSI)
  - National Institute of Standards and Technology (NIST)
  - Electric Power Research Institute (EPRI)
  - International Electro-technical Commission (IEC) etc.
- Purpose of Power Quality Standards
  - Protect utility and end user equipment from failing or mis-operating when the voltage, current, or frequency deviates from normal
  - Provides protection by setting measurable limits as to how far the voltage, current, or frequency can deviate from normal
  - By setting limits, PQ standards help utilities and their customers gain agreement as to what are acceptable and unacceptable levels of service

1. IEEE Guidelines, Standards & Recommended Practices II

- To help the power quality industry to compare the results of power quality measurements from different instruments, the IEEE developed IEEE Standard 159-1995 *Recommended Practices for Monitoring Electric Power Quality*

- Factors Influencing the Development of Standards
  - Description and **characterisation** of the phenomenon
  - **Major sources** of harmonic problems
  - **Impact** on other equipment and on the power system
  - Mathematical description of the phenomenon using **indices** or statistical analysis to provide a quantitative assessment of its significance
  - **Measurement techniques** and guidelines
  - Emission **limits** for different types and **classes** of equipment
  - Immunity or **tolerance level** of different types of equipment
  - **Testing methods** and procedures for compliance with the limits
  - **Mitigation** guidelines

1.1 Harmonic Standards

- IEC **(International Electrotechnical Commission)**, based in Geneva
- IEC $\rightarrow$ Electromagnetic Compatibility (EMC) Standards, to deal with power quality issues
  - **IEC 61000 series**: Harmonics and inter-harmonics as one of the conducted low-frequency electromagnetic phenomena
- **IEEE 519 - 1992** document: provides guidelines on harmonics

1.1.1 IEC 61000 Series I

- Provides internationally accepted information for the control of power system harmonic (and inter-harmonic) distortion
- **IEC 61000 1-4**
  - Provides the rationale for limiting power frequency conducted harmonic and inter-harmonic current emissions from equipment in the frequency range up to 9 kHz
- **IEC 61000 2-1**
  - Outlines the major sources of harmonics in three categories of equipment
    - Power system equipment (HVDC converters and FACTS devices)
    - Industrial loads (Static power converters and electric arc furnaces)
    - Residential loads (Appliances powered by rectifiers with smoothing capacitors (mostly PCs and TVs)) receivers))
- **IEC 61000 2-2**

1.1.1 IEC 61000 Series II

- Compatibility levels of the harmonic and inter-harmonic voltage distortion in public low-voltage power industry systems

- **IEC 61000 2-4**
  - Provides harmonic and inter-harmonic compatibility levels for industrial plant
- **IEC 61000 2-12**
  - Deals with compatibility levels for low-frequency conducted disturbances, in this case relating to medium voltage power supply systems
- **IEC 61000 3-2 and 3-4**
  - Limits for harmonic current emissions by equipment with input currents of 16 A and below per phase
- **IEC 61000 3-6**
  - Indicates the capability levels for harmonic voltages in low and medium-voltage networks as well as planning levels for MV, HV and EHV power systems

1.1.1 IEC 61000 Series III

- Assessment of emission limits for distorting loads in MV and HV power systems

- **IEC 61000 3-12**
  - Provides limits for the harmonic currents produced by equipment connected to low-voltage systems with input currents equal to and below 75 A per phase and subject to restricted connection
- **IEC 61000 4-7**
  - Testing and measurement techniques
  - General guide on harmonic and inter-harmonic measurements and instrumen for power systems and equipment connected thereto
- **IEC 61000 4-13**
  - Testing and measurement techniques with reference to harmonics and inter-harmonics, including mains signalling at a.c. power ports as well as low-frequency immunity tests

1.1.2 IEEE 519 - 1992 I

- Identifies the major **sources of harmonics** in power systems
- Illustrates the typical distorted **wave shapes**, the **harmonic order numbers** and the **level** of each harmonic component in the distortion caused by harmonic sources
- **Harmonic sources**
  - Power converters
  - Arc furnaces
  - Static VAR compensators
  - Inverters of dispersed generation
  - Electronic phase control of power
  - Cycloconverters
  - Switch mode power supplies
  - Pulse-width modulated (PWM) drives
- Describes how the system may **respond** to the presence of harmonics
  - Parallel resonance

1.1.2 IEEE 519 - 1992 II

- Series resonance
- Effect of system loading on the magnitude of these resonances

- Effects of harmonic distortion on the operation of various **devices or loads** are also included
  - Motors and generators
  - Transformers
  - Power cables
  - Capacitors
  - Electronic equipment
  - Metering equipment
  - Switchgear
  - Relays
  - Static power converters

1.1.2 IEEE 519 - 1992 III

- Interference to the telephone networks as a result of harmonic distortion in the power systems is discussed with reference to the **C-message weighting system** created jointly by Bell Telephone Systems and Edison Electric Institute
- Describes the analysis methods and measurement requirements for assessing the levels of harmonic distortion in the power system
- Methods for the calculation of harmonic currents, system frequency responses and modelling of various power system components for the analysis of harmonic propagation
- **Measurements**
  - Lists various harmonic monitors that are currently available
  - Describes the accuracy and selectivity (the ability to distinguish one harmonic component from others) requirements on these monitors

1.1.2 IEEE 519 - 1992 IV

- Averaging or snap-shot techniques that can be used to smooth-out the rapidly fluctuating harmonic components and thus reduce the overall data bandwidth and storage requirements

- Methods for designing **reactive power compensation** for systems with harmonic distortion
  - Reactive compensation devices → TCR and TSC etc. → Harmonic distortion
- Outlines the various techniques for reducing the amount of harmonic current penetrating into the a.c. systems
- Recommended practices are suggested to both individual consumers and utilities for controlling the harmonic distortion to tolerable levels
- Describes **notching**
  - Distortion caused on the line voltage waveform by the commutation process between valves in some power electronic devices
  - Analyses the converter commutation phenomenon

1.1.2 IEEE 519 - 1992 V

- Describes the notch depth and duration with respect to the system impedance and load current
- Limits are outlined in terms of the notch depth, THD of supply voltage and notch area for different supply systems

1.2 Voltage Sag (Dip) Standards

- **System Average RMS (variation) Frequency Index Voltage ($SARFI_v$)**
  - Quantifies three voltage sag parameters into one index. ie number of voltage sags, period of measurement, and the number of end users affected by the voltage sag

$$SARFI_x = \frac{\Sigma N_i}{N_T}$$

  - x = rms voltage threshold. Possible values 140, 120, 110, 90, 80, 70, 50 and 10
  - N_i = Number of customers experiencing voltage deviations with magnitudes above Y% for $x > 100$ or below Y% for $x < 100$ due to event i
  - N_T = Number of customers served from the section of the system to be assessed

1.3 Transients or Surges Standards

- ANSI/IEEE C62.41-1991
- IEEE Guide for Surge Voltages in Low Voltage AC Power Circuits, deals with transients in a building

1.4 Harmonic Standards

- IEEE 519-1992, *Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*
- Recognizes that the primary source of harmonic currents is non-linear loads located on the end-user (utility customer) side of the meter
- IEEE 519-1992 defines harmonic limits on the utility side of the meter as the total harmonic distortion (THD) and on the end-user side of the meter as total distortion demand (TDD)
- It sets the voltage distortion limits or THD that the utility can supply to the end user at the point of common coupling

1.5 IEEE 1250

- Serves as a primer to Power Quality for both utility professionals and Industrial Consumers
- Serves as a directory to other power quality standards

1.6 IEEE 1453

- Defines flicker
- Defines how to measure flicker
- Provides guidelines on how to conduct flicker studies
- Provides guidance on emission limits

1.7 IEEE 1159

- Serves a definitions document on power quality phenomenon

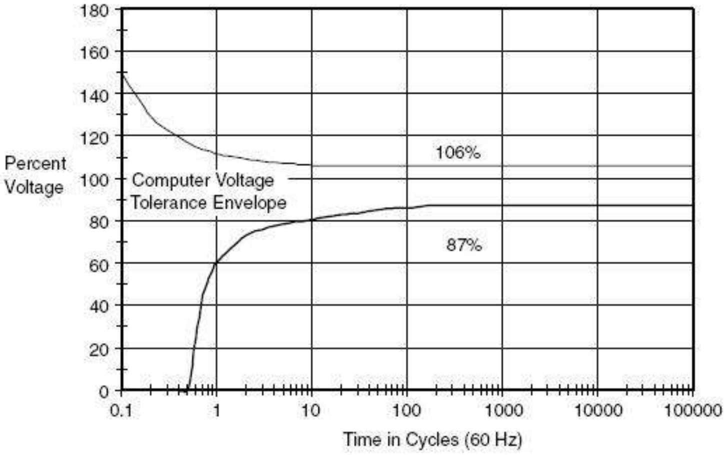
1.8 Grounding and Wiring Standards

- Primary standards for wiring and grounding are
  - IEEE Standard 446: Emergency and Standby Power Systems for Industrial and Commercial Applications (The Orange Book)
  - IEEE Standard 141-1993: Electric Power Distribution for Industrial Plants (The Red Book)
  - IEEE Standard 142-1991: Grounding of Industrial and Commercial Power Systems (The Green Book)
  - IEEE Standard 1100: Powering and Grounding Sensitive Electronic Equipme

1.9 CBEMA and ITI Curves I

- Used to represent the power quality
- Curve is adapted from IEEE Standard which is used in the analysis of power quality monitoring results
- Developed by CBEMA to describe the tolerance of mainframe computer equipment to the magnitude and duration of voltage variations on the power system
- This curve has become a standard design target for sensitive equipment to be applied on the power system and a common format for reporting power quality variation data

1.9 CBEMA and ITI Curves II



- Axes represent magnitude and duration of the event

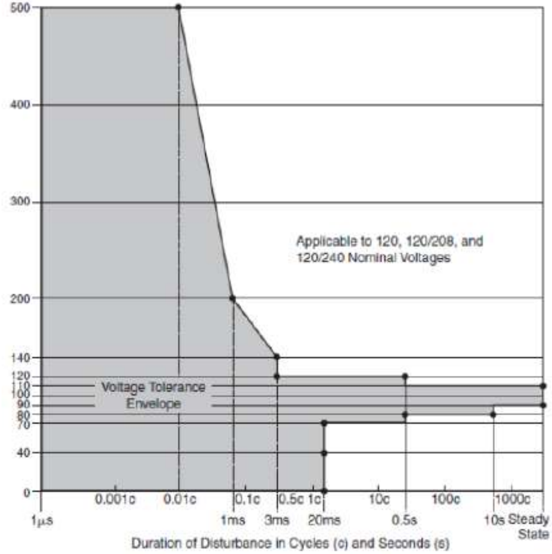
1.9 CBEMA and ITI Curves III

- Points below the envelope are presumed to cause the load to drop out due to lack of energy
- Points above the envelope are presumed to cause other malfunctions such as insulation failure, overvoltage trip, and over excitation

1.10 Information Technology Industry Council (ITI) I

- CBEMA organization has been replaced by ITI, a modified curve has been developed that specifically applies to common 120 V computer equipment
- Concept is similar to the CBEMA Curve
- This curve has been applied to general power quality evaluation like its predecessor curve

1.10 Information Technology Industry Council (ITI) II



ITI curve for susceptibility of 120-V computer equipment.

1.11 Power Quality Standards in India

- Indian government electricity regulatory authorities use reliability indices (developed by IEEE)
  1. System Average Interruption Duration Index (SAIDI)
  2. System Average Interruption Frequency Index (SAIFI)
  3. Consumer Average Interruption Duration Index (CAIDI)
  4. Electricity Supply Monitoring Initiative (ESMI)

1.11.1 System Average Interruption Duration Index (SAIDI)

- Average duration of interruptions per consumers during the year
- **Ratio of the annual duration of interruptions (sustained) to the number of consumers**
- If duration is specified in minutes, SAIDI is given as consumer minutes
- $SAIDI = \frac{Total\ \ duration\ \ of\ \ sustained\ \ interruptions\ \ in\ \ a\ \ year}{Total\ \ number\ \ of\ \ consumers}$

1.11.2 System Average Interruption Frequency Index (SAIFI)

- Average number of sustained interruptions per consumer during the year
- **Ratio of the annual number of interruptions to the number of consumers**
- $SAIFI = \frac{Total\ \ number\ \ of\ \ sustained\ \ interruptions\ \ in\ a\ \ year}{Total\ \ number\ \ of\ \ consumers}$

1.11.3 Average Interruption Duration Index (CAIDI)

- Average duration of an interruption, calculated based on the total number of sustained interruptions in a year
- Ratio of the total duration of interruptions to the total number of interruptions during the year
- $CAIDI = \frac{Total\ duration\ of\ sustained\ interruptions\ in\ a\ year}{Total\ number\ of\ sustained\ interruptions\ in\ a\ year}$
- $CAIDI = \frac{SAIDI}{SAIFI}$

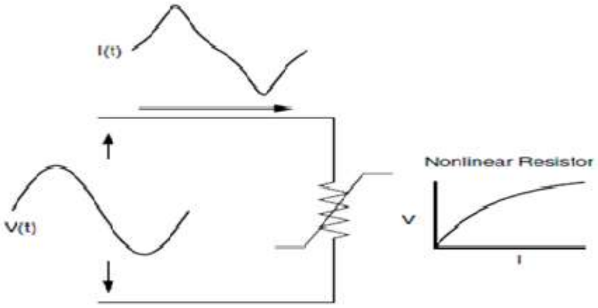
1.11.4 Electricity Supply Monitoring Initiative (ESMI)

- ESMI executes basic monitoring of supply continuity and voltage levels at ordinary consumer locations, in order to get an idea of the actual situation in the field and to increase the accountability of electricity utilities
- First three ESMI data loggers were installed in Pune City

2. Harmonics I

- Electricity generation
  - Generators emf can be considered practically sinusoidal
  - Produced at constant frequencies of 50 Hz or 60 Hz
- Generation of Harmonics
  - When a source of sinusoidal voltage is applied to a nonlinear device or load, the resulting current is not perfectly sinusoidal
  - In the presence of system impedance, non-sinusoidal current causes a non-sinusoidal voltage drop and, therefore, produces voltage distortion at the load terminals $\rightarrow$ **Harmonics**
- Harmonics are integral multiples of fundamental frequency that, when added together, result in a distorted waveform
- Harmonic distortions are caused by non-linear devices in the power system
- Non-linear device: current is not proportional to the applied voltage

2. Harmonics II

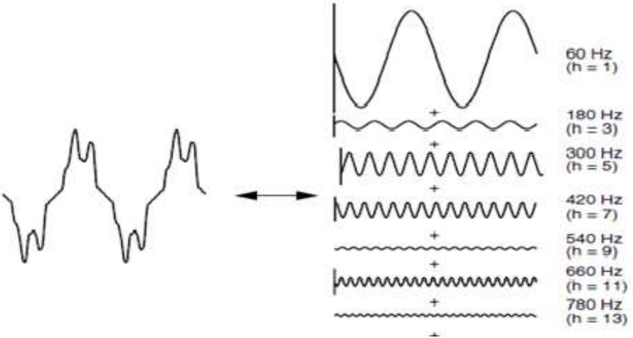


- While the applied voltage is perfectly sinusoidal, the resulting current is distorted. Increasing the voltage by a few percent may cause the current to double and take on a different wave shape. This is the source of most harmonic distortion in a power system
- Any periodic, distorted waveform can be expressed as a sum of sinusoids

2. Harmonics III

- When a waveform is identical from one cycle to the next, it can be represented as a sum of pure sine waves in which the frequency of each sinusoid is an integer multiple of the fundamental frequency of the distorted wave → Harmonic of the fundamental
- The sum of sinusoids is referred to as a Fourier series
- Fourier series concept is universally applied in analysing harmonic problems

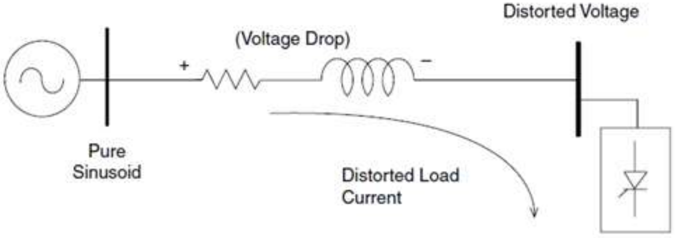
2. Harmonics IV



- When both the positive and negative half cycles of a waveform have identical shapes, the Fourier series contains only odd harmonics
- Presence of even harmonics is often a clue that there is something wrong - either with the load equipment or with the transducer used to make the measurement

2. Harmonics V

- Higher order harmonics (above the range of the 25th to 50th, depending on the system) are negligible for power system analysis. While they may cause interference with low-power electronic devices, they are usually not damaging to the power system
- Harmonic currents flowing through the system impedance result in harmonic voltages at the load



2.1 Triplen Harmonics

- Triplen harmonics are the odd multiples of the third harmonic (h 3, 9, 15, 21,)
- Triplen harmonics deserve special consideration because the system response is often considerably different for triplens than for the rest of the harmonics
- Triplens become an important issue for grounded-wye systems with current flowing on the neutral
- Two typical problems are overloading the neutral and telephone interferenc

2.2 Harmonics Vs Transients

- Transient waveforms exhibit the high frequencies only, after there has been an abrupt change in the power system. These frequencies have no relation to the system fundamental frequency. Harmonics, by definition, occur in the steady state and are integer multiples of the fundamental frequency
- Transients are usually dissipated within a few cycles. The waveform distortion that produces the harmonics is present continually, or at least for several seconds
- Transients are associated with changes in the system such as switching of a capacitor bank. Harmonics are associated with the continuing operation of a load.

2.3 Mechanism of Harmonic Generation I

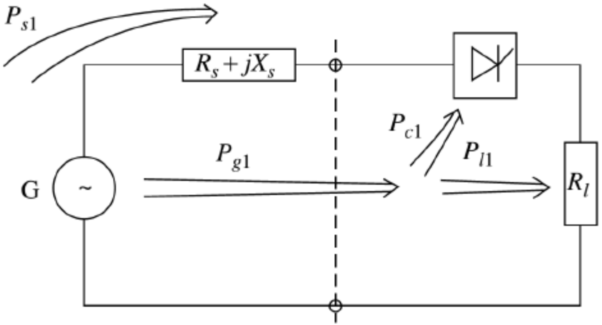


Figure 1 : Power flow at the fundamental frequency

2.3 Mechanism of Harmonic Generation II

- Generator (G) feeds a purely resistive load R_l through a line with impedance $(R_s + jX_s)$ and a static converter
- Generator supplies power (P_{g1}) to the point of common coupling (PCC) of the load with other consumers
  - P_{l1}: Power transferred to load
  - P_{c1}: Converted to power at different frequencies in the static converter
  - P_{s1}: Power loss at fundamental frequency in the resistance of the transmissio and generation system (R_{s1})

2.3 Mechanism of Harmonic Generation III

- Harmonic Power Flow

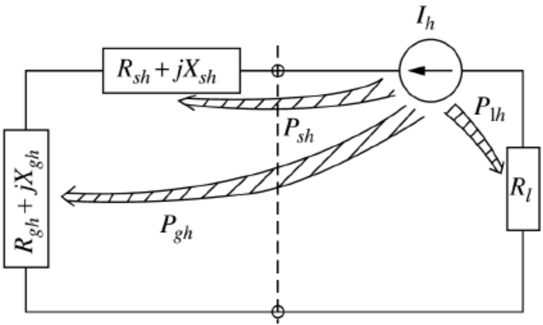
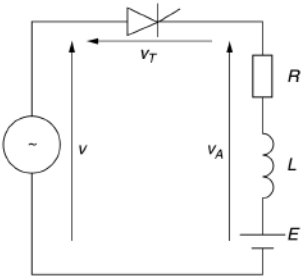


Figure 2 : Harmonic power flow

2.3 Mechanism of Harmonic Generation IV

- As the internal voltage of the generator has been assumed perfectly sinusoidal, the generator only supplies power at the fundamental frequency $\rightarrow$ Generators emf is short-circuited in figure
- AC line and generator are represented by their harmonic impedances $(R_{sh} + jX_{sh})$ and $(R_{gh} + jX_{gh})$
- In diagram the static converter appears as a source of harmonic currents
- A small proportion of fundamental power (P_{c1}) is transformed into harmonic power (P_h)
- $P_h = P_{sh} + P_{gh} + P_{lh}$
  - P_{sh}: Harmonic power consumed in the system resistance (R_{sh})
  - P_{gh}: Harmonic power consumed in the generator resistance (R_{gh})
  - P_{lh}: Harmonic power consumed in the load resistance (R_{lh})
- Total power loss consists of the fundamental frequency component (P_{s1}) and the harmonic power caused by the presence of the converter $(P_{sh} + P_{gh} + P_{lh})$

2.3 Mechanism of Harmonic Generation V



- V: Source of sinusoidal voltage
- E: Constant e.m.f. of a battery with negligible internal resistance
- Thyristor turns ON at $\omega t = \alpha$ and OFF at $\omega t = \beta$
- Thyristor voltage drop during conduction is neglected

2.3 Mechanism of Harmonic Generation VI

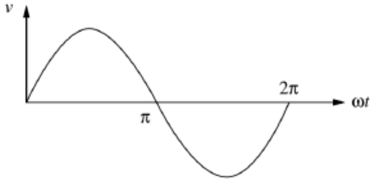


Figure 3 : Voltage source waveform

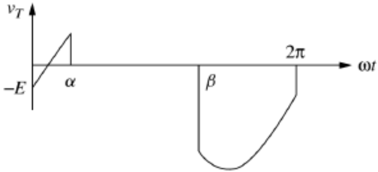


Figure 4 : Voltage across the thyristor

2.3 Mechanism of Harmonic Generation VII

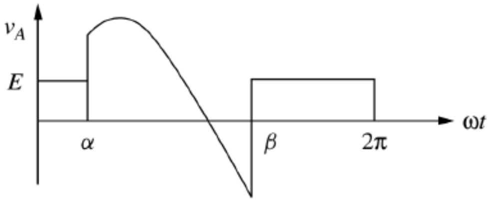


Figure 5 : Load voltage waveform

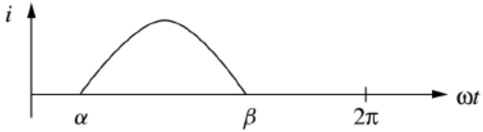


Figure 6 : Current waveform

2.3 Mechanism of Harmonic Generation VIII

- Load voltage V_A can be replaced by the three components derived from the Fourier transformation

$$V_A = V_{A1} + V_{Ah} + V_{A0}$$

  - Fundamental component

$$v_{A1} = \sqrt{2} V_{A1} \sin(\omega t + \theta_1)$$

  - Harmonic content

$$V_{Ah} = \sum_{h=2}^{n} \sqrt{2} V_{Ah} \sin(h\omega t + \theta_h)$$

  - DC component

2.3 Mechanism of Harmonic Generation IX

$$V_{A0} = \frac{1}{T}\int_0^T V_A \, dt = V_{dc}$$

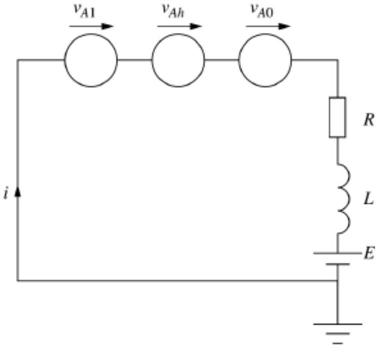


Figure 7 : Load voltage components of the circuit

2.3 Mechanism of Harmonic Generation X

- Similarly current can be replaced by the three components

$$i_1 = \sqrt{2} I_1 \sin(\omega t + \xi_1)$$

$$i_h = \sum_{h=2}^{n} \sqrt{2} I_h \sin(h\omega t + \xi_h)$$

$$I_0 = \frac{V_{dc} - E}{R}$$

- Active power generated by the source

2.3 Mechanism of Harmonic Generation XI

$$P_G = V_1 I_1 \cos\xi_1$$

- Power supplied to the load

$$P_A = P_{A1} + P_{Ah} + P_{A0}$$

  - Fundamental component of power supplied to the load

$$P_{A1} = V_{A1} I_1 \cos(\theta_1 - \xi_1) = I_1^2 R$$

  - Harmonics power supplied to the load

$$P_{Ah} = \sum_{h=2}^{n} V_{Ah} I_h \cos(\theta_h - \xi_h) = \sum_{h=2}^{n} I_h^2 R$$

