BEEE

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Objectives

- Define basic components of electricity
- Recognize the 3 electrical classifications of materials
- Compare and contrast AC vs. DC
- Explain the concept of grounding
- Use Ohm's law and Watt's law to express the relationship between current, voltage, and resistance

Electricity can be broken down into:

- Electric Charge
- Voltage
- Current
- Resistance

Negative & Positive Charges

- What do the effects of electricity in TV, radio, a battery, and lightening all have in common?
- Basic particles of electric charge with opposite polarities.

Electrons

- The smallest amount of electrical charge having the quality called negative polarity.
- Electrons orbit the center of atoms.

Protons

- The proton is a basic particle with positive polarity.
- Protons are located in the nucleus of atoms along with neutrons, particles which have neutral polarity.

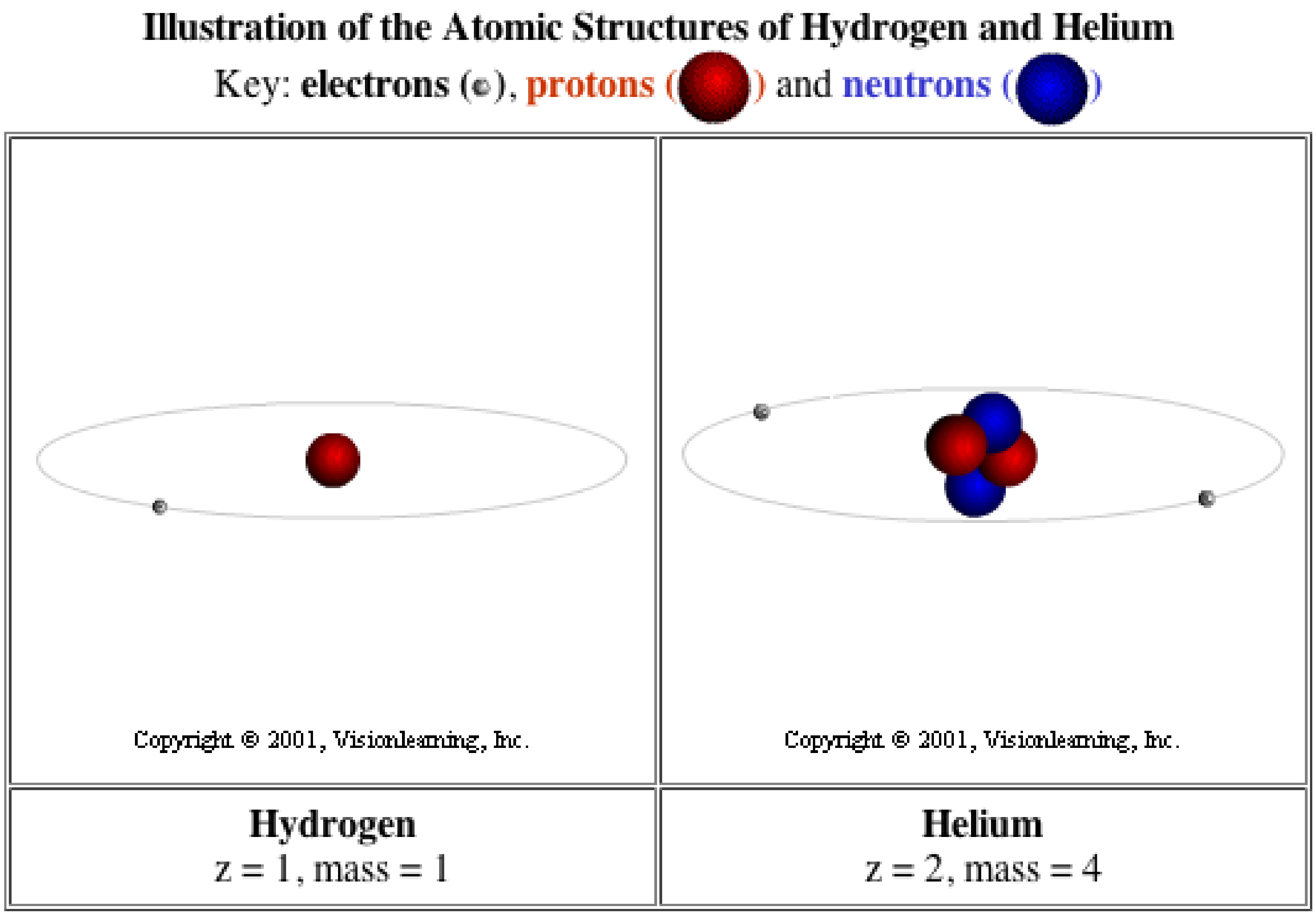
Illustration of the Atomic Structures of Hydrogen and Helium
Key: electrons ( ), protons ( ) and neutrons ( )
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Hydrogen
z = 1, mass = 1
Helium
z = 2, mass = 4

Electrically, all materials fall into 1 of 3 classifications:

- Conductors
- Insulators
- Semi-Conductors

Conductors

- Have 1 valence electron
- Materials in which electrons can move freely from atom to atom are called conductors.
- In general all metals are good conductors.
- The purpose of conductors is to allow electrical current to flow with minimum resistance.

Insulators

- Have 8 valence electrons
- Materials in which electrons tend to stay put and do not flow easily from atom to atom are termed insulators.
- Insulators are used to prevent the flow of electricity.
- Insulating materials such as glass, rubber, or plastic are also called **dielectrics**, meaning they can store charges.
- Dielectric materials are used in components like capacitors which must store electric charges.

Semi-Conductors

- Have 4 valence electrons
- Materials which are neither conductors nor insulators
- Common semi conductor materials are carbon, germanium and silicone.
- Used in components like transistors

The Symbol for Charge

- The symbol for charge is Q which stands for quantity.
- The practical unit of charge is called the coulomb (C).
- One coulomb is equal to the amount of charge of 6.25×10^{18} electrons or protons stored in a dielectric.

Voltage

- Potential refers to the the possibility of doing work.
- Any charge has the potential to do the work of attracting a similar charge or repulsing an opposite charge.
- The symbol for potential difference is E (for electromotive force)
- The practical unit of potential difference is the volt (V)
- 1 volt is a measure of the amount of work required to move 1C of charge

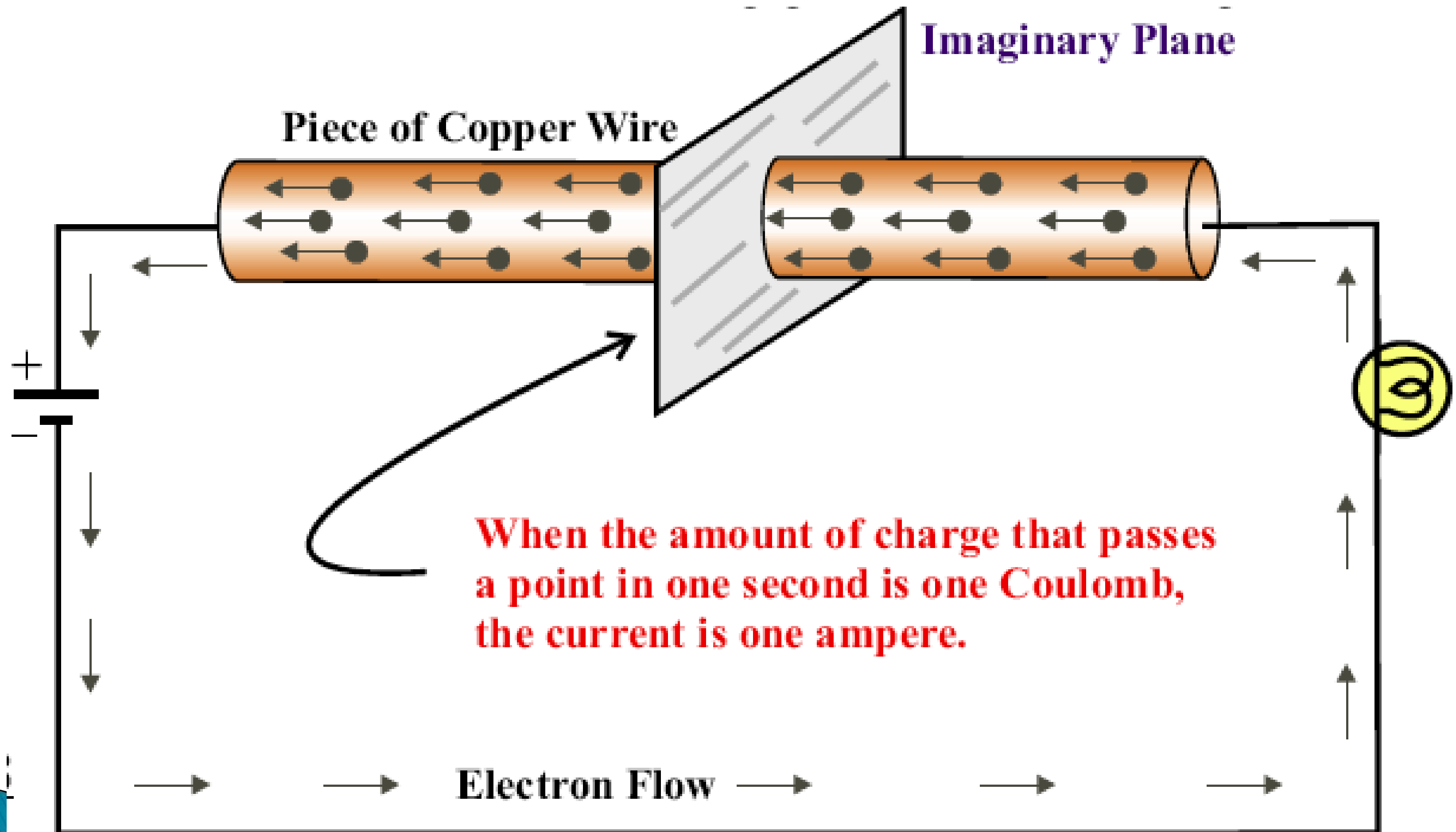
Current

- When a charge is forced to move because of a potential difference (voltage) current is produced.
- In conductors - free electrons can be forced to move with relative ease, since they require little work to be moved.
- So current is charge in motion.
- The more electrons in motion the greater the current.

Amperes

- Current indicates the intensity of the electricity in motion. The symbol for current is I (for intensity) and is measured in **amperes.**
- The definition of current is: $I = Q/T$
- Where I is current in amperes, Q is charge in coulombs, and T is time in seconds.

1 ampere = 1 coulomb per second



Resistance

- Opposition to the flow of current is termed **resistance.**
- The fact that a wire can become hot from the flow of current is evidence of resistance.
- Conductors have very little resistance.
- Insulators have large amounts of resistance.

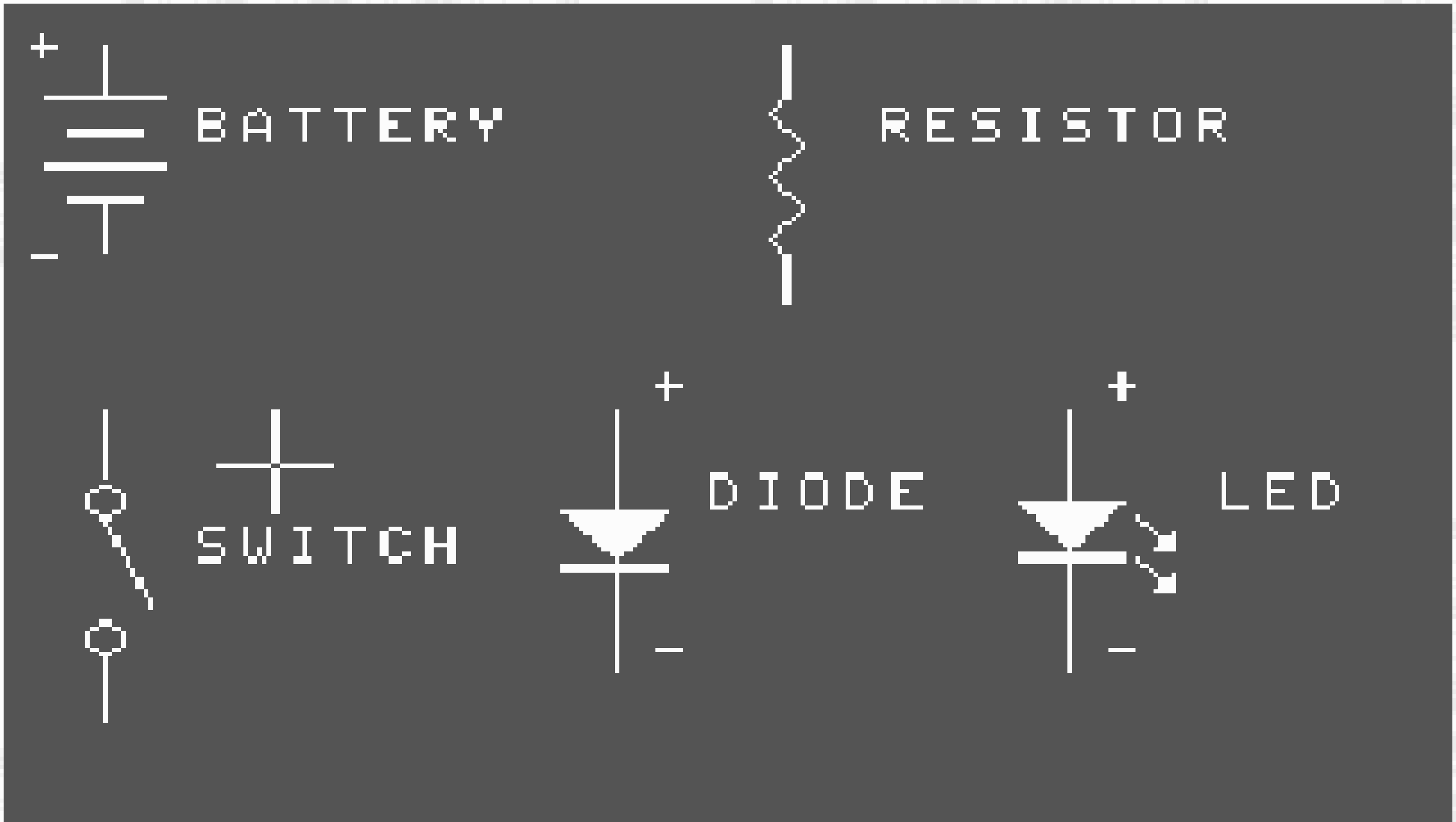
Ohms

- The practical unit of resistance is the **ohm** designated by the Greek letter omega: Ω
- A resistor is an electronic component designed specifically to provide resistance.

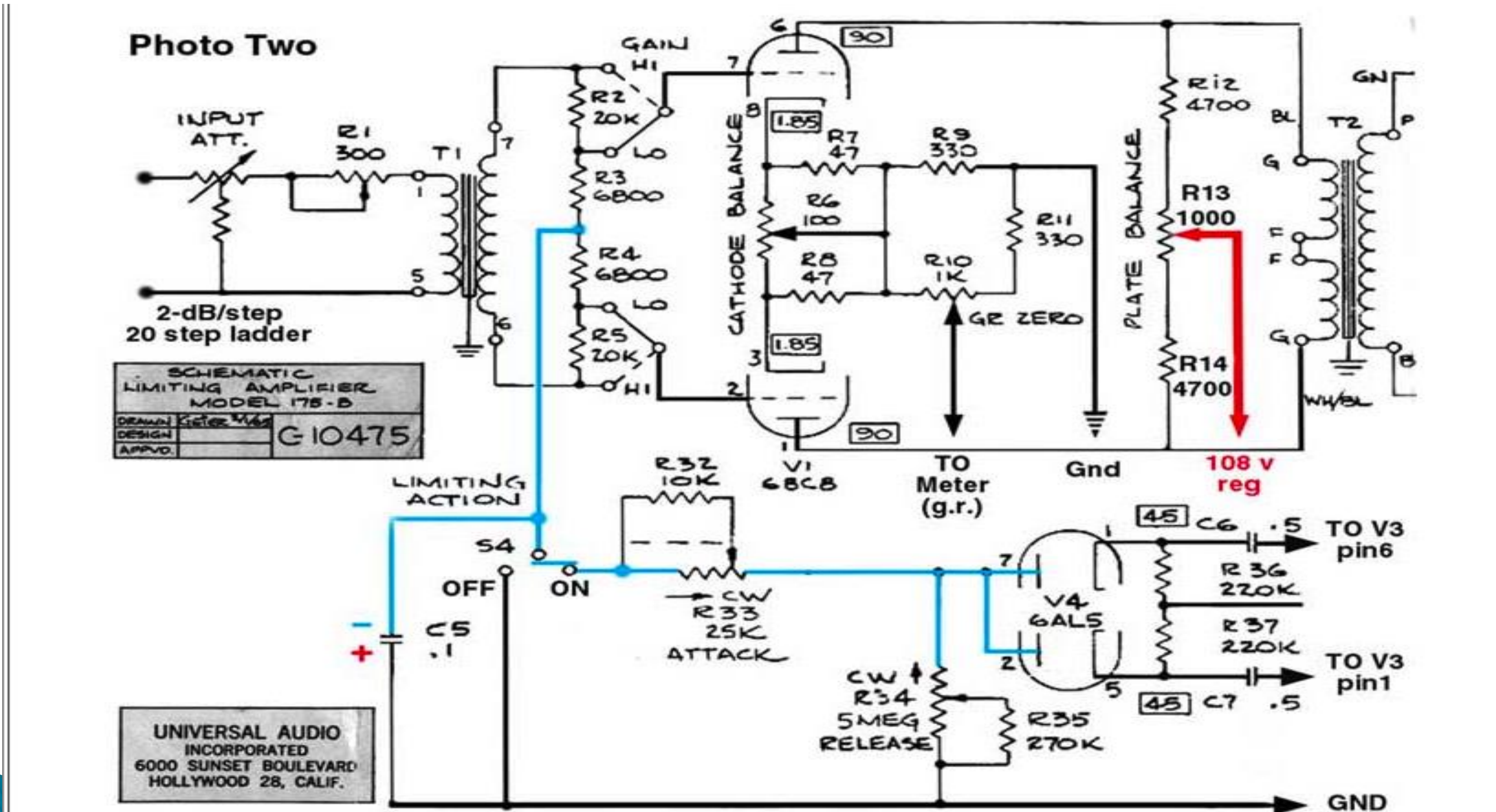
Closed Circuits

- In applications requiring the use of current, electrical components are arranged in the form of a circuit.
- A circuit is defined as a path for current flow.

