

# **Power System Quality and Reliability**

**ECEg-6312**

**WEEK 4**

**Sources, Definitions & Standards of Harmonics**

**Course Instructor: Demsew Mitiku (PhD)**

**April 2026**

# Topic Overview

---

**This weeks discussion covers the following main topics:**

- Definitions and standards of harmonics
- Sources of harmonics
- Harmonic calculations
  - Harmonic distortion indices (THD, TDD)
- Impact on equipment and system losses
- Simulations of harmonics

# Learning Outcomes

---

**After this lesson, students should be able to:**

- Define harmonics and identify their main sources in power systems
- Interpret harmonic limits based on international standards (e.g., IEEE 519)
- Perform harmonic analysis and calculate distortion indices (THD, TDD)
- Evaluate the impact of harmonics on equipment performance and system losses
- Simulate and analyze harmonic behavior using MATLAB/Simulink

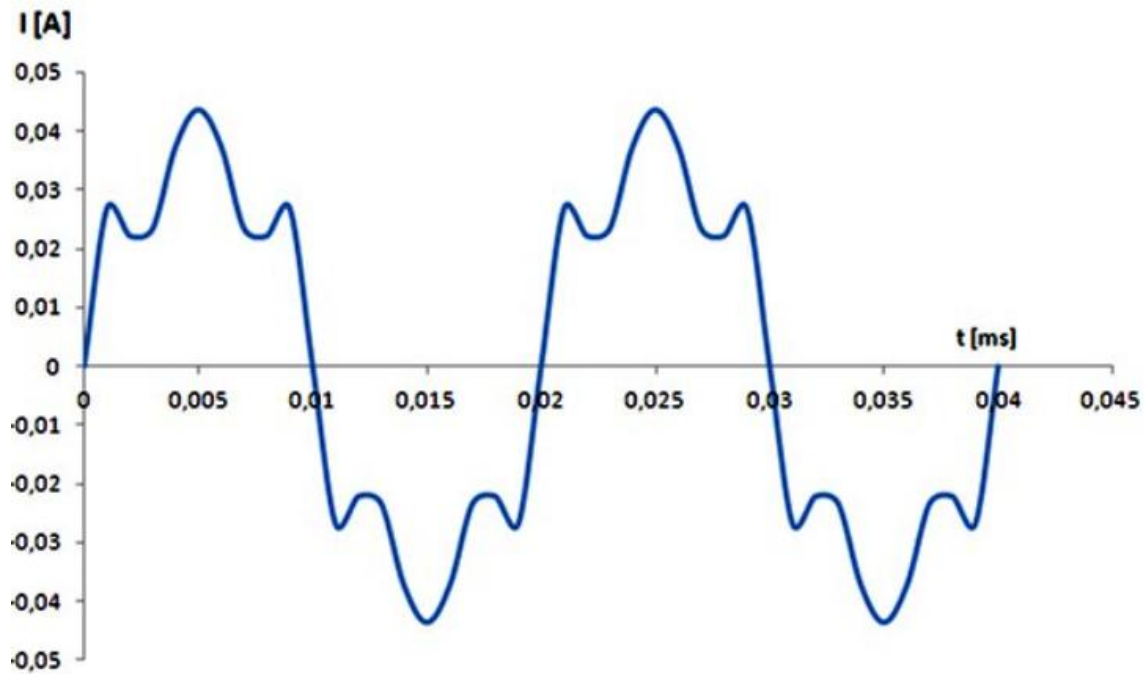