2.3 Mechanism of Harmonic Generation XII

- DC power

$$P_{A0} = V_{dc} I_0 = E I_0 + I_0^2 R$$

- Thyristor behaves like an energy converter → the ideal voltage source combines with the fundamental component of the current waveform to generate the total power PG
- $P_G = P_A$ since thyristor losses have been ignored

$$P_G = P_A = I^2 R + E I_0$$

- Current root mean square (r.m.s.) value

$$I = \sqrt{I_0^2 + I_1^2 + \sum_{h=2}^{n} I_h^2}$$

3. Harmonic Indices

Harmonic Indices

1. Total Harmonic Distortion (THD)
2. Total Demand Distortion (TDD)
3. Telephone Interference Factor (TIF)
4. Distortion Index (DIN)
5. C-Message Weighted Index

3.1 Total Harmonic Distortion (THD) I

- Commonly used harmonic index which relates to the voltage waveform
- **Effective value of the harmonic components of a distorted waveform**
- **Root mean square (r.m.s.) of the harmonics expressed as a percentage of the fundamental component**

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

- *Vn*: Single frequency r.m.s. voltage at harmonic n
- N: Maximum harmonic order to be considered
- V_1: Fundamental line to neutral r.m.s. voltage

3.1 Total Harmonic Distortion (THD) II

- For most applications, it is sufficient to consider the harmonic range from the 2nd to the 25th, but most standards specify up to the 50th
- THD is the potential heating value of the harmonics relative to the fundamental

$$THD = \frac{\sqrt{\sum_{n=2}^{N} (V_n)^2}}{V_1}$$

- THD gives the idea about how much additional heat will be produced when a distorted voltage is applied across a resistive load

3.1 Total Harmonic Distortion (THD) III

$$V_{rms} = \sqrt{\sum_{n=1}^{N} (V_n)^2} = V_1\sqrt{1 + THD^2}$$

3.1 Total Harmonic Distortion (THD) IV

$$V_{rms} = \sqrt{V_1^2 + V_2^2 + V_3^2 + \ldots..}$$

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + \ldots.}}{V_1}$$

$$THD^2 = \frac{V_2^2 + V_3^2 + \ldots.}{V_1^2}$$

$$1 + THD^2 = \frac{V_2^2 + V_3^2 + \ldots}{V_1^2} + 1 = \frac{V_1^2 + V_2^2 + V_3^2 + \ldots}{V_1^2}$$

$$V_1\sqrt{1 + THD^2} = \frac{\sqrt{V_1^2 + V_2^2 + V_3^2 + \ldots}}{} = V_{rms}$$

$\Longrightarrow$

$$V_{rms} = V_1\sqrt{1 + THD^2}$$

3.1 Total Harmonic Distortion (THD) V

Advantages

- Quick measure of distortion
- Can be easily calculated

Disadvantages

- Does not provide amplitude information
- Detailed information about the harmonic spectrum is not available

3.2 Total Demand Distortion (TDD) I

- Current levels can be characterised by a THD value but it can be misleading **when the fundamental load current is low**
- High THD value for input current may not be of significant concern if the load is light, since the magnitude of the harmonic current is low, even though its relative distortion to the fundamental frequency is high. To avoid such ambiguity a total demand distortion (TDD) factor is used

$$\mathrm{TDD} = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{I_R}$$

3.2 Total Demand Distortion (TDD) II

- Since electrical power supply systems are designed to withstand the rated or maximum load current, the impact of current distortion on the system will be more realistic if the assessment is based on the designed values, rather than on a reference that fluctuates with the load levels
- TDD is similar to THD except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current
- Distortion is expressed as a percentage of some rated or maximum value(eg. load current magnitude)

$$TDD = \frac{\sqrt{\sum_{n=2}^{N} (I_n)^2}}{I_{rated}}$$

Problem I

Q)A three-phase purely resistive load of 50 kW rating is supplied directly from a 50 Hz three-phase 415 V (phase-to-phase) bus. At the time of measuring, the load was consuming 41.5 kW and the voltage waveform contained 11 V of negative-sequence fifth harmonic and 8 V of positive-sequence seventh harmonic. Assuming that the load resistance varies with the square root of the harmonic order h,calculate the THD and TDD indices at the point of connection.

$$R_1 = \frac{V_1^2}{P_1} = \frac{(415/\sqrt{3})^2}{(41\,500/3)} = 4.15\ \Omega$$

$$R_5 = R_1\sqrt{h} = 4.15\sqrt{5}\ \Omega$$

$$R_7 = R_1\sqrt{h} = 4.15\sqrt{7}\ \Omega$$

Problem II

$$I_r = \frac{50}{415\sqrt{3}} = 69.56 \text{ A}$$

$$I_1 = \frac{(V_1/\sqrt{3})}{R_1} = \frac{(415/\sqrt{3})}{4.15} = 57.735 \text{ A}$$

$$I_5 = \frac{(V_5/\sqrt{3})}{R_5} = \frac{(11/\sqrt{3})}{(4.15\sqrt{5})} = 0.6844 \text{ A}$$

$$I_7 = \frac{(V_7/\sqrt{3})}{R_7} = \frac{(8/\sqrt{3})}{(4.15\sqrt{7})} = 0.4207 \text{ A}$$

Problem III

$$\text{THD}v = \frac{\sqrt{(V_5^2 + V_7^2)}}{V_1} = \frac{\sqrt{(11^2 + 8^2)}}{415} = 0.03276$$

$$\text{THD}i = \frac{\sqrt{(I_5^2 + I_7^2)}}{I_1} = \frac{\sqrt{(0.68438)^2 + (0.42066)^2}}{57.735} = 0.01391$$

$$\text{TDD}i = \frac{\sqrt{(I_5^2 + I_7^2)}}{I_r} = \frac{\sqrt{(0.68438)^2 + (0.42066)^2}}{69.56} = 0.01155$$

3.3 Telephone Interference Factor (TIF)

- TIF is the measure of telephone noise as a result of harmonics from the power system in the proximity
- TIF is defined in terms of Fourier Series Coefficients
- Root of the sum of squares is weighted using factors(weights) that reflect response of human ear

$$TIF = \frac{\sqrt{\sum_{n=1}^{N} (W_n V_n)^2}}{\sqrt{\sum_{n=1}^{N} (V_n)^2}}$$

- W_n are the TIF weighting factors obtained by physiological and audio tests
- It gives the idea about how current in a power circuit induces voltage in an adjacent communication system

3.4 Distortion Index (DIN) I

- Distortion Index

$$DIN = \frac{\sqrt{\sum_{n=2}^{N} (V_n)^2}}{\sqrt{\sum_{n=1}^{N} (V_n)^2}} = \frac{THD}{\sqrt{THD^2 + 1}}$$

3.4 Distortion Index (DIN) II

$$DIN = \frac{\sqrt{V_2^2 + V_3^2 + ...}}{V}$$

$$= \frac{\sqrt{V_2^2 + V_3^2 + ...}}{\sqrt{V_1^2 + V_2^2 + V_3^2 + ...}}$$

$$= \frac{\left(\sqrt{V_2^2 + V_3^2 + ...}\right) / V_1}{\left(\sqrt{V_1^2 + V_2^2 + V_3^2 + ...}\right) / V_1}$$

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

3.5 C-Message Weighted Index

- C-Message weighted index is very similar to TIF except that the weights C_n are used instead of W_n
- C_n are determined from listening tests to indicate the relative annoyance or speech impairment by an interfacing signal of frequency as heard through a "500-type" telephone set

$$CMWI = \frac{\sqrt{\sum_{n=1}^{N} (C_n V_n)^2}}{\sqrt{\sum_{n=1}^{N} (V_n)^2}}$$

4. Power Quality Costs Evaluation

- Economic Impacts of Power Quality
- PQ Cost Categories

4.1 Economic Impacts of Power Quality

Categories

- Direct Economic Impacts
- Indirect Economic Impacts

4.1.1 Direct Economic Impacts

- Loss of production
- Unrecoverable down time and resources (e.g. raw material, labour, capital)
- Process restart costs
- Spoilage of (semi-) finished production
- Equipment damage
- Direct costs associated with human health and safety etc.

4.1.2 Indirect Economic Impacts

- Cost to an organization of revenue / income being postponed
- Financial cost of loss of market share
- Cost restoring brand equity

4.1.3 Social Economic Impacts

- Uncomfortable building temperatures as related to reduction in efficient working/health and safety
- Personal injury or fear, also as related to reduction in efficiency, health and safety
- Evacuating neighbouring residential buildings as an indirect social impact in the event of failure of industrial safety, as it relates to the additional costs incurred by an organization that has to carry out these measures

4.2 PQ Cost Categories

- Staff Cost
- Work in Progress
- Equipment Malfunctioning
- Equipment Damage
- Other Costs
- Specific Costs
- Savings

4.2.1 Staff Cost

- Personnel rendered unproductive through disrupted Workflow/process
- Can be either calculated by either:
  - Multiplying the total number of person-hours of staff who are unable to work and average person-hour rate of staff who are unable to work
    OR
  - by estimating the percentage of plant activity which was stopped and multiplying by the idle time of such stoppage
- This value is then compared to the total production time of the plant

4.2.2 Work in Progress

This category includes:

- Cost of raw materials involved in the production of services which was inevitably lost
- Labour involved in the production of services which was inevitably lost
- Labour needed to makeup for lost production, sales or services (such as overtime pay, extra shifts etc.)

4.2.3 Equipment Malfunctioning

- If the equipment is affected, the consequence can be the slowing down of the company's activity or part of the production running out of specification.
- In this case the percentage of such slowdown is calculated taking into account additional idle time, the value of products running out of specification and /or the value of insufficient quality products.

4.2.4 Equipment Damage

- If the operating equipment is affected, the consequence can be damage to it, the shortening of its lifetime, components wearing out permanently and the need for additional maintenance or repair. This cost component includes
  - Cost of equipment being damaged (complete or scrapped) or the cost of its repair . This category typically includes transformers, capacitors, motors, cables, contactors, relays, protective equipment, electronic equipme and lighting bulbs.
  - Cost to run and/or rent backup equipment if necessary
  - Additional maintenance costs because of excessive equipment components wearing out. Usually this includes bearings and, if a machine is unbalanced due to distorted power, insulating, disconnecting any protective/signalling components and resets or reinstallation

4.2.5 Other Costs

- This category usually includes
  - Penalties due to contract non-delivery or late delivery
  - Environmental fines/penalties
  - Cost of evacuation of personnel and equipment (this can also include ensuring the safety of external communities)
  - Cost of personnel injury (including the on-costs incurred through inability to work)
  - Increased insurance rates (equipment, personnel, corporate liability)
  - Compensation paid out

4.2.6 Specific Costs

- For some disturbances, some specific cost categories can be identified.
- By operating electrical equipment in a non-linear environment, additional eddy currents, heat dissipation and consequent energy loss may be experienced.
- Other possible problems which may arise from harmonic pollution refer to the correct measurement of electric energy consumption and problems related to the utility imposing penalties for harmonic pollution of the surrounding distribution network.
- Flicker can cause migraine and can be responsible for so-called sick building syndrome, which reduces personnel productivity. This can be defined foe example as a comparison of staff error rates between flicker-free and flicker environments.

4.2.7 Savings

- To make the total calculation fair and complete, savings also resulting from PQ disturbances are calculated. These usually includes
  - Savings from unused materials or inventory
  - Savings from wages that were not paid
  - Savings on the energy bill
- Savings are deducted from the gross PQ cost to obtain the cost of PQ for the plant.

5. Harmonic Sources

- Harmonic Sources
  - Harmonic Sources from **Commercial Loads**
    - Single Phase Power Supplies
    - Fluorescent Lighting
    - Adjustable Speed Drives
  - Harmonic Sources from **Industrial Loads**
    - Three Phase Power Converters
    - Arcing Devices
    - Saturable Devices

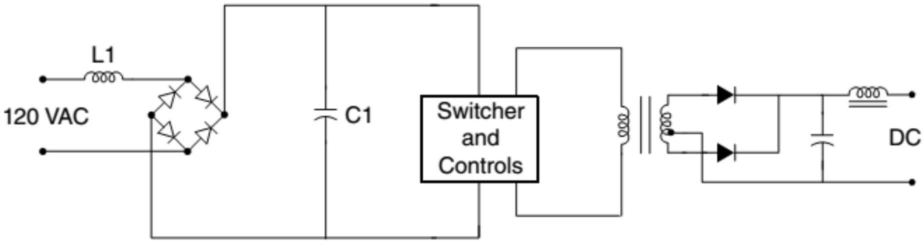
5.1 Harmonic Sources from Commercial Loads

- Commercial facilities: office complexes, department stores, hospitals, and Internet data centres
- Large number of small harmonic-producing loads
  - Fluorescent lighting with electronic ballasts
  - Adjustable-speed drives for the heating, ventilation, and air conditioning (HVAC) loads
  - Elevator drives
  - Sensitive electronic equipment supplied by single-phase switch-mode power supplies
- Voltage distortion levels depend on both the circuit impedances and the overall harmonic current distortion

5.1.1 Single-phase Power Supplies I

- Advancements in semiconductor device technology
- Power electronic devices
  - Adjustable-speed motor drives
  - Electronic power supplies
  - DC motor drives
  - Battery chargers
  - Electronic ballasts
- DC power for modern electronic & microprocessor-based office equipment is commonly derived from single phase full wave diode bridge rectifiers
- **Switch mode power supplies**
  - DC to DC conversion techniques to achieve a smooth dc output
  - Small and lightweight
  - Compact size
  - Efficient operation
  - Lack of need for a transformer

5.1.1 Single-phase Power Supplies II



- No large ac side inductance → input current to the power supply comes in very short pulses as the capacitor C_1 regains its charge on each half cycle
- Very high third harmonic content in the current

5.1.1 Single-phase Power Supplies III

- Third harmonic current components are additive in the neutral of a three phase system → overloading of neutral conductors
- Transformer overheating due to a combination of harmonic content of the current, stray flux, and high neutral currents

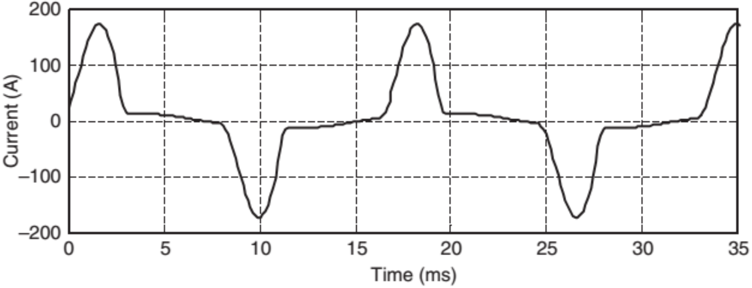


Figure 8 : SMPS current waveform

5.1.1 Single-phase Power Supplies IV

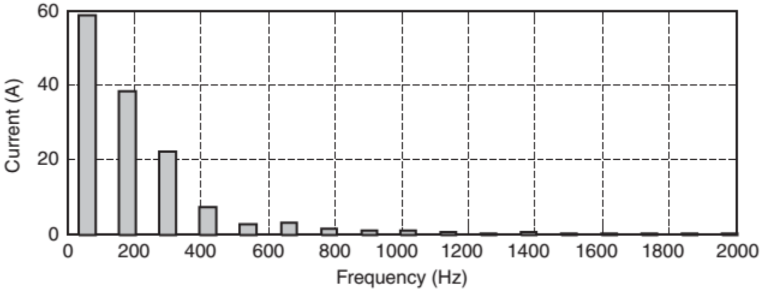


Figure 9 : SMPS current harmonic spectrum

5.1.2 Fluorescent Lighting I

- Lighting typically accounts for 40 to 60 percent of a commercial building load
- Fluorescent lights are a popular choice for energy savings
- Fluorescent lights are **discharge lamps**
  - Require a ballast to provide a high initial voltage to initiate the discharge for the electric current to flow between two electrodes in the fluorescent tube
  - Once th discharge is established, the voltage decreases as the arc current increases
  - Its a short circuit between the two electrodes, and the ballast has to quickly reduce the current to a level to maintain the specified lumen output. Thus, a ballast is also a current limiting device in lighting applications

5.1.2 Fluorescent Lighting II

Types of ballasts

1. **Magnetic ballasts**
   - Made up of an iron-core transformer with a capacitor encased in an insulating material
   - Single magnetic ballast can drive one or two fluorescent lamps
   - Operates at the line fundamental frequency
   - Iron core magnetic ballast contributes additional heat losses
   - Inefficient
2. **Electronic ballasts**
   - Employs a switch mode type power supply to convert the incoming fundamental frequency voltage to a much higher frequency voltage typically in the range of 25 to 40 kHz
     - Small inductor is sufficient to limit arc current
     - High frequency eliminates or greatly reduces the 100 or 120 Hz flicker associated with an iron-core magnetic ballast
   - Single electronic ballast typically can drive up to four fluorescent lamps

5.1.2 Fluorescent Lighting III

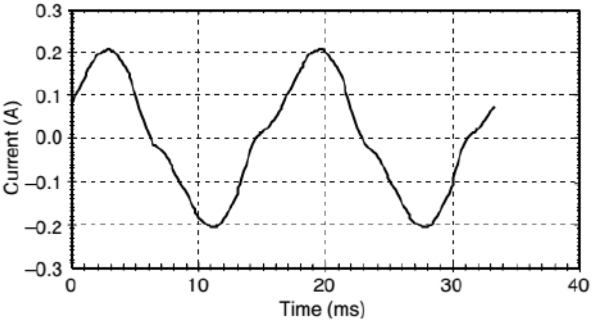


Figure 10 : Fluorescent lamp with magnetic ballast current waveform

5.1.2 Fluorescent Lighting IV

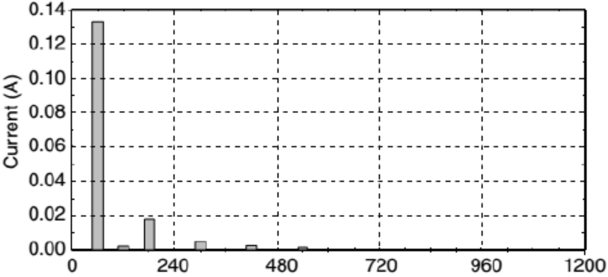


Figure 11 : Fluorescent lamp with magnetic ballast current harmonic spectrum

- Magnetic ballasts are sources of harmonics themselves since the main harmonic distortion comes from the behaviour of the arc
- In figure, current THD is a moderate 15 percent

5.1.2 Fluorescent Lighting V

- Electronic ballasts, which employ switch mode power supplies, can produce double or triple the standard magnetic ballast harmonic output

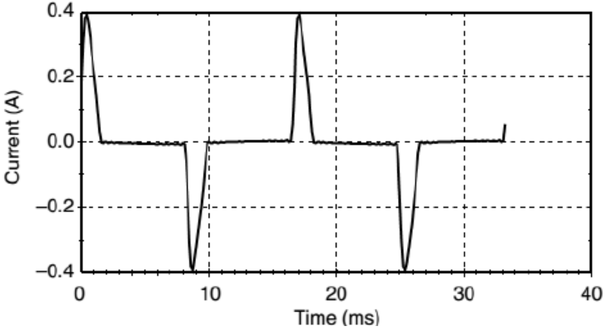


Figure 12 : Fluorescent lamp with electronic ballast current waveform

5.1.2 Fluorescent Lighting VI

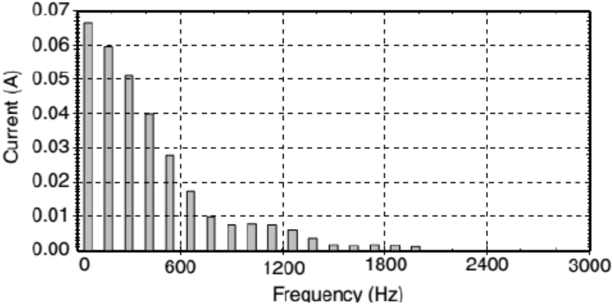


Figure 13 : Fluorescent lamp with magnetic ballast current harmonic spectrum

- Fluorescent lamp with an electronic ballast that has a current THD of 144 percent

5.1.2 Fluorescent Lighting VII

- A current THD greater than 32 percent is considered excessive according to ANSI C82.11-1993, High Frequency Fluorescent Lamp Ballasts
- Electronic ballasts are equipped with **passive filters** to reduce the input current harmonic distortion to less than 20 percent
- Delta connected supply transformer reduces the amount of triplen-harmonic currents flowing onto the power supply system

5.1.3 Adjustable Speed Drives

- Commonly used in elevator motors and in pumps and fans in HVAC systems
- ASD consists of an **electronic power converter** that converts AC voltage and frequency into variable voltage and frequency
- Variable voltage and frequency allows the ASD to control motor speed

5.2 Harmonic Sources from Industrial Loads

- Nonlinear industrial loads having relatively low power factor
  1. Three phase power converters
  2. Arcing devices
  3. Saturable devices
- Injects harmonic currents into the power system, causing harmonic distortion in the voltage
- Capacitor banks can be utilized to improve the power factor but it may give rise to resonance conditions within the facility
- Resonance conditions cause motor and transformer overheating, and misoperation of sensitive electronic equipment

5.2.1 Three-phase Power Converters I

- Three phase electronic power converters do not generate third harmonic currents
- Still they are significant sources of harmonics at their characteristic frequencies

Used in

1. DC Drives
2. AC Drives
   a. CSI type ASD
   b. VSI type ASD

5.2.1 Three-phase Power Converters II

1. DC drives

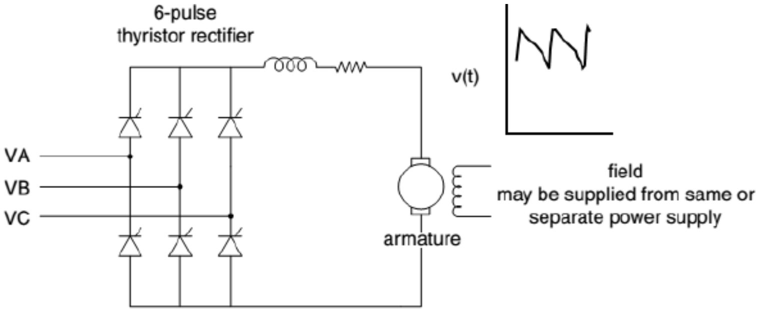


Figure 14 : Six pulse DC ASD

- Rectification
- Simple control systems
- Offers a wider speed range and higher starting torque

5.2.1 Three-phase Power Converters III

- Purchase and maintenance costs for dc motors are high
- Most DC drives use the six-pulse rectifier
  - Two largest harmonic currents for the six pulse drive are the fifth and seventh
- 12 pulse rectifier reduces thyristor current duties and reduces some of the larger ac current harmonics
  - Eliminates about 90 percent of the fifth and seventh harmonics
  - More costly
  - Transformer is generally required

5.2.1 Three-phase Power Converters IV

2. AC Drives

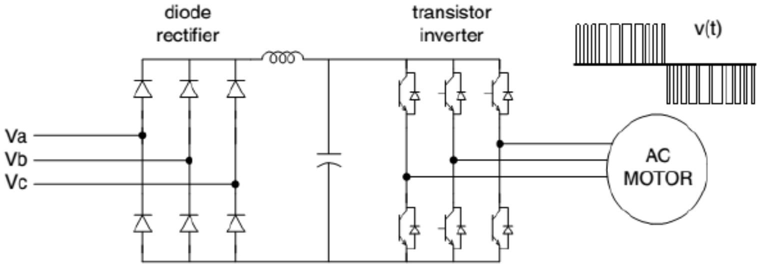


Figure 15 : PWM ASD

- Rectifier output is inverted to produce a variable frequency ac voltage for the motor