Common Electronic Component Symbols



A Complex Audio Circuit



The vacuum tube predecessor to the classic 1176, this is the front-end of the **Universal Audio 175-B**
(version 175-C had a ratio switch like the 1176).

Open Circuits

An Open Circuit

Current can only exist where there is a conductive path (e.g. A length of wire). In the circuit shown in Figure 4- 6, I= 0 since there is no conductor between points a & b. We referred to this is an ***open circuit***.

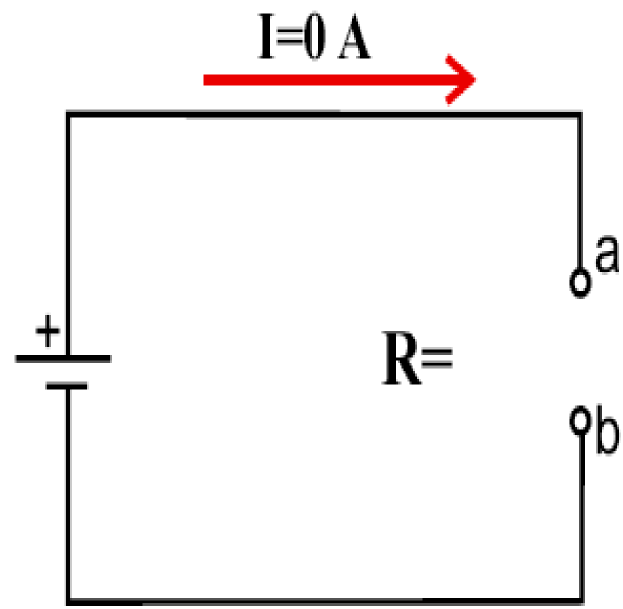


Fig 4-6 **An open circuit has infinite resistance**

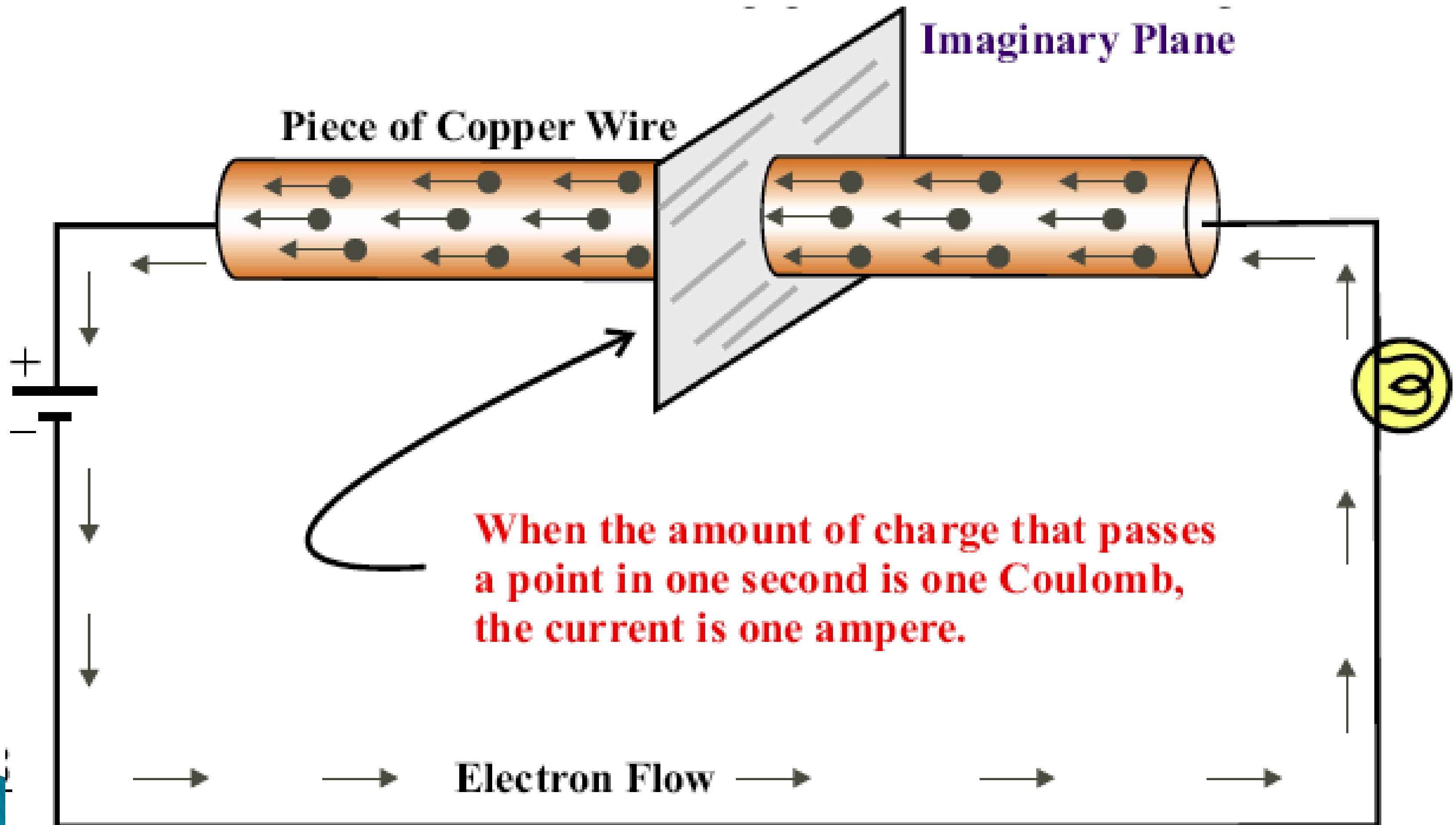
The Circuit is a Load on the Voltage Source

- The circuit is where the energy of the source (battery) is carried by means of the current through the the various components.
- The battery is the **source**, since it provides the potential energy to be used.
- The circuit components are the **load resistance** - they determines how much current the source will produce.

Direction of Electron Flow

- The direction of electron flow in our circuit is from the negative side of the battery, through the load resistance, back to the positive side of the battery.
- Inside the battery, electrons move to the negative terminal due to chemical action, maintaining the potential across the leads.

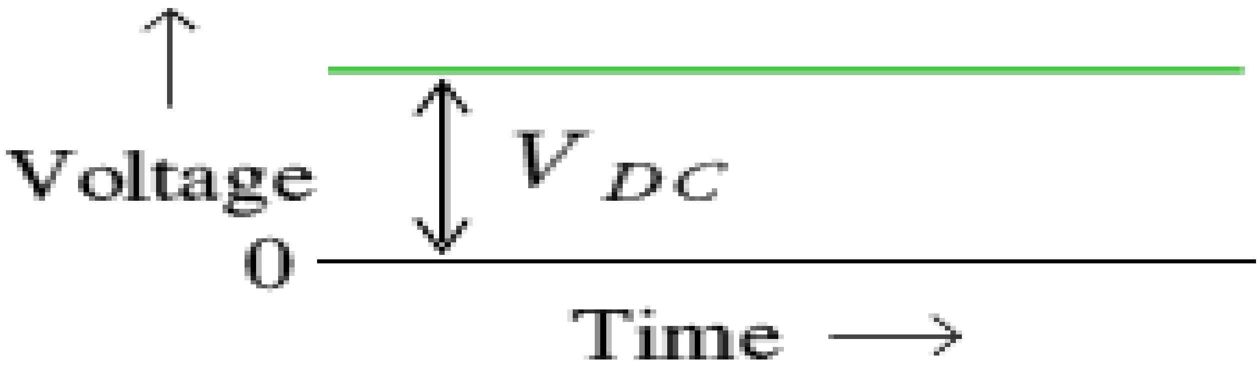
Electron Flow in a Simple Circuit



DC

- Circuits that are powered by battery sources are termed **direct current** circuits.
- This is because the battery maintains the same polarity of output voltage. The plus and minus sides remain constant.

Waveform of DC Voltage



4.1a Steady Voltage

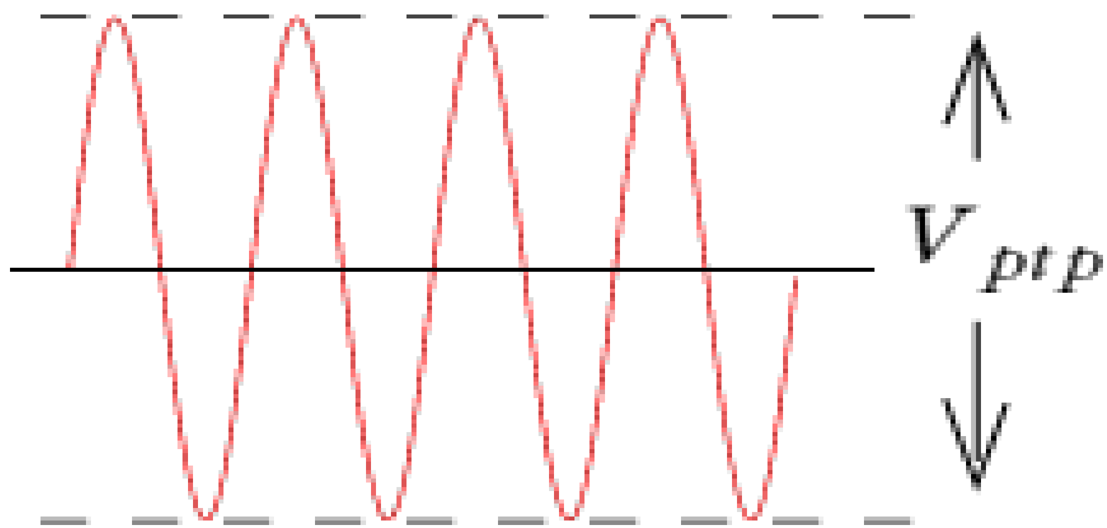
Characteristics of DC

- It is the flow of charges in just one direction and...
- The fixed polarity of the applied voltage which are characteristics of DC circuits

AC

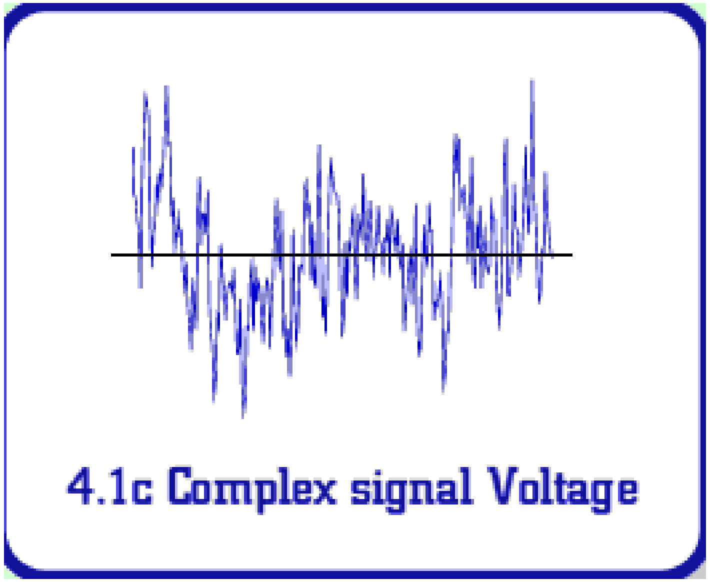
- An alternating voltage source periodically alternates or reverses in polarity.
- The resulting current, therefore, periodically reverses in direction.
- The power outlet in your home is 60 cycle ac - meaning the voltage polarity and current direction go through 60 cycles of reversal per second.
- All audio signals are AC also.

Waveform of AC Voltage



4.1b Sinewave Voltage

Complex Voltage



4.1c Complex signal Voltage

This is a more realistic view of what
an audio signal's voltage would look like

Comparison of DC & AC

DC Voltage	**AC Voltage**
Fixed polarity	Reverses polarity
Can be steady or vary in magnitude	Varies in magnitude between reversals in polarity
Steady value cannot be stepped up or down by a transformer	Used for electrical power distribution
Electrode voltage for tube and transistor amps	I/O signal for tube and transistor amps
Easier to measure	Easier to amplify

Heating Effects the same for both AC and DC current

Many Circuits Include both AC & DC Voltages

- DC circuits are usually simpler than AC circuits.
- However, the principles of DC circuits also apply to AC circuits.

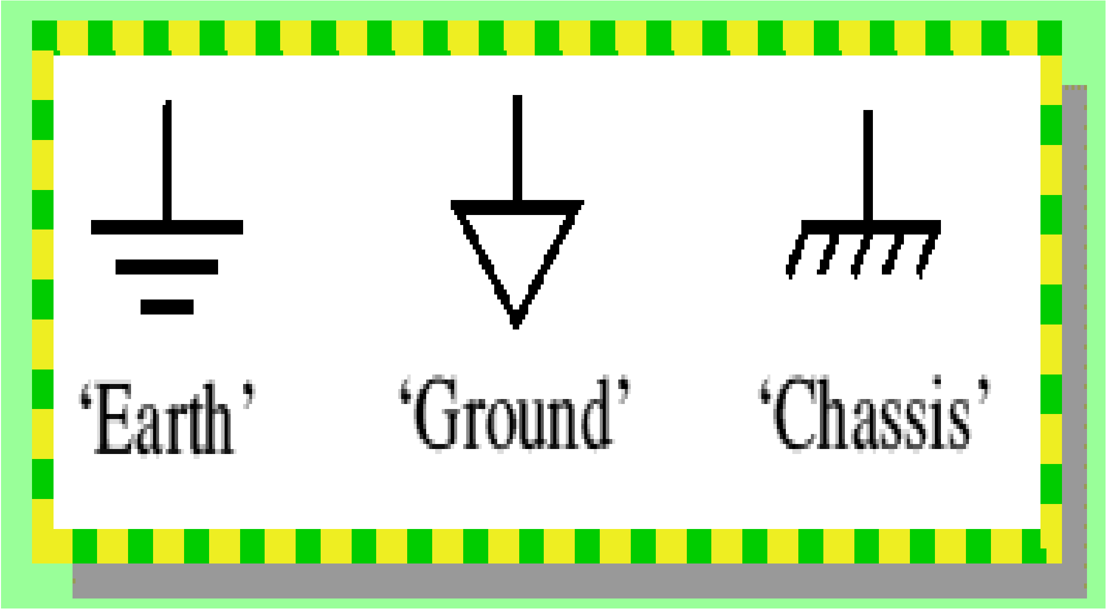
Impedance

- Impedance is resistance to current flow in AC circuits and its symbol is Z.
- Impedance is also measured in ohms.

Grounding

- In the wiring of practical circuits one side of the voltage source is usually grounded for safety.
- For 120 V - ac power lines in homes this means one side of the voltage source is connected to a metal cold water pipe.
- For electronic equipment, the ground just indicates a metal chassis, which is used as a common return for connections to the source.