# 1. Definitions Harmonics

---

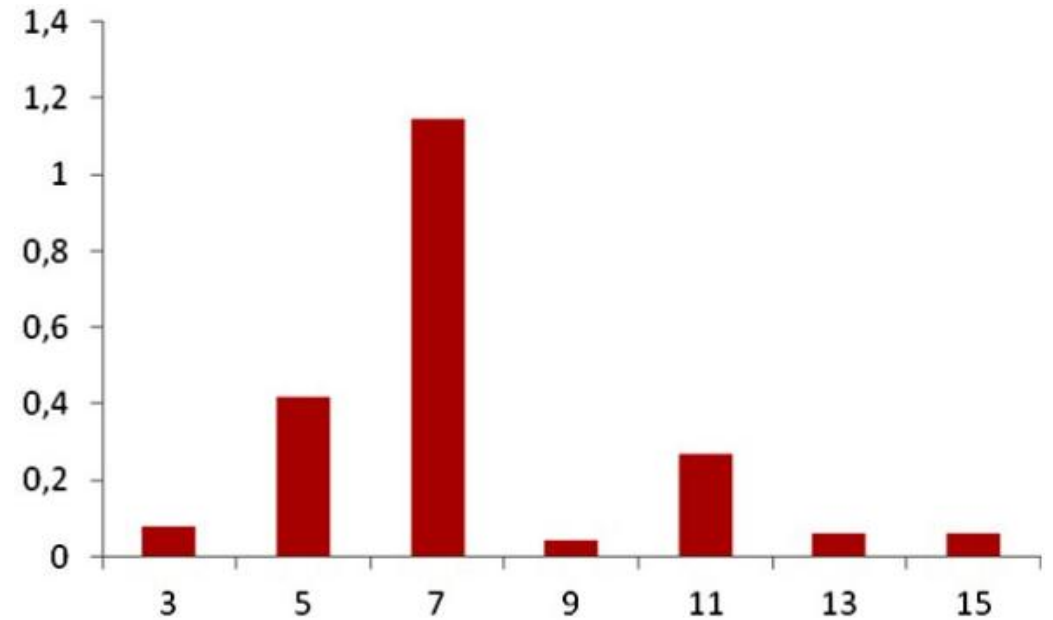
## A. Harmonics

- Sinusoidal components of a periodic waveform whose frequencies are integer multiples of the fundamental frequency ( $f_0$ )
- Represent distortion caused by nonlinear loads
- Expressed as:  $f_n = n \cdot f_0$  , where  $n = 2, 3, 4, \dots$
- Example: for a 50 Hz power systems; 100 Hz, 150 Hz, 200 Hz, 250 Hz, where  $n = 2, 3, 4, \dots$

# Cont'd...



a). Distorted current waveform.



b). Current harmonic spectrum.

**Figure 1:** A distorted voltage waveform demonstrating current harmonic [1].

# Cont'd...

## B. Interharmonics

- Frequency components that are not integer multiples of the fundamental frequency
- Typically arise from power electronic switching, cycloconverters, and variable frequency drives
- Can appear as discrete frequencies or broadband spectra.
- Example: for a 50 Hz power systems; 75 Hz, 125 Hz, 175 Hz, 225 Hz, where  $n = 1.5, 2.5, 3.5, 4.5, \dots$