5.2.1 Three-phase Power Converters V

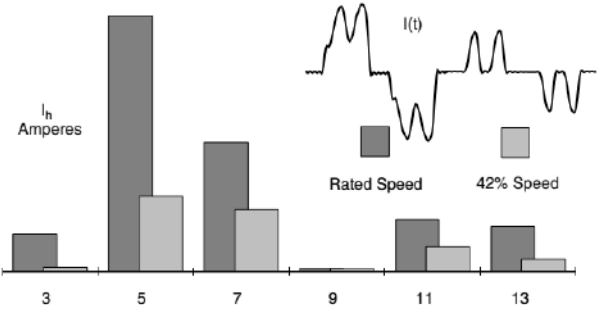


Figure 16 : Effect of PWM ASD speed on AC current harmonics

- Harmonic current distortion in adjustable speed drives is not constant
- Waveform changes significantly for different speed and torque values
- Drive injects considerably higher magnitude harmonic currents at rated speed

5.2.1 Three-phase Power Converters VI

a. CSI type ASD

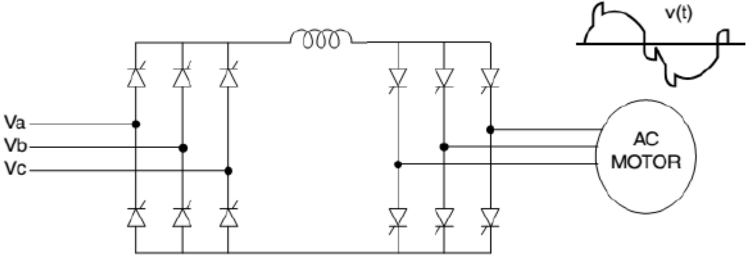


Figure 17 : CSI type ASD

- CSI requires a constant current input; hence, a series inductor is placed in the DC link
- CSI drives have good acceleration/deceleration characteristics

5.2.1 Three-phase Power Converters VII

- CSI requires a motor with a leading power factor (synchronous or induction with capacitors) or added control circuitry to commutate the inverter thyristors
- Thyristors in current source inverters must be protected against inductive voltage spikes, which increases the cost of this type of drive

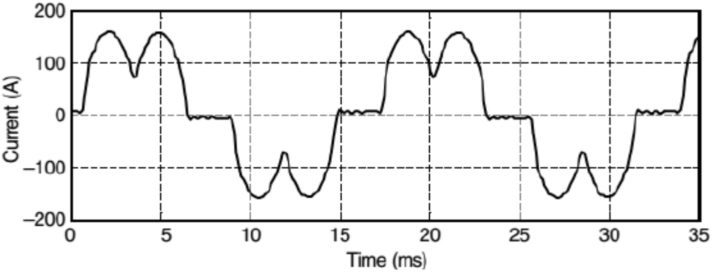


Figure 18 : Current waveform of CSI type ASD

5.2.1 Three-phase Power Converters VIII

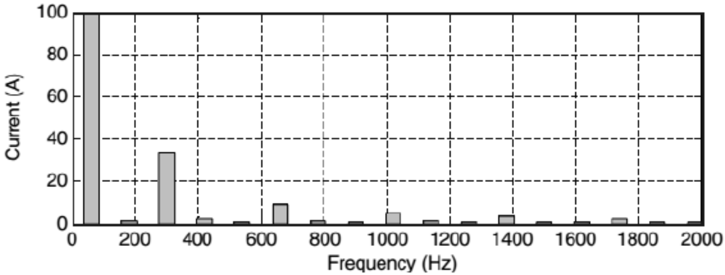


Figure 19 : Current harmonic spectrum of CSI type ASD

5.2.1 Three-phase Power Converters IX

b. VSI type ASD

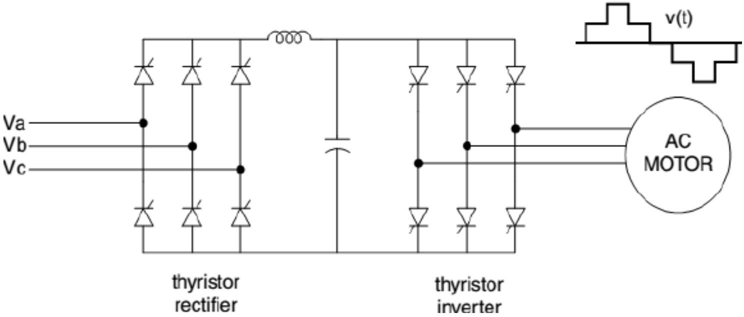


Figure 20 : VSI type ASD

- VSI requires a constant DC (ie, low ripple) voltage input to the inverter stage. This is achieved with a capacitor or LC filter in the DC link

5.2.1 Three-phase Power Converters X

- Uses PWM techniques to synthesize an AC waveform as a train of variable width dc pulses
- Inverter uses either SCRs, gate turn off (GTO) thyristors, or power transistors
- In PWM drives, it is not necessary to vary rectifier output voltage to control motor speed. This allows the rectifier thyristors to be replaced with diodes, and the thyristor control circuitry to be eliminated
- Very high power drives employ SCRs and 6 pulse or 12 pulse inverters
- VSI drives are limited to applications that do not require rapid changes in speed

5.2.1 Three-phase Power Converters XI

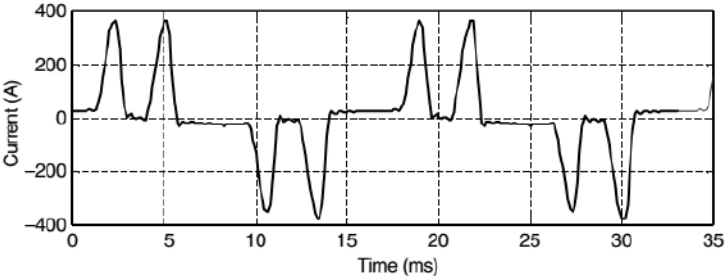


Figure 21 : Current waveform of PWM type ASD

5.2.1 Three-phase Power Converters XII

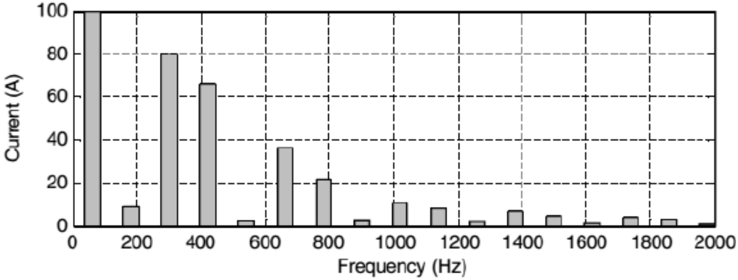


Figure 22 : Current harmonic spectrum of PWM type ASD

- It has much higher distortion levels
- Input to the PWM drive is designed like a three phase version of the switch mode power supply in computers
- Rectifie feeds directl5y from the AC bus to a large capacitor on the dc bus

5.2.1 Three-phase Power Converters XIII

- With little intentional inductance, the capacitor is charged in very short pulses, creating the distinctive rabbit ear AC side current waveform with very high distortion
- PWM drives are being applied for loads up to 500 hp

5.2.2 Arcing Devices I

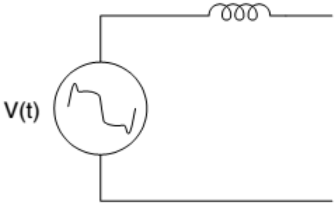


Figure 23 : Equivalent circuit for an arcing device

- Arc furnaces, Arc welders, Discharge type lighting (fluorescent, sodium vapour, mercury vapor) with magnetic ballasts
- Arc is a voltage clamp in series with a reactance that limits current to a reasonable value

5.2.2 Arcing Devices II

- Voltage-current characteristics of electric arcs are nonlinear
- Following arc ignition, the voltage decreases as the arc current increases, limited only by the impedance of the power system. This gives the arc the appearance of having a negative resistance for a portion of its operating cycle such as in fluorescent lighting applications.
- In electric arc furnace applications, the limiting impedance is primarily the furnace cable and leads with some contribution from the power system and furnace transformer.
- Currents in excess of 60,000 A are common
- Electric arc itself is actually best represented as a source of voltage harmonics.
- Arc magnitude is largely a function of the length of the arc
- Impedance of ballasts or furnace leads acts as a buffer so that the supply voltage is only moderately distorted

5.2.2 Arcing Devices III

- Arcing load appears to be a relatively stable harmonic current source
- Harmonic content of an arc furnace load and other arcing devices is similar to that of the magnetic ballast
- Three phase arcing devices can be arranged to cancel the triplen harmonics through the transformer connection

5.2.3 Saturable Devices I

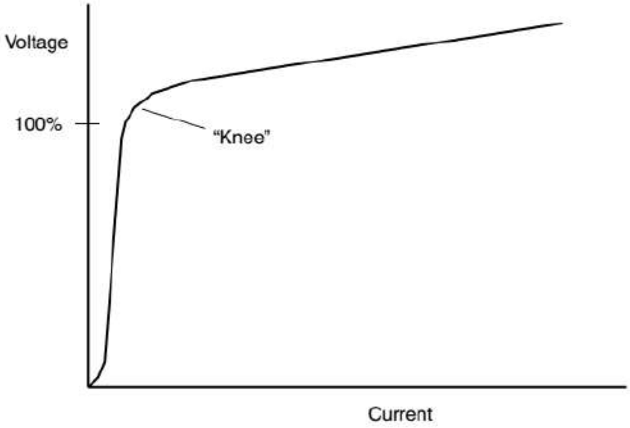


Figure 24 : Transformer magnetizing characteristic

5.2.3 Saturable Devices II

- Transformers and other electromagnetic devices with a steel core, including motors
- Harmonics are generated due to the nonlinear magnetizing characteristics of the steel
- Power transformers are designed to normally operate just below the "knee" point of the magnetizing saturation characteristic
- Operating flux density of a transformer is selected based on a complicated optimization of steel cost, no-load losses, noise, and numerous other factors
- A high-cost penalty on the no-load losses or noise will generally result in more steel in the core and a higher saturation curve that yields lower harmonic currents
- Transformer exciting current is rich in harmonics at normal operating voltage but it is typically less than 1 percent of rated full load current

5.2.3 Saturable Devices III

- Harmonic voltage distortion from transformer over excitation is generally only apparent under these light load conditions

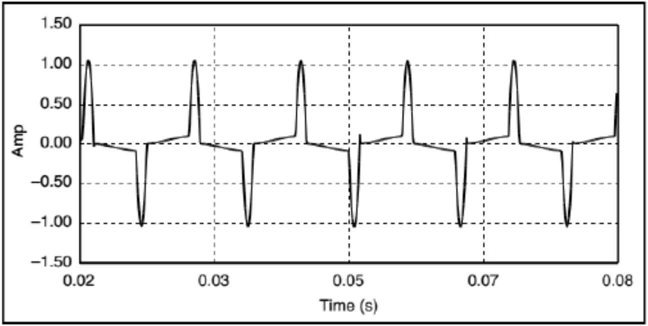


Figure 25 : Transformer magnetizing current

5.2.3 Saturable Devices IV

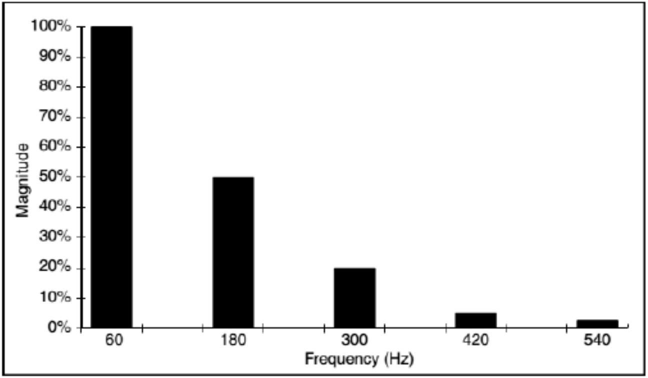


Figure 26 : Transformer magnetizing current harmonic spectrum

- Motors also exhibit some distortion in the current when overexcited

6. Effects of Power System Harmonics I

- Harmonic currents produced by nonlinear loads are injected back into the supply systems
  - Harmonic currents can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading
  - Harmonic currents can also cause interference with telecommunication lines and errors in power metering
- Heating Effects: The flow of harmonic current will lead to excess heating in all equipment. This heat can be expected to raise equipment temperature, and lead to reduced insulation life.

6. Effects of Power System Harmonics II

- Effects of Harmonics on
  - **RL Loads**
    - A significant portion of the system load has impedance characteristics consisting of passive resistive or RL networks
    - Incandescent lighting and resistance type heating
    - With constant fundamental voltage, the per unit increase in power due to voltage distortion for this class of loads is limited to the distortion factor squared
    - The incandescent lamp is one of the devices of this load group which is most sensitive to increased heating effects
    - Large distortion factors will significantly shorten the bulb life
  - **Arc Lamps**
    - Exhibit nonlinear resistance characteristics
    - When the resistance declines, the current increases
    - A ballast is required to place the lamp operating point in the safe region for all line voltage conditions throughout the range of various lamp characteristics

6. Effects of Power System Harmonics III

- During normal lamp operation, the ballast functions as a series current limiting element
- With inductive ballasts, the influence of voltage distortion would be roughly described by the distortion factor
- It would appear that modest distortion factor would not cause a large shift in the lamp operating point
- Capacitive ballasts must be viewed with some concern, as the ballast reactance would drop as the frequency of the harmonic rises

Motors and Generators

- Machines may be characterized as presenting relatively low impedance to harmonics as compared with the effective impedance seen by the fundamental voltage
- Additional heating losses
- Requires proper ventilation and cooling

6. Effects of Power System Harmonics IV

- **Transformers**
  - Current harmonics cause an increase in copper losses
  - Voltage harmonics cause stray flux losses, insulation stresses and possible resonances (at the harmonic frequency) between transformer windings and line capacitances
  - The overall effect of losses is an increase in the transformer heating
  - Transformer losses caused by both harmonic voltages and harmonic currents are frequency dependent
  - The losses increase with increasing frequency and, therefore, higher frequency harmonic components may be more important than lower frequency components in causing transformer heating
- **Capacitor Banks**
  - Additional heating and losses
- **Switchgear**
  - Harmonic components in the current waveform can affect the current interruption capability of the switchgear
  - The problem is that the harmonic components can result in high di/dt magnitudes at the current zeroes, making interruption more difficult

6. Effects of Power System Harmonics V

- **Fuses**
  - A significant level of harmonic current in a fuse causes excess heating, which can cause shifts in the time-current characteristic of the device
  - This can be particularly noticeable during low magnitude faults
- **Metering Devices**
  - Metering and instrumentation are affected by harmonic currents particularly if resonant conditions occur which cause high harmonic voltage on the circuits
  - Induction disc devices such as watt-hour meters and over-current relays are designed to monitor only fundamental current, but harmonic currents from non-linear loads and/or phase unbalances caused by harmonic distortion can cause erroneous operation of these devices
- **Protective Relays**
  - Harmonics affect relays in various ways leading to possible relay misoperation
  - Relays that depend on crest voltages and/or current or voltage zeroes for their operation are obviously affected by harmonic distortion on the wave

Also refer "Electrical Power System Quality" by R. C. Dugan (Section 5.10)

References

1. *"Electrical Power System Quality" - R. C. Dugan*
2. "*Power Quality*" - C. Sankaran
3. "*Power Quality*" - G. T. Heydt
4. "*Power System Harmonics*" - Jose Arillaga
5. "*Understanding Power Quality Problems*" - Math H. Bollen
6. "*Handbook of Power Quality*" - Angelo Baggini

Thank You

*for internal private circulation only

Power Quality

(EE-465)

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by

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Module 3: Overview I

1. Harmonic Analysis I

- Nonlinear devices → Harmonics in Voltage and Current
- Fourier postulated that **"any continuous function repetitive in an interval (T) can be represented by the summation of a DC component, a fundamental sinusoidal component and a series of higher-order sinusoidal components (called harmonics) at frequencies which are integer multiples of the fundamental frequency".**
- **Harmonic analysis**: Process of calculating the magnitudes and phases of the fundamental and higher-order harmonics of the periodic waveform → Fourier series
- Fourier series establishes a relationship between a time-domain function and that function in the frequency domain
- Fourier transform and its inverse are used to map any function in the interval from $-\infty$ to ∞, in either the time or frequency domain.

1. Harmonic Analysis II

- Fourier series represents the special case of the Fourier transform applied to a periodic signal
- Data is usually available in the form of a sampled time function, represented by a time series of amplitudes, separated by fixed time intervals of limited duration → Discrete Fourier transform (DFT) is used
- Implementation of DFT by means of the Fast Fourier transform (FFT)

2. Fourier Series and Coefficients I

- Fourier series of a periodic function x(t),

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

- This is the **frequency-domain representation** of the periodic function
  - a_0 : Average value of the function x(t)
  - a_n and b_n :Coefficients of the fourier series (ie, Rectangular components of the n_{th} harmonic

2. Fourier Series and Coefficients II

- n^{th} harmonic vector,

$$A_n \angle \phi_n = a_n + jb_n$$

$$A_n = \sqrt{a_n^2 + b_n^2}$$

$$\phi_n = \tan^{-1}\left(\frac{b_n}{a_n}\right)$$

- a_0 can be obtained by integrating from -T/2 to +T/2 (ie, over a period T)

2. Fourier Series and Coefficients III

$$\int_{-T/2}^{T/2} x(t)\mathrm{d}t = \int_{-T/2}^{T/2} \left[a_0 + \sum_{n=1}^{\infty} a_n \cos\left(\frac{2\pi nt}{T}\right) + b_n \sin\left(\frac{2\pi nt}{T}\right) \right] \mathrm{d}t$$

$$= a_0 \int_{-T/2}^{T/2} \mathrm{d}t + \sum_{n=1}^{\infty} \left[a_n \int_{-T/2}^{T/2} \cos\left(\frac{2\pi nt}{T}\right) \mathrm{d}t + b_n \int_{-T/2}^{T/2} \sin\left(\frac{2\pi nt}{T}\right) \mathrm{d}t \right]$$

$$a_0 \int_{-T/2}^{T/2} \mathrm{d}t = a_0\, T$$

2. Fourier Series and Coefficients IV

- Other integrals are zero
- Constant coefficient of the Fourier series (a_0),

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

- a_0 is the area under the curve of x(t)from -T/2 to +T/2, divided by the period of the waveform, T
- a_n coefficients can be determined by multiplying x(t) by $\cos(2\pi mt/T)$, where m is any fixed positive integer, and integrating between -T/2 and +T/2

2. Fourier Series and Coefficients V

$$\int_{-T/2}^{T/2} x(t)\cos\left(\frac{2\pi mt}{T}\right)\mathrm{d}t = \int_{-T/2}^{T/2}\left[a_0 + \sum_{n=1}^{\infty}\left[a_n\cos\left(\frac{2\pi nt}{T}\right) + b_n\sin\left(\frac{2\pi nt}{T}\right)\right]\right]\cos\left(\frac{2\pi mt}{T}\right)\mathrm{d}t$$

$$= a_0\int_{-T/2}^{T/2}\cos\left(\frac{2\pi mt}{T}\right)\mathrm{d}t + \sum_{n=1}^{\infty}\left[a_n\int_{-T/2}^{T/2}\cos\left(\frac{2\pi nt}{T}\right)\times\cos\left(\frac{2\pi mt}{T}\right)\mathrm{d}t + b_n\int_{-T/2}^{T/2}\sin\left(\frac{2\pi nt}{T}\right)\cos\left(\frac{2\pi mt}{T}\right)\mathrm{d}t\right]$$

2. Fourier Series and Coefficients VI

- First term on the right-hand side is zero, as are all the terms in b_n since $\sin(2\pi nt/T)$ and $\cos(2\pi mt/T)$ are orthogonal functions for all n and m
- Terms in a_n are zero, being orthogonal, unless m=n

$$\int_{-T/2}^{T/2} x(t)\cos\left(\frac{2\pi mt}{T}\right)\mathrm{d}t = a_n \int_{-T/2}^{T/2} \cos^2\left(\frac{2\pi nt}{T}\right)\mathrm{d}t$$
$$= \frac{a_n}{2}\int_{-T/2}^{T/2} \cos\left(\frac{4\pi nt}{T}\right)\mathrm{d}t + \frac{a_n}{2}\int_{-T/2}^{T/2} \mathrm{d}t$$

- First term on the right-hand side is zero while the second term equals $a_n T/2$
- Coefficients a_n,

2. Fourier Series and Coefficients VII

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

- Similarly coefficients b_n,

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

- Because of the periodicity of the integrands, the interval of integration can be taken more generally as t and t+T
- If the function x(t)is piecewise continuous (i.e. has a finite number of vertical jumps) in the interval of integration, the integrals exist and Fourier coefficients can be calculated.