Common Symbols/ Names for Ground in Electric Circuits

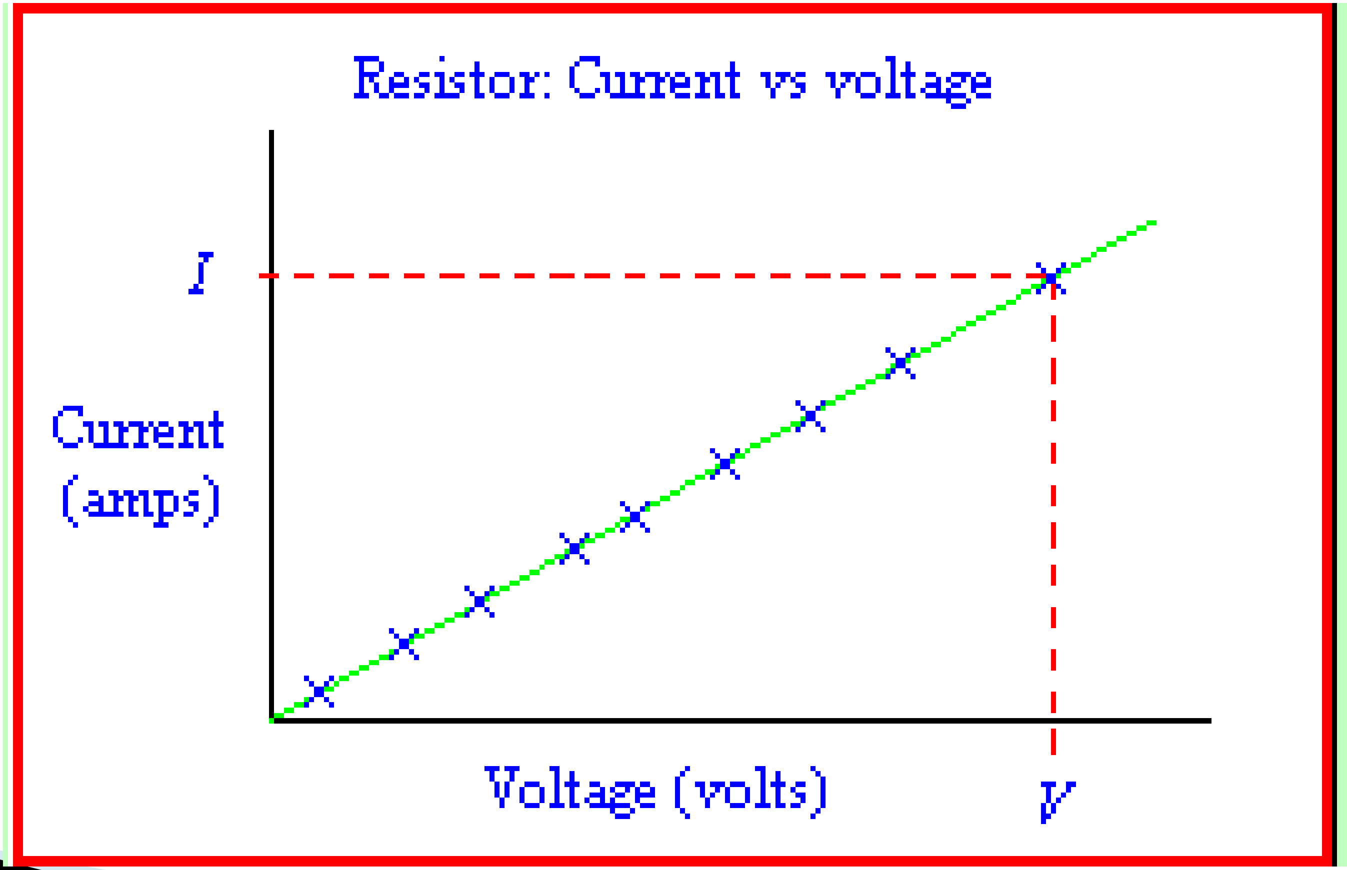


Ohm's Law

- The amount of current in a circuit is dependent on its resistance and the applied voltage. Specifically I = E/R
- If you know any two of the factors E, I, and R you can calculate the third.
- Current I = E/R
- Voltage E = IR
- Resistance R = E/I

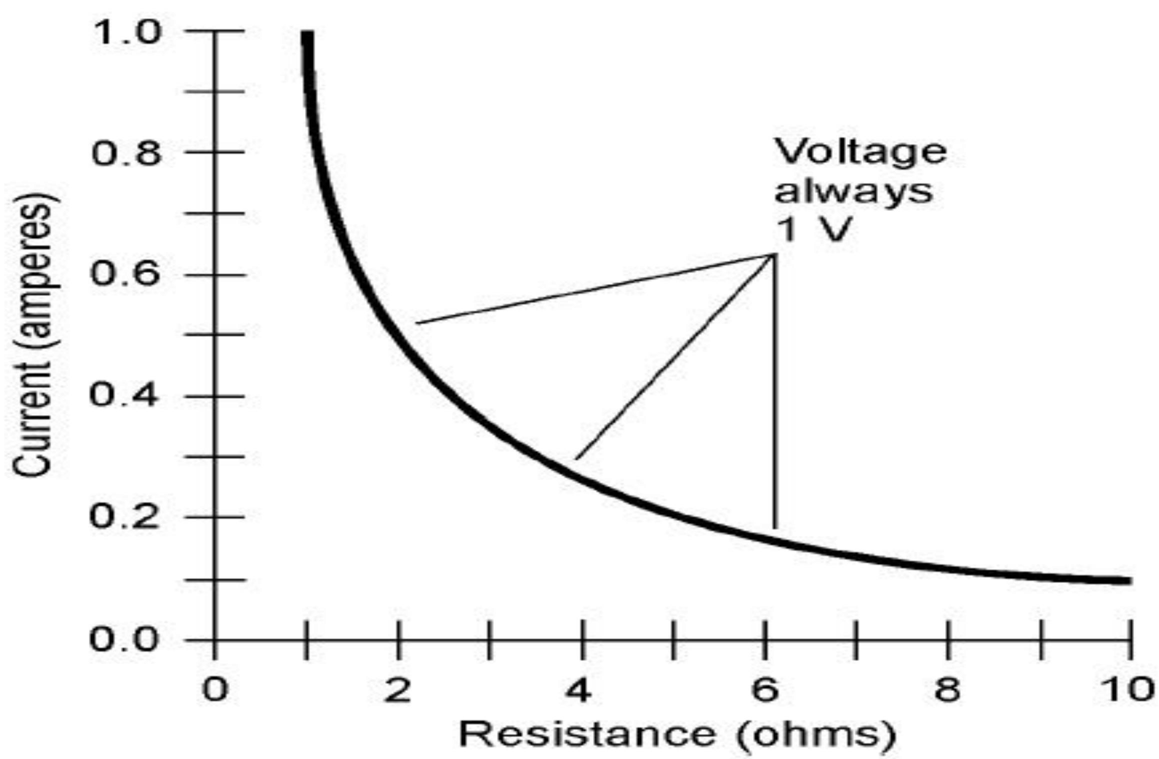
Current is Directly Proportional to Voltage for a Constant Resistance

OHM's LAW



Current is Inversely Proportional to Resistance for a Constant Voltage

OHM's LAW



Power

- The unit of electrical power is the watt.
- Power is how much work is done over time.
- One watt of power is equal to the work done in one second by one volt moving one coulomb of charge. Since one coulomb a second is an ampere:
- Power in watts = volts x amperes
- $P = E \times I$

3 Power Formulas

- $P = E \times I$
- $P = I^2 \times R$
- $P = E^2 / R$

Conversion Factors

Prefix	Symbol	Relation to basic unit	Examples
Mega	M	1,000,000 or $1x10^6$	$5M\Omega$ = $5x10^6\ \Omega$
Kilo	k	1,000 or $1x10^3$	18kV = $18x10^3$ V
Milli	m	.001 or $1x10^{-3}$	48 mA = $48x10^{-3}$A
Micro	μ	.000001 or $1x10^{-6}$	15μV = $15x10^{-6}$V

Electrical

Safety

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DEFINITION

- A physical agency caused by the motion of electrons, protons, and other charged particles, manifesting itself as an attraction, repulsion, magnetic, luminous, and heating effects, etc.

ELEMENTS & ATOMS

- Every known substance – solid, liquid or gas is composed of elements
- An atom is the smallest particle of an element that retains all the properties of that element
- Each element has it’s own kind of atom

ATOMS

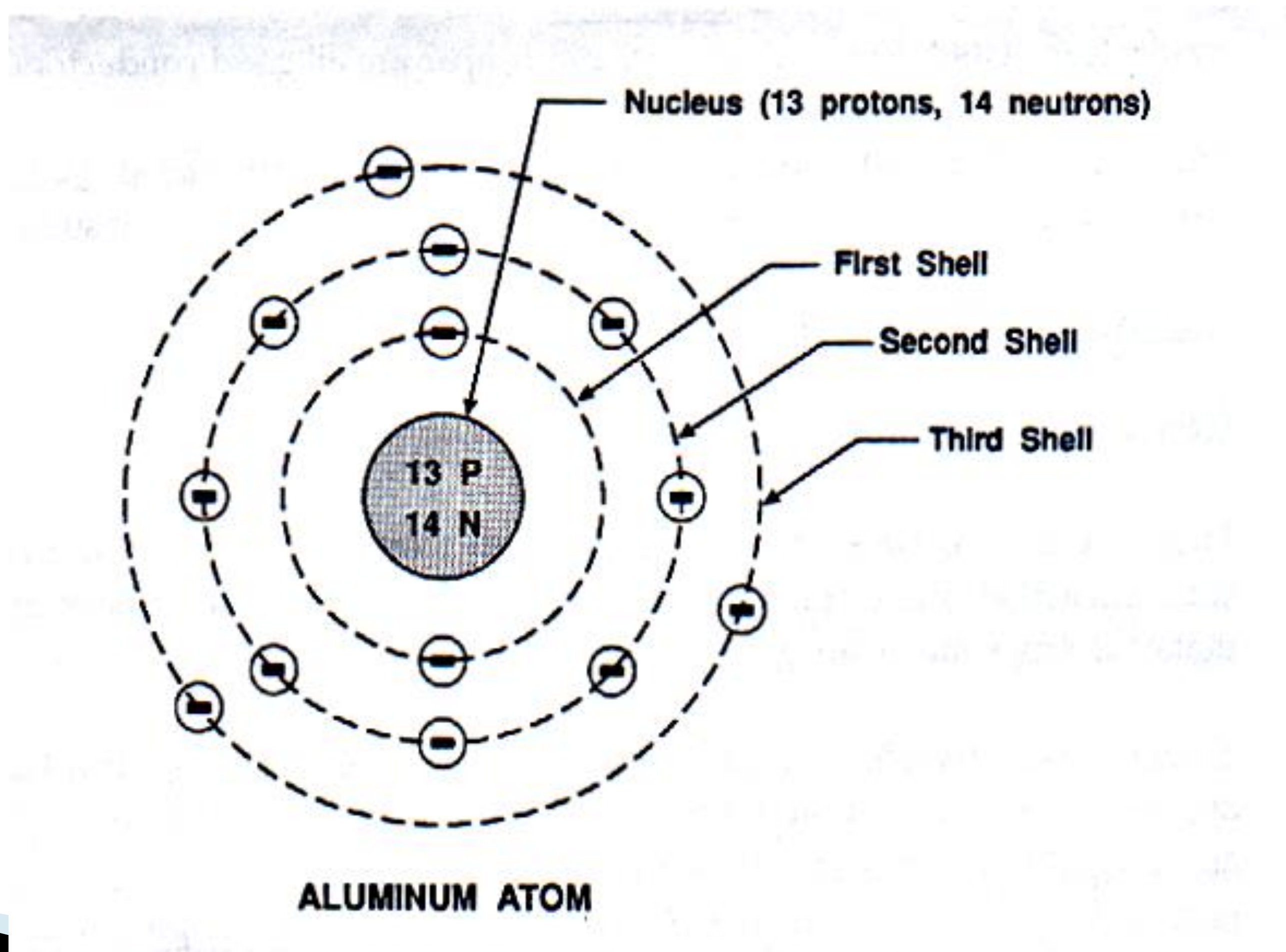
- Inner part composed of protons & neutrons
- Outer part composed of electrons
- Protons = positive charge
- Neutrons = no charge
- Electrons = negative charge

ATOMS

- Each element has a definite number of electrons ----and the same number of protons

- They are oppositely charged and therefore attract each other. This tends to hold the electrons in orbit around the atom.

ELECTRICALLY BALANCED ATOM



FREE ELECTRONS

- Some atoms are easily moved out of orbit
- The ability to move or flow is the basis of current electricity
- If channeled in a given direction, a flow of electrons occurs --- when flowed through a conductor it is **dynamic electricity**

ELECTICAL MATERIALS

- CONDUCTOR – contains many free electrons --- gold, copper, silver, aluminum
- INSULATOR – contains few free electrons- Usually non-metallic such as wood, rubber, glass, etc

GENERATING ELECTRICITY

- Friction, pressure, heat, light, chemical reaction, and magnetism
- Magnetism is most practical & inexpensive method
- Electricity is produced when a magnet is moved past a piece of wire, or wire is moved through a magnetic field

VOLTAGE, CURRENT, & RESISTANCE

- VOLTAGE – unit of measurement of electromotive force (EMF)
- CURRENT – Continuous movement of electrons past a given point. (measured in amperes)
- RESISTANCE – Opposition to movement of electrons. Makes it possible to generate heat, control current flow, & supply correct voltage to devices

OHM'S LAW

- George Simon Ohm
  - Formulated a mathematical relationship between:
    - Current
    - Voltage
    - Resistance
  - Resistance = Impedance
    - Resistance = DC
    - Impedance = AC
    - Interchangeable – Most Branch circuits

DIRECT CURRENT

- Always flows in one direction
- Used to charge batteries, run some motors, operate magnetic lifting devices and welding equipment.

ALTERNATING CURRRENT

- More common in electrical work
- Changes rapidly in both direction and value
- Power companies produce power cheaper with alternating current

ELECTRICAL HAZARDS

- SHOCK. Electric shock occurs when the human body becomes part of the path through which current flows.
- The direct result can be electrocution.
- The indirect result can be injury resulting from a fall or movement into machinery because of a shock

ELECTRICAL HAZARDS

- BURNS. Burns can result when a person touches electrical wiring or equipment that is energized.
- ARC-BLAST. Arc-blasts occur from high-amperage currents arcing through the air. This can be caused by accidental contact with energized components or equipment failure.

Arc Flash and Arc Blasts

- Arc Flash:
  - 80%–Burns due to ignition of clothing
  - Temperature– 35,000 F
  - Fatal Burns–10 ft.
  - 2000 people hospitalized with burns
  - Molten metal
- Arc Blast:
  - Pressure Wave
  - Heat
  - Molten metal
  - Destruction of structures and life

Arc Blast

- Cause
  - Short Circuit caused by working on energized equipment
    - Dropped Tool
  - Occurs in milliseconds
  - Temp: 30,000 degrees
  - Air expands very violently
    - 15 tons of pressure

ELECTRICAL HAZARDS

- ARC-BLAST. The three primary hazards associated with an arc-blast are:
- Thermal radiation.
- Pressure Wave.
- Projectiles.

ELECTRICAL HAZARDS

- EXPLOSIONS. Explosions occur when electricity provides a source of ignition for an explosive mixture in the atmosphere.

ELECTRICAL HAZARDS

- FIRES. Electricity is one of the most common causes of fires both in the home and in the workplace. Defective or misused electrical equipment is a major cause.