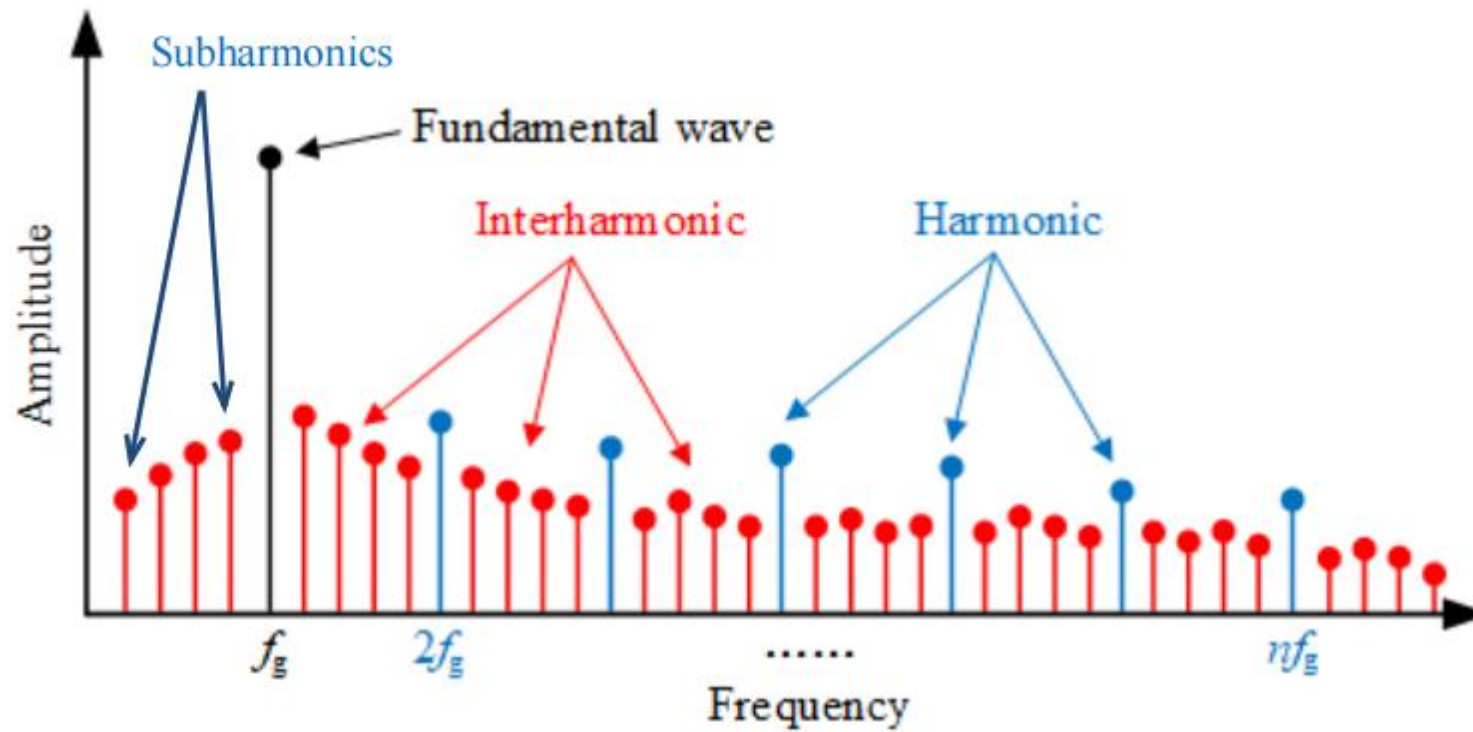
# Cont'd...

---

## C. Subharmonics

- Frequency components lower than the fundamental frequency (fractional multiples of  $f_0$  )
- Occur due to system oscillations, arc furnaces, and certain converter operations
- May cause flicker and low-frequency instability.
- Example: for a 50 Hz power systems; 5 Hz, 10 Hz, 15 Hz, 25 Hz, 40 Hz, where  $n = 0.1, 0.2, 0.3, 0.5, 0.8, \dots$

# Cont'd...



**Figure 2:** Diagram of the harmonic, interharmonic, and subharmonic spectrum [2].

## 2. Harmonic Standards

---

- Harmonic standards define acceptable limits for voltage and current distortion
- Aim to ensure power quality, equipment safety, and system reliability
- Provide guidelines for utilities and end-users
- Most Common Harmonic Standards Worldwide:
  - IEEE 519-2022 (USA & globally adopted) and IEC 61000 Series (International / Europe)
  - EN 50160 (Europe)
  - G5/5 (United Kingdom)
  - AS/NZS 61000 (Australia & New Zealand)

# 2.1. IEEE Harmonic Standard

---

- IEEE Std 519-2022 is the latest revision of the IEEE harmonic control standard, superseding IEEE 519-2014 [3].
- It remains the most widely referenced global guideline for harmonic distortion control at the Point of Common Coupling (PCC).
- **System-level** standard applied at the Point of Common Coupling (PCC)
- Defines limits for voltage and current distortion level based on system voltage level and short-circuit ratio ( $I_{sc}/I_L$ ) respectively.

# Cont'd...

- According to IEEE Std 519, Voltage Distortion Limit is summarized in **Table 1**.