2. Fourier Series and Coefficients VIII

- In terms of angular frequency,

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

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

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

- Periodic function x(t),

$$x(t) = a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega t) + b_n \sin(n\omega t)]$$

3. Fourier Transforms I

- Fourier analysis, when applied to a continuous, periodic signal in the time domain, yields a series of **discrete frequency components in the frequency domain**
- By allowing the integration period to extend to infinity, the spacing between the harmonic frequencies (ω) tends to zero and the Fourier coefficients c_n become a continuous function, such that

$$X(f) = \int_{-\infty}^{\infty} x(t)\mathrm{e}^{-\mathrm{j}2\pi f T}\,\mathrm{d}t$$

- X(f): **Forward transform**

3. Fourier Transforms II

- Expression for the time domain function x(t) in terms of X(f)

$$x(t) = \int_{-\infty}^{\infty} X(f) e^{j2\pi f T} \, df$$

- x(t): **Reverse or inverse transform**
- X(f) is known as the **spectral density function** of x(t) → **Fourier transform pair**

$$X(f) = \text{Re } X(f) + j \text{ Im } X(f)$$

3. Fourier Transforms III

- Real part of X(f)

$$\text{Re } X(f) = \frac{1}{2}[X(f) + X(-f)] = \int_{-\infty}^{\infty} x(t)\cos 2\pi f t \; dt$$

- Imaginary part of (f)

$$\text{Im } X(f) = \frac{1}{2}j[X(f) - X(-f)] = -\int_{-\infty}^{\infty} x(t)\sin 2\pi f T \; dt$$

- Amplitude spectrum of the frequency signal

$$|X(f)| = [(\text{Re } X(f))^2 + (\text{Im } X(f))^2]^{\frac{1}{2}}$$

3. Fourier Transforms IV

- Phase spectrum

$$\phi(f) = \tan^{-1}\left[\frac{\text{Im} \;\; X(f)}{\text{Re} \;\; X(f)}\right]$$

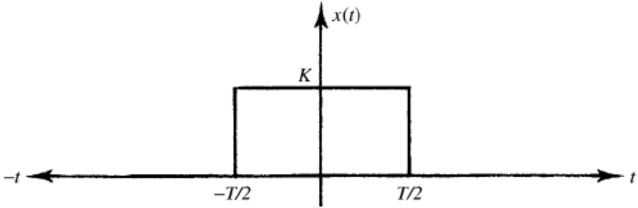
- Inverse Fourier transform in terms of the magnitude and phase spectra components,

$$x(t) = \int_{-\infty}^{\infty} |X(f)| \cos[2\pi f T - \phi(f)] \, \mathrm{d}f$$

3. Fourier Transforms V

1. Consider a rectangular function defined by

$$x(t) = K \text{ for } |t| \leq T/2$$
$$= 0 \text{ for } |t| > T/2$$



- Function is continuous over all t but is zero outside the limits (-T/2,T/2)
- Fourier transform

3. Fourier Transforms VI

$$X(f) = \int_{-\infty}^{\infty} x(t) e^{-j2\pi f T}\, dt$$

$$= \int_{-T/2}^{T/2} K e^{-j2\pi f T}\, dt$$

$$= \frac{-K}{\pi f} \cdot \frac{1}{2j} [e^{-j\pi f T} - e^{j\pi f T}]$$

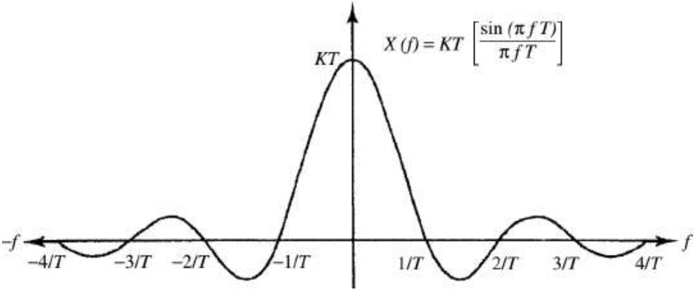
$$\sin\phi = \frac{1}{2j}(e^{j\phi} - e^{-j\phi})$$

$$X(f) = \frac{K}{\pi f} \sin(\pi f T)$$

$$= K T \left[\frac{\sin(\pi f T)}{\pi f T} \right]$$

- Term in brackets, is known as the **sinc function** and is shown in the figure

3. Fourier Transforms VII



- Function is **continuous**
- Function has zero value at the points f=n/T for n= ±1, ±2,...
- Side lobes decrease in magnitude as 1/T
- The interval 1/T is the **effective bandwidth** of the signal

4. Discrete Fourier Transform I

- In the case where the frequency domain spectrum and time domain function are sampled function (total of N samples per period), then Fourier transform pair made up of discrete components

$$X(f_k) = 1/N \sum_{n=0}^{N-1} x(t_n) e^{-j2\pi kn/N}$$

$$x(t_n) = \sum_{k=0}^{N-1} X(f_k) e^{j2\pi kn/N}$$

$$X(f_k) = 1/N \sum_{n=0}^{N-1} x(t_n) W^{kn}$$

4. Discrete Fourier Transform II

- $W = e^{-j2\pi/N}$
- Over all frequency components in matrix form

$$
\begin{bmatrix} X(f_0) \\ X(f_1) \\ \vdots \\ X(f_k) \\ \vdots \\ X(f_{N-1}) \end{bmatrix}
= 1/N
\begin{bmatrix}
1 & 1 & \cdots & 1 & \cdots & 1 \\
1 & W & \cdots & W^{k} & \cdots & W^{N-1} \\
\vdots & \vdots & \ddots & & & \vdots \\
1 & W^{k} & \cdots & W^{k^2} & \cdots & W^{k(N-1)} \\
\vdots & \vdots & & \vdots & \ddots & \vdots \\
1 & W^{N-1} & \cdots & W^{(N-1)k} & \cdots & W^{(N-1)^2}
\end{bmatrix}
\cdot
\begin{bmatrix} x(t_0) \\ x(t_1) \\ \vdots \\ x(t_k) \\ \vdots \\ x(t_{N-1}) \end{bmatrix}
$$

4. Discrete Fourier Transform III

- In general

$$[X(f_k)] = 1/N[W^{kn}][x(t_n)]$$

- [X(fk)]: Vector representing the N components of the function in the frequency domain
- [x(tn)]: Vector representing the N samples of the function in the time domain

4. Discrete Fourier Transform IV

- Calculation of the N frequency components from the N time samples requires a total of N^2 complex multiplications to implement in the above form
- Each element in the matrix $[W^{kn}]$ represents a unit vector with a clockwise rotation of $2n\pi/N(n = 0, 1, 2, ..., (N-1))$ introduced between successive components
- if N=8 then,

$$W = e^{-j2\pi/8}$$
$$= \cos\frac{\pi}{4} - j\sin\frac{\pi}{4}$$

4. Discrete Fourier Transform V

$$W^0 = -W^4 = 1$$
$$W^1 = -W^5 = (1/\sqrt{2} - j1/\sqrt{2})$$
$$W^2 = -W^6 = -j$$
$$W^3 = -W^7 = -(1/\sqrt{2} + j1/\sqrt{2})$$

- These can be thought of as unit vectors rotated through $\pm 0^o, \pm 45^o, \pm 90^o$ and $\pm 135^o$ respectively
- W^8 is a complete rotation $\implies W^8 = 1$

4. Discrete Fourier Transform VI

- Value of the elements of W^{kn} for kn > 8 can be obtained by subtracting full rotations, to leave only a fraction of a rotation, the values for which are shown above.
  - ie, if k=5 and n=6, then kn $= 30$ and $W^{30} = W^{3\times 8+6} = W^{6} = j$
  - There are only four unique absolute values of W^{kn}

4. Discrete Fourier Transform VII

- Matrix $[W^{kn}]$ for N=8,

1	1	1	1	1	1	1	1
1	W	$-j$	W^3	-1	$-W$	j	$-W^3$
1	$-j$	-1	j	1	$-j$	-1	j
1	W^3	j	W	-1	$-W^3$	$-j$	$-W$
1	-1	1	-1	1	-1	1	-1
1	$-W$	$-j$	$-W^3$	-1	W	j	W^3
1	j	-1	$-j$	1	j	-1	$-j$
1	$-W^3$	j	$-W$	-1	W^3	$-j$	W

4. Discrete Fourier Transform VIII

- DC component of the frequency spectrum, $X(f_0)$ obtained by the algebraic addition of all the time domain samples, divided by the number of samples, is the average value of all the samples
- Each time sample is weighted by a rotation dependent on the row number
  - For $X(f_1)$, each successive time sample is rotated by 1/N of a revolution
  - For$X(f_2)$, each sample is rotated by 2/N revolutions, and so on.

5. Fast Fourier Transform I

- For large values of N, the computational time and cost of executing the N^2 complex multiplications of the DFT can become prohibitive
- **Fast Fourier Transform (FFT)**
  - Calculation procedure which takes advantage of the similarity of many of the elements in the matrix $[W^{kn}]$
  - Uses only $N/2\ log_2 N$ multiplications
  - For $N = 1024$ $(ie,\ 2^{10})$
    - No of computations in DFT $= N^2 = 1024^2 = 1048576$
    - No of computations in FFT $= N/2\ log_2 N = (1024/2) log_2 1024 = 5120$
    - Saving in computation time by a factor of over 200

$$W^{N/2} = -W^0$$

$$W^{(N+2)/2} = -W^1$$

- Re-ordering the rows of the full matrix $[W^{kn}]$

5. Fast Fourier Transform II

- If rows are denoted by a binary representation, then the re-ordering is by bit reversal
- Case with N=8
  - Row 1 is (000)
  - Row 2 is (001) and Row 5 is (100) $\implies$ rows 2 and 5 are interchanged
  - Row 4 is (100) and 7 are represented as 011 and 110 and are also interchanged
  - Rows 1, 3, 6 and 8 have binary representations which are symmetrical with respect to bit reversal and hence remain unchanged

5. Fast Fourier Transform III

- Corresponding matrix is

1	1	1	1	1	1	1	1
1	-1	1	-1	1	-1	1	-1
1	$-j$	-1	j	1	$-j$	-1	j
1	j	-1	$-j$	1	j	-1	$-j$
1	W	$-j$	W^3	-1	$-W$	j	$-W^3$
1	$-W$	$-j$	$-W^3$	-1	W	j	W^3
1	W^3	j	W	-1	$-W^3$	$-j$	$-W$
1	$-W^3$	j	$-W$	-1	W^3	$-j$	W

5. Fast Fourier Transform IV

- New matrix can be separated into $log_2 8 (= 3)$ factor matrices
- Each factor matrix has only two non-zero elements per row, the first of which is unity

5. Fast Fourier Transform V

1	1						
1	-1						
		1	$-j$				
		1	j				
				1	W		
				1	$-W$		
						1	W^3
						1	$-W^3$

5. Fast Fourier Transform VI

1		1					
	1		1				
1		-1					
	1		-1				
				1		$-j$	
					1		$-j$
				1		j	
					1		j

5. Fast Fourier Transform VII

1				1			
	1				1		
		1				1	
			1				1
1				−1			
	1				−1		
		1				−1	
			1				−1

5. Fast Fourier Transform VIII

- Re-ordering of the $[W^{kn}]$ matrix results in a frequency spectrum which is also re-ordered
- To obtain the natural order of frequencies, it is necessary to reverse the previous bit reversal
- Using $N = 2^m$, it is possible to represent n and k by m bit binary numbers such that

$$n = n_{m-1}2^{m-1} + n_{m-2}2^{m-2} + \cdots + 4n_2 + 2n_1 + n_0$$
$$k = k_{m-1}2^{m-1} + k_{m-2}2^{m-2} + \cdots + 4k_2 + 2k_1 + k_0$$

where

$$n_i = 0, 1 \text{ and } k_i = 0, 1$$

5. Fast Fourier Transform IX

- For N=8,

$$n = 4n_2 + 2n_1 + n_0$$
$$k = 4k_2 + 2k_1 + k_0$$

- where n_2, n_1, n_0 and k_2, k_1, k_0 are binary bits (n_2, k_2 most significant and n_0, k_0 least significant)

$$X(k_2, k_1, k_0) = \sum_{n_2=0}^{1} \sum_{n_1=0}^{1} \sum_{n_0=0}^{1} \frac{1}{N} x(n_2, n_1, n_0) W$$

5. Fast Fourier Transform X

- Thus, computations can be performed in three independent stages

$$A_1(k_0, n_1, n_0) = \sum_{n_2=0}^{1} \frac{1}{N} x(n_2, n_1, n_0) W^{4k_0 n_2}$$

$$A_2(k_0, k_1, n_0) = \sum_{n_1=0}^{1} A_1(k_0, n_1, n_0) W^{2(k_0+2k_1)n_1}$$

$$A_3(k_0, k_1, k_2) = \sum_{n_0=0}^{1} A_2(k_0, k_1, n_0) W^{(k_0+2k_1+4k_2)n_0}$$

5. Fast Fourier Transform XI

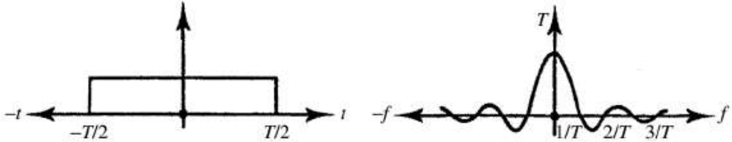
- A_3 coefficients contain the required X(k) coefficients but in reverse binary order
  - Order of A_3 in binary form is $k_0 k_1 k_2$
  - Order of X(k)in binary form is $k_2 k_1 k_0$

$$\begin{array}{ccccccc} & & \text{Binary} & & \text{Reversed} & & \\ A_3(3) & = & A_3(011) & = & X(110) & = & X(6) \\ A_3(4) & = & A_3(100) & = & X(001) & = & X(1) \\ A_3(5) & = & A_3(101) & = & X(101) & = & X(5) \end{array}$$

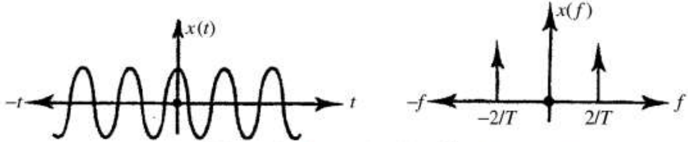
6. Window Function I

- **Windowing**
  - In any practical measurement of a time domain signal, it is normal to limit the time duration over which the signal is observed
  - The process of limiting the time duration of time domain signal is called as **windowing**
  - Useful for the measurement of non-stationary signals, which may be divided into short segments of a quasi-stationary nature with an implied infinite periodicity
- Effect of windowing can be seen by defining a time domain function which lies within finite time limits and outside of these, the function is zero
- eg. Rectangular window

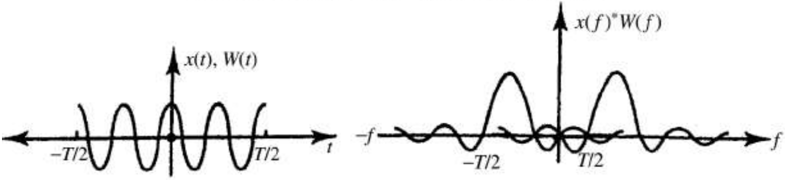
6. Window Function II



Rectangular window function and frequency spectrum



Periodic function x(t)=Acos(4πt/T) and frequency spectrum



Infinite periodic function viewed through a rectangular time window

6. Window Function III

- Signal x(t)is of fundamental frequency f_1 only, with a sampled frequency spectrum
- W(t) are integer multiples of f_1 and lie at the zero crossings of X(f)
- Application of a window function has the effect of multiplying each point of a time domain signal by the corresponding time point of the window function
- Within a rectangular window, the signal is just itself, but outside of this the signal is completely attenuated
- There is significant power in the frequencies of the side lobes about the fundamental frequency, which is not present in the infinite fundamental frequency waveform

6. Window Function IV

Picket Fence

- Combination of the DFT and window function produces a response equivalent to filtering the time domain signal through a series of filters with centre frequencies at integer multiples of $1/T$, where T is the sampling period
- Filter characteristic and the associated leakage are determined by the particular window function chosen
- Resulting spectrum can be considered as the true spectrum viewed through a picket fence with only frequencies at points corresponding to the gaps in the fence being visible
- When the signal being analysed is not one of these discrete, orthogonal frequencies, then, because of the non-ideal nature of the DFT filter, it will be seen by more than one such filter, but at a reduced level in each

6. Window Function V

- The effect can be reduced by adding a number of zeros, usually equivalent to the original record length, to the data to be analysed. This is called **zero padding**
- Effective increase in the sampling period T introduces extra DFT filters at points between the original filters. The bandwidth of the individual filters still depends upon the original sample period and is therefore unchanged

6. Window Function VI

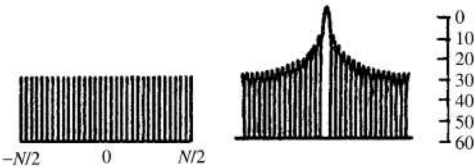
Choice of Window Function

- The objective in choosing a window is to obtain a **main-lobe width which is as narrow as possible**, so that it only includes the spectral component of interest, **with minimal side-lobe levels** to reduce the contribution from interfering spectral components
- These two specifications are interrelated for realisable windows and a compromise is made between main-lobe width compression and side-lobe level reduction

6. Window Function VII

- **Rectangular window function**

$$W(t) = \begin{cases} 1 & \text{for } -T/2 < t < T/2 \\ 0 & \text{otherwise} \end{cases}$$



  - Effective bandwidth is 1/T, where T is the window length
  - Side lobe levels are large (13 dB from the main lobe for the first side lobe)
  - Side lobe's rate of decay with frequency is slow (being 20 dB per decade)

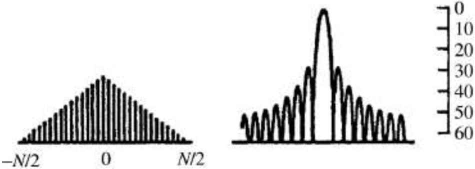
6. Window Function VIII

- $\implies$ When evaluating the fundamental component of a signal, interfering spectral components near to it will be weighted heavily, contributing greater interference to the fundamental component than for the other windows
- When the duration of the rectangular window is equal to an integer multiple of the period of a periodic signal, the rectangular window ideally results in **zero spectral leakage and high spectral resolution**
- When the rectangular window spans exactly one period, the zeros in the spectrum of the window coincide with all the harmonics excepting one. This results in no spectral leakage under ideal conditions
- The duration of the rectangular window can be matched through the use of a **phase-locked loop**

6. Window Function IX

- **Triangular window**

$$W(t) = \begin{cases} 1 + 2t/T & \text{for } -T/2 < t < 0 \\ 1 - 2t/T & \text{for } 0 < t < -T/2 \\ 0 & \text{otherwise} \end{cases}$$

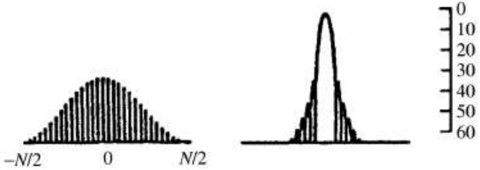


  - Amplitude of the multiplying window is reduced linearly to zero from the window centre
  - Reduction of the side-lobe at the expense of main-lobe width and a consequent reduction in frequency resolution

6. Window Function X

- **Cosine-squared** or **Hanning window**

$$W(t) = \frac{1}{2}\left(1 - \cos\frac{2\pi t}{T}\right) \quad \text{for } -\frac{T}{2} < t < \frac{T}{2}$$

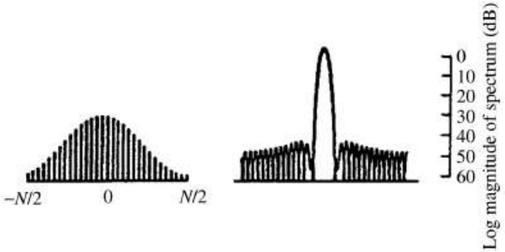


- Main lobe noise bandwidth is greater than that for the rectangular window, ie, 1.5T
- Highest side lobe is at 32 dB
- Side-lobe fall-off rate is 60 dB per decade
- Reduces the effect of spectral leakage

6. Window Function XI

- **Hamming window**

$$W(t) = 0.54 - 0.46\cos\frac{2\pi t}{T} \quad \text{for } -\frac{T}{2} < t < \frac{T}{2}$$



  - Hamming window is obtained by mounting the Hanning window on a small rectangular pedestal (but limiting the maximum of the function to unity)

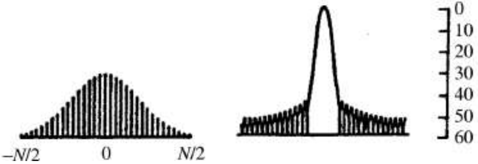
6. Window Function XII

- Second side lobe of the rectangular function coincides with the first side lobe of the Hanning function, and since these are in opposite phase, they can be scaled to cancel each other
- Highest side-lobe level is42 dB
- Remaining side lobes are dominated by the rectangular function and have a fall-off rate of 20 dB per decade
- Improvement in main-lobe noise bandwidth (to 1.4/T)

6. Window Function XIII

- **Gaussian function**

$$W(t) = \exp(-t^2/2\sigma^2)$$



  - Ideal window
  - Single main lobe
  - No side lobes
  - Gaussian function transforms the Fourier transform to another Gaussian function
  - On a decibel scale, its shape is that of an inverted parabola, with a characteristic which becomes successively steeper

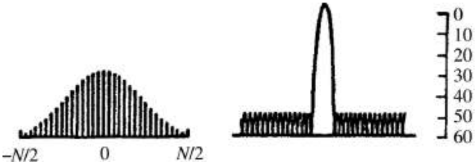
6. Window Function XIV

- Theoretically Gaussian function is defined between infinite time limits. For practical use, the function is truncated at three times the half-amplitude width, which is 7.06 times the standard deviation. As a consequence, side lobes are established in the power spectrum but these are of the order of44 dB down
- Main-lobe noise bandwidth is wider than the previous windows, ie, 1.9/T

6. Window Function XV

- **Dolph-Chebyshev function**

$$W(t) = \frac{(-1)^r \cos[N\cos^{-1}[\beta\cos(\pi r/N)]]}{\cosh[n\cosh^{-1}(\beta)]} \quad \text{for } 0 < r < N-1$$



  - where r is an integer, N is the number of discrete samples of the window function

$$\beta = \cosh\left[\frac{1}{N}\cosh^{-1}(10^{\alpha})\right]$$

6. Window Function XVI

$$\cosh^{-1} x = \begin{cases} \pi/2 - \tan^{-1}[x/\sqrt{(1-x^2)}] & \text{for } |x| < 1.0 \\ 1n[x + \sqrt{(x^2-1)}] & \text{for } |x| > 1.0 \end{cases}$$

- provides the narrowest possible main-lobe width for a given specified side-lobe level, which is constant on a decibel scale
- Side-lobe levels can be controlled
- With $\alpha = 4.0$, the side lobes are at 80 dB (0.01%) with respect to the main lobe

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Thank You

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Power Quality

(EE-465)

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by

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Module 4: Overview I

1. Power Quality Monitoring
2. Power Quality Monitoring Considerations
   - Objectives
   - Procedures for Performing Monitoring
     - Monitoring as part of a facility site survey
     - Determining what to monitor
     - Choosing monitoring locations
     - Options for permanent power quality monitoring equipment
     - Disturbance monitor connections
     - Setting monitor thresholds
     - Quantities and duration to measure
     - Finding the source of a disturbance
3. Power Quality Measurement Equipment
   - Types of Instruments
   - Wiring and Grounding Testers
   - Multimeters
   - Digital Cameras

Module 4: Overview II

- Oscilloscopes
- Disturbance Analyzer
- Harmonic Spectrum Analyzer
- Flicker Meters
- Smart Power Quality Monitors

1. Power Quality Monitoring

- Improves system-wide power quality performance
- Equipments sensitive to power disturbances
  - Computer networking facilities
  - Telecommunication facilities
  - Semiconductor and electronics manufacturing facilities
  - Biotechnology and pharmaceutical laboratories
  - Financial data-processing centres etc.
- Process of **gathering, analyzing, and interpreting** raw measurement data into useful information
  - Gathering data: carried out by continuous measurement of voltage and current over an extended period
  - Analysis and interpretation of data:
    - Manual
    - Automatic: signal processing and artificial intelligence systems to automatica analyze and interpret raw data into useful information with minimum human intervention

2. Power Quality Monitoring Considerations

Power Quality Monitoring Considerations

- Objectives
- Procedures for Performing Monitoring

2.1 Objectives I

1. To characterize system performance
   - To understand system performance and to match it with the needs of customers
   - System characterization is a **proactive approach**
   - To quickly identify problems
   - Can offer information to customers to help them match their sensitive equipments characteristics with realistic power quality characteristics
2. To characterize specific problems
   - To match the needs of specific customers
   - By modifying the power system or by installing equipment within the customers premises
   - Monitoring becomes essential to establish the benchmarks for the differentia service
   - To verify whether the utility achieves contracted levels of power quality

2.1 Objectives II

3. As part of predictive or just-in-time maintenance
   - Analysis of gathered data can provide information relating to specific equipment performance
     - Repetitive arcing fault from an underground cable may signify impending cable failure
     - Repetitive capacitor-switching restrikes may signify impending failure on the capacitor-switching device
   - Equipment maintenance can be quickly ordered to avoid catastrophic failure $\rightarrow$ prevents major power quality disturbances
   - **Comprehensive monitoring approach:** permanently installed monitoring system with automatic collection of information about steady-state power quality conditions and energy use as well as disturbances

2.2 Procedures for Performing Monitoring

- Monitoring as part of a facility site survey
- Determining what to monitor
- Choosing monitoring locations
- Options for permanent power quality monitoring equipment
  1. Digital fault recorders (DFRs)
  2. Smart relays and other IEDs
  3. Voltage recorders
  4. In-plant power monitors
  5. Special-purpose power quality monitors
  6. Revenue meters
- Disturbance monitor connections
- Setting monitor thresholds
- Quantities and duration to measure
- Finding the source of a disturbance

2.2.1 Monitoring as part of a facility site survey I

- Site surveys are performed to evaluate concerns for power quality and equipment performance throughout a facility
- Helps to obtain as much information as possible about the customer facility
- Discussions with customer
- Site surveys
  - Inspection of wiring and grounding concerns
  - Equipment connections
  - Voltage and current characteristics throughout the facility
  - Power quality monitoring along with infrared scans and visual inspections

2.2.1 Monitoring as part of a facility site survey II

- Information from site surveys
  1. Nature of the problem (data loss, nuisance trips, component failures, control system malfunctions, etc)
  2. Characteristics of the sensitive equipment experiencing problems (equipment design information or at least application guide information)
  3. The times at which problems occur
  4. Coincident problems or known operations (e.g., capacitor switching) that occur at the same time
  5. Possible sources of power quality variations within the facility (motor starting, capacitor switching, power electronic equipment operation, arcing equipment, etc.)
  6. Existing power conditioning equipment being used
  7. Electrical system data (one-line diagrams, transformer sizes and impedances load information, capacitor information, cable data, etc.)