EFFECTS ON THE HUMAN BODY

Depends on:

- Current and Voltage
- Resistance
- Path through body
- Duration of shock

Effects of AC Electricity

- More than 3 mA– Painful shock– cause indirect accident
- More than 10 mA– Muscle contraction – "No Let Go" danger
- More than 30 mA– Lung paralysis, usually temporary

Effects of AC Electricity

- More than 50 mA– Ventricular fibrillation, usually fatal
- 100 mA to 4 A– Certain ventricular fibrillation, fatal
- Over 4 A– Heart paralysis, severe burns

Effects

- Protection
  - Circuit Breakers
  - Fuses
  - 15 or 20 amps
  - Property/equipment protection

Conductors

- American Wire Gauge
  - 12 gauge – 20 amps (Safely)
  - 14 gauge – 15 amps
  - 10 gauge – 30 amps
- What determines amount of amps through a circuit?
  - How much the equipment draws
  - How much “stuff” plugged in

Protective Devices

- Fuses
- Circuit Breakers
  - Trip or break circuit breakers if conductors exceed their ampacity

Summary

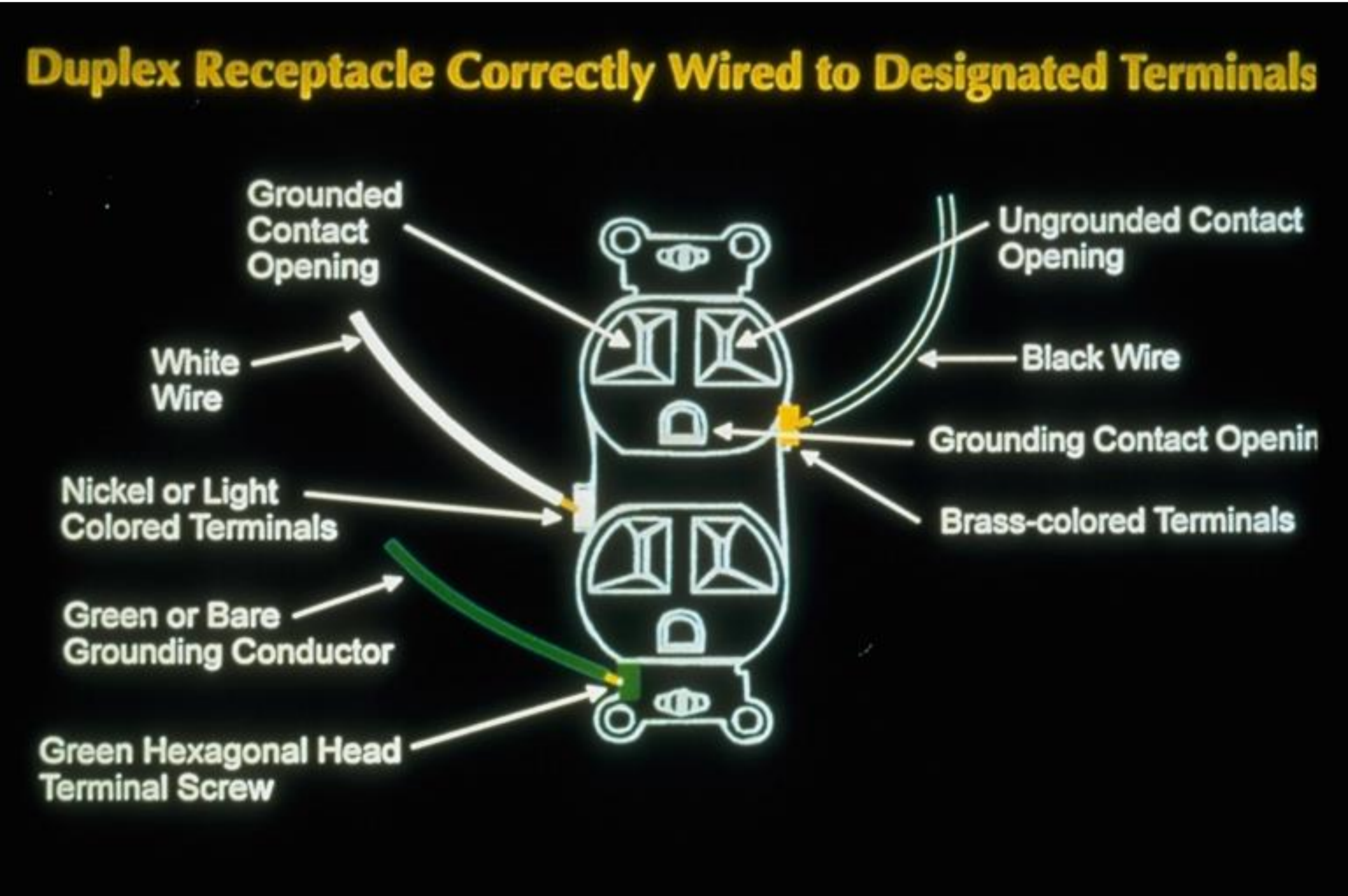
- Current (I)
- Voltage (E or v)
- Resistance (R) (Ohms)

Electrocution Triangle

- Electricity (levels)
- Time
- Path

Wires

- Black = hot = Ungrounded Conductor
- White = neutral = Grounded Conductor (connected to grounding electrode/Grounding rod)



Duplex Receptacle Correctly Wired to Designated Terminals
Grounded Contact Opening
Ungrounded Contact Opening
White Wire
Black Wire
Grounding Contact Openin
Nickel or Light Colored Terminals
Brass-colored Terminals
Green or Bare Grounding Conductor
Green Hexagonal Head Terminal Screw

How to check

- Wiring Checks
  - Testers
  - Different types

Instruments

- Normal 3 light Tester
  - Won't check resistance to ground
- Others – Check what the 3 light tester will
  - Also checks resistance for ground

Double Insulated

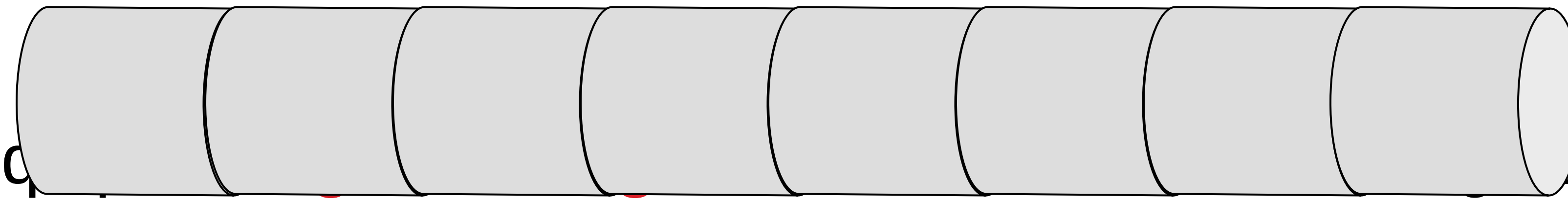
- Indicators
  - No ground pin
  - Plastic tool case
  - Listed by NTL
  - Marked as double insulated
    - Square in a square
    - Marked "double insulated"

Grounding Conductors

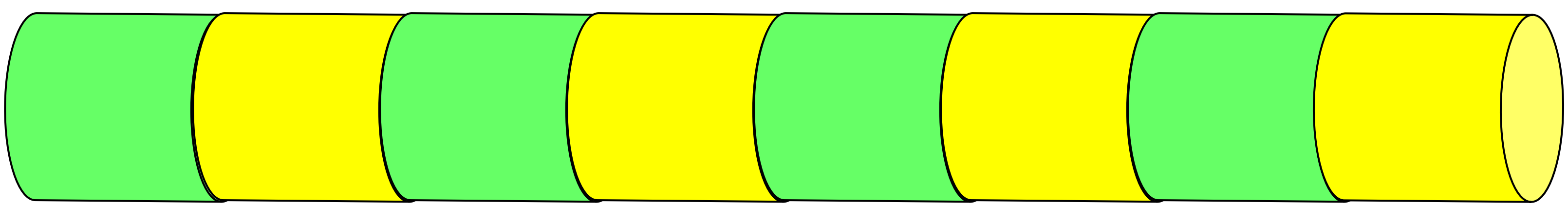
- **Equipment grounding conductor** acts as a safeguard against insulation failure or faults in the other circuit conductors
- **Not an energized conductor** under normal conditions.
- Energized if a leak or fault in the normal current path
- Directs current back to the source
- Enabling fuses or circuit breakers to operate

Identification of Conductors

- **Grounded conductor** i.d. and distinguished from other conductors w/ white or gray



- Eq[illegible]shed w/ **green**, green w/ yellow stripes, or bare



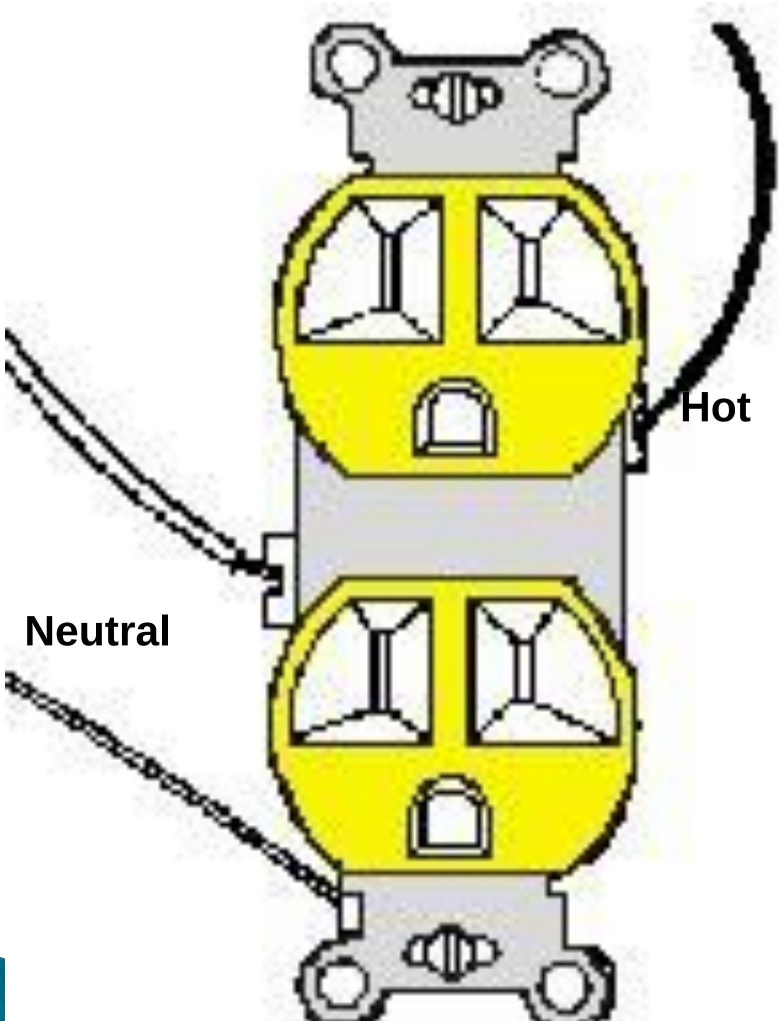
Polarity of connections

- Improper connection of these conductors *('hot and neutral')* is most prevalent on smaller branch circuits:
  - Standard 120 volt receptacle outlets
  - Cord-and plug-connected equipment

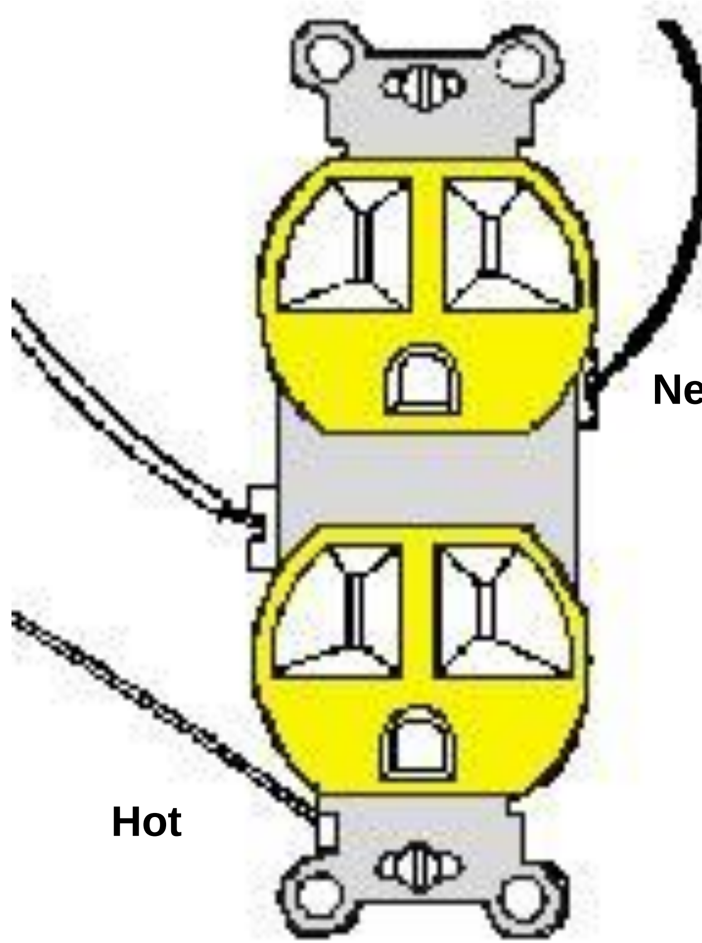
Reversed Polarity

- *Reversed polarity* is a condition when the grounded conductor (neutral) is incorrectly connected to the ungrounded (hot) terminal of a plug, receptacle, or other type of conductor

Normal Wiring



1910.304(a)(2) Reverse Polarity



1910.304(a)(2)
NEC Article 200-11

Grounding

- There are two kinds of grounding:
  - 1. Electrical circuit or system grounding
  - 2. Electrical equipment grounding

Electrical System Grounding

- One conductor of the circuit is intention grounded to earth
- Protects circuit from lightning, or other high voltage contact

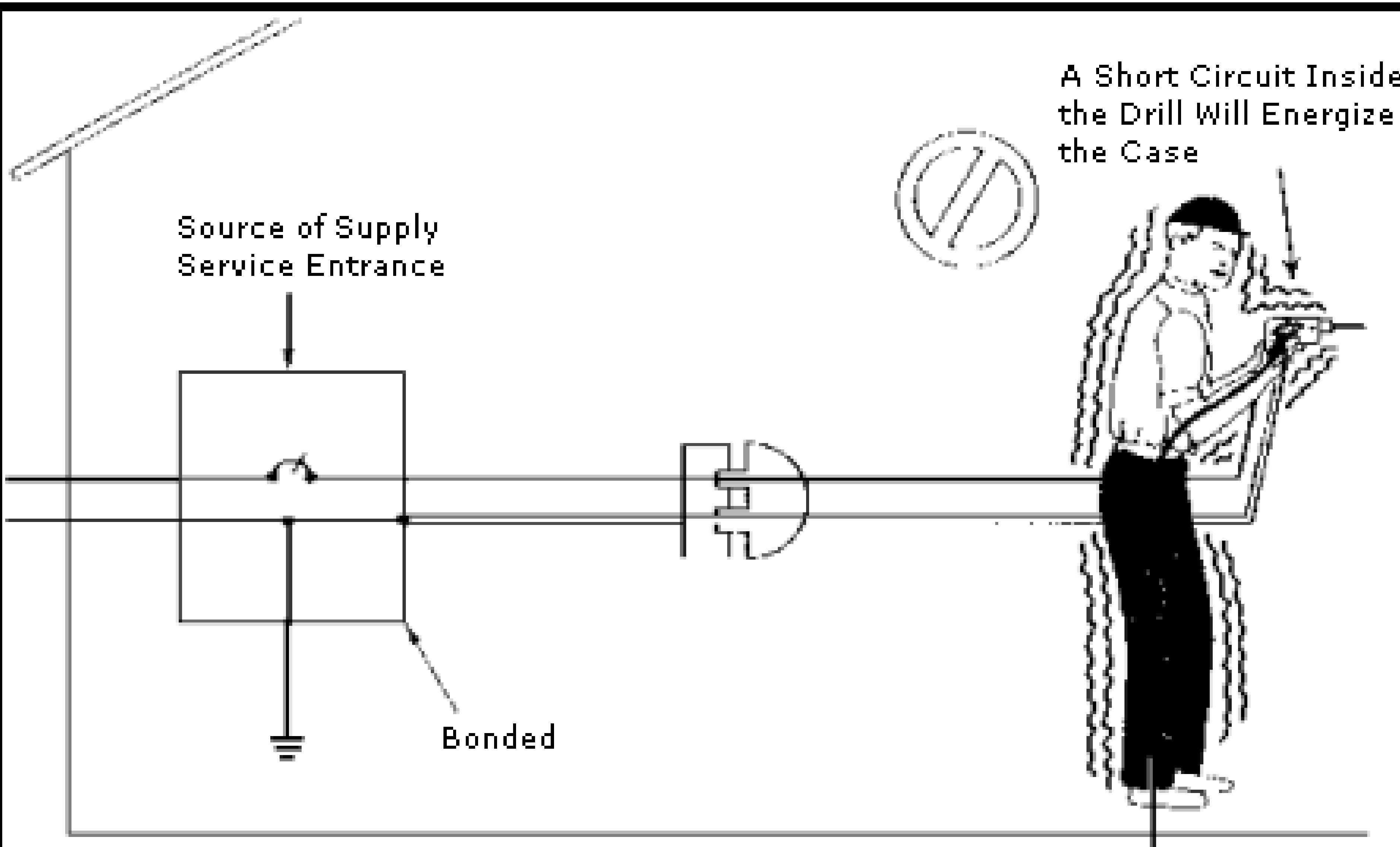
Equipment Grounding

- All metal frames & enclosures of equipment are grounded by a permanent connection or bond