**Table 1: IEEE Std 519 Voltage Distortion Limit (THD).**

Bus Voltage (kV) at PCC	Individual Harmonics (%)	Total Harmonic Distortion, THDs (%)
$\leq 1\text{kV}$	5.0	8.0
1 kV - 69 kV	3.0	5.0
69 kV - 161 kV	1.5	2.5
$> 161\text{ kV}$	1.0	1.5

# Cont'd...

---

- According to IEEE Std 519, total demand distortion ( $TDD_I$ ) instead of  $THD_I$  for compliance evaluation.
- Current distortion limits depend on the short circuit ratio:

$$\frac{I_{SC}}{I_L}$$

- where
  - $I_{sc}$  is maximum short circuit current at PCC
  - $I_L$  is maximum demand load current

# Cont'd...

**Table 2: IEEE Std 519 Current Distortion Limits (TDDI)**

$\frac{I_{SC}}{I_L}$	Harmonic Order					
	h<11	11≤h<17	17 ≤h<23	23 ≤h<35	h≥ 35	TDD
≤ 20	4 %	2 %	1.5 %	0.6 %	0.3 %	5 %
20 - 50	7 %	3.5 %	2.5 %	1 %	0.5 %	8 %
50 - 100	10 %	4.5 %	4 %	1.5 %	0.7 %	12 %
100 - 1000	12 %	5.5 %	5 %	2 %	1 %	15 %
> 1000	15 %	7 %	6 %	2.5 %	1.4 %	20 %

## 2.2. IEC Harmonic Standards

---

- The IEC harmonic standards are part of the broader Electromagnetic Compatibility (EMC) framework and are widely used in Europe and many other regions [4].
- General Framework
  - Based on IEC 61000 series (EMC standards)
  - Focuses on equipment-level harmonic emission limits
  - Ensures compatibility between devices connected to public low-voltage networks
  - Applies mainly to manufacturers and end-user equipment

# Cont'd...

---

- **IEC 61000-3-2**
  - Applies to equipment with input current  $\leq 16$  A per phase
  - Covers household and light industrial loads (Computers, TVs, LED lights, small appliances)
  - Defines limits for individual harmonic current components (up to 40<sup>th</sup> order)
- **IEC 61000-3-2**
  - Applies to equipment with input current 16 A to 75 A per phase
  - Covers medium-power industrial equipment
  - Provides limits based on: System impedance and Short-circuit ratio at PCC

# Principle of IEC Harmonic Standards

---

- Focus on emission limits (what the device injects into the grid)
- Not directly system-wide limits (unlike IEEE 519)
- Based on:
  - Individual harmonic current limits
  - Standard test conditions
  - Defined network impedance models
- Harmonic currents measured at equipment terminals and
- Test performed under standardized supply conditions

# Comparison of IEEE and IEC Standards

---

- **IEEE 519 Standard:**
  - System-level standard
  - Applies at PCC
  - Focus on overall network performance
- **IEC 61000 Series Standards:**
  - Equipment-level standards
  - Applies to individual devices
  - Focus on emission control