2.2.1 Monitoring as part of a facility site survey III

- Site survey should verify the one-line diagrams, electrical system data, wiring and grounding integrity, load levels, and basic power quality characteristics
- Data forms can be used to organize the power quality monitoring results

2.2.2 Determining what to monitor

- Power quality issues
  - Very high frequency impulses caused by lightning strokes
  - Current chopping during circuit interruptions
  - Long-term over-voltages caused by a regulator tap switching problem
- Categories of power quality variations along with methods for characterizin the variations and the typical causes of the disturbances
- Characterization of
  - Transients: high-frequency sampling of the actual waveform
  - Voltage sags: plot of the rms voltage versus time
  - Outages: time duration
  - Harmonic distortion levels: steady-state sampling with results analysis of trends over time
  - Normal voltage variations: steady-state sampling with results analysis of trends over time

2.2.3 Choosing monitoring locations I

- Measurements from strategic locations can be used to determine character of the overall system
- Monitoring locations should be at actual customer service entrance locations
  - Can also characterize the customer load current variations and harmonic distortion levels
  - Reduced transducer costs
  - Provides indications of the origin of the disturbances
- Locate monitors as close as possible to the equipment affected by power quality variations (especially high frequency transients)

2.2.3 Choosing monitoring locations II

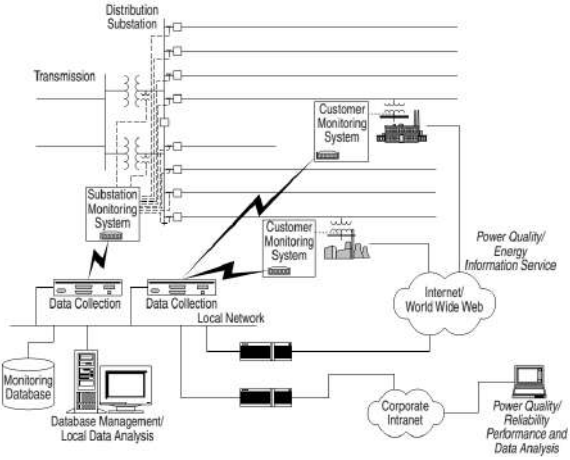


Figure 1 : Power quality monitoring concept

2.2.3 Choosing monitoring locations III

- A good approach is to monitor
  - At substation
    - Substation is the PCC for most rms voltage variation
    - Voltage sag experienced at the substation during a feeder fault is experienced by all the customers on other feeders supplied from the same substation bus
  - At selected customer service entrance locations
    - Customer equipment sensitivity and location

2.2.4 Options for permanent power quality monitoring equipment I

Equipment that have the capability to record power quality information:

1. **Digital Fault Recorders (DFRs)**
   - Used at substations
   - Trigger on fault events and record the voltage and current waveforms that characterize the event
   - Used for characterizing rms disturbances (eg: voltage sags during power system faults)
   - Periodic waveform capture for calculating harmonic distortion levels
2. **Smart Relays and Intelligent Electronic Devices (IEDs)**
   - Monitoring capability
   - Capability to record disturbances
   - Make the information available to an overall monitoring system controller
   - located on feeder circuits as well as at the substation

2.2.4 Options for permanent power quality monitoring equipment II

3. **Voltage Recorders**
   - Monitors steady state voltage variations on distribution systems
   - Provides the maximum, minimum, and average voltage within a specified sampling window (eg: 2 s)
   - Can characterize a voltage sag magnitude adequately
   - It will not provide the duration with a resolution less than 2 s
4. **In-plant Power Monitors**
   - Monitoring systems in industrial facilities
   - Located at the service entrance
   - Capabilities for wave shape capture for evaluation of harmonic distortion levels, voltage profiles for steady state rms variations and triggered wave shape captures for voltage sag conditions
   - Also have transient monitoring capabilities

2.2.4 Options for permanent power quality monitoring equipment III

5. **Special-purpose Power Quality Monitors**
   (eg: Power Quality Monitor used in EPRI DPQ project)
   - Designed to measure the full range of power quality variations
   - Monitoring of voltage and current on all three phases plus the neutral
   - 14 bit analog-to-digital (A/D) board provides a sampling rate of 256 points per cycle for voltage and 128 points per cycle for current
   - Allows the detection of voltage harmonics as high as the 100^{th} and current harmonics as high as the 50^{th}
   - Can record both triggered and sampled data
   - Triggering should be based upon rms thresholds for rms variations and on wave shape for transient variations
   - Simultaneous voltage and current monitoring with triggering of all channels during a disturbance is possible
   - Suitable for substations, feeder locations and customer service entrance locations

2.2.4 Options for permanent power quality monitoring equipment IV

6. **Revenue Meters**
   - Monitor the voltage and current
   - Recording of power quality information
   - Information from revenue meters can be incorporated into an overall power quality monitoring system

2.2.5 Disturbance monitor connections

- Recommended practice is to provide input power to the monitor from a circuit other than the circuit to be monitored
- Monitors may have input filters and/or surge suppressors
- Grounding of power disturbance monitor is essential
- Ground connection of the disturbance monitor and the power supply must be connected to earth ground
- Use insulated gloves while operating the instrument

2.2.6 Setting monitor thresholds

- Disturbance monitors are designed to detect conditions that are abnormal
- It is necessary to define the range of conditions that can be considered normal
- Collect a lot of disturbance data and then use the data collected to select appropriate thresholds for longer duration monitoring
- Thresholds are essentially fixed in the instruments, and algorithms may be adjusted internally based on the disturbances being recorded

2.2.7 Quantities and duration to measure

- Voltages provide information about the quality of power being delivered to a facility and characterize the transients and voltage sags that may affect customer equipment
- Current measurements are used to characterize the generation of harmonics by nonlinear loads on the system
- Duration of monitoring depends on the monitoring objectives
  - Voltage sags during remote faults on the utility system
  - Capacitor switching
  - Harmonic distortion and flicker problems

2.2.8 Finding the source of a disturbance

- Correlate the disturbance waveform with possible causes
- High frequency voltage variations
  - Limited to locations close to the source of the disturbance
  - Low voltage (600 V and below) wiring often damps out high frequency components very quickly due to circuit resistance
  - high frequency components will only appear when the monitor is located close to the source of the disturbance
- Power interruptions
  - Power interruptions close to the monitoring location will cause a very abrupt change in the voltage
  - Power interruptions remote from the monitoring location will result in a decaying voltage due to stored energy in rotating equipment and capacitors
- Harmonic voltage distortion
  - Highest harmonic voltage distortion levels will occur close to capacitors that are causing resonance problems

3. Power Quality Measurement Equipment I

- Power quality phenomena include
  - A wide range of frequencies → very fast transient overvoltages (**microsecond** time frame) to long-duration outages (**hours or days** time frame)
  - **Steady-state phenomena**, such as harmonic distortion, and intermittent phenomena, such as voltage flicker
- Development of standard measurement procedures and equipment
- More functions that can be performed with a single instrument is preferred

3.1 Types of Instruments I

- Basic categories of instruments which measure steady-state signals or disturbances on the power system directly are
  1. Wiring and grounding test devices
  2. Multimeters
  3. Oscilloscopes
  4. Disturbance analyzers
  5. Harmonic analyzers and spectrum analyzers
  6. Combination disturbance and harmonic analyzers
  7. Flicker meters
  8. Energy monitors

3.1 Types of Instruments II

- Other instruments that help to solve power quality problems by measuring ambient conditions are
  - **Infrared meters**
    - Useful; in detecting loose connections and overheating conductors
    - Can help to prevent power quality problems due to arcing, bad connections, and overloaded conductors
  - **Magnetic gauss meters**
    - Used to measure magnetic field strengths
    - Noise problems related to electromagnetic radiation
  - **Electric field meters**
    - Used to measure the strength of electric fields
    - Noise problems related to electromagnetic
  - **Static electricity meters**
    - Used to measure static electricity in the vicinity of sensitive equipment
    - Electrostatic discharge (ESD) can cause power quality problems

3.1 Types of Instruments III

- Important factors for selecting measurement instruments are
  - Number of channels (voltage and/or current)
  - Temperature specifications of the instrument
  - Ruggedness of the instrument
  - Input voltage range (e.g., 0 to 600 V)
  - Power requirements
  - Ability to measure three-phase voltages
  - Input isolation (isolation between input channels and from each input to ground)
  - Ability to measure currents
  - Housing of the instrument (portable, rack-mount, etc.)
  - Ease of use (user interface, graphics capability, etc.)
  - Documentation
  - Communication capability (modem, network interface)
  - Analysis software

3.2 Wiring and Grounding Testers

- Problems with wiring and/or grounding within the facility
- Can be identified by visual inspection of wiring, connections, and panel boxes
- Wiring and grounding testers can also be used
  - Detection of isolated ground shorts and neutral-ground bonds
  - Ground impedance and neutral impedance measurement or indication
  - Detection of open grounds, open neutrals, or open hot wires
  - Detection of hot/neutral reversals or neutral/ground reversals
- Three-phase wiring testers can test phase rotation and phase-to-phase voltages

3.3 Multimeters I

- For quick checking of the voltage and/or current levels within a facility
- Overloading of circuits, undervoltage and overvoltage problems, and unbalances between circuits can be detected
  - Phase-to-ground voltages
  - Phase-to-neutral voltages
  - Neutral-to-ground voltages
  - Phase-to-phase voltages (three-phase system)
  - Phase currents
  - Neutral currents
- Multimeters are calibrated to give an **rms indication** for the measured signal

3.3 Multimeters II

- Different methods for calculating rms value
  1. **Peak method**
     - Assuming the signal to be a sinusoid, the meter reads the peak of the signal and divides the result by 1.414 (square root of 2) to obtain the rms
  2. **Averaging method**
     - Determines the average value of a rectified signal
     - For a sinusoidal signal, average value is related to the rms value by a constant

$$V_{rms} = (\pi/(2\sqrt{2}))V_{avg}$$

  3. **True rms**
     - rms value of a signal is a measure of the heating that will result if the voltage is impressed across a resistive load
     - Use a thermal detector to measure a heating value
     - Modern digital meters → digital calculation of the rms value by squaring the signal on a sample by-sample basis, averaging over the period, and then taking the square root of the result

3.3 Multimeters III

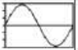
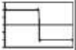
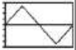
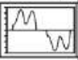
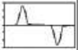
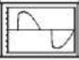
		Meter Type		
		True RMS	Peak Method	Average Responding
		Circuit Type		
		RMS Converter	Peak / 1.414	Sine Avg. X 1.11
Sine Wave		100 %	100 %	100 %
Square Wave		100 %	82 %	110 %
Triangle Wave		100 %	121 %	96 %
ASD Current		100 %	127 %	86 %
PC Current		100 %	184 %	60 %
Light Dimmer		100 %	113 %	84 %

Figure 2 : Comparison of Methods for Measuring Voltages and Currents with Multimeters

3.4 Digital Cameras

- For documentation purposes
- Used in field measurements
- Typical items to record photographically during field measurements include
  - Nameplates of transformers, motors, etc.
  - Instrumentation setups
  - Transducer and probe connections
  - Key waveform displays from instruments
  - Substations, switchgear arrangements, arrester positions, etc.
  - Dimensions of key electrical components such as cable lengths
- **Video cameras** $\rightarrow$ useful when there is moving action or random events: flashovers

3.5 Oscilloscopes I

- useful while performing real-time tests
- Waveforms of voltage and current
- Magnitudes of the voltages and currents
- Hand-held instruments with the capability to display waveforms as well as performing signal processing
- Ideal for initial plant surveys
- Capability to analyze harmonics
- **Digital Oscilloscope**
  - Data storage facility
  - Waveform can be saved and analyzed
  - Waveform analysis capability → energy calculation, spectrum analysis
  - Communication capability → waveform data can be uploaded to a personal computer for additional analysis with a software package

3.5 Oscilloscopes II

Figure 3 : Handheld Oscilloscope

3.5 Oscilloscopes III

Figure 4 : Digital Oscilloscope

3.6 Disturbance Analyzer I

- Developed for power quality measurements
- Can measure a wide variety of system disturbances from very short duration transient voltages to long-duration outages or undervoltages
- Threshold values can be set
- Can be used to record disturbances over a period of time
- Information is recorded on a paper or disk/memory

3.6 Disturbance Analyzer II

Categories

1. **Conventional Analyzers**
    - Summarize events with specific information
        - Overvoltage and undervoltage magnitudes
        - Sags and surge magnitude and duration
        - Transient magnitude and duration
    - Difficult to determine the characteristics of a disturbance or a transient from the summary information
    - Used for initial checks at a problem location

3.6 Disturbance Analyzer III

2. **Graphics-based Analyzers**
   - Save the disturbance information
   - Print the actual waveform along with the descriptive information
   - Easy to determine the characteristics of a disturbance from its waveform

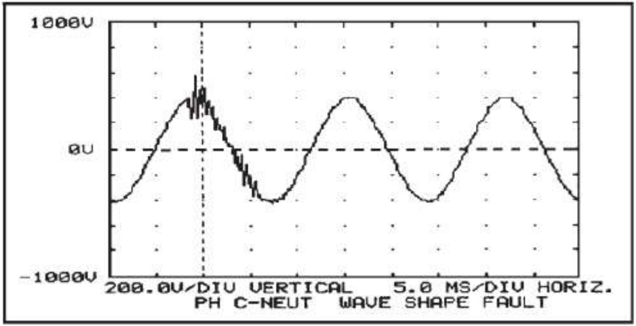


Figure 5 : Graphics-based Analyzer Output

3.6 Disturbance Analyzer IV

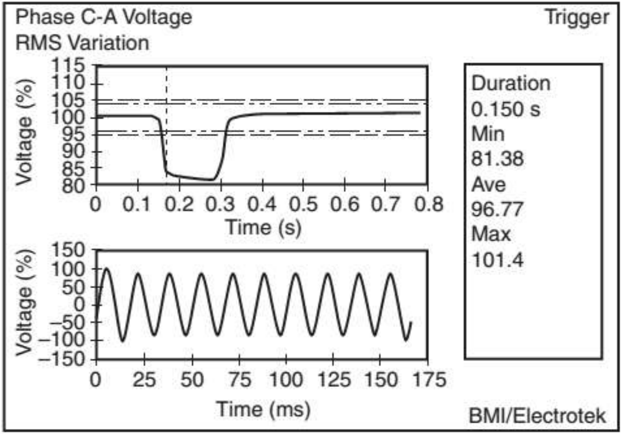


Figure 6 : Output from Disturbance Analyzer

3.6 Disturbance Analyzer V

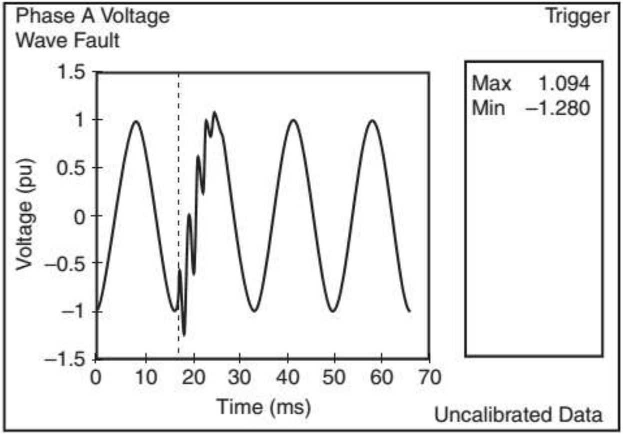


Figure 7 : Output from Disturbance Analyzer

3.6 Disturbance Analyzer VI

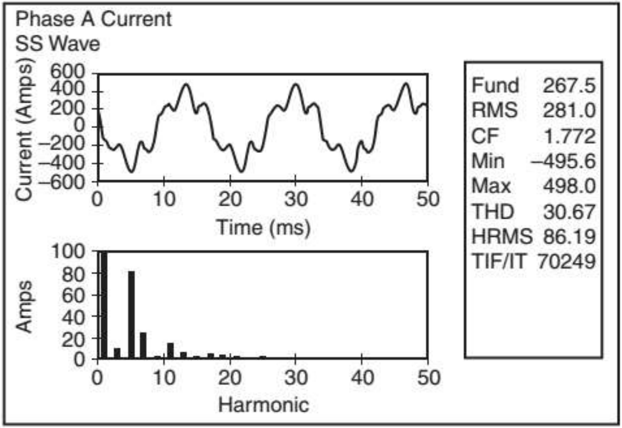


Figure 8 : Output from Harmonic Analyzer

3.7 Harmonic Spectrum Analyzer I

- Compute fast Fourier transform (FFT) calculations to determine the harmonics
- Harmonic measurements include
  - Capability to measure **both voltage and current** simultaneously so that harmonic power flow information can be obtained
  - Capability to measure **both magnitude and phase** angle of individual harmonic components (also needed for power flow calculations)
  - **Synchronization** and a **sampling rate** fast enough to obtain accurate measurement of harmonic components
  - Capability to **characterize the statistical nature** of harmonic distortion levels (harmonics levels change with changing load conditions and changing system conditions)

3.7 Harmonic Spectrum Analyzer II

Categories of instruments for harmonic analysis

1. **Simple Meters**
   - To make a quick check of harmonic levels at a problem location
   - Portable and hand-held meters are ideal
   - Use microprocessor-based circuitry to perform the necessary calculations
     - To determine individual harmonics up to the 50^{th} harmonic
     - To calculate rms value
     - To determine THD
     - To find the telephone influence factor (TIF)
   - Some instruments can also calculate harmonic powers (magnitudes and angles) and can upload stored waveforms and calculated data to a personal computer

3.7 Harmonic Spectrum Analyzer III

2. **General-purpose Spectrum Analyzers**
   - Designed to perform **spectrum analysis** on waveforms
   - Have very powerful capabilities for a reasonable price
3. **Special-purpose Power System Harmonic Analyzers**
   - Designed specifically for power system harmonic analysis
   - Based on the FFT with sampling rates specifically designed for determining harmonic components in power signals
   - Has communications capability for remot monitoring

3.8 Flicker Meters I

- Use exactly tuned filters and statistical analysis to evaluate the level of voltage flicker
- **Flicker curves** are used as guides for utilities to evaluate the severity of flicker within their system

Flicker Standards

- IEEE Standards 141-1993 and 519-1992 both contain flicker curves
- IEC Standard 61000-4-15 is a very comprehensive approach to flicker measurement
  - IEC flicker meter can be used for measuring flicker

3.8 Flicker Meters II

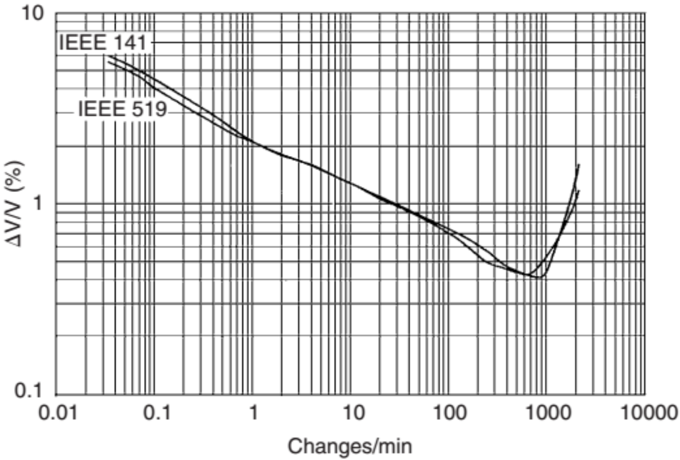


Figure 9 : Flicker curves from IEEE Standards 141 and 519

3.8 Flicker Meters III

Flicker Measurement Techniques

1. **RMS Strip Charts**
   - If sudden rms voltage deviations occurred with specified frequencies exceeding values found in flicker curves → **Voltage Flicker**

3.8 Flicker Meters IV

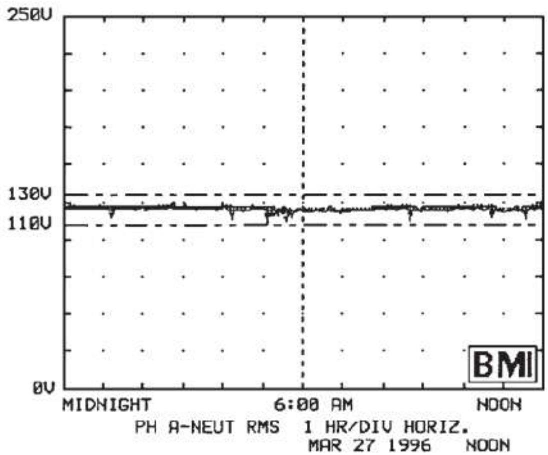


Figure 10 : Sample graph of RMS voltage variations

3.8 Flicker Meters V

- Figure shows large voltage deviations up to 9 V rms ($\Delta V/V = \pm$ 8 percent on a 120 V base)
- For a 120 V system, any sudden total change in voltage greater than 7 V rms results in objectionable flicker, regardless of the frequency
- **Advantages**
  - This method is quite simple
  - Required rms data is easy to acquire
- **Disadvantages**
  - Lack of accuracy
  - Inability to obtain the exact frequency content of the flicker

3.8 Flicker Meters VI

2. **Fast Fourier Transform**
   - Take raw samples of the actual voltage waveforms
   - Implement a fast Fourier transform on the demodulated signal (flicker signal only) to extract the various frequencies and magnitudes found in the data
   - Compare the calculated data with flicker curve
   - **Advantage**
     - This technique more accurately quantifies the data measured due to the magnitude and frequency of the flicker being known
   - **Disadvantage**
     - Difficulty in quantifying flicker levels when the flicker-producing load contains multiple flicker signals

3.8 Flicker Meters VII

3. **Flicker Meters**
   - Demodulates the flicker signal, weights it according to established flicker curves, and performs statistical analysis on the processed data.