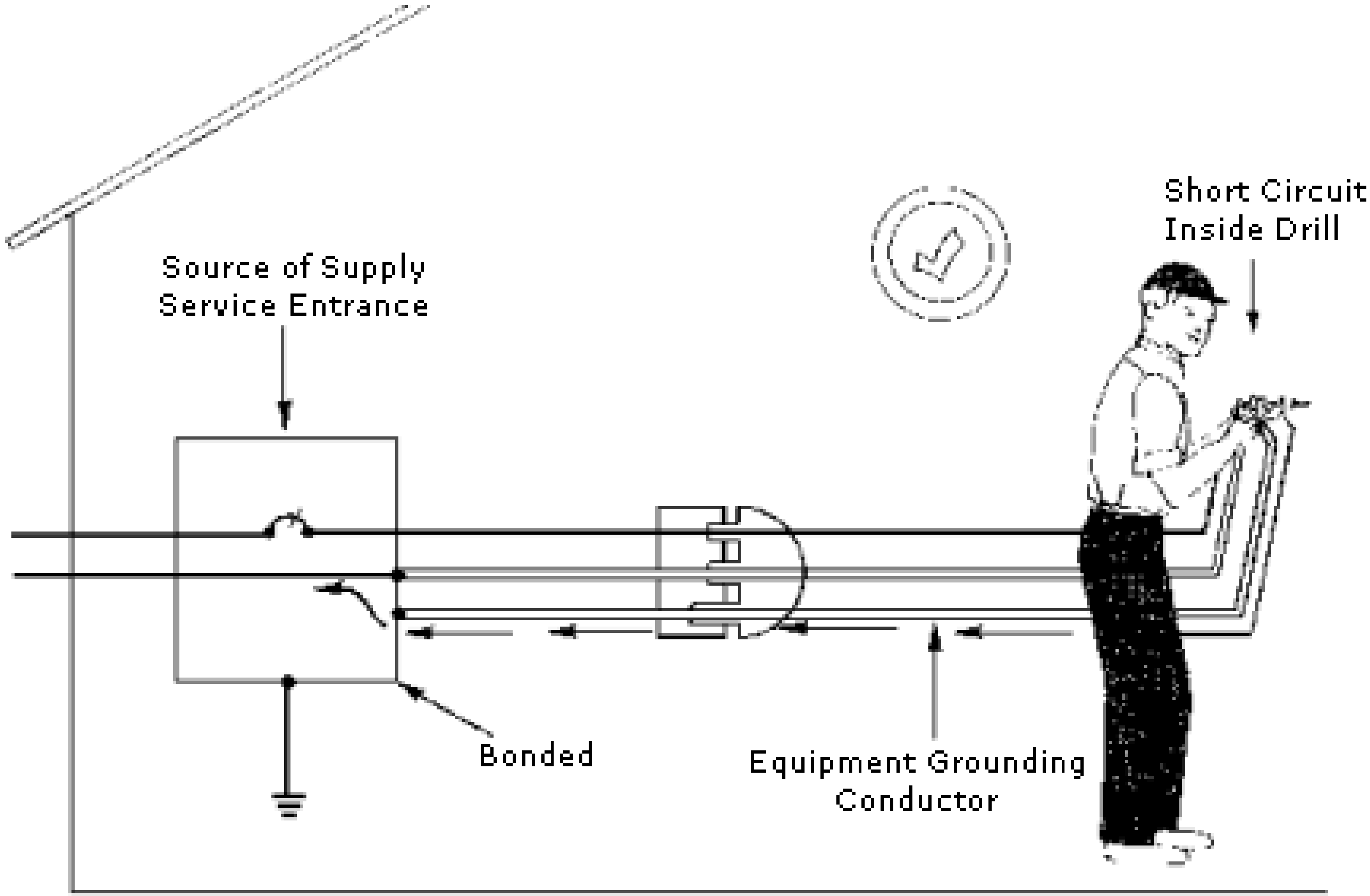
- The equipment gro provides a path for dangerous fault current to return to the system ground at the supply source should a fault occur

Grounding Equipment Connected by Cord and Plug

- Exposed non-current carrying metal parts of cord and plug connected equipment which may become energized shall be grounded
- If in a hazardous location
- If operated at over 150 volts



CORD- AND PLUG-CONNECTED EQUIPMENT WITHOUT A GROUNDING CONDUCTOR



CORD- AND PLUG-CONNECTED EQUIPMENT
WITH A GROUNDING CONDUCTOR

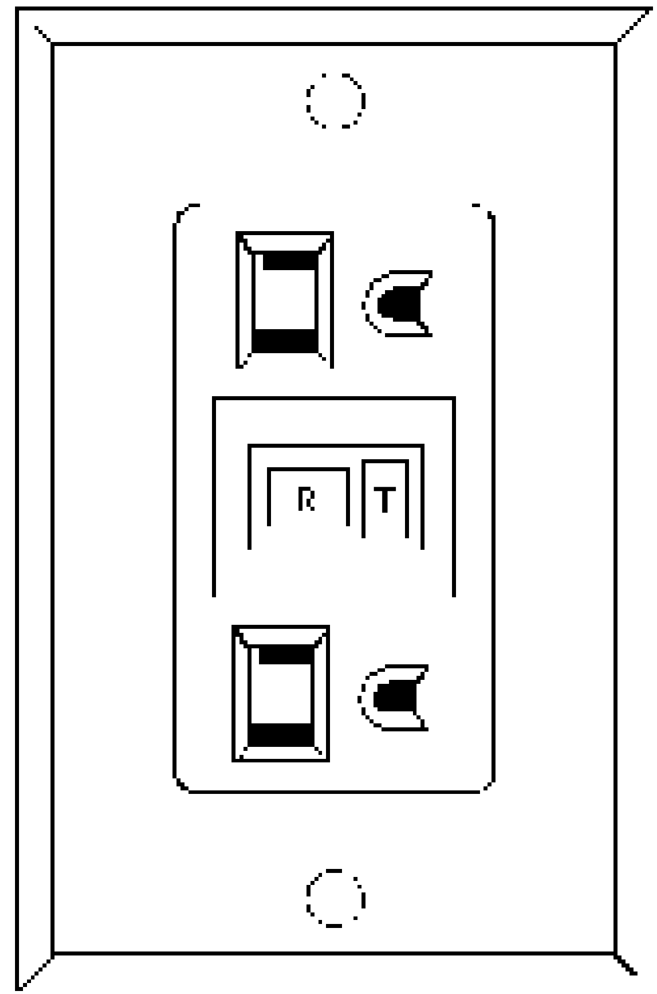
Note that properly bonded conduit and associated metal enclosures can also serve as a grounding conductor.

Ground fault circuit interrupters (GFCI's)

- A GFCI is **<u>not</u>** an overcurrent device like a fuse or circuit breaker
- GFCI's are designed to sense an imbalance in current flow over the normal path

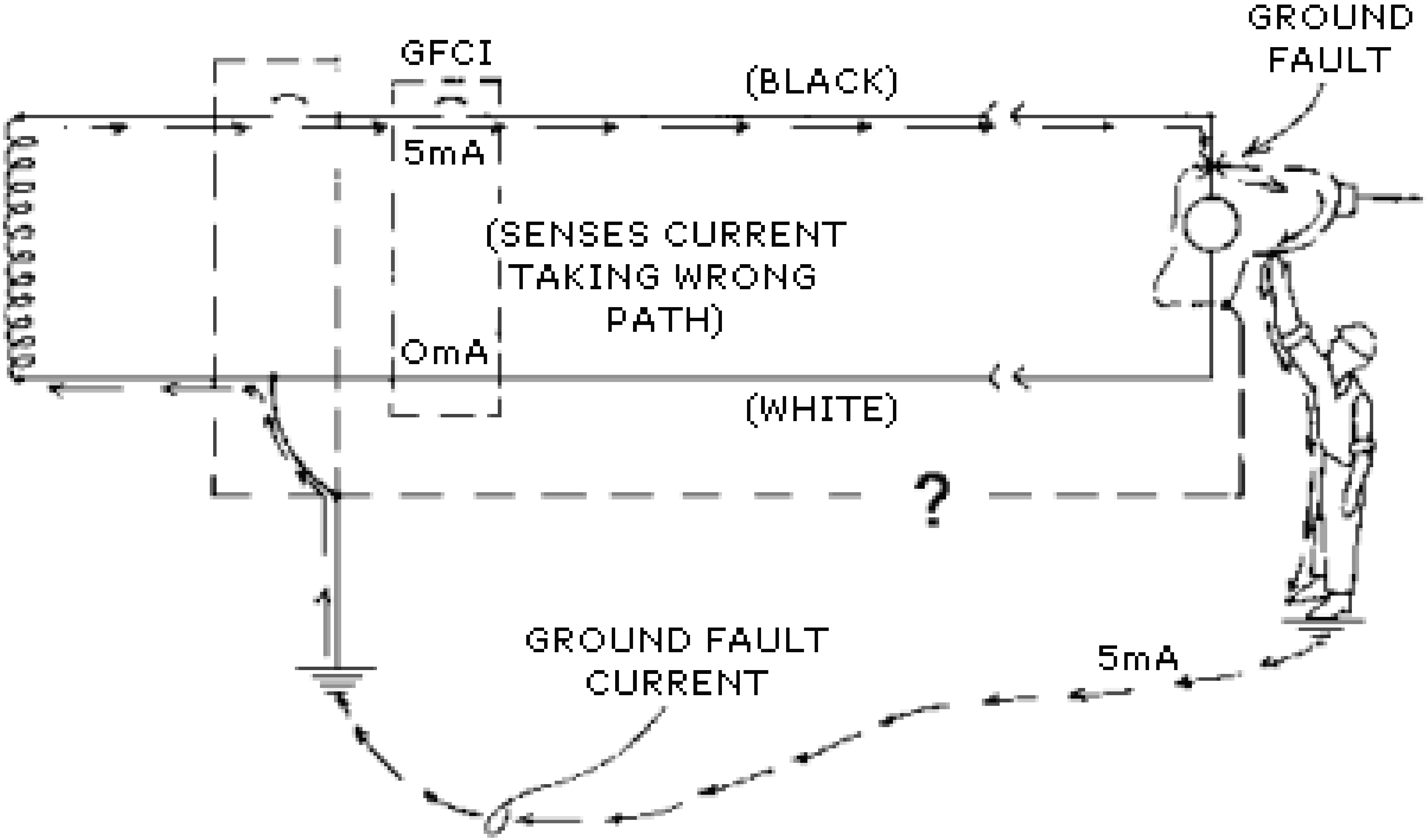
Ground fault circuit interrupters (GFCI's)

- GFCI contains a special sensor that monitors the strength of the magnetic field around each wire in the circuit when current is flowing
- The field is proportional to the amount of current flow



Ground fault circuit interrupters (GFCI's)

- If the current flowing in the *black (ungrounded)* wire is within 5 milliampers of the current flowing in the *white (grounded)* all the current will flow in the normal path
- If the current flow differs by more than 5mA +/- 1mA, the GFCI will quickly open the circuit



HOW THE GFCI PROTECTS PEOPLE

(BY OPENING THE CIRCUIT WHEN CURRENT FLOWS THROUGH A GROUND-FAULT PATH)

Testing GFCI's

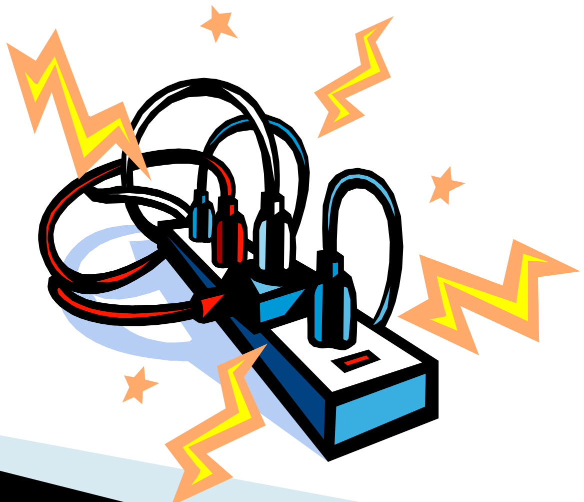
- GFCI's are complex mechanisms, they must be tested on a regular basis
- ***Installation must be correct according to the listing & labeling requirements or the GFCI will not protect as designed***
- For permanently mounted types, once a month testing is recommended
- **Portable GFCI's should be tested before each use!**
- GFCI's have a test-circuit which imposes an artificial ground fault when the test button is pushed

Conductors Entering Boxes, Cabinets or Fittings

- All pull boxes, junction boxes and fittings must be provided with approved covers
- If covers are metal they must be grounded.
- Each outlet box must have a cover, faceplate or fixture canopy

Judgment of application

- There are usually citations when the usage is obviously not temporary; and,
- When the cord is extended to some distant outlet in order to avoid providing a fixed outlet where needed



Identification, Splices and Terminations

- Flexible cords shall only be used in continuous lengths, no taps or splices

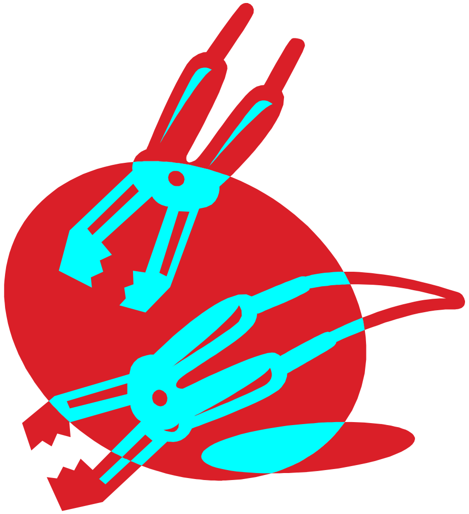
Damaged cord improperly repaired

Identification, Splices and Terminations

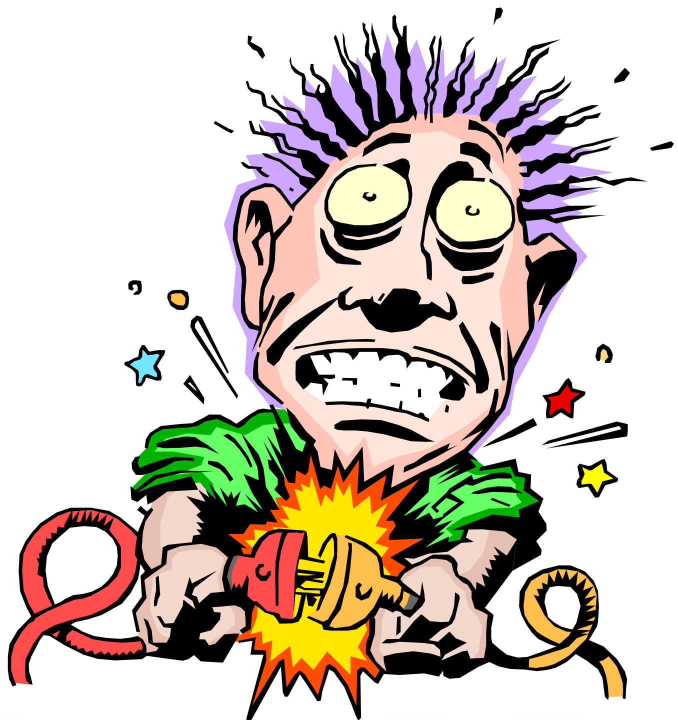
- Flexible cords shall be connected to devices and fittings so that strain relief is provided which will prevent pull from being directly transmitted to joints or terminal screws

Footnote to Table S-4

- (1) Workers in these groups do not need to be trained if their work or the work of those they supervise does not bring them or their employees close enough to exposed parts of electric circuits operating at 50 volts or more to ground for a hazard to exist.