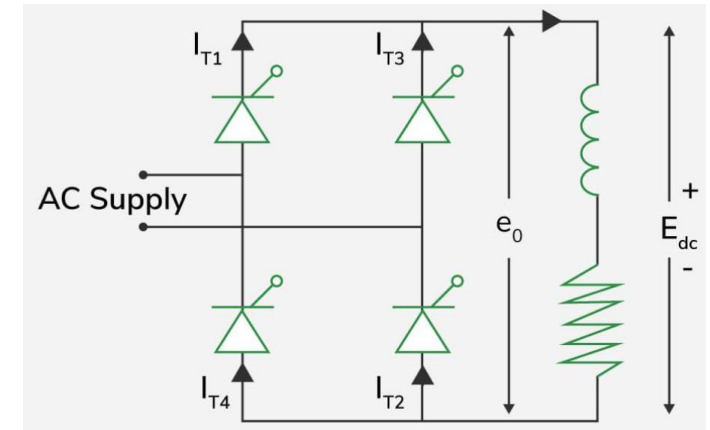
# 3. Sources of Harmonics

---

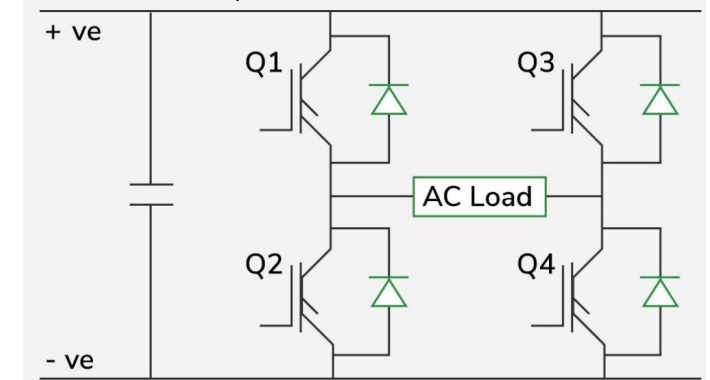
- **Harmonics** in modern power systems originate primarily from nonlinear behavior of electrical devices and switching operations.
- **These sources can be classified as follows:**
  - Power Electronic Converters
  - Adjustable Speed Drives (ASDs / VFDs)
  - Nonlinear Industrial Loads and Single-Phase Electronic Loads
  - Magnetic Core Nonlinearity
  - Power System Operation and Switching Events
  - Distributed Energy Resources (DERs)

# 3.1. Power Electronic Converters

- Represent the dominant source of harmonics in modern power systems due to high-speed switching.
- Include diode rectifiers, thyristor-controlled converters, PWM inverters, HVDC links, and DC–DC converters.
- Harmonic magnitude is influenced by:
  - Firing angle (thyristor-based converters)
  - Modulation index (PWM inverters)
  - Switching frequency and filter design
- Higher pulse number converters (12-pulse, 24-pulse) significantly reduce low-order harmonics



a). AC–DC converters



b). DC–AC converters

**Figure 3:** Power Electronics converters

## 3.2. Variable Speed Drives (VFDs)

- A VFDs are among the largest contributors of harmonics in **industrial distribution** systems
- **Typical structure:**
  - Front-end rectifier (diode or thyristor)
  - DC link (capacitor/inductor filtering)
  - Inverter stage (PWM-based switching)
- **Harmonic generation mechanisms:**
  - Nonlinear rectifier draws non-sinusoidal input current
  - DC link ripple couples switching harmonics back to AC side
  - Inverter switching introduces high-frequency components

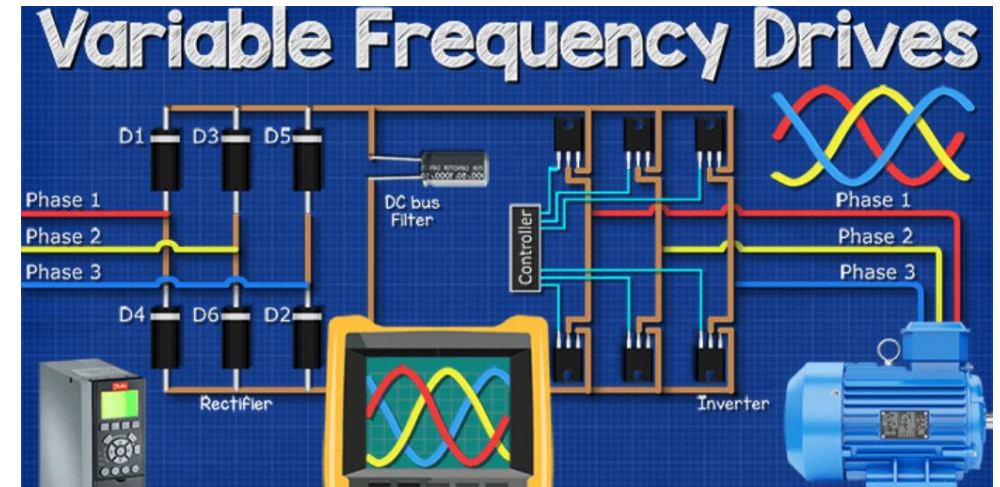


Figure 4: Variable Speed Drive

## 3.3. Nonlinear Industrial Loads

---

- Include arc furnaces, welding machines, induction heating systems, and large industrial rectifier loads.
- These loads exhibit strong time-varying and nonlinear V–I characteristics, making harmonic generation stochastic in nature.
- Harmonic behavior characteristics:
  - Non-periodic and fluctuating harmonic spectra
  - Presence of both harmonics and interharmonics due to arc instability and control variability
  - Wideband frequency distortion rather than discrete harmonic orders