Three sections of Flicker Meter

a. **Demodulator**
   - Input waveform is demodulated
   - Removes the carrier signal
   - DC offset and higher-frequency terms (side bands) are produced

b. **Filters**
   - Removes unwanted terms using filters
   - Modulating (flicker) signal remains

c. **Statistical Analysis**
   - Statistical analysis of the measured flicker

IEC Flicker Meter

- IEC Standard 61000-4-15

3.8 Flicker Meters VIII

- IEC flicker meter consists of five blocks

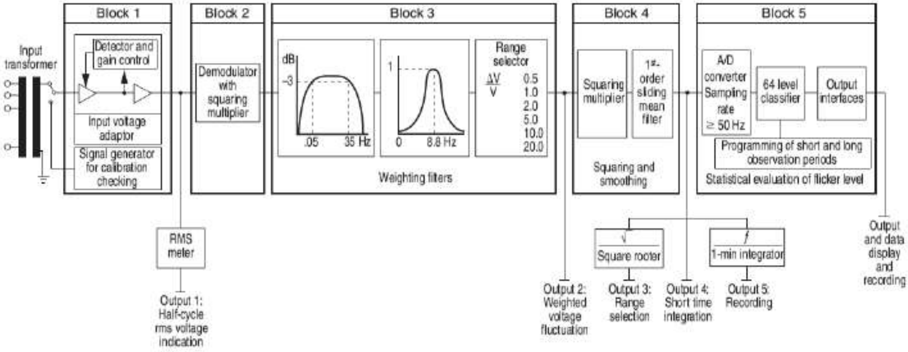


Figure 11 : Diagram of the IEC flicker meter

3.8 Flicker Meters IX

1. **Block 1**
   - Input voltage adapter
   - Scales the input half-cycle rms value to an internal reference level
   - Allows flicker measurements to be made based upon a percent ratio rather than be dependent upon the input carrier voltage level
2. **Block 2**
   - Squaring demodulator
   - Squares the input to separate the voltage fluctuation (modulating signal) from the main voltage signal (carrier signal)
   - Simulates the behaviour of the incandescent lamp

3.8 Flicker Meters X

3. **Block 3**
   - Filters
   - Serve to filter out unwanted frequencies produced from the demodulator
   - Weight the input signal according to the incandescent lamp eye-brain response
   - Transfer function for the weighting filter is

$$H(s) = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1{}^2} \cdot \frac{1 + s/\omega_2}{(1 + s/\omega_3)(1 + s/\omega_4)}$$

4. **Block 4**
   - Squaring multiplier and sliding mean filter
   - Voltage signal is squared to simulate the nonlinear eye-brain response
   - Sliding mean filter averages the signal to simulate the short term storage effect of the brain
   - Output of block 4 is considered to be the instantaneous flicker level
   - A level of 1 on the output of block 4 corresponds to perceptible flicker

3.8 Flicker Meters XI

5. **Block 5**
   - Consists of a statistical analysis of the instantaneous flicker level
   - Output of block 4 is divided into suitable classes which creates a histogram
   - Probability density function is created based upon each class, and from this a cumulative distribution function can be formed

3.8 Flicker Meters XII

Flicker level evaluation can be divided into two categories

1. **Short-term Flicker Severity (P_{ST})**
   - Short-term evaluation of flicker severity P_{ST}
   - Based upon an observation period of 10 min
   - P_{ST} can be determined as

$$P_{ST} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}}$$

   - Percentages $P_{0.1}, P_{1s}, P_{3s}, P_{10s}$ and P_{50s} are the flicker levels that are exceeded 0.1, 1.0, 3.0, 10.0, and 50.0 percent of the time respectively
   - P_{ST} **of 1.0** on the output of block 5 represents the **objectionable (or irritable) limit of flicker**

3.8 Flicker Meters XIII

2. **Long-term Flicker Severity (P_{LT})**
   - For cases where the duty cycle is long or variable
   - Arc furnaces, or disturbances on the system that are caused by multiple loads operating simultaneously
   - P_{LT} can be determined as

$$P_{LT} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{STi}^{3}}{N}}$$

   - N is the number of P_{ST} readings and is determined by the duty cycle of the flicker-producing load
   - The purpose is to capture one duty cycle of the fluctuating load
   - If the duty cycle is unknown, the recommended number of P_{ST} readings is 12 (2-h measurement window)

3.8 Flicker Meters XIV

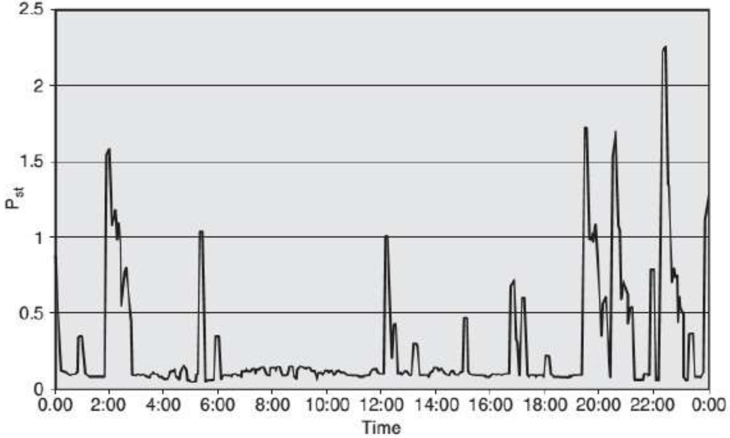


Figure 12 : Flicker variations at the PCC with an arc furnace characterized by the P_{ST} levels for a 24-h period

3.9 Smart Power Quality Monitors I

- Capability to locally analyze, interpret, and determine what is happening in the power system
- Collect the data, turn them into useful information, and disseminate it to users
- Power quality monitors with integrated intelligent systems
- Information is directly created within the instrument and immediately available to the users
- Proactive manner instead of reactive manner

3.9 Smart Power Quality Monitors II

Smart Power Quality Monitor developed by Electrotek Concepts, Dranetz-BMI, EPRI, and the Tennessee Valley Authority (TVA)

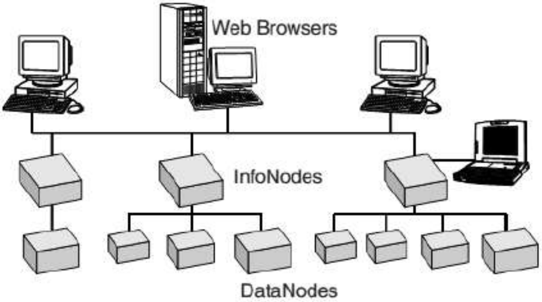


Figure 13 : Signature System Architecture

3.9 Smart Power Quality Monitors III

- System consists of data acquisition, data aggregation, communication, Web-based visualization, and enterprise management components
  - Data acquisition component (DataNode) is designed to measure the actual power system voltages, currents, and other quantities
  - Data aggregation, communication, Web-based visualization, and enterprise management components are performed by a mission-specific computer system called the InfoNode
  - Communication between the data acquisition device and the InfoNode is accomplished through serial RS-232/485/422 or Ethernet communications using industry standard protocols (UCA MMS and Modbus)
  - One or more data acquisition devices, or DataNodes, can be connected to an InfoNode
  - InfoNode acts as a special-purpose database manager and Web server

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1. *"Electrical Power System Quality" - R. C. Dugan*
2. "*Power Quality*" - C. Sankaran
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5. "*Understanding Power Quality Problems*" - Math H. Bollen
6. "*Handbook of Power Quality*" - Angelo Baggini

Thank You

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Power Quality

(EE-465)

S7 - EE, 2020

by

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Module 5: Overview I

1. Harmonic Filters I

- Elimination of harmonics in power system
- Filters are installed near or close to the points of distortion $\rightarrow$ ensures that harmonic current do not interact with power system
- Filters are designed to provide a **bypass** for the harmonic currents, **to block** them from entering the power system, or to **compensate** them by locally supplying harmonic currents and/or voltage

1. Harmonic Filters II

Factors to be considered for the selection of filters

- Number & Type of elements (one, two or more passive and/or active)
- Topology (Shunt, series or both)
- Supply System (single phase or 3 phase)
- Power rating (low, medium, high-power)
- Compensated variable(harmonic current, harmonic voltage, reactive power and phase balancing or multiple compensating)
- Converter type (Voltage source inverter or current source inverter)
- Control technique and reference current generation method

2. Classification of Filters

1. **Passive Filter**
   - Provides a **low impedance path to ground** for harmonic signals
     a) Shunt Passive Filter: Single tuned filter, second order damped filter, 3rd order damped filter, C-type filter
     b) Series Passive Filter
     c) Passive series-parallel filter
2. **Active Filter**
   - Injects harmonic signals which are 180^0 out of phase with the harmonic signals present in the system
     a) Series Active Filter
     b) Shunt Active Filter
     c) Combination of series active and shunt active filter (UPQC)
3. **Hybrid Filter**
   - Combination of active and passive Filter

3. Passive Filter I

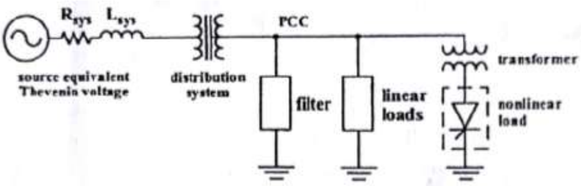
- Commonly used
- **Inductance, capacitance, and resistance** elements configured and tuned to control harmonics
- Either to inject a **series high impedance** to block the harmonic currents or to create a **shunt low impedance** path to divert the harmonic currents path
- Installed either in **shunt connection** or **series connection**
- While shunt connected passive filters carry only a fraction of line current, series filters are subjected to full line current. Moreover, the reactive power compensation capability of shunt connected passive filters and the lower installation cost of shunt filters make series passive filters non preferable

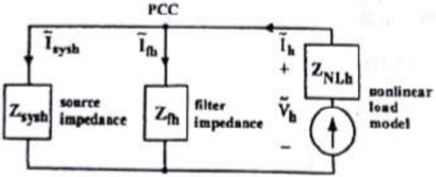
3. Passive Filter II

- **Advantages**
  - Cheap & Economical
  - High efficiency
  - Maintenance is simple
- **Disadvantages**
  - Resonance may occur between the source impedance and the filter impedanc which results in amplification of harmonics
  - Large size
  - Fixed compensation character
- Passive filters are employed either to **shunt the harmonic currents off the line** or to **block their flow between parts of the system** by tuning the elements to create a resonance at a selected frequency

3. Passive Filter III

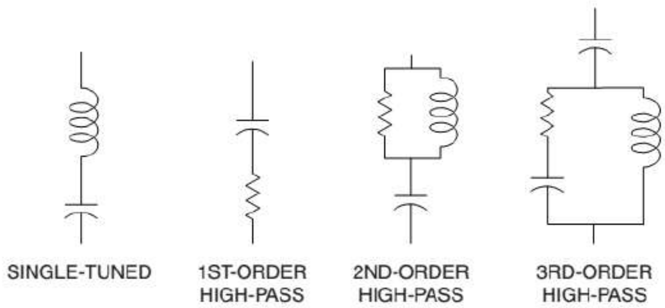
Passive Filter Configurations





3. Passive Filter IV

Shunt Passive Filter

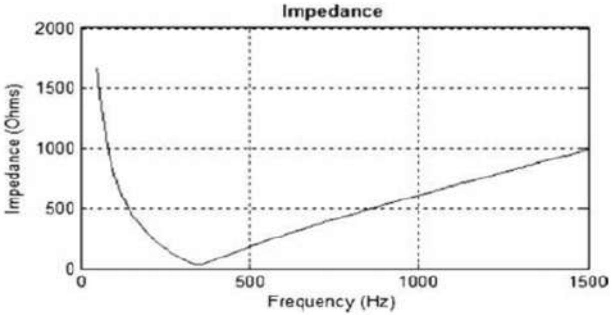


3.1 Single Tuned Filter I

- **Single-tuned notch filter**
- Tuned to only one harmonic frequency
- Notch filter is tuned to present a low impedance to a particular harmonic current and is connected in shunt with the power system. Thus, harmonic currents are diverted from their normal flow path on the line through the filter.
- If other harmonic frequencies are to be filtered out, **additional tuned filters** are applied in parallel.
- Notch filters can provide **power factor correction** in addition to harmonic suppression
- When applying harmonic filters, the units are almost never tuned to the exact harmonic frequency. For example, the 5^{th} harmonic frequency may be designed for resonance at the 4.7^{th} harmonic frequency

3.1 Single Tuned Filter II

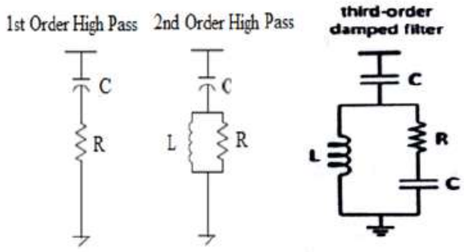
- Impedance vs frequency curve



3.1 Single Tuned Filter III

- Advantages
  - Simple configuration
  - Only capacitor and inductor components
  - Quality factor of the filter is high which provides maximum attenuation of one harmonic
  - Negligible losses
  - Low maintenance requirement

3.2 High Pass Filters I



- High pass filters are provided with damping resistor, which reduces the quality factor of the filter
- Low quality factor increases the bandwidth of the filter and making it suitable for a range of harmonic frequencies greater than the cut-off frequency

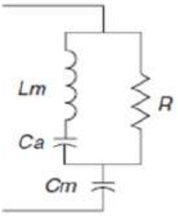
3.2 High Pass Filters II

- High pass filters are effective for harmonic frequencies greater than the cut-off frequencies of the filter
- First order high pass filters shows higher losses at fundamental frequency, so first order type high pass filters are rarely used
- second order high pass filters show less losses at fundamental frequency when compared with the first order types
- Third order type filters are the most effective form in the loss performance. But their filtering performance is inferior to that of the second order types

3.2 High Pass Filters III

- **Advantages**
  - Effective for a range of harmonic because of high bandwidth and low quality factor
  - Less sensitive to variation in the fundamental frequency and component values
  - Negligible fundamental frequency and losses in the resistor of third order filter
- **Disadvantages**
  - It requires larger installed MVAR rating than multiple single tuned filters in order to meet same specified performance
  - Higher losses in the filter compared to single tuned filters
  - Complex filter because of many components

3.3 C Filters I

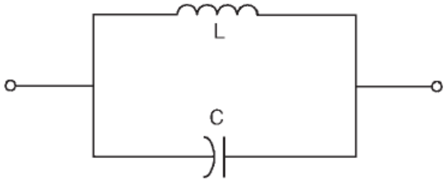


- Capable to reducing multiple harmonic frequencies simultaneously in industrial and utility systems. They can attenuate a wide range of steady state and time-varying harmonic and interharmonic frequencies generated by electronic converters, induction furnaces, cyclo-converters etc.

3.3 C Filters II

- Configuration of a C filter is nearly identical to that of the second-order high-pass filter
- Main distinction between the two configurations is that the C filter possesses an auxiliary capacitor (C_a) in series with the inductor L_m
- Auxiliary capacitor C_a is sized in such a way that its capacitive reactance cancels out L_m at the fundamental frequency, bypassing the damping resistance R
- For this reason, the losses associated with R are practically eliminated, allowing a C filter to be tuned to a low frequency

4. Series Passive Filters I

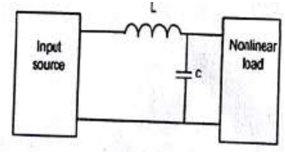


- Series passive filter is connected in series with the load
- Inductance and capacitance are connected in parallel and are tuned to provide a high impedance at a selected harmonic frequency
- High impedance blocks the flow of harmonic currents at the tuned frequency only

4. Series Passive Filters II

- At fundamental frequency, the filter would be designed to yield a low impedance, thereby allowing the fundamental current to follow with only minor additional impedance and losses
- Series filters are used to block a single harmonic current
- Use of the series filters is limited in blocking multiple harmonic currents. Each harmonic current requires a series filter tuned to that harmonic. This arrangement can create significant losses at the fundamental frequenc

5. Passive Shunt-Series Filter



- Combination of shunt and series connected branch is used
- Series branch blocks harmonics
- Shunt branch allows harmonics to flow into the ground
- It can't be used for low order harmonics because high blocking impedance at low order tuning frequency will have significant voltage drop at fundamental frequency which will reduce the AC bus voltage

Shunt Filter I

- Single-tuned notch filter
- Economical
- Tuned to present a low impedance to a particular harmonic current
- Connected in shunt with the power system
- Harmonic currents are diverted from their normal flow path on the line through the filter
- It can provide power factor correction in addition to harmonic suppression
- Air-core reactor or Dry-type iron-core reactor
- Capacitors are connected in wye or star configuration
- Each capacitor is fused with a current-limiting fuse to minimize damage in case of a can failure

Shunt Filter II

Filter arrangement

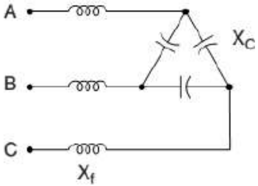


Figure 1 : Typical low-voltage filter configuration

Shunt Filter III

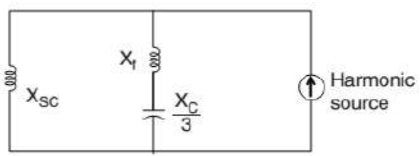


Figure 2 : Equivalent circuit of system with filter

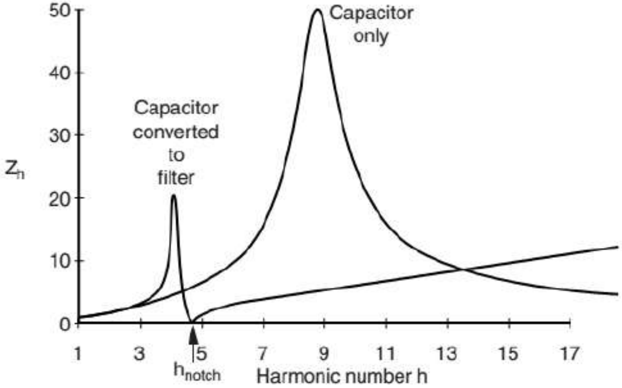
- 480 V filter arrangement is shown in the figure
- Delta-connected low-voltage capacitor bank converted into a filter by adding an inductance in series with the phases
- Notch harmonic h_{notch} is related to the fundamental frequency reactances by

Shunt Filter IV

$$h_{\text{notch}} = \sqrt{\frac{X_C}{3X_F}}$$

- X_C = Reactance of one leg of the delta rather than the equivalent line-to-neutral capacitive reactance

Shunt Filter V



- Shunt filter creates a sharp parallel resonance point at a frequency below the notch frequency. This resonant frequency must be safely away from any significant harmonic or other frequency component that may be produced by the load

Shunt Filter VI

- Filters are commonly tuned slightly lower than the harmonic to be filtered to provide a margin of safety in case there is some change in system parameters that would raise the notch frequency. If they were tuned exactly to the harmonic, changes in either capacitance or inductance with temperature or failure might shift the parallel resonance higher into the harmonic being filtered
- To avoid problems with this resonance, filters are added to the system starting with the lowest significant harmonic found in the system
  - ie, installing a seventh-harmonic filter usually requires that a fifth-harmonic filter also be installed. The new parallel resonance with a seventh-harmonic filter alone is often very near the fifth, which is generally disastrous
- The delta filter configuration does not admit zero-sequence currents because the capacitor is delta-connected, which makes it ineffective for filtering zero-sequence triplen harmonics

Shunt Filter VII

- Capacitors on utility distribution systems are more commonly wye-connected. This gives the option of controlling the zero sequence triplen harmonics simply by changing the neutral connection
- Placing a reactor in the neutral of a capacitor is a common way to force the bank to filter only zero-sequence harmonics. This technique is often employed to eliminate telephone interference
- Passive filters should always be placed on a bus where the short-circuit reactance X_{SC} can be expected to remain constant. While the notch frequency will remain fixed, the parallel resonance will move with system impedance
- Filters must be designed with the capacity of the bus

6. Active Filter I

- Employs power electronics, installed in series or in parallel with the non-linear load, to provide the harmonic currents required by non-linear loads
- Avoids harmonics currents entering power system
- Based on sophisticated power electronics
- Much more expensive than passive filters
- Active power conditioning to compensate undesirable harmonic currents
- Replaces a portion of distorted current waveform from the non-linear load
- Produces harmonic currents of equal magnitude but with 180^o phase shift so that it cancel the harmonic components of distorted current due to non-linear loads

6. Active Filter II

- **Advantages**
  - Do not resonate with the system
  - Good response to changing loads and harmonic variations
  - Can work independently of the system impedance characteristics
  - Can also address more than one harmonic at a time
  - Can combat other power quality problems such as flicker
- **Disadvantages**
  - Expensive
  - Not feasible for small facilities

6. Active Filter III

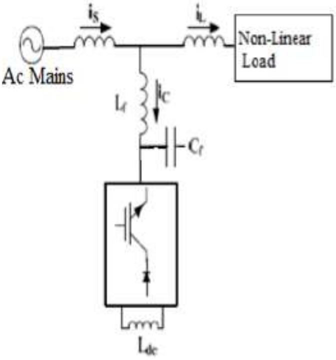
Classification

- Converter type: Current Source Inverter(CSI) or Voltage Source Inverter (VSI)
- Topology: Shunt, series, or a combination of both
- Based on the number of phases: Two-wire (single phase) and three- or four-wire three-phase systems

6. Active Filter IV

Converter Type Classification

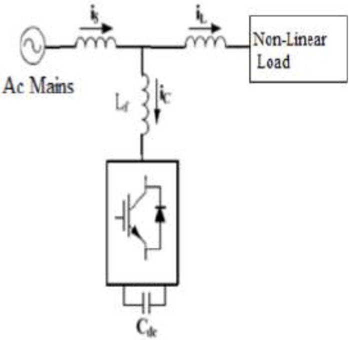
1. Current Source Inverter(CSI) Type APF



- Power circuit acts as a non sinusoidal current source with a DC link inductor (L_{dc}) as an energy storage element

6. Active Filter V

2. Voltage Source Inverter(VSI) Type APF

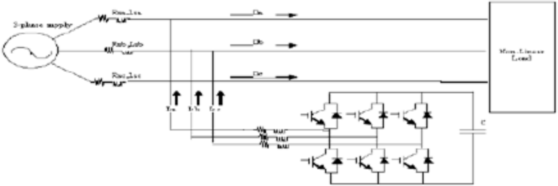


- Power circuit has a DC link capacitor (C_{dc}) as an energy storage element

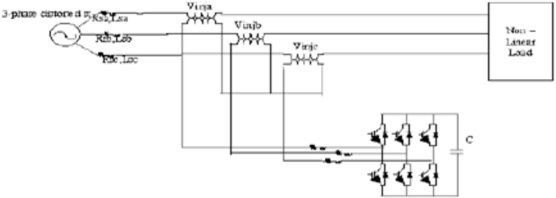
6. Active Filter VI

Supply-System Based Classification

1. Three-phase Three-wire DSTATCOM

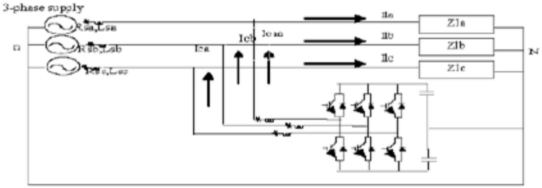


2. Three-phase Three-wire DVR



6. Active Filter VII

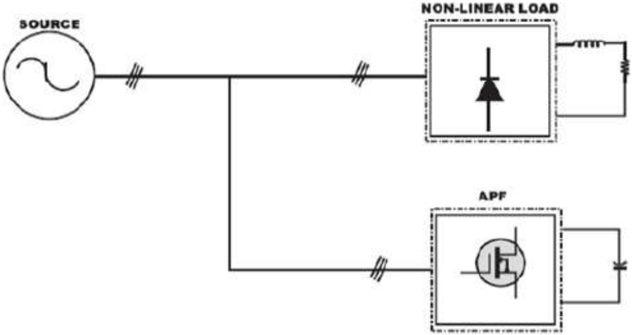
3. Three-phase Four-wire DSTATCOM



6. Active Filter VIII

Topology Based Classification

1. Shunt Active Power Filter

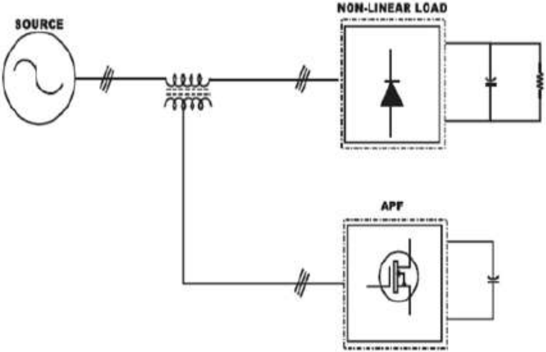


6. Active Filter IX

- DSTATCOM
- Used to eliminate current harmonics, reactive power compensation and balancing unbalanced currents
- Used at the load end as the current harmonics are injected by nonlinear loads
- Shunt APF injects equal compensating currents, opposite in phase, to cancel harmonics and/or reactive components of the nonlinear load current at the point of connection
- It can also be used as a static VAR compensator (STATCOM) in the power system network for stabilizing and improving the voltage profile

6. Active Filter X

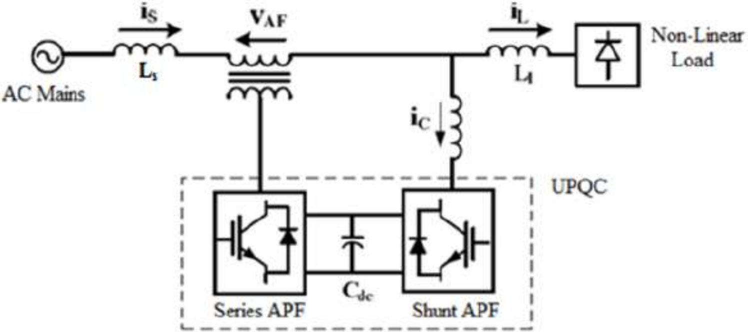
2. Series Active Filter



- Connected before the load in series with the mains
- Eliminates voltage harmonics
- Balances and regulates the terminal voltage of the load or line

6. Active Filter XI

3. Combination of Series Active and Shunt Active Power Filter



- DC-link storage element (either inductor or dc-bus capacitor) is shared between two current source or voltage-source bridges operating as active series and active shunt compensators
- Used in single-phase as well as three-phase configurations

