Ohm's Law for AC Circuits with Sinusoidal Current. Power in an Alternating Current Circuit. Voltage Resonance.

Senior lecturer: Dosbayev Zh.M.

Introduction

- Introduction to Ohm's Law
- Alternating Current and Sinusoidal Waveform
- Ohm's Law for Alternating Current
- Impedance in AC Circuits
- Power in Alternating Current Circuits
- Phase Angle and Its Significance
- Resonance in AC Circuits
- Consequences of Resonance
- Conclusion
- Used literature

Introduction to Ohm's Law

Definition of Ohm's Law
- **Ohm's Law** states that the current (I) flowing through a conductor between two points is directly proportional to the voltage (V) across the two points and inversely proportional to the resistance (R) of the conductor.

Formula
- The basic formula is expressed as: $V = I \cdot R$
  - Where:
    - V = Voltage (in volts)
    - I = Current (in amperes)
    - R = Resistance (in ohms)

Application in AC Circuits
- In alternating current (AC) circuits, Ohm's Law still applies, but we need to consider the concept of **impedance** instead of resistance.
- **Impedance (Z)** accounts for both the resistance and the reactance (the opposition to change in current due to capacitors and inductors).

Key Points
- **AC Current**: Unlike direct current (DC), the current in AC circuits changes direction periodically, typically in a sinusoidal manner.
- **Complex Form**: The relationship in AC circuits can be expressed as: $V = I \cdot Z$
  - Here, Z includes both resistive and reactive components.
- Understanding Ohm's Law is fundamental for analyzing and designing AC circuits, as it helps predict how voltage, current, and impedance interact.

Alternating Current and Sinusoidal Waveform

Definition of Alternating Current (AC)
- **Alternating Current (AC)** is an electric current that periodically reverses direction.
- Unlike direct current (DC), where the flow of electric charge is in one direction, AC changes its direction and magnitude over time.

Sinusoidal Current
- The most common form of AC is **sinusoidal current**, which varies in a smooth, wave-like pattern.
- This waveform is mathematically described by the sine function, leading to smooth oscillations.

Mathematical Representation
- A sinusoidal current can be expressed with the following equation:

$$I(t) = I_{\max} \cdot \sin(2\pi f t + \phi)$$

- Where:
  - I(t) = instantaneous current at time t
  - Imax= maximum current (peak value)
  - f= frequency (in hertz)
  - ϕ = phase angle (in radians)

Alternating Current and Sinusoidal Waveform

Graphical Representation
- **Graph**: Include a graph showing a sine wave.
  - The x-axis represents time, while the y-axis represents current.
  - Key points:
    - The peak (maximum current) occurs at 90∘ (or $\pi/2$ radians).
    - The current crosses zero at 0∘ (0 radians) and 180∘(π radians), indicating direction change.

Importance of Sinusoidal Waveform
- **Advantages**:
  - Sinusoidal waves are easy to generate and transform.
  - They are the basis for many electrical systems and devices, such as transformers and motors.

  - **Harmonics**:
  - While sinusoidal is the ideal form, real-world AC can have harmonic distortions, which are integer multiples of the fundamental frequency.

Ohm's Law for Alternating Current

Application of Ohm's Law in AC Circuits
- Ohm's Law applies to AC circuits, but we replace resistance with **impedance**.
- Impedance accounts for both resistive and reactive components in the circuit, influencing how voltage and current behave.

Impedance (Z)
- **Definition**: Impedance is the total opposition to the flow of alternating current in a circuit and is represented as:

$$Z = R + jX$$

- Where:
  - Z = Impedance (in ohms)
  - R = Resistance (real part, in ohms)
  - X = Reactance (imaginary part, in ohms)
  - j = Imaginary unit (used to represent the phase shift in AC circuits)

  Formula for AC Circuit
  - The modified Ohm's Law for AC circuits can be expressed as: V=I·Z
- Here, V is the voltage across the impedance, I is the current through the impedance, and Z is the total impedance.

$$V = I \cdot Z$$

Ohm's Law for Alternating Current

Key Points

- **Reactance:**

  - Reactance (X) can be capacitive ($X_C = -\frac{1}{\omega C}$) or inductive ($X_L = \omega L$), where:

    - $\omega = 2\pi f$ (angular frequency)

    - C = capacitance (in farads)

    - L = inductance (in henries)

- **Total Impedance:**

  - The total impedance in a circuit may be calculated using:

$$Z = \sqrt{R^2 + X^2}$$

- **Phase Relationship:**

  - The phase angle (ϕ) between voltage and current can be derived from:

$$\tan(\phi) = \frac{X}{R}$$

  - This phase difference is crucial for understanding power factor and circuit behavior.