## 3.4. Switching Operation

- Harmonics can be introduced or amplified due to power systems switching operations and dynamic system conditions.
- Major sources:
  - Capacitor bank switching (energization and de-energization)
  - Transformer energization (inrush current with high harmonic content)
  - Line switching and breaker operations
  - Fault occurrence and clearing processes
- Transient during switching events and saturation of transformer cores during energization leading to harmonic generation

## 3.5. Distributed Energy Resources

---

- Include grid-tied PV inverters, wind turbine converters (DFIG/full-scale), battery energy storage systems (BESS), and EV chargers.
- Interface to the grid via power electronic converters, making DERs a growing harmonic source in modern distribution networks.
- **Harmonic generation mechanisms:**
  - PWM switching in inverters produces high-frequency harmonics and sidebands
  - Controllers in DERs can introduce interharmonics under weak-grid conditions
  - LCL filters may interact with grid impedance, causing resonance peaks

# 4. Harmonic Calculations

- In power systems, **harmonic analysis** is performed in the frequency domain using Fourier series techniques.
- Any periodic non-sinusoidal waveform can be decomposed into a sum of sinusoidal components at different frequencies.

$$V(t) = \sum_{n=1}^{\infty} V_n \sin(n\omega t + \varphi_n)$$

- where,  $n$  is the harmonic order,  $n=1$  represents the fundamental frequency signal,  $n \geq 2$  represents harmonic frequencies,  $\varphi_n$  is the phase angle of the  $n^{\text{th}}$  harmonic component,  $V_n$  is the amplitude (magnitude) of the  $n^{\text{th}}$  harmonic voltage component

# 4.1. RMS Value of a Distorted Waveform

- The Root Mean Square (RMS) represents the effective value of a voltage/current of a distorted waveform.
- For a voltage signal with harmonics, the RMS value of the distorted waveform is:

$$V_{RMS} = \sqrt{\sum_{n=1}^{\infty} V_n^2}$$

- A distorted signal consists of:
  - Fundamental component (  $V_1$ , at frequency  $f_o$ )
  - Harmonic components ( $V_2, V_3, \dots$ ) at multiples of  $f_o$

## 4.2. Harmonic Indices

---

- **Purpose:**
  - Quantify the level of waveform distortion caused by harmonics using voltage and current parameters.
  - Used to evaluate power quality, system performance, and compliance with international standards (IEC, IEEE).
- **Main Harmonic Distortion Indices:**
  - Total Harmonic Distortion (THD)
  - Individual Harmonic Distortion (IHD)
  - Total Demand Distortion (TDD)

# Total Harmonic Distortion (THD)

- Measures overall distortion relative to the fundamental component
- Evaluated for both voltage and current.
- Voltage THD:

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\%$$

- Current THD:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \times 100\%$$

# Individual Harmonic Distortion (IHD)

- Measures the contribution of a single harmonic order,  $h$ .
- Evaluated for both voltage and current.
- Voltage IHD:

$$IHD_V = \frac{V_n}{V_1} \quad n > 1$$

- Current IHD:

$$IHD_I = \frac{I_n}{I_1} \quad n > 1$$

# Total Demand Distortion (TDD)

- Total Demand Distortion (TDD) is a harmonic distortion index that measures the level of current distortion relative to the maximum demand load current
- It is primarily used for system-level harmonic evaluation at the Point of Common Coupling (PCC)

$$TDD = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \times 100\%$$

- where,  $I_n$  = RMS value of the nth harmonic current and  $I_L$  is the maximum demand load current (fundamental reference current at PCC)

## 4.3. Harmonic Impedance

- Harmonic impedance is the effective impedance of a power system at a specific harmonic frequency
- It determines how the system responds to harmonic currents injected by nonlinear loads
- Unlike fundamental frequency analysis, impedance varies with harmonic order:

$$Z(n\omega) = R + jn\omega L + \frac{1}{jn\omega C}$$

- As harmonic order increases:
  - Inductive reactance increases and capacitive reactance decreases.