6. Active Filter XII

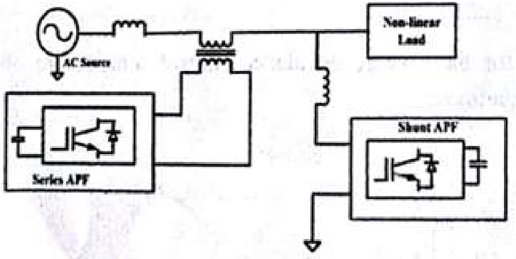
- Considered as an ideal AF which eliminates voltage and current harmonics and is capable of giving clean power to critical and harmonic-prone loads, such as computers, medical equipment, etc.
- High cost and complex control because of the presence of large number of solid-state devices

7. Hybrid Filter I

- Combination of an active series filter and passive shunt filter
- Significantly reduces the rating of the active filter
- Solid-state devices used in the active series part can be of reduced size and cost and a major part of the hybrid filter is made of the passive shunt L-C filter
- Used to eliminate lower order harmonics
- It has the capability of reducing voltage and current harmonics at a reasonable cost
- Types
  1. Shunt APF and Series APF
  2. Shunt APF and Series Passive Filter
  3. APF in Series with Shunt Passive Filter
  4. Series APF with Shunt Connected Passive Filter

7. Hybrid Filter II

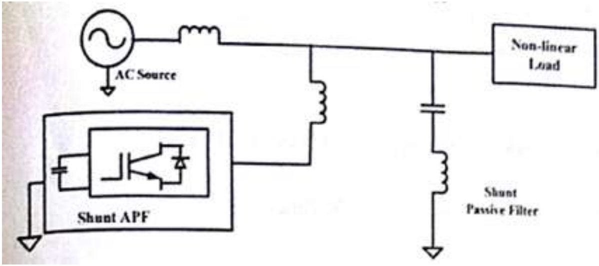
1. Shunt APF and Series APF



- Has advantages of both series connected APF and shunt connected APF
- Elimination of voltage harmonics as well as current harmonics
- Filter control configuration is very complex
- Not commonly used

7. Hybrid Filter III

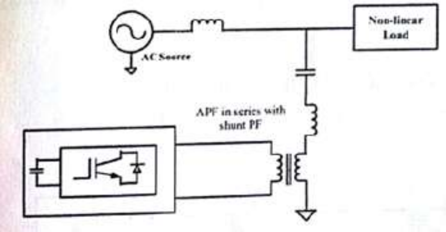
2. Shunt APF and Series Passive Filter



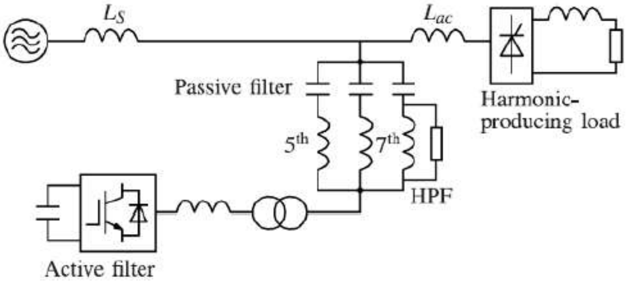
- Power rating of APF depends on the order of frequencies filtering out
- APF used for filtering out low order harmonics have low power rating with reduced size and cost
- Shunt APF filters out low order harmonics
- Shunt Passive Filter is designed to filter out higher order harmonics

7. Hybrid Filter IV

3. APF in Series with Shunt Passive Filter



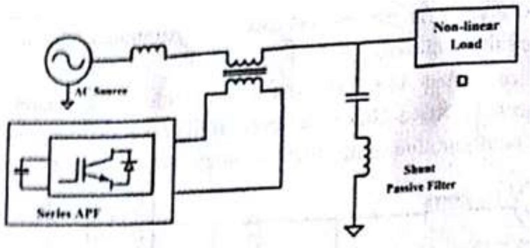
7. Hybrid Filter V



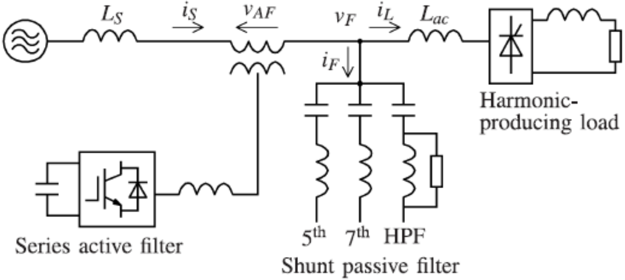
- APF is connected in series with a shunt connected passive filter
- Passive filter reduces the stress on power electronic switches
- Used in medium and high voltage systems

7. Hybrid Filter VI

4. Series APF with Shunt Connected Passive Filter



7. Hybrid Filter VII



- Passive filter does not require any additional control circuit
- Low cost
- Series APF provides low impedance for low frequency components
- Shunt filter provides low impedance for high frequency components
- Reduces both current and voltage harmonics

8. Power Conditioners I

- Device intended to improve the quality of the power that is delivered to load equipment
- Device that acts in one or more ways to deliver a voltage of proper level and characteristics to enable load equipment to function properly
- In some uses, power conditioners refers to a voltage regulator with at least one other function to improve power quality(pf correction, noise suppression ,transient impulse protection etc)
- AC power conditioner is the typical power conditioner that provides clean ac power to sensitive electrical equipment
- Main function is to preserve power parameters within the limits required for the load, although each appliance is designed to solve one specific power quality issue

8. Power Conditioners II

- Isolation Transformer, Voltage Regulator, Uninterruptible Power Supply (UPS), Rotary UPS, Surge Arrestors, Harmonic Filters (Passive and Active), DSTATCOM, Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC)

References

1. *"Electrical Power System Quality" - R. C. Dugan*
2. "*Power Quality*" - C. Sankaran
3. "*Power Quality*" - G. T. Heydt
4. "*Power System Harmonics*" - Jose Arillaga
5. "*Understanding Power Quality Problems*" - Math H. Bollen
6. "*Handbook of Power Quality*" - Angelo Baggini

Thank You

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Power Quality

(EE-465)

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by

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Module 6: Overview I

1. Electromagnetic Interference
   - Introduction
   - Frequency Classification
   - Electrical Fields
   - Magnetic Fields
   - EMI Terminology
     - Decibel (DB)
     - Radiated Emission
     - Conducted Emission
     - Attenuation
     - Common Mode Rejection Ration (CMRR)
     - Noise
     - Common Mode Noise
     - Transverse Mode Noise
     - Bandwidth
     - Filter
     - Shielding

- Power Frequency Fields
- High Frequency Fields

2. Power Quality Management in Smart Grid
   - Power Quality Issues
   - Power Quality issues of Grid connected Renewable Energy Sources
   - Power Quality Conditioners for Smart Grid

1.1 EMI - Introduction I

- Electricity and magnetism are interrelated
- Any conductor carrying electrical current has an associated magnetic field
- Magnetic field can induce voltages or currents in a conductive medium exposed to the field
- **Altering one changes the other** consistent with certain principles of electromagnetic dependency
- Electrical circuits are carriers of electricity as well as propagators of magnetic fields
- Relationship between electrical current and magnetic field is put to productive use in many applications
  - Generators, motors, transformers, induction heating furnaces, electromagnet etc.

1.1 EMI - Introduction II

- Power quality: how electromagnetic phenomena affect electrical and electronic devices in an adverse manner
- Effect of electromagnetism on sensitive devices is called **Electromagnetic Interference (EMI)**

1.2 Frequency Classification I

Frequency Classification	Frequency Range	Application
ELF	3–30 Hz	Detection of buried objects
SLF	30–300 Hz	Communication with submarines, electrical power
ULF	300–3000 Hz	Telephone audio range
VLF	3–30 kHz	Navigation, sonar
LF	30–300 kHz	Navigation, radio beacon
MF	300–3000 kHz	AM, maritime radio
HF	3–30 MHz	Shortwave radio, citizen's band
VHF	30–300 MHz	Television, FM, police, mobile
UHF	300–3000 MHz	Radar, television, navigation
SHF	3–30 GHz	Radar, satellite
EHF	30–300 GHz	Radar, space exploration

1.2 Frequency Classification II

- Classification of Frequency Spectrum
  - ELF: Extremely Low Frequency
  - SLF: Super Low Frequency
  - ULF: Ultra Low Frequency
  - VLF: Very Low Frequency
  - LF: Low Frequency
  - MF:Medium Frequency
  - HF: High Frequency
  - VHF: Very High Frequency
  - UHF: Ultra High Frequency
  - SHF: Super High Frequency
  - EHF: Extremely High Frequency
- EMI is more readily associated with signals in the low frequency range

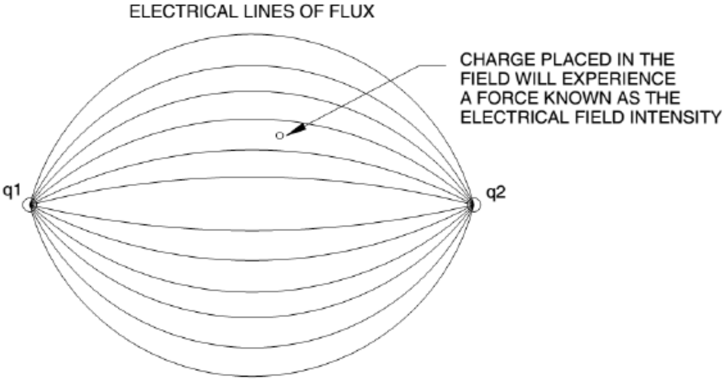
1.3 Electrical Fields I

- Properties of electromagnetism: electrical and magnetic fields
- **Electrical field is present whenever an electrical charge (q) placed in a dielectric or insulating medium experiences a force acting upon it** → Electrical fields are forces
- Electric field exists whenever a charge differential exists between two points in a medium
- The force is proportional to the product of the two charges and inversely proportional to the square of the distance between the two points
- If two charges, q_1 and q_2, are placed at a distance of 'd' meters apart in a dielectric medium of relative permittivity equal to ϵ_R, the force (F) acting between the two charges is given by Coulombs law:

$$F = q_1 q_2 / \varepsilon_O \varepsilon_R d^2$$

1.3 Electrical Fields II

- **Permittivity of free space**, $\epsilon_0 = 8.854 \times 10^{-12}$ F/m
- Electrical forces may be visualized as lines of force between two points, between which exists a charge differential



1.3 Electrical Fields III

- Two quantities describe the electrical field: **electrical field intensity (E)** and **electrical flux density (D)**
- Electrical field intensity is the force experienced by a unit charge placed in the field
- A unit charge has an absolute charge equal to 1.602×10^{-19} C

$$\mathbf{E} = q_1/\varepsilon_O\varepsilon_R d^2$$

- Electric field intensity varies as the square of the distance from the location of the charge
- The farther q_1 is located away from q_2, the lower the field intensity experienced at q_2 due to q_1
- **Electric flux density** is the number of electric lines of flux passing through a unit area

1.3 Electrical Fields IV

- If Ψ number of electric flux lines pass through an area A(m^2), then electric flux density,

$$D = \psi / A$$

- The ratio between the electric flux density and the field intensity is the **permittivity of free space** (ϵ_0)

$$\varepsilon_O = D/\mathbf{E} = 8.854 \times 10^{-12} \text{ F/m}$$

- In other mediums besides free space, E reduces in proportion to the relative permittivity of the medium. This means that the electric flux density D is independent of the medium.
- Electrical field intensity is the primary measure of electrical fields applicable to power quality
- Most field measuring devices indicate electric fields in the units of volts/meter

1.4 Magnetic Fields I

- Magnetic fields exist when two poles of the opposite orientation are present: the north pole and the south pole
- Two magnetic poles of strengths m_1 and m_2 placed at a distance of d meters apart in a medium of relative permeability equal to μ_R will exert a force (F) on each other given by Coulombs law,

$$F = m_1 m_2 / \mu_O \mu_R d^2$$

- Permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$ H/m
- **Magnetic field intensity (H)**, is the force experienced by a unit pole placed in a magnetic field

$$\mathbf{H} = F/m$$

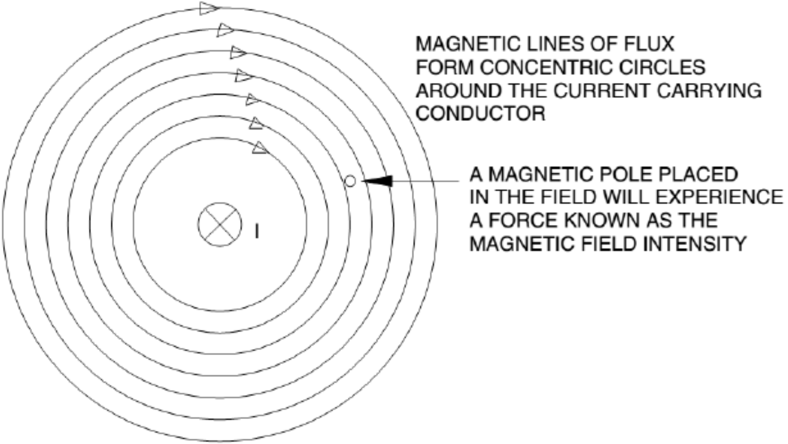
- If m_2 is a unit pole, the field intensity at m_2 due to m_1

1.4 Magnetic Fields II

$$\mathbf{H} = m_1/\mu_O\mu_R d^2$$

- Magnetic field intensity varies as the square of the distance from the source of the magnetic field
- As the distance between m_1 and m_2 increases, the field intensity decreases
- Magnetic fields are associated with the flow of electrical current in a conductor
- When current flows in a conductor, magnetic flux lines are established
- Unlike electrical fields, which start and terminate between two charges, magnetic flux lines form concentric tubes around the conductor carrying the electrical current

1.4 Magnetic Fields III



1.4 Magnetic Fields IV

- **Magnetic flux density (B)** is the number of flux lines per unit area of the medium
- If Φ number of magnetic lines of flux pass through an area of A(m_2), the flux density $B = \Phi/A$
- The relationship between the magnetic flux density and the magnetic field intensity is known as the permeability of the magnetic medium (μ)
- In a linear magnetic medium undistorted by external factors,

$$\mu = \mu_R \times \mu_O$$

- Permeability of free space (μ_0)
- Relative permeability of the magnetic medium with respect to free space (μ_R)
- In free space, $\mu_R = 1 \implies \mu = \mu_0 = 4\pi \times 10^7$ H/m

1.4 Magnetic Fields V

- In a linear medium,

$$\mu = B/H$$

- In free space,

$$\mu_o = B/H$$

- Magnetic field intensity is expressed in units of ampere-turns per meter
- Flux density is expressed in units of tesla (T)
- One tesla is equal to the flux density when 10^8 lines of flux lines pass through an area of 1 m_2
- Gauss (G) = One magnetic line of flux passing through an area of 1 cm^2
- Both electrical and magnetic fields are capable of producing interference in sensitive electrical and electronic devices

1.4 Magnetic Fields VI

- Electric Field
  - Electrical fields are due to potential or charge difference between two points in a dielectric medium
  - Electrical fields exert a force on any electrical charge (or signal) in its path and tend to alter its amplitude or direction or both
- Magnetic Field
  - Magnetic fields are due to the flow of electrical current in a conducting medium
  - Magnetic fields induce currents in an electrical circuit placed in their path, which can alter the signal level or its phase angle or both

1.5 EMI Terminology I

- Terms unique to electromagnetic phenomena
  - Decibel (DB)
  - Radiated Emission
  - Conducted Emission
  - Attenuation
  - Common Mode Rejection Ration (CMRR)
  - Noise
  - Common Mode Noise
  - Transverse Mode Noise
  - Bandwidth
  - Filter
  - Shielding

1.5.1 Decibel (DB)

- Used to express the ratio between two quantities (Voltage, current, or power)
- For voltages and currents,

$$dB = 20 \log (V_1/V_2) \text{ or } 20 \log (I_1/I_2)$$

- If a filter can attenuate a noise of 10 V to a level of 100 mV, then

$$\text{Voltage attenuation} = V_1/V_2 = 10/0.1 = 100$$

$$\text{Attenuation (dB)} = 20 \log 100 = 40$$

- For power,

$$dB = 10 \log (P_1/P_2)$$

- If the power input into an amplifier is 1W and the power output is 10W, then power gain (in dB) is equal to 10 log 10 = 10

1.5.2 Radiated Emission

- Radiated emission: measure of the level of EMI propagated in air by the source
- Radiated emission requires a carrier medium such as air or other gases
- Usually expressed in volts/meter (V/m) or microvolts per meter (V/m)

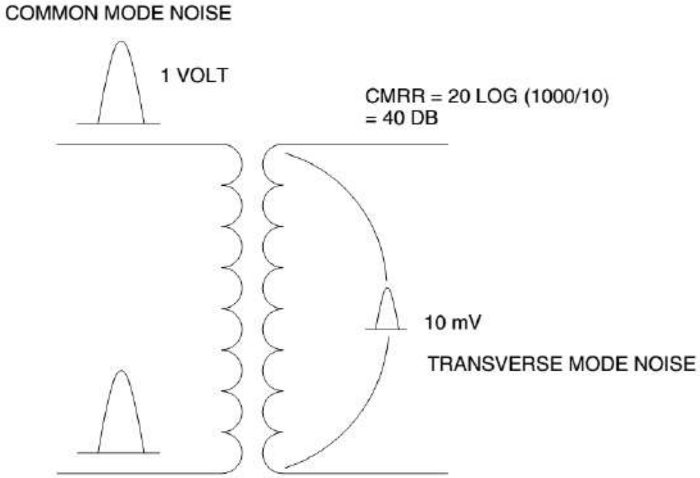
1.5.3 Conducted Emission

- Conducted emission: Measure of the level of EMI propagated via a conducting medium such as power, signal, or ground wires
- Expressed in millivolts (mV) or microvolts (V)

1.5.4 Attenuation

- Attenuation: Ratio by which unwanted noise or signal is reduced in amplitude
- Usually expressed in decibels (dB)

1.5.5 Common Mode Rejection Ration (CMRR) I



1.5.5 Common Mode Rejection Ration (CMRR) II

- Common mode rejection ratio (CMRR): Ratio between the common mode noise at the input of a power handling device and the transverse mode noise at the output of the device
- Common mode noise is typically due to either coupling of propagated noise from an external source or stray ground potentials, and it affects the line and neutral (or return) wires of a circuit equally
- Common mode noise is converted to transverse mode noise in the impedance associated with the lines
- Filters or shielded isolation transformers reduce the amount by which common mode noise is converted to transverse mode noise

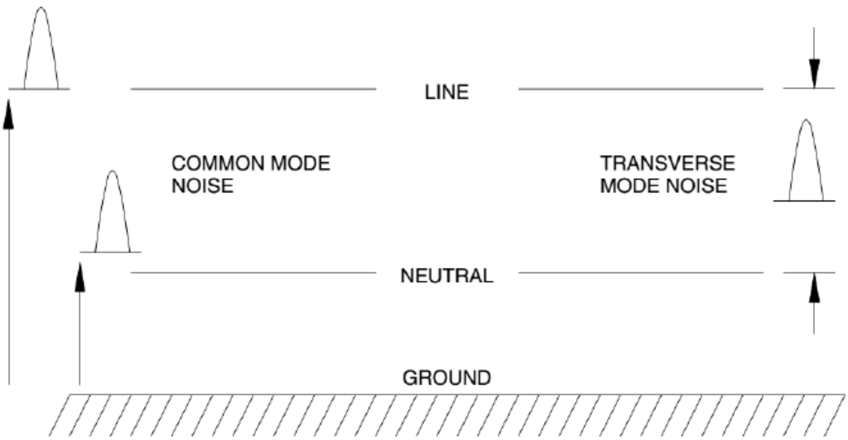
1.5.6 Noise

- Electrical noise, or noise: Unwanted electrical signals that produce undesirable effects in the circuits in which they occur

1.5.7 Common Mode Noise

- Common mode noise: Present equally and in phase in each current carrying wire with respect to a ground plane or circuit
- Caused by radiated emission from a source of EMI
- Can also couple from one circuit to another by inductive or capacitive means
- Lightning discharges may also produce common mode noise in power wiring

1.5.8 Transverse Mode Noise I



- Transverse mode noise: Noise present across the power wires to a load

1.5.8 Transverse Mode Noise II

- It is referenced from one power conductor to another including the neutral wire of a circuit
- Produced due to power system faults or disturbances produced by other loads
- Can be due to conversion of common mode noise in power equipment or power lines

1.5.9 Bandwidth

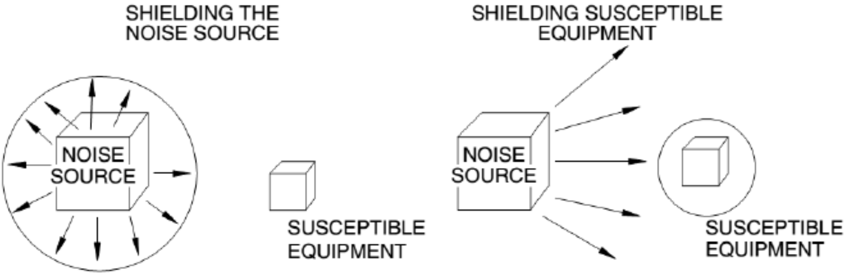
- Bandwidth: Range of frequencies
- Eg: Bandwidth of 300 kHz to 300 MHz is assigned to radio broadcast and marine communication
- Any filter intended to filter out the noise due to these sources must be designed for this particular bandwidth

1.5.10 Filter

- Filter consists of passive components such as R, L, and C to divert noise away from susceptible equipment
- Applied at the source of the noise to prevent noise propagation to other loads present in the system or at the load to protect a specific piece of equipment
- Choice of the type of filter would depend on the location of the noise source, the susceptibility of the equipment, and the presence of more than one noise source

1.5.11 Shielding

- Metal enclosure or surface intended to prevent noise from interacting with a susceptible piece of equipment
- Shielding may be applied at the source or at the susceptible equipment

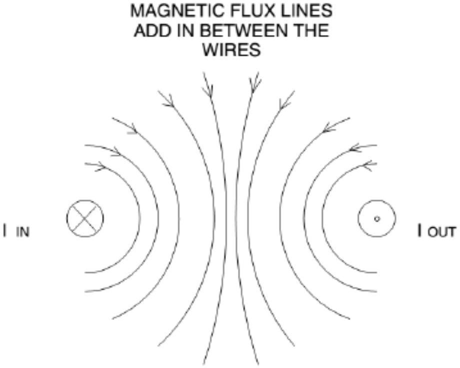


1.6 Power Frequency Fields I

- **Super low frequency (SLF) fields**
- Generated by the fundamental power frequency voltage and currents and their harmonics
- Power frequency fields do not easily interact with other power, control, or signal circuits due to the super low frequency
- Power frequency electrical fields do not easily couple to other circuits through stray capacitance between the circuits
- Power frequency magnetic fields tend to be confined to low reluctance paths that consist of ferromagnetic materials
- Power frequency currents set up magnetic fields that are free to interact with other electrical circuits and can induce noise voltages at the power frequency

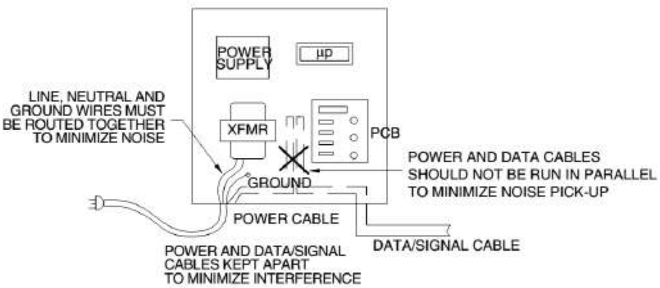
1.6 Power Frequency Fields II

- In a power circuit, magnetic fields caused by the currents in the supply and return wires essentially cancel out outside the space occupied by the wires; however, magnetic fields can exist in the space between the wires



1.6 Power Frequency Fields III

- Power wiring to a piece of equipment is self-contained, with the line, neutral, and ground wires all installed within the same conduit. The net EMF outside the conduit with this arrangement is negligible. Once the power wires enter an enclosure containing sensitive devices, special care should be exercised in the routing of the wires
- Proper and improper ways to route wires within an enclosure



