Chapter 23

Transformers and Coupled Circuits

Transformer Construction

- Transformer is a magnetically coupled circuit
- It consists of two coils wound on a common core

Transformer Construction

- Power flows from one circuit to the other circuit
  - Through the medium of the magnetic field

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Transformer Construction

- There is no electrical connection between the two coils
- Coil (winding) on side of the transformer to which we apply power is called primary

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Transformer Construction

- Coil on side to which we connect the load is called the secondary

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Transformer Construction

- Iron-core transformers
  - Generally used for low-frequency applications (such as audio and power)
- Iron core provides an easy path for magnetic flux

Transformer Construction

- Two basic construction types
  - Core and shell
- Each type uses laminated sheets of metal to reduce eddy currents

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Transformer Construction

- Air-core and ferrite-core types
  - Used for high-frequency applications (such as radio frequencies)

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Transformer Construction

- These do not have high hysteresis and eddy-current losses of iron-core transformers
- Ferrite
  - Increases coupling between coils while maintaining low losses

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Transformer Construction

- Transformer may be used to change polarity of an ac voltage
  - Depending on the directions of its windings

Transformer Construction

- If most of the flux produced by one of the coils links the other
  - Coils are tightly coupled
  - Otherwise loosely coupled
- All transformer operations are described by Faraday's law

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Voltage Ratio for Ideal Transformers

- If we apply Faraday's law, where *N* is the number of turns and ϕ is the flux, then

$$e_p = N_p \frac{\Delta\Phi}{\Delta t}$$

$$e_s = N_s \frac{\Delta\Phi}{\Delta t}$$

$$\frac{e_p}{e_s} = \frac{N_p}{N_s}$$

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Voltage Ratio for Ideal Transformers

- Ratio of primary voltage to secondary voltage
  - Equal to ratio of the number of turns

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The Turns Ratio

- Turns ratio (or the transformation ratio)
  - $a = N_p/N_s$
- Also, $e_p/e_s = a$

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The Turns Ratio

- A step-up transformer
  - Secondary voltage is higher than the primary voltage ($a < 1$)
- A step-down transformer
  - Secondary voltage is lower ($a > 1$)

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The Current Ratio

- In an ideal transformer
  - Power in equals power out (η = 100%)
- Ratios of the current are

$$e_p i_p = e_s i_s$$

$$\frac{i_p}{i_s} = \frac{e_s}{e_p} = \frac{1}{a}$$

The Current Ratio

- If voltage is stepped up
  - Current is stepped down, and vice versa

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Reflected Impedance

- A load impedance $\mathbf{Z}_L$ connected directly to a source is seen as $\mathbf{Z}_L$
- Impedance will be seen by the source differently
  - If a transformer is connected between the source and the load

Reflected Impedance

- Reflected impedance, $\mathbf{Z}_p$, is given by
  - $\mathbf{Z}_p = a^2\mathbf{Z}_L$

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Reflected Impedance

- Load characteristics do not change
  - Capacitive loads still look capacitive, etc.
- A transformer can make a load look larger or smaller
  - Depending on the turns ratio

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Reflected Impedance

- Using a transformer
  - We can match loads to sources (such as amplifiers)
- Relates to the maximum power theorem discussed in a previous section

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Transformer Ratings

- Transformers are rated in terms of voltage and apparent power
- Rated current can be determined from these ratings

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Transformer Ratings

- By dividing the apparent power rating by the voltage rating
  - Rated current is determined, regardless of the power factor

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Power Supply Transformers

- Used to convert the incoming 120 V source to voltage levels required by circuit
- Some have a multi-tapped secondary winding to provide different voltages for different applications

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Power Supply Transformers

- Typically, an incoming voltage is
  - Stepped down
  - Rectified
  - Smoothed by a filter
  - Passed through a voltage regulator

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Transformers in Power Systems

- Transformers are used at generating stations to raise voltage for transmission
  - This lowers losses in the transmission lines
- At the user end
  - Voltage is stepped down

Transformers in Power Systems

- Transformers have a split secondary
  - This permits both 120-V and 240-V loads to be supplied from the same transformer
- For residential use
  - Single phase is used

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Isolation Applications

- Transformers are sometimes used to isolate equipment
- Isolation transformers are often used to make measurements involving high voltages

Isolation Applications

- They can also ensure that a grounded metal chassis is not connected to a hot wire

Isolation Applications

- Readings can be made on an oscilloscope
  - Must have a grounded lead without shorting circuit components across ground connections by using a 1:1 transformer

Impedance Matching

- A transformer can be used to raise or lower apparent impedance of a load
- Impedance matching
  - Sometimes used to match loads to amplifiers to achieve maximum power transfer

Impedance Matching

- If load and source are not matched
  - A transformer, with the proper turns ratio, can be inserted between them

Autotransformers

- In autotransformers
  - Primary circuit is not electrically isolated from its secondary
  - They cannot be used as isolation transformers

Autotransformers

- Smaller and cheaper than conventional transformers with the same load kVA

Practical Iron-Core Transformers

- Non-ideal transformers have several effects that cause loss of power
- Leakage flux
  - Will appear as small inductances in series with the windings

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Practical Iron-Core Transformers

- Winding resistance
- Core losses due to eddy currents and hysteresis
- Magnetizing current

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Transformer Efficiency

- Efficiency is ratio of output power to input power
  - Given as a percentage.
- Losses
  - Due to power losses in the windings and in core

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Transformer Efficiency

- Large transformers can have efficiencies of 98 to 99 percent
- Smaller transformers have efficiencies of about 95 percent

Transformer Tests

- Losses may be determined by making tests on transformers
- Short-circuit tests
  - Determine losses due to resistance of windings
- Open-circuit tests will determine core losses

Voltage and Frequency Effects

- As applied voltage increases, core flux increases, causing greater magnetization current
  - Therefore, transformers should be operated only at or near their rated voltage

Voltage and Frequency Effects

- At very low frequencies
  - Core flux and the magnetizing current increases
    - Causing large internal voltage drops
- At very high frequencies
  - Stray capacitances and inductances cause voltage drops

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Loosely Coupled Circuits

- Circuits without an iron core, where only a portion of the flux produced by one coil links another
- Cannot be characterized by turns ratios
  - They are characterized by self- and mutual inductances

Loosely Coupled Circuits

- Expressed by coefficient of coupling
  – Air-core
  – Ferrite-core transformers
  – General inductive circuit coupling

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Loosely Coupled Circuits

- Self-induced voltage in a coil is
  – $v = L\, di/dt$
- Mutually induced voltage of a coil is
  – $v = M\, di/dt$
  – *M* is mutual inductance between coils

Loosely Coupled Circuits

- In each coil
  - Induced voltage is the sum of its self-induced voltage
  - Plus voltage mutually induced due to the current in the other coil

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Loosely Coupled Circuits

- Coefficient of coupling, *k*
  - Describes degree of coupling between coils
- Mutual inductance depends on *k*:

$$M = k\sqrt{L_1 L_2}$$

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Loosely Coupled Circuits

- Coupled impedance is

$$\mathbf{Z}_{\text{in}} = \mathbf{Z}_p + \frac{(\omega M)^2}{\mathbf{Z}_s + \mathbf{Z}_L}$$

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