# 5. Impacts of Harmonics

- **In general, harmonics have a negative impact on power system:**
  - Harmonics degrade power system efficiency, reliability, and power quality
  - Increase thermal stress, electrical losses, and operational risks
  - Losses generally increase with harmonic current magnitude:

$$loss \propto I_n^2$$

- **On transformers:**
  - Increased copper ( $I^2R$ ) and core losses
  - Result: excess heating and derating of transformer capacity

# Cont'd...

---

- **Impacts on Motors:**
  - Development of torque pulsations
  - Increased mechanical vibration and acoustic noise
  - Additional rotor and stator heating which can reduced ocerall efficiency and lifetime
- **Capacitor Bank Effects**
  - Exposure to harmonic overcurrent
  - Risk of parallel/series resonance with system impedance
  - Increased dielectric stress leading to premature failure

# Cont'd...

---

- **Cable and Line Effects:** Increased losses due to
  - Skin effect (current concentrates at conductor surface at higher frequencies)
  - Proximity effect (uneven current distribution between conductors)
  - Higher overall  $I^2R$  losses and thermal stress
- **Protection System Effects**
  - Relay misoperation and False tripping due to waveform distortion
  - Errors in measurement devices (CTs, digital relays, meters)
  - Reduced reliability of protection coordination

# Example

- **A transformer** is energized with a fundamental current of 100 A, and the current contains a 5th harmonic component of 20 A. The transformer has a winding resistance of 0.02  $\Omega$  for the fundamental frequency.
  - Calculate the copper loss caused by the fundamental current.
  - Calculate the copper loss caused by the 5th harmonic current.
  - Calculate the total copper loss in the transformer.
- **Given:** Fundamental current,  $I_1 = 100\text{A}$ , harmonic current,  $I_5 = 20\text{A}$ , and

$$R = 0.02\Omega$$

# Example

## Solution:

1. Copper Loss due to Fundamental Current

$$P_{cu,1} = I_1^2 R$$

$$P_{cu,1} = (100)^2 \times 0.02 = 10000 \times 0.02 = 200 \text{ W}$$

2. Copper Loss due to 5<sup>th</sup> Harmonic Current: Higher frequency currents also cause copper loss:

$$P_{cu,5} = I_5^2 R$$

$$P_{cu,5} = (20)^2 \times 0.02 = 400 \times 0.02 = 8 \text{ W}$$

3. Total Copper Loss

$$P_{cu,total} = P_{cu,1} + P_{cu,5}$$

$$P_{cu,total} = 200 + 8 = 208 \text{ W}$$

# 6. Simulations of Harmonics

---

- **Harmonic Simulation should be done to:**
  - Model, analyze, and visualize waveform distortion in power systems
  - Validate theoretical harmonic calculations (Fourier-based methods)
  - Study impact of harmonics on voltage, current, losses, and equipment
- **Common Simulation Platforms**
  - MATLAB/Simulink, PSCAD / EMTDC,
  - ETAP, DIgSILENT PowerFactory
- **Most widely used in academic and industry studies for harmonic simulation.**

# Cont'd...

---

- **Typical Harmonic Simulation Workflow:**
  - Model nonlinear load (e.g., rectifier, inverter, VFD)
  - Run time-domain simulation of voltage and current waveforms
  - Apply FFT (Fast Fourier Transform) to extract frequency components
- **Compute:**
  - Harmonic spectrum
  - THD, TDD
  - RMS distortion levels

# References

---

- [1] D. Pejovski, D. Trajkovski, and K. Najdenkoski, “Harmonic analysis of no-load current in distribution transformers,” in Proc. 4th Student Conf. Energy Efficiency and Sustainable Development, Skopje, Macedonia, Nov. 2016.
- [2] M. Mao, X. Ni, Z. Xu, H. Sun, and C. Yin, “A comprehensive analysis of the influencing factors of interharmonics on a distributed PV grid-connected power generation system,” *Energies*, vol. 17, no. 23, p. 5958, 2024, doi: 10.3390/en17235958.
- [3] Institute of Electrical and Electronics Engineers, Recommended Practice for Monitoring Electric Power Quality, IEEE 1159, IEEE Power and Energy Society, New York, USA.
- [4] International Electrotechnical Commission, Electromagnetic Compatibility (EMC) – Part 2: Environment – Compatibility Levels for Low-Frequency Conducted Disturbances, IEC 61000 Series, Geneva, Switzerland.

**Thank You!**