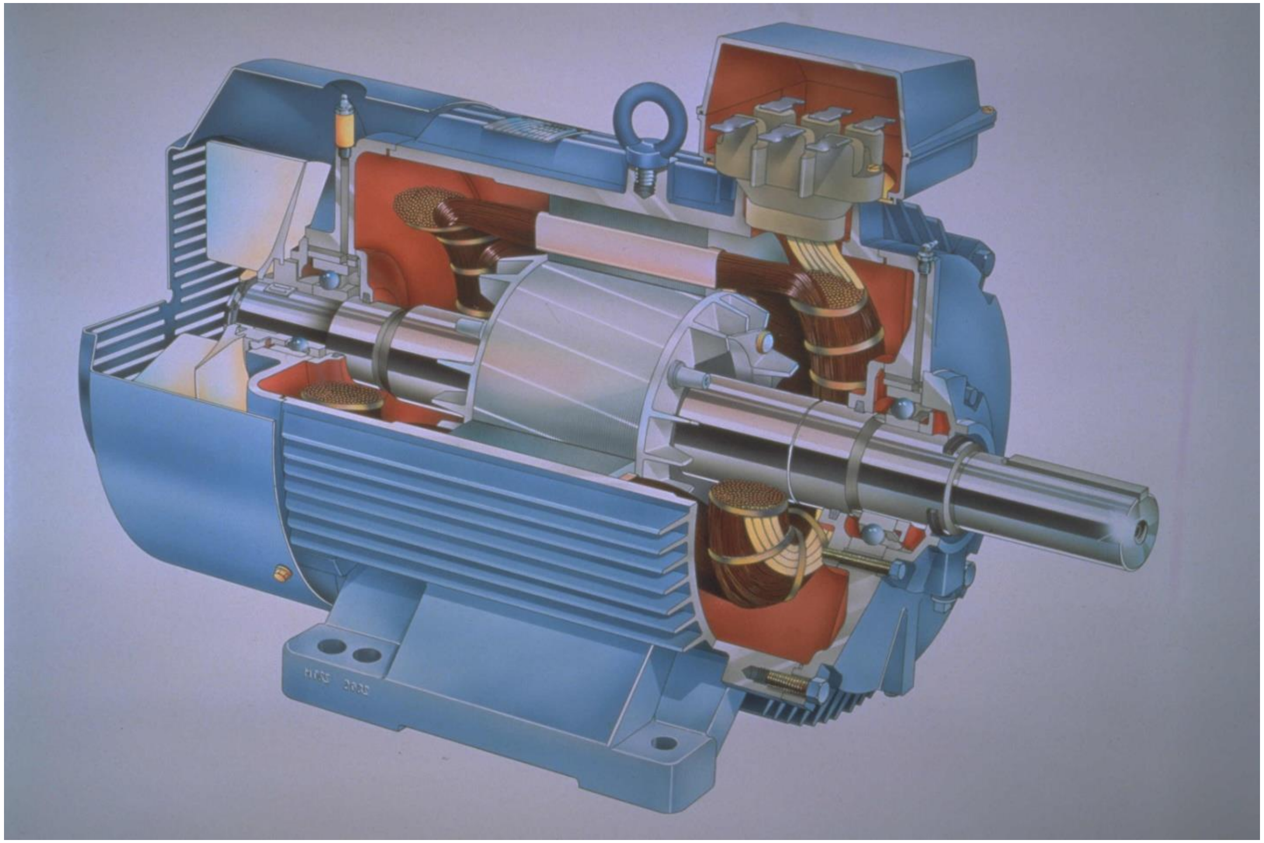


Work Shouldn't be...



Shocking!

Induction Motors



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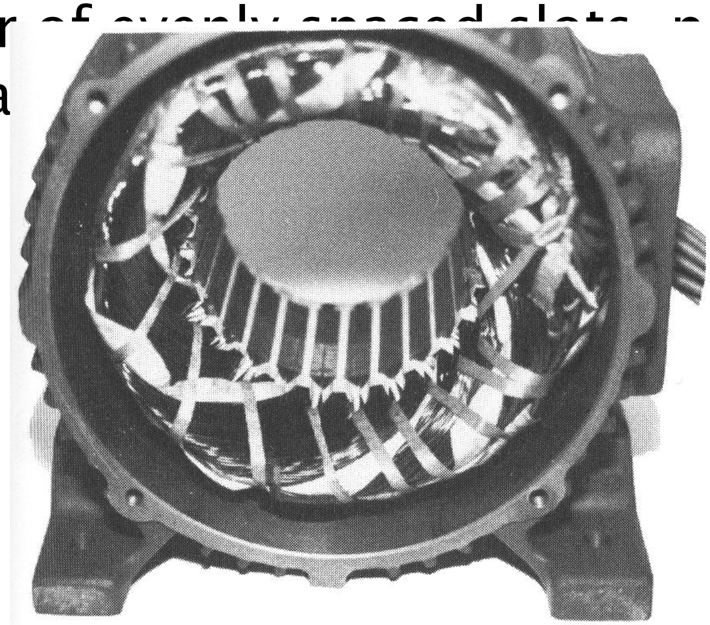
Introduction

- Three-phase induction motors are the most common and frequently encountered machines in industry
    - simple design, rugged, low-price, easy maintenance
    - wide range of power ratings: fractional horsepower to 10 MW
    - run essentially as constant speed from zero to full load
    - speed is power source frequency dependent
        - not easy to have variable speed control
        - requires a variable-frequency power-electronic drive for optimal speed control

Construction

- An induction motor has two main parts
  - a stationary stator
    - consisting of a steel frame that supports a hollow, cylindrical core
    - core, constructed from stacked laminations (why?), having a number [illegible] providing the space for the sta[illegible]

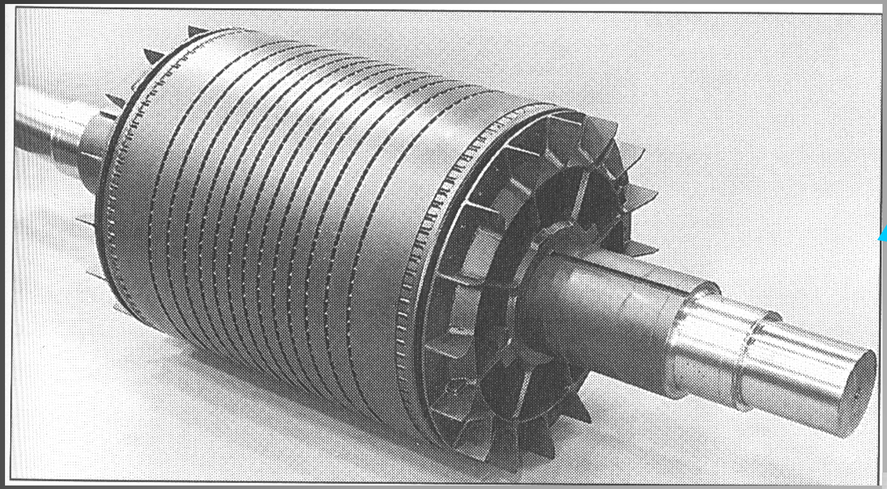


Stator of IM

Construction

- a revolving rotor
  - composed of punched laminations, stacked to create a series of rotor slots, providing space for the rotor winding
  - one of two types of rotor windings
  - conventional 3-phase windings made of insulated wire (wound-rotor) » similar to the winding on the stator
  - aluminum bus bars shorted together at the ends by two aluminum rings, forming a squirrel-cage shaped circuit (squirrel-cage)
- Two basic design types depending on the rotor design
  - squirrel-cage
  - wound-rotor

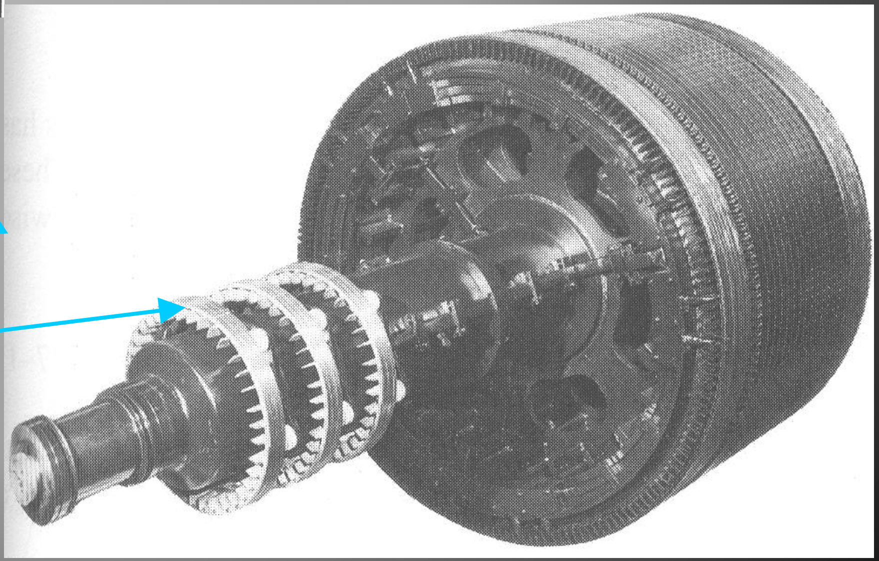
Construction



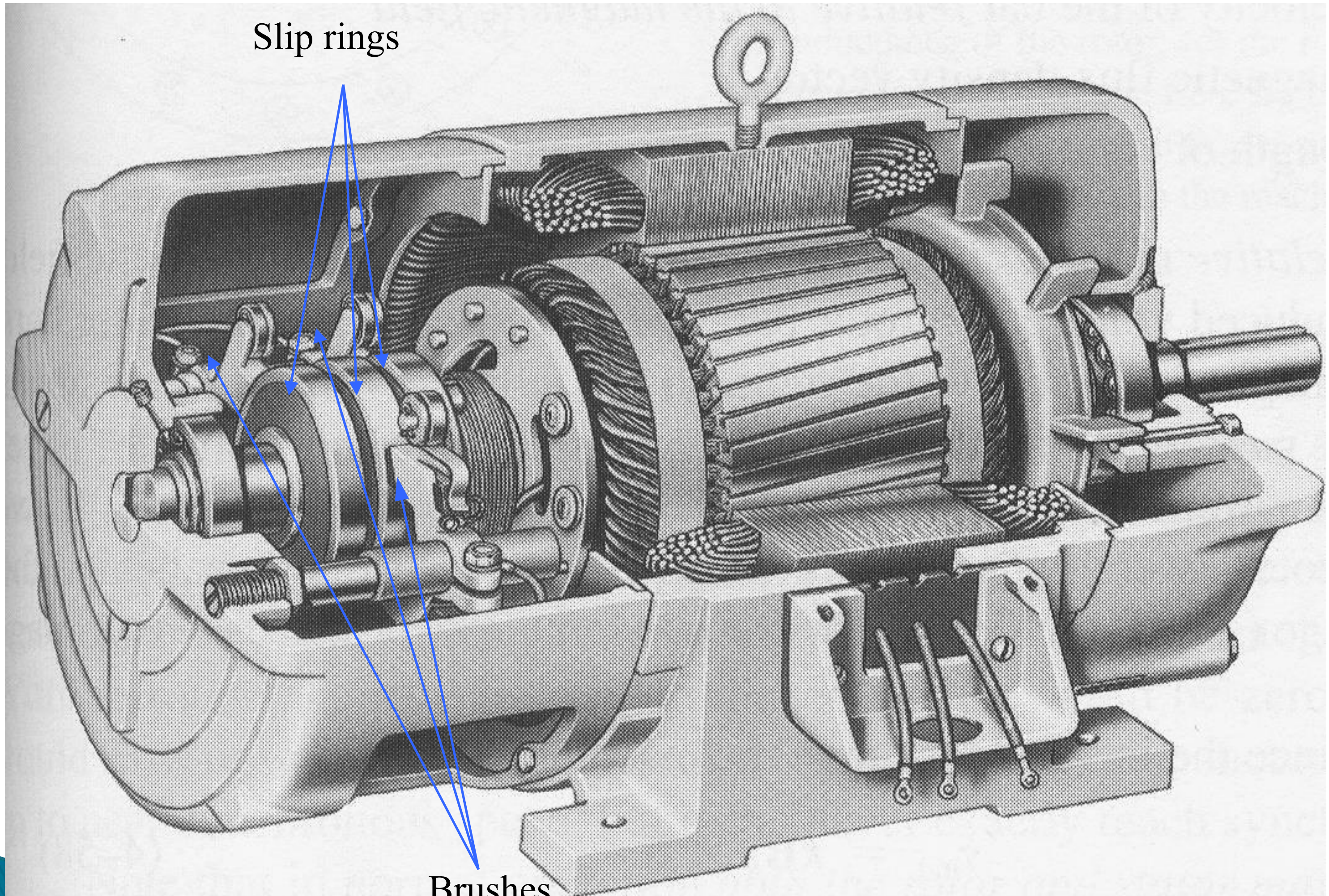
Squirrel cage rotor

Wound rotor

Notice the slip rings



Construction



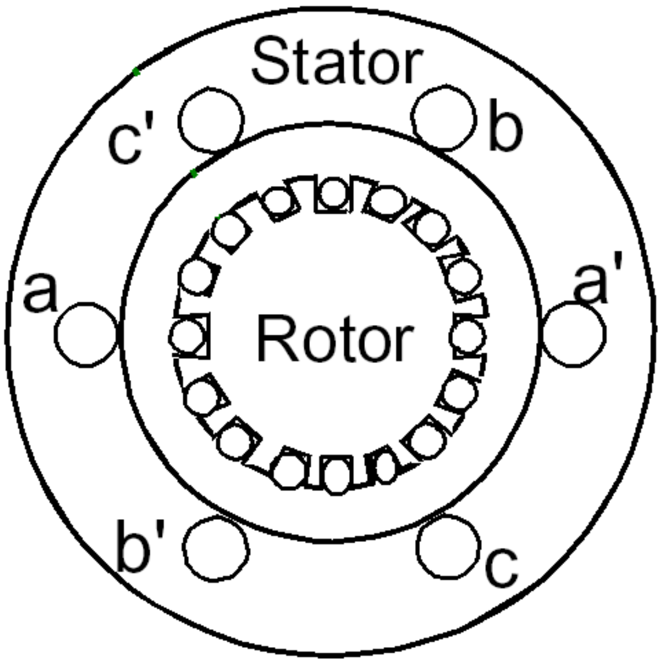
Cutaway in a typical wound-rotor IM. Notice the brushes and the slip rings

Rotating Magnetic Field

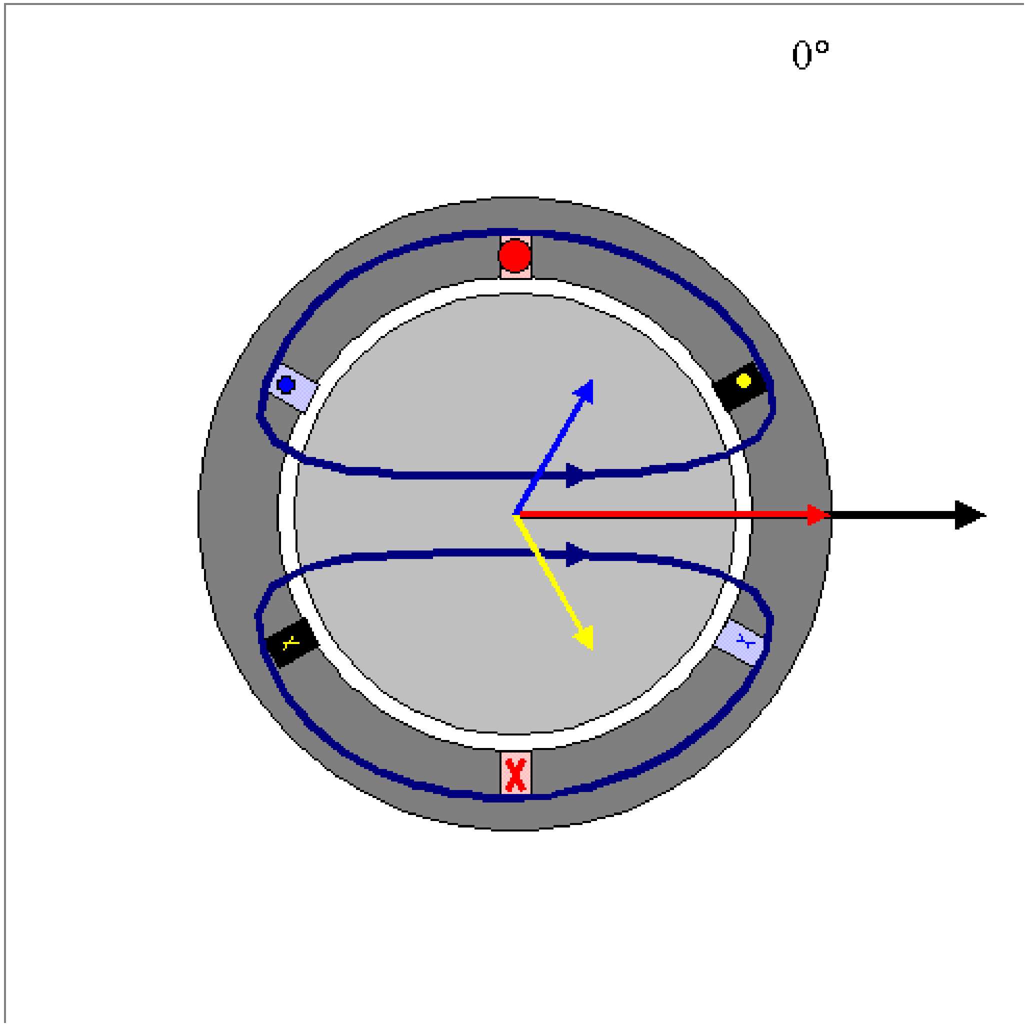
- Balanced three phase windings, i.e. mechanically displaced 120 degrees form each other, fed by balanced three phase source
- A rotating magnetic field with constant magnitude is produced, rotating with a speed

$$n_{sync} = \frac{120 f_e}{P} \quad rpm$$

Where f_e is the supply frequency and P is the no. of poles and n_{sync} is called the synchronous speed in *rpm* (revolutions per minute)



Rotating Magnetic Field



Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings
- Due to the fact that the rotor windings are short circuited, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings
- The rotor current produces another magnetic field
- A torque is produced as a result of the interaction of those two magnetic fields

$$\tau_{ind} = kB_R \times B_S$$

Where τ_{ind} is the induced torque and B_R and B_S are the magnetic flux densities of the rotor and the stator respectively

Induction motor speed

- At what speed will the IM run?
  - Can the IM run at the synchronous speed, why?
  - If rotor runs at the synchronous speed, which is the same speed of the rotating magnetic field, then the rotor will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed
  - When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced

Induction motor speed

- So, the IM will always run at a speed lower than the synchronous speed
- The difference between the motor speed and the synchronous speed is called the *Slip*

$$n_{slip} = n_{sync} - n_m$$

Where n_{slip}= slip speed

n_{sync}= speed of the magnetic field

n_m = mechanical shaft speed of the motor

The Slip

$$s = \frac{n_{sync} - n_m}{n_{sync}}$$

Where s is the *slip*

Notice that : if the rotor runs at synchronous speed

$$s = 0$$

if the rotor is stationary

$$s = 1$$

Slip may be expressed as a percentage by multiplying the above eq. by 100, notice that the slip is a ratio and doesn't have units

Example 7-1 (pp.387-388)

A 208-V, 10hp, four pole, 60 Hz, Y-connected induction motor has a full-load slip of 5 percent

1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?