Impedance in AC Circuits

Definition of Impedance
- **Impedance (Z)** is the measure of opposition that a circuit presents to the flow of alternating current (AC).
- It combines both resistance and reactance into a single complex quantity.

Components of Impedance
- **Resistance (R):**
    - The part of impedance that opposes current flow in a purely resistive manner.
    - Measured in ohms (Ω).

    - **Reactance (X):**
    - The part of impedance that opposes current flow due to capacitors and inductors.
    - Can be:
        - **Inductive Reactance (XL):**
            - Caused by inductors; increases with frequency.
            - Formula:
            $$X_L = \omega L = 2\pi f L$$

            - Where L is inductance in henries.

        - **Capacitive Reactance (XC):**
            - Caused by capacitors; decreases with frequency.
            - Formula:
            $$X_C = -\frac{1}{\omega C} = -\frac{1}{2\pi f C}$$

            - Where C is capacitance in farads.

Impedance in AC Circuits

Total Impedance Calculation
- The total impedance in an AC circuit can be calculated using the formula:

$$Z = \sqrt{R^2 + X^2}$$

- This formula illustrates how resistance and reactance combine to form the total opposition to current flow.

Phasor Representation
- Impedance can be represented in the complex plane:
  - The horizontal axis represents resistance (R).
  - The vertical axis represents reactance (X).
- The angle (ϕ) between the impedance vector and the real axis represents the phase difference between voltage and current.

Importance of Impedance in Circuit Design
- **Circuit Behavior**: Understanding impedance is essential for predicting how AC circuits will behave, especially under varying frequencies.
- **Resonance Conditions**: Impedance is crucial in determining resonance conditions in circuits, which can enhance or dampen circuit performance.
- **Power Factor**: Impedance affects the power factor of a circuit, influencing the efficiency of power delivery.

Power in Alternating Current Circuits

Types of Power in AC Circuits
1. Active Power (P):
1. Also known as **real power**.
2. The actual power consumed by the circuit to perform work, measured in watts (W).
3. Formula:

$$P = V \cdot I \cdot \cos(\phi)$$

Where:
1. VVV = voltage (RMS value)
2. III = current (RMS value)
3. $\cos(\phi)$\cos(\phi)$\cos(\phi)$ = power factor (ratio of active power to apparent power)

2. Reactive Power (Q):
1. The power stored and released by reactive components (inductors and capacitors), measured in volt-amperes reactive (VAR).
2. Formula:

$$Q = V \cdot I \cdot \sin(\phi)$$

3. It does not perform any real work but is essential for maintaining electric and magnetic fields in AC systems.
3. Apparent Power (S):
1. The total power in an AC circuit, combining both active and reactive power, measured in volt-amperes (VA).
2. Formula:

$$S = V \cdot I$$

3. Apparent power can be visualized as the hypotenuse of a right triangle, where the other two sides represent active and reactive power.

Power in Alternating Current Circuits

Power Triangle
- The relationship between active, reactive, and apparent power can be visualized using a power triangle:
  - The horizontal leg represents active power (P).
  - The vertical leg represents reactive power (Q).
  - The hypotenuse represents apparent power (S).

Power Factor
- The **power factor (PF)** is defined as:

$$PF = \frac{P}{S} = \cos(\phi)$$

- It indicates the efficiency of power usage in an AC system. A power factor of 1 (or close to it) means that most of the power is being effectively converted into useful work.

Importance of Power in AC Circuits
- **Efficiency**: Understanding the different types of power is crucial for improving energy efficiency in electrical systems.
- **Load Management**: Helps in managing loads and preventing overloading of electrical systems.
- **Design Considerations**: Influences the design and selection of electrical equipment, ensuring they operate effectively under varying loads.

Phase Angle and Its Significance

Definition of Phase Angle
- The **phase angle (ϕ)** is the angle between the voltage and current waveforms in an AC circuit.
- It is measured in degrees or radians and represents the time difference between the peak values of voltage and current.