1.6 Power Frequency Fields IV

- Besides keeping the supply and return wires in close proximity, it is also important to avoid long parallel runs of power and signal circuits. Such an arrangement is prone to noise pickup by the signal circuit.
- Power and signal circuits should be brought into the enclosure via separate raceways or conduits
- These steps help to minimize the possibility of low-frequency noise coupling between the power and the signal circuits
- Interaction between the low frequency fields and computer video monitor
- The net electromagnetic fields due to the high current bus or cable contained in the vault can interact with computer video monitors and produce severe distortions
- The distortions might include ghosting, skewed lines, or images that are unsteady

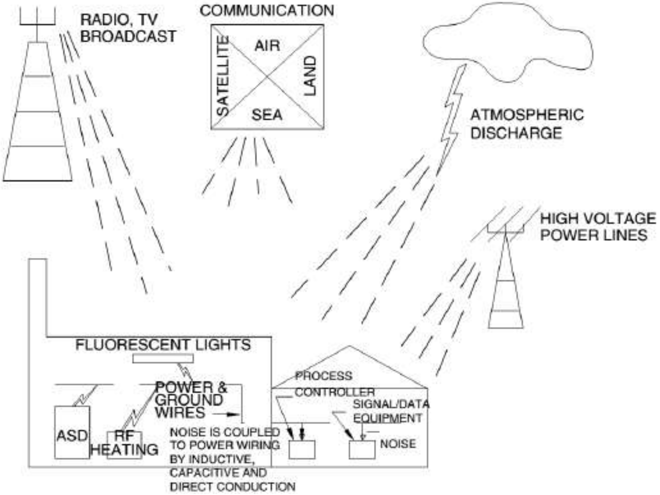
1.6 Power Frequency Fields V

- Practical solution is to provide a shielding between the electrical vault and the affected workspaces
- Shielding may be in the form of sheets of high conductivity metal such as aluminium
- When a low-frequency magnetic field penetrates a high-conductivity material, eddy currents are induced in the material. The eddy currents, which set up magnetic fields that oppose the impinging magnetic field, create a phenomenon called **reflection**
- When a material such as low carbon steel is used for shielding low-frequency magnetic fields, the magnetic fields are absorbed as losses in the ferrous metal
- High-permeability material such as Mu-metal is highly effective in shielding low-frequency magnetic fields but they are very expensive

1.6 Power Frequency Fields VI

- Magnetic fields as low as 10 mG can interact with a computer video monitor and produce distortion
- In typical commercial buildings, low-frequency magnetic fields range between 2 and 5 mG

1.7 High Frequency Fields I

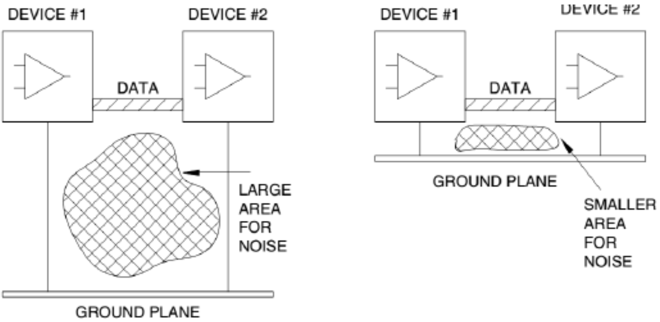


1.7 High Frequency Fields II

- EMI is commonly associated with high-frequency noise
- Common high-frequency EMI sources are radio, television, and microwave communication towers; marine or land communication; atmospheric discharges; radio-frequency heating equipment; adjustable speed drives; fluorescent lighting; and electronic dimmers
- Produce interference ranging from a few kilohertz to hundreds of megahert and perhaps higher
- Federal Communications Commission (FCC) have issued maximum limits for radiated and conducted emission for data processing
- FCC specifies two categories of devices: **Class A** and **Class B**
  - Class A devices are intended for use in an industrial or a commercial installation
  - Class B devices are intended for use in residential environments
  - Since class B devices are more apt to be installed in close proximity to sensitive equipment, class B limits are more restrictive than class A limits

1.7 High Frequency Fields III

- Location and orientation of the ground plane within a device can have a major impact on the equipment functionality

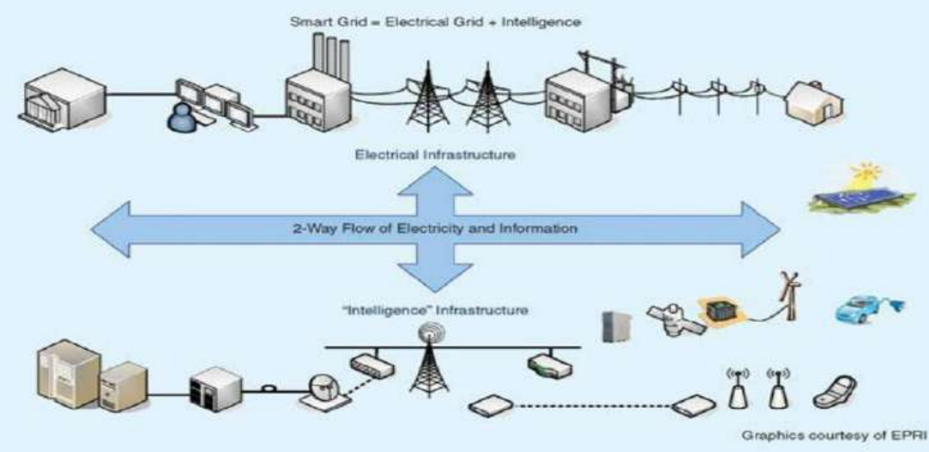


- Proper and improper ways to provide a ground plane or wire for equipment
- In figure (a), noise coupling is increased due to the large area between the signal and the ground wires

1.7 High Frequency Fields IV

- In figure (b), noise is kept to a minimum by keeping this area small
- **As much as possible, effective area between the signal wires, between the power wires, and between the wires and the ground should be kept as small as practical**

2. Power Quality Management in Smart Grid I



2. Power Quality Management in Smart Grid II

- Smart Grid: Electrical Grid with Automation, Communication and IT systems that can monitor power flows from points of generation to points of consumption and control the power flow or curtail the load to match generation in real time or near real time
- Enables two-way flow of electricity and data with digital communications technology enabling to detect, react and pro-act to changes in usage and multiple issues
- Have self-healing capabilities
- Customers become active participants
- Transformation from centralized electrical grid system to a distributed electrical system $\rightarrow$ Smart Grids

2. Power Quality Management in Smart Grid III

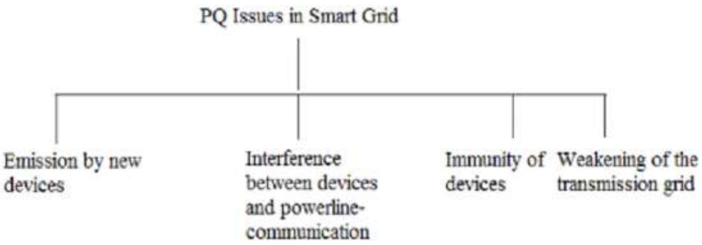
- Smart Grids are characterized by
  - **Intelligence**: capable of sensing overloads and re-routing power to prevent or minimize a potential outrage
  - **Efficient**: capable of meeting increased consumer demand without adding infrastructure
  - **Accommodating**: accepting energy from virtually any fuel source including solar and wind as easily and transparently as coal and natural gas; capable of integrating energy storage technologies
  - **Motivating**: enabling real-time communication between the consumer and utility so consumers can tailor their energy consumption based on individual preference like price
  - **Opportunistic**: creating new opportunities and markets by means of its ability to capitalize on plug and play innovation wherever and whenever appropriate
  - **Quality** : capable of delivering the power quality necessary - free of sags, spikes, disturbances, and interruption

2. Power Quality Management in Smart Grid IV

  - **Resilient**: increasingly resistant to attack and natural disaster as it becomes decentralized and reinforced with smart grids security protocols

- Aims of smart grid
  - Better, more efficient and more flexible use of the network
  - Price reduction of the network use
  - Introduction of more customer option
  - Better PQ, especially in voltage control and voltage sag impact
  - Self-healing to give better reliability

2.2 Power Quality Issues I



2.2 Power Quality Issues II

1. Emission by new devices
   - In smart grid, there will be growth in production at lower voltage levels (distributed generation) and in new types of consumption such as charging station for electric vehicles, expended high-speed railways, etc
   - New types of loads may cause harmonic production emission
   - Harmonic emission due to distributed generation is rather limited
   - Most existing end-user equipment like computer, television, lamps, etc emits exclusively at the lower odd integer harmonics
2. Interference between devices and power line-communication
   - Smart grid have a ability to communicate between devices, customers, distributed generators, and the grid operator
   - Communication channels are common
   - Power line-communication is commonly used
   - Power line-communication could introduce new disturbances which results in further reduction in power line communication, it may also result in radiated disturbances, possibly interfering with radio broadcasting and communication

2.2 Power Quality Issues III

3. Immunity of devices
    - Due to the voltage-quality disturbance, simultaneous tripping of many distributed generators can occur in smart grid
    - As smart grid attempts to maintain a balance between production and consumption, mass tripping of consumption could have similar adverse consequences
4. Weakening of the transmission grid
    - Use of distributed generation and of large wind parks will result in the reduction of the amount of conventional generation connected to the transmission system. The fault level will consequently be reduced, and power-quality disturbances will spread further

2.2 Power Quality issues of Grid connected Renewable Energy Sources I

- For grid connection of renewable energy sources, Grid-tie Inverters are used
- Use of Inverter is to take energy from grid when renewable energy is insufficient and supply energy when more power is generated
- The connection of grid with renewable energy and disconnection is done in 100ms
- Main function of converter in PV array connected grid system is to correct the magnitude and phase of the output of PV system by taking the feedback from utility grid. And in case of wind turbine connected grid system it works as isolation of mechanical and electrical frequencies

2.2 Power Quality issues of Grid connected Renewable Energy Sources II

- Technical issues associated with grid connected systems:Power Quality Issues, Power and voltage fluctuations, Storage, Protection issues, Islandin harmonics, voltage and frequency fluctuations etc.

Power quality issues of grid connected renewable energy sources

1. **Inrush Current**
    - The small inevitable difference between renewable energy source voltage and grid voltage can produce transient inrush current that flows between the REG and the distribution system at the time of connection
    - Inrush current decays to zero at an exponential rate
    - Inrush current can cause a temporary voltage sag at the neighbouring buses, thermal stress of the power components, or nuisance trips of the protection systems

2.2 Power Quality issues of Grid connected Renewable Energy Sources III

- Severity and duration of the produced inrush current depends on the system impedance, magnitude and sign of the flux linkage of the coupling transformer, and nonlinear magnetic saturation characteristic of the coupling transformer

2.2 Power Quality issues of Grid connected Renewable Energy Sources IV

2. **Safety and Protection**
   - Safety problems in REGs may arise at the time of fault occurrence and unintended islanding in specific parts of utility grids
   - Under the islanding condition, REGs may sense the loads or part of the system even after the network has been disconnected from the utility grid
   - Installed REGs can also increase fault levels and problems related to protection coordination and isolation
3. **Under voltage / Overvoltage**
   - REGs such as PV systems are usually intended to operate near unity power factor to optimize solar energy use. Therefore, these systems only inject active power into the utility side of the grid, which may change the rate of reactive power flow in the system, and the nearby buses may experience under/overvoltage problems because of the lack of reactive power.

2.2 Power Quality issues of Grid connected Renewable Energy Sources V

4. **Output Power Fluctuation**
   - Output power fluctuations happen frequently
   - Minute-to-minute variations in wind speed or solar irradiance
   - The severity of such phenomenon depends on weather conditions, installatio geographical condition and topology of the system
   - Power fluctuations may increase overloading or under-loading, unacceptable voltage fluctuations, and voltage flicker
5. **Harmonic Distortion**
   - Harmonic distortions occur because of the power inverters used in REG systems without the application of proper filters
   - Harmonic distortion can increase the risk of parallel and series resonances, overheating in capacitor banks and transformers, neutral over-current, and false operation of protective devices

2.2 Power Quality issues of Grid connected Renewable Energy Sources VI

- Grid-connected inverters for DG applications put out very low levels of harmonic current, and because of their distribution on the network are unlikely to cause harmonic issues, even at high penetration levels

6. **Frequency Fluctuation**
   - Any imbalance between power production and power consumption can result in frequency fluctuation
   - Small REG systems cause negligible frequency fluctuations compared with large REG systems
   - At increased penetration levels, REG systems can increase the severity of this problem
   - Frequency fluctuations can damage electrical machines
7. **Voltage Imbalance**
   - At high PV penetrations, the cumulative size of all systems connected to each phase should be as equal as possible

2.2 Power Quality issues of Grid connected Renewable Energy Sources VII

- All systems above a minimum power output level of between 5 to 10kW typically should have a balanced three phase output

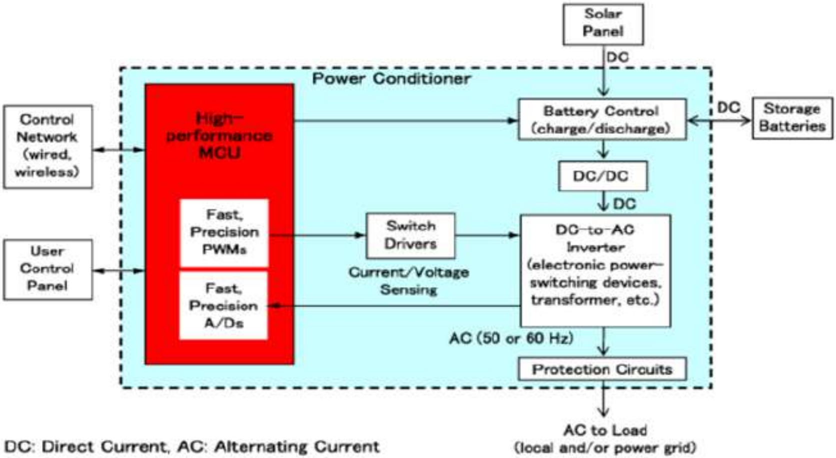
8. **Grid-Derived Voltage Fluctuations**
   - Inverters are generally configured to operate in grid voltage-following mode and to disconnect DG when the grid voltage moves outside set parameters
   - This is both to help ensure they contribute suitable power quality as well as help to protect against unintentional islanding
   - Where there are large numbers of DG systems or large DG systems on a particular feeder, their automatic disconnection due to the grid voltage being out of range can be problematic because other generators on the network will suddenly have to provide additional power

2.3 Power Quality Conditioners for Smart Grid I

- Power conditioner (also known as a line conditioner or power line conditioner) is a device intended to improve the quality of power that is delivered to electrical load equipment
- Role of a Power Quality Conditioner
  - Deliver voltage & current of the proper level and characteristics to enable load equipment to function properly
  - Ensure efficient power transfer between utility grid & micro grid
  - Isolate each micro grid and the utility grid from there respective noises and disturbances
  - Energy creation i.e. to convert DC power generated by Solar panels to AC
  - Integration with energy storage system

2.3 Power Quality Conditioners for Smart Grid II

- Block Diagram



2.3 Power Quality Conditioners for Smart Grid III

- Types
  1. Distribution Static Compensator (DSTATCOM)
  2. Active power filters
     a. Shunt active power filters
     b. Series active power filters
     c. Hybrid Active Power Filters
  3. Unified Power Quality conditioner (UPQC)

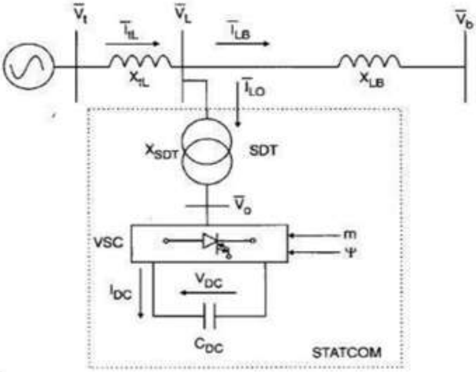
2.3 Power Quality Conditioners for Smart Grid IV

Distribution Static Compensator (DSTATCOM)

- DSTATCOM is a custom power device based on a voltage Source Converter (VSC) shunt connected to the distribution networks
- DSTATCOM is normally used to precisely regulate system voltage, improve voltage profile, reduce voltage harmonics and for load compensatio
- D-STATCOM can also mitigate voltage dips and can compensate both magnitude and phase angle by injecting reactive or reactive power to the point of connection with the grid

2.3 Power Quality Conditioners for Smart Grid V

- Block Diagram



2.3 Power Quality Conditioners for Smart Grid VI

- VSC connected in shunt with the ac system provides a multifunctional topology which can be used for up to three quite distinct purposes: voltage regulation and compensation of reactive power, correction of power factor, and elimination of current harmonics.

2.3 Power Quality Conditioners for Smart Grid VII

Active Filters

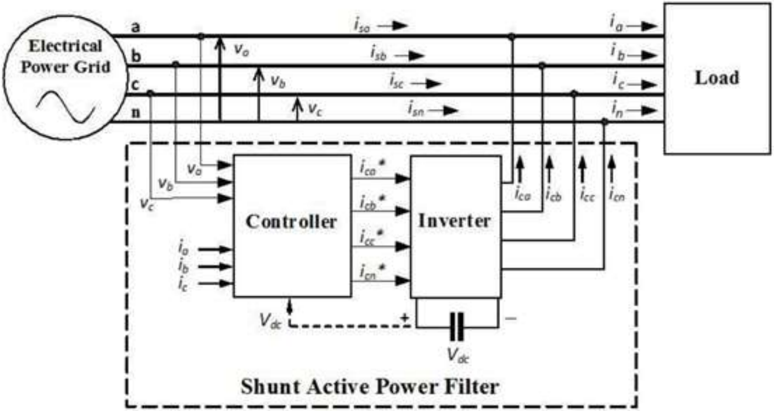
- Active power filter technology is a full fledged technique for providing compensation for reactive power, harmonics and neutral current in ac networks
- Active filters are also used to terminate the voltage harmonics, to regulate terminal voltage, to inhibit voltage flicker and to advance voltage balance in 3- phase systems

2.3 Power Quality Conditioners for Smart Grid VIII

Shunt Active Power Filter

- Compensates current harmonics by injecting equal-but opposite harmonic compensating current
- Operates as a current source injecting the harmonic components generated by the load but phase shifted by 180deg
- They are usually connected across the load to compensate for all current related problems such as reactive power compensation, power factor correction, current harmonics and load unbalance compensation

2.3 Power Quality Conditioners for Smart Grid IX

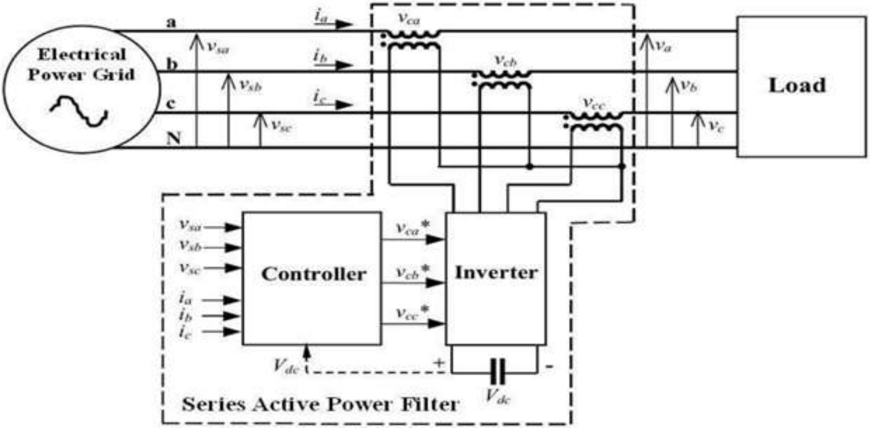


2.3 Power Quality Conditioners for Smart Grid X

Series Active Filter

- It compensate current system distortion caused by nonlinear loads
- The high impedance imposed by the series APF is created by generating a voltage of the same frequency as that of harmonic component that needs to be eliminated
- It act as a controlled voltage source and can compensate all voltage related problems such as voltage harmonics, voltage sags & swells, voltage flicker etc.

2.3 Power Quality Conditioners for Smart Grid XI

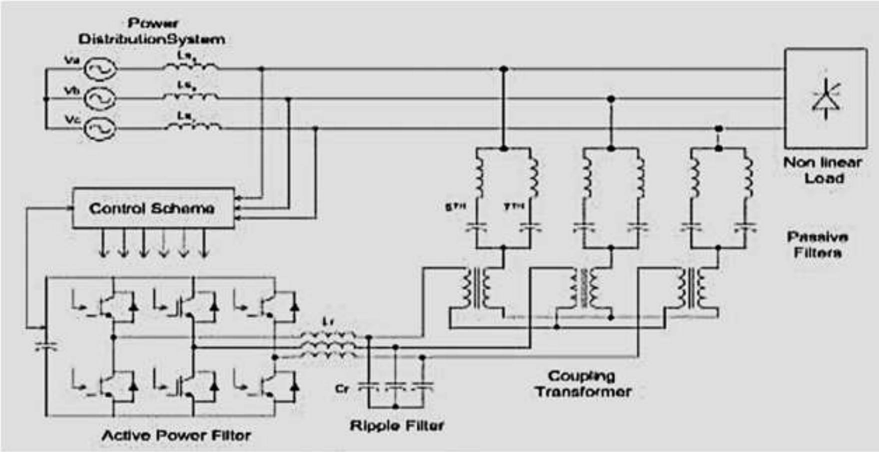


2.3 Power Quality Conditioners for Smart Grid XII

Hybrid Active Power Filter

- By controlling the amplitude of the voltage fundamental component across the coupling transformer, the PF of the power distribution system can be adjusted
- The control of the load power factor imposed a higher voltage across the filter capacitor
- This type of configuration is very convenient for compensation of high power medium voltage non linear loads

2.3 Power Quality Conditioners for Smart Grid XIII

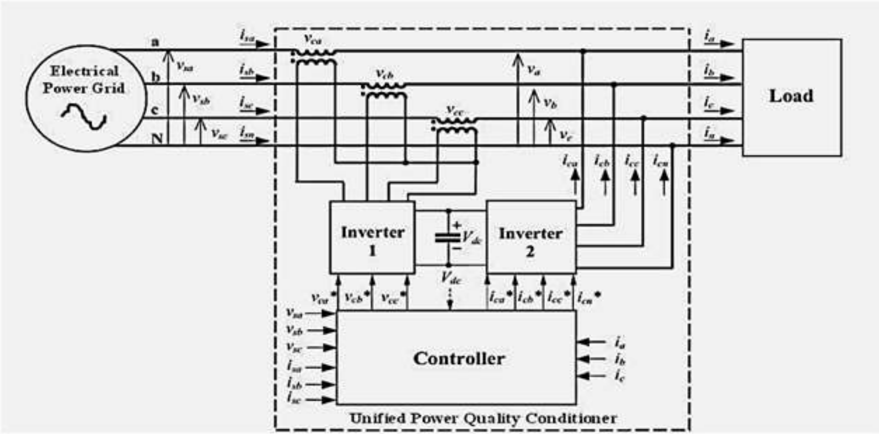


2.3 Power Quality Conditioners for Smart Grid XIV

Unified Power Quality Conditioner (UPQC)

- Unified Power Quality Conditioner (UPQC) combines the Shunt Active Power Filter with the Series Active Power Filter, sharing the same DC Link, in order to compensate both voltages and currents, so that the load voltages become sinusoidal and at nominal value, and the source currents become sinusoidal and in phase with the source voltages.
- UPQC can compensate both voltage related problems such as voltage harmonics, voltage sags/swells, voltage flicker as well as current related problems like reactive power compensation, power factor correction, current harmonics and load unbalance compensation.
- There is a significant increase in interest for using UPQC in distributed generation associated with smart grids because of availability of high frequency switching devices and advanced fast computing devices (microco DSP, FPGA) at lower cost.

2.3 Power Quality Conditioners for Smart Grid XV



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Thank You