Solution

1. $$n_{sync} = \frac{120 f_e}{P} = \frac{120(60)}{4} = 1800\ rpm$$

2. $$n_m = (1-s)n_s$$
$$= (1-0.05)\times 1800 = 1710\ rpm$$

3. $$f_r = sf_e = 0.05\times 60 = 3Hz$$

4. $$\tau_{load} = \frac{P_{out}}{\omega_m} = \frac{P_{out}}{2\pi \frac{n_m}{60}}$$
$$= \frac{10\,hp \times 746\,watt/hp}{1710\times 2\pi \times (1/60)} = 41.7\ N.m$$

Problem 7-2 (p.468)

A 220-V, three-phase, two-pole, 50-Hz induction motor is running at a slip of 5 percent. Find:

(a) The speed of the magnetic fields in revolutions per minute

(b) The speed of the rotor in revolutions per minute

(c) The slip speed of the rotor

(d) The rotor frequency in hertz

SOLUTION

(a) The speed of the magnetic fields is

$$n_{sync} = \frac{120 f_e}{P} = \frac{120(50 \text{ Hz})}{2} = 3000 \text{ r/min}$$

(b) The speed of the rotor is

$$n_m = (1 - s)\, n_{sync} = (1 - 0.05)(3000 \text{ r/min}) = 2850 \text{ r/min}$$

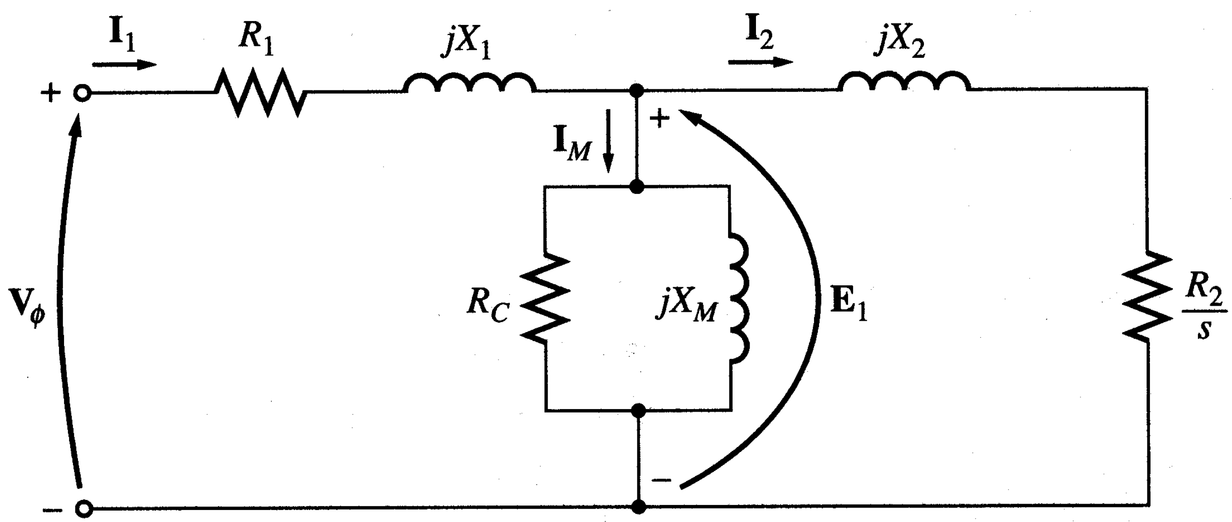
(c) The slip speed of the rotor is

$$n_{slip} = s n_{sync} = (0.05)(3000 \text{ r/min}) = 150 \text{ r/min}$$

(d) The rotor frequency is

$$f_r = \frac{n_{slip} P}{120} = \frac{(150 \text{ r/min})(2)}{120} = 2.5 \text{ Hz}$$

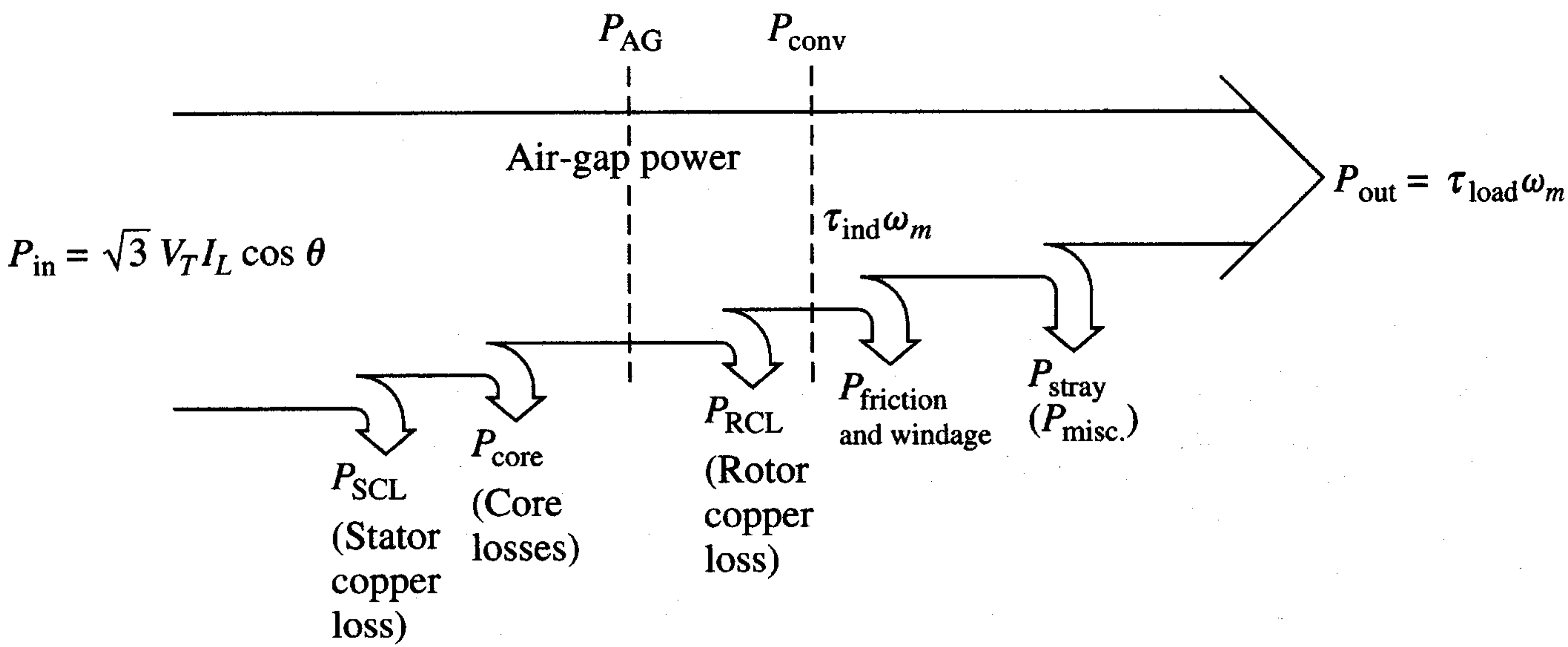
Equivalent Circuit



Power losses in Induction machines

- Copper losses
  - Copper loss in the stator (P_{SCL}) = $I_1^2 R_1$
  - Copper loss in the rotor (P_{RCL}) = $I_2^2 R_2$
- Core loss (P_{core})
- Mechanical power loss due to friction and windage
- How this power flow in the motor?

Power flow in induction motor



Power relations

$$P_{in} = \sqrt{3}\, V_L I_L \cos\theta = 3 V_{ph} I_{ph} \cos\theta$$

$$P_{SCL} = 3\, I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core})$$

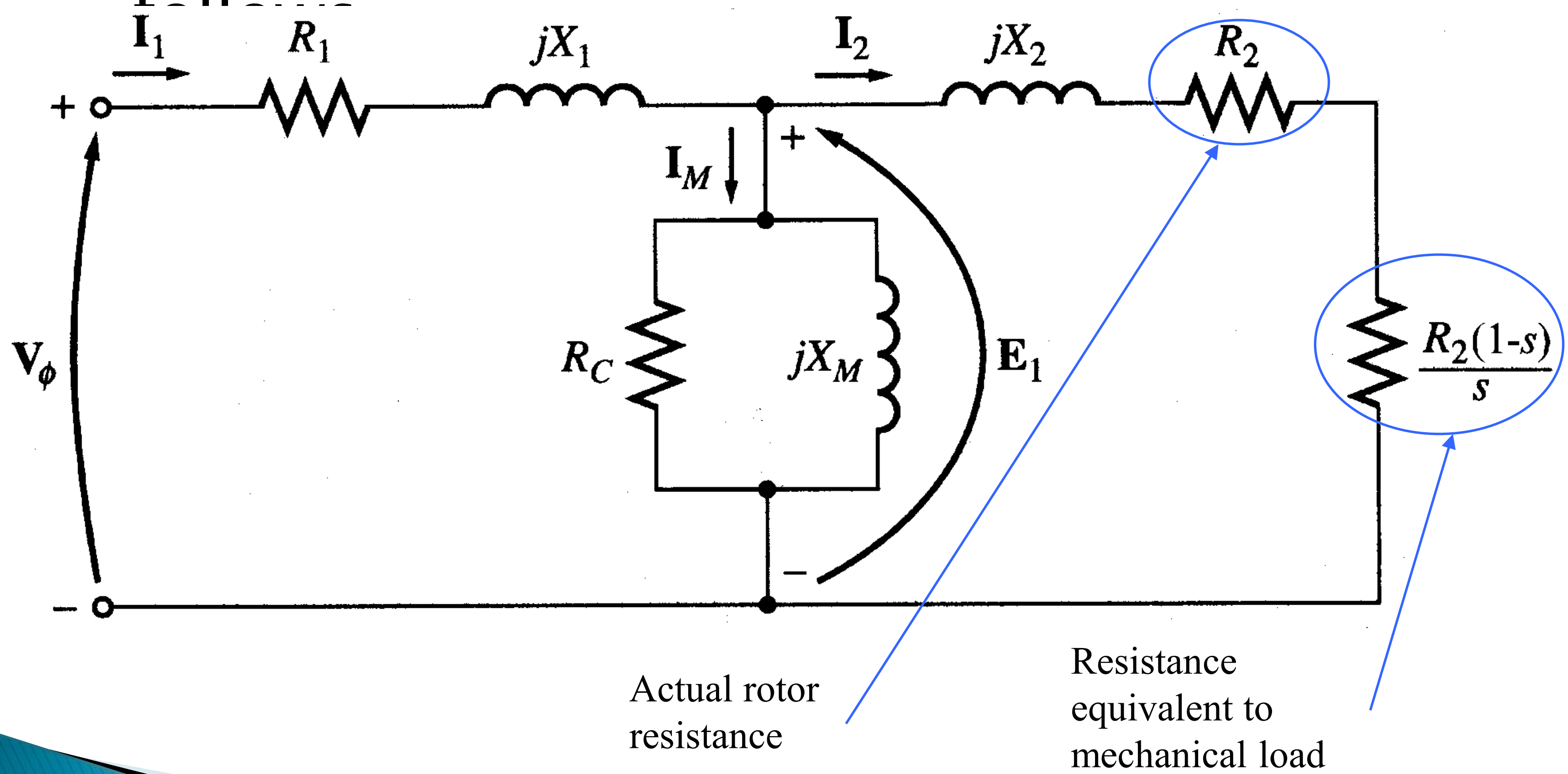
$$P_{RCL} = 3 I_2^2 R_2$$

$$P_{conv} = P_{AG} - P_{RCL}$$

$$P_{out} = P_{conv} - (P_{f+w} + P_{stray})$$

Equivalent Circuit

- We can rearrange the equivalent circuit as follows



Power relations

$$P_{in} = \sqrt{3}\, V_L I_L \cos\theta = 3 V_{ph} I_{ph} \cos\theta$$

$$P_{SCL} = 3\, I_1^2 R_1$$

$$P_{AG} = P_{in} - (P_{SCL} + P_{core}) \quad = P_{conv} + P_{RCL} \quad = 3 I_2^2 \frac{R_2}{s} \quad = \frac{P_{RCL}}{s}$$

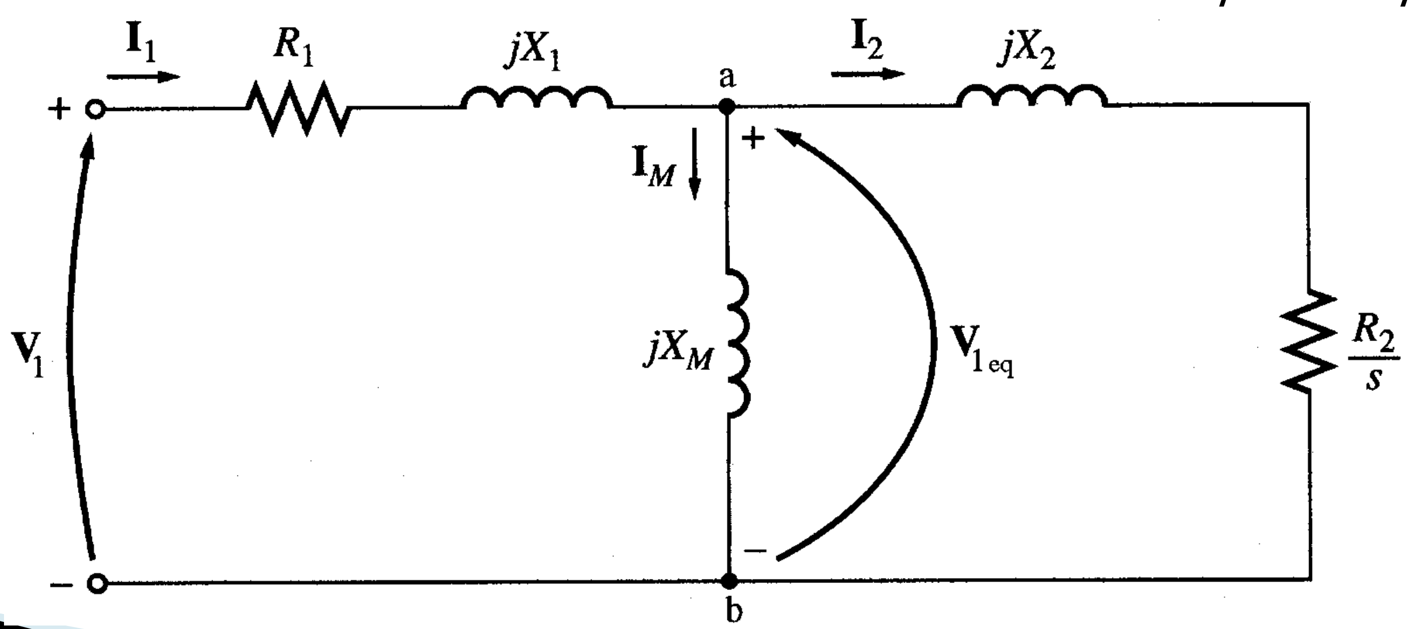
$$P_{RCL} = 3 I_2^2 R_2$$

$$P_{conv} = P_{AG} - P_{RCL} \quad = 3 I_2^2 \frac{R_2 (1-s)}{s} \quad = \frac{P_{RCL}(1-s)}{s}$$