Calculation of Phase Angle
- The phase angle can be calculated using the relationship between resistance and reactance:

$$\tan(\phi) = \frac{X}{R}$$

- Where:
  - X = total reactance (inductive or capacitive)
  - R = resistance
- Alternatively, it can be determined from the power factor:

$$\phi = \cos^{-1}(PF)$$

Phase Angle and Its Significance

Importance of Phase Angle
1. **Power Factor**:
    1. The phase angle directly affects the power factor of the circuit:

$$PF = \cos(\phi)$$

    A smaller phase angle (closer to 0) indicates a higher power factor, meaning more efficient power usage.
    2. **Circuit Behavior**:
    1. The phase angle determines how voltage and current interact in the circuit:
        1. **Leading Phase**: In a capacitive circuit, current leads voltage (e.g., capacitors).
        2. **Lagging Phase**: In an inductive circuit, current lags behind voltage (e.g., inductors).
    2. This behavior influences how energy is stored and released in reactive components.
3. **Resonance Conditions**:
    1. In resonant circuits, the phase angle can approach 0 or 180 degrees, indicating maximum power transfer or minimal impedance.
    2. Understanding resonance helps in tuning circuits for optimal performance.
4. **Transient Analysis**:
    1. The phase angle is crucial for analyzing transient responses in AC circuits, helping predict how systems react to sudden changes.

Visualization
- **Phasor Diagram**: Include a phasor diagram to illustrate the relationship between voltage and current vectors:
    - Voltage vector (V) and current vector (I) are represented as arrows in the complex plane.
    - The angle between them is the phase angle (ϕ\phi$\phi$), highlighting leading or lagging conditions.

Conclusion
- The phase angle is a fundamental concept in AC circuit analysis, affecting power factor, circuit efficiency, and overall system performance.

Resonance in AC Circuits

Definition of Resonance
- **Voltage resonance** occurs in an AC circuit when the reactive components (inductors and capacitors) are arranged such that the inductive reactance (XL) equals the capacitive reactance (XC).
- At this point, the circuit can oscillate at a specific frequency, known as the **resonant frequency**.

Resonant Frequency
- The resonant frequency (f0f_0f0) can be calculated using the formula:

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

- Where:
  - L = inductance (in henries)
  - C = capacitance (in farads)

Conditions for Resonance
- At resonance:

$$X_L = X_C$$

The impedance of the circuit is minimized, ideally becoming purely resistive.
- The total impedance (Z) is at its minimum value, which can lead to significantly higher current in the circuit.

Resonance in AC Circuits

Effects of Resonance

1. **Increased Voltage and Current**:
    1. At resonance, the voltage across the reactive components can significantly exceed the supply voltage, leading to higher currents.
    2. This can be visualized in a resonant circuit as the buildup of oscillating energy.

2. **Quality Factor (Q)**:
    1. The **quality factor (Q)** of a resonant circuit is a measure of its selectivity and sharpness of resonance:

$$Q = \frac{f_0}{\Delta f}$$

   Where Δf is the bandwidth of the resonance.
   A higher Q indicates a sharper resonance, meaning the circuit can select a narrower range of frequencies effectively.

   3. **Potential Issues**:
   1. **Overvoltage**: The increase in voltage can lead to component damage if not managed properly.
   2. **Instability**: Systems that are overly resonant may become unstable, causing unwanted oscillations.

Applications of Resonance

- **Tuning Circuits**: Used in radios and communication devices to select specific frequencies.
- **Filter Design**: Employed in audio and signal processing to allow or block certain frequency ranges.
- **Induction Heating**: Utilized in applications where heating is achieved through resonant circuits.

Visualization

- **Resonance Curve**: Include a graph showing the relationship between impedance and frequency, highlighting the peak at the resonant frequency where the impedance is minimized.

Conclusion

- Understanding voltage resonance is crucial for designing and analyzing AC circuits, ensuring efficient operation and preventing potential issues related to excessive voltage and current.

Consequences of Resonance

Increased Voltage and Current Amplitude
- At resonance, the circuit can experience a dramatic increase in both voltage and current.
- This amplification occurs because the reactive components (inductors and capacitors) effectively store and release energy, leading to oscillations that can significantly exceed the source values.

Potential Issues
1. **Overvoltage**:
   1. The voltage across reactive components can exceed the power supply voltage, potentially damaging components.
   2. Insulation breakdown may occur, leading to circuit failure or safety hazards.
2. **Overcurrent**:
   1. Increased current can lead to overheating and failure of circuit elements, such as wires and components not rated for the high currents.
   2. Protective devices, such as fuses and circuit breakers, may trip or fail to protect the circuit.
3. **Equipment Damage**:
   1. Excessive voltage and current levels can damage sensitive electronic components, reducing the lifespan of devices and systems.
   2. Continuous operation at resonant conditions can lead to catastrophic failures.

Applications of Resonance
- **Inductive and Capacitive Circuits**:
  - In certain applications, resonance is exploited to enhance performance, such as in:
    - **LC Circuits**: Used in tuning and filtering applications, allowing specific frequencies to resonate while rejecting others.
    - **RF Circuits**: In radio frequency applications, resonance helps select desired frequencies for transmission and reception.
- **Audio Systems**:
  - In audio applications, resonance can enhance sound quality by tuning speakers and amplifiers to desired frequencies, but must be managed to avoid distortion.

Consequences of Resonance

Mitigating Resonance Effects
1. Damping:
1. Adding resistive components can dampen oscillations and reduce peak voltages and currents, enhancing stability.
2. Damping can be achieved using resistors or specialized damping circuits.

2. Circuit Design:
1. Careful design and selection of components can minimize the risks associated with resonance.
2. Engineers must consider resonant frequencies during design to avoid unintended resonance in critical applications.

3. Monitoring and Protection:
1. Incorporating monitoring systems can help detect excessive voltage and current levels, allowing for timely intervention.
2. Circuit protection devices, such as surge protectors and fuses, can prevent damage due to unexpected resonance.

Conclusion

Key Takeaways
- **Ohm's Law in AC Circuits**:
  - Ohm's Law applies to AC circuits through the concept of impedance, which combines resistance and reactance.
  - Understanding the relationship between voltage, current, and impedance is essential for effective circuit analysis.
- **Power in AC Circuits**:
  - AC circuits exhibit three types of power: active (real), reactive, and apparent. Each plays a vital role in circuit performance.
  - The power factor is crucial for determining efficiency, impacting how effectively electrical power is utilized.
- **Phase Angle**:
  - The phase angle (ϕ\phi$\phi$) between voltage and current is fundamental to understanding AC circuit behavior.
  - It influences the power factor and helps determine the relationship between reactive and resistive components.
- **Voltage Resonance**:
  - Resonance can lead to significant increases in voltage and current, which can be beneficial in some applications but may pose risks of overvoltage and overcurrent.
  - The resonant frequency is critical for tuning circuits and maximizing performance in RF applications.

Importance of Understanding AC Circuit Concepts
- Mastery of these concepts is essential for electrical engineers and technicians to design, analyze, and troubleshoot AC circuits effectively.
- Awareness of resonance and its consequences helps prevent potential issues, ensuring safe and efficient operation of electrical systems.

Future Considerations
- As technology advances, the importance of understanding AC circuit principles will continue to grow, especially with the rise of smart technologies and renewable energy systems.
- Ongoing education and training in AC circuit theory will be vital for professionals in the electrical engineering field.

Questions and Answers
- Invite questions from the audience to clarify concepts and engage in further discussion on topics related to Ohm's Law, power in AC circuits, and resonance.

Used literature

Books:
- "Electrical Engineering: Principles and Applications" by Allan R. Hambley
  - This book provides a comprehensive overview of electrical engineering concepts, including AC circuits and resonance.
- "Fundamentals of Electric Circuits" by Charles K. Alexander and Matthew N.O. Sadiku
  - A detailed resource covering circuit analysis, including AC circuit theory and impedance.
- "The Art of Electronics" by Paul Horowitz and Winfield Hill
  - A practical guide to electronics that includes discussions on AC circuits and resonant behavior.

Textbooks:
- "AC Circuit Analysis" by J. David Irwin and R. Mark Nelms
  - Focuses specifically on AC circuit theory, providing detailed explanations of concepts like impedance and resonance.
- "Electric Circuits" by James W. Nilsson and Susan Riedel
  - A widely used textbook that covers basic and advanced concepts in circuit analysis, including AC and resonance topics.

Online Resources:
- Khan Academy: Offers free online courses on electrical engineering concepts, including videos on Ohm's Law and AC circuits.
- MIT OpenCourseWare: Provides access to course materials for electrical engineering, including lectures on AC circuit analysis.
- Electronics Tutorials: Websites that offer tutorials on AC circuit fundamentals, including explanations of voltage resonance and power calculations.
- Research Papers and Articles:
- Search for scholarly articles on AC circuit theory and resonance in databases like IEEE Xplore, ScienceDirect, or Google Scholar.
- Look for articles that discuss practical applications and implications of resonance in electrical systems.