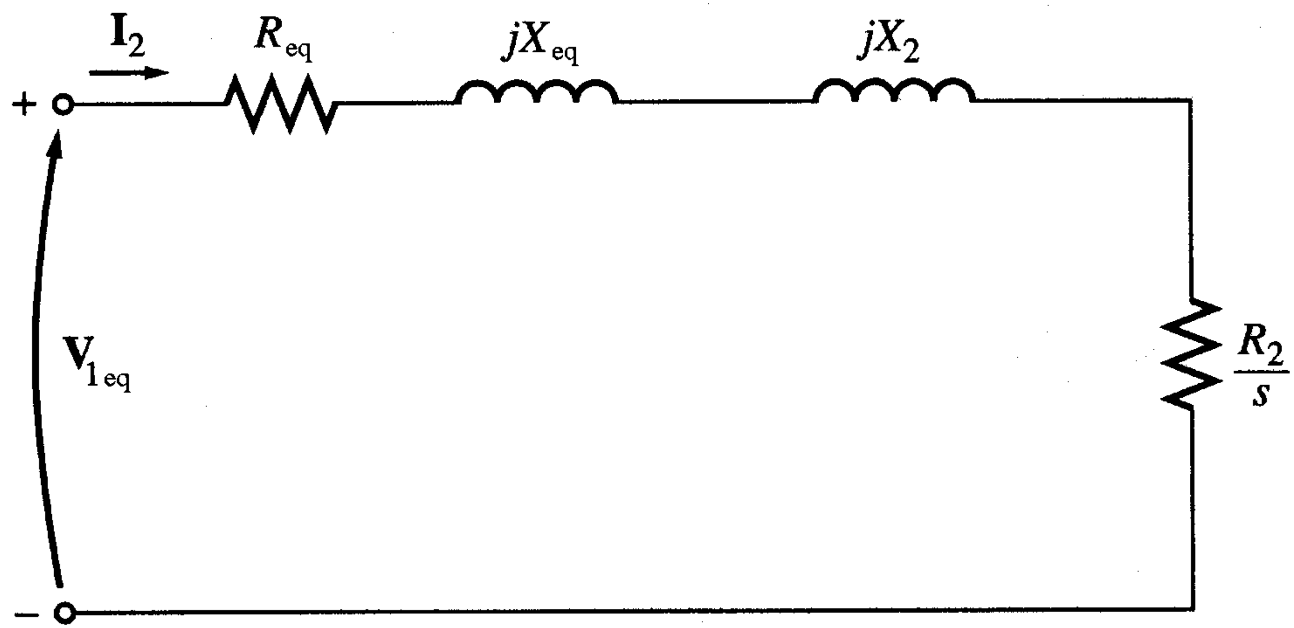
$$P_{out} = P_{conv} - (P_{f+w} + P_{stray})$$

Torque, power and Thevenin's Theorem

- Thevenin's theorem can be used to transform the network to the left of points 'a' and 'b' into an equivalent voltage source V_{1eq} in series with equivalent impedance $R_{eq}+jX_{eq}$



Torque, power and Thevenin's Theorem



$$V_{1eq} = V_1 \frac{jX_M}{R_1 + j(X_1 + X_M)}$$

$$R_{eq} + jX_{eq} = (R_1 + jX_1) // jX_M$$

Torque, power and Thevenin's Theorem

$$I_2 = \frac{V_{1eq}}{Z_T} = \frac{V_{1eq}}{\sqrt{\left(R_{eq} + \frac{R_2}{s}\right)^2 + (X_{eq} + X_2)^2}}$$

Then the power converted to mechanical (P_{conv})

$$P_{conv} = I_2^2 \frac{R_2(1-s)}{s}$$

And the internal mechanical torque (T_{conv})

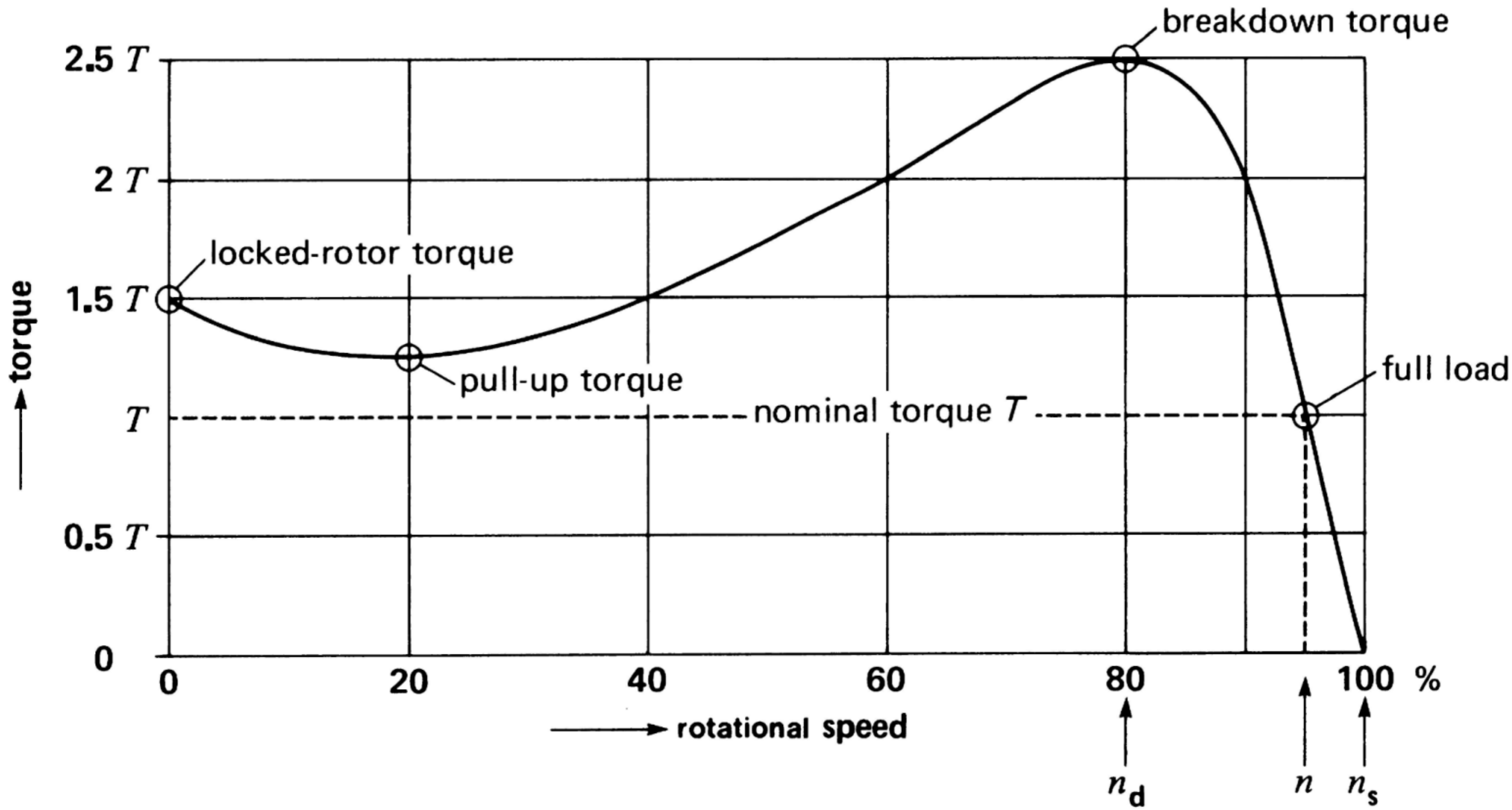
$$T_{conv} = \frac{P_{conv}}{\omega_m} = \frac{P_{conv}}{(1-s)\omega_s} = \frac{I_2^2 \frac{R_2}{s}}{\omega_s}$$

Torque, power and Thevenin's Theorem

$$T_{conv} = \frac{1}{\omega_s}\left(\frac{V_{1eq}}{\sqrt{\left(R_{eq}+\frac{R_2}{s}\right)^2 + (X_{eq}+X_2)^2}}\right)^2\left(\frac{R_2}{s}\right)$$

$$T_{conv} = \frac{1}{\omega_s}\frac{V_{1eq}^2\left(\frac{R_2}{s}\right)}{\left(R_{eq}+\frac{R_2}{s}\right)^2 + (X_{eq}+X_2)^2}$$

Torque–speed characteristics



Typical torque-speed characteristics of induction motor

Maximum torque

- Maximum torque occurs when the power transferred to R_2/s is maximum.
- This condition occurs when R_2/s equals the magnitude of the impedance $R_{eq} + j(X_{eq} + X_2)$

$$\frac{R_2}{s_{T_{\max}}} = \sqrt{R_{eq}^2 + (X_{eq} + X_2)^2}$$

$$s_{T_{\max}} = \frac{R_2}{\sqrt{R_{eq}^2 + (X_{eq} + X_2)^2}}$$

Maximum torque

- The corresponding maximum torque of an induction motor equals

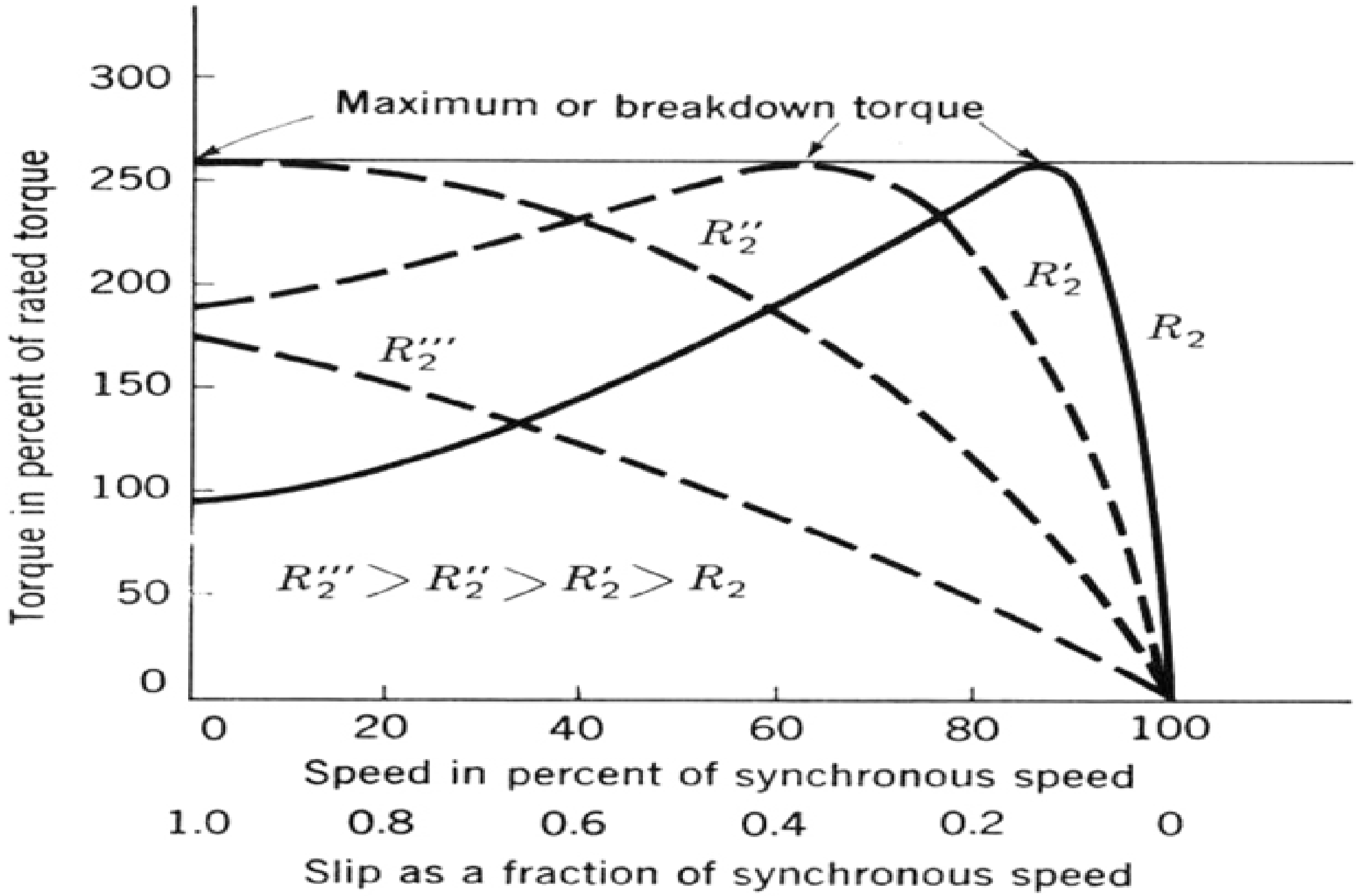
$$T_{\max} = \frac{1}{2\omega_s}\left(\frac{V_{eq}^2}{R_{eq} + \sqrt{R_{eq}^2 + (X_{eq} + X_2)^2}}\right)$$

- The slip at maximum torque is directly proportional to the rotor resistance R_2
- The maximum torque is independent of R_2

Maximum torque

- Rotor resistance can be increased by inserting external resistance in the rotor of a wound-rotor induction motor.
- The value of the maximum torque remains unaffected but the speed at which it occurs can be controlled.

Maximum torque



Effect of rotor resistance on torque-speed characteristic

Problem 7-5 (p.468)

A 50-kW, 440-V, 50-Hz, six-pole induction motor has a slip of 6 percent when operating at full-load conditions. At full-load conditions, the friction and windage losses are 300 W, and the core losses are 600 W. Find the following values for full-load conditions:

(a) The shaft speed n_m

(b) The output power in watts

(c) The load torque τ_{load} in newton-meters

(d) The induced torque τ_{ind} in newton-meters

(e) The rotor frequency in hertz

Solution to Problem 7-5 (p.468)

(a) The synchronous speed of this machine is

$$n_{\text{sync}} = \frac{120 f_e}{P} = \frac{120(50\text{ Hz})}{6} = 1000\text{ r/min}$$

Therefore, the shaft speed is

$$n_m = (1-s)\, n_{\text{sync}} = (1-0.06)(1000\text{ r/min}) = 940\text{ r/min}$$

(b) The output power in watts is 50 kW (stated in the problem).

(c) The load torque is

$$\tau_{\text{load}} = \frac{P_{\text{OUT}}}{\omega_m} = \frac{50\text{ kW}}{(940\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 508\text{ N}\cdot\text{m}$$

(d) The induced torque can be found as follows:

$$P_{\text{conv}} = P_{\text{OUT}} + P_{\text{F\&W}} + P_{\text{core}} + P_{\text{misc}} = 50\text{ kW} + 300\text{ W} + 600\text{ W} + 0\text{ W} = 50.9\text{ kW}$$

$$\tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_m} = \frac{50.9\text{ kW}}{(940\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 517\text{ N}\cdot\text{m}$$

(e) The rotor frequency is

$$f_r = sf_e = (0.06)(50\text{ Hz}) = 3.00\text{ Hz}$$

Problem 7-7 (pp.468-469)

A 208-V, two-pole, 60-Hz Y-connected wound-rotor induction motor is rated at 15 hp. Its equivalent circuit components are

$R_1 = 0.200\ \Omega$	$R_2 = 0.120\ \Omega$	$X_M = 15.0\ \Omega$
$X_1 = 0.410\ \Omega$	$X_2 = 0.410\ \Omega$	
$P_{\text{mech}} = 250\ \text{W}$	$P_{\text{misc}} \approx 0$	$P_{\text{core}} = 180\ \text{W}$

For a slip of 0.05, find

(a) The line current I_L

(b) The stator copper losses P_{SCL}

(c) The air-gap power P_{AG}

(d) The power converted from electrical to mechanical form P_{conv}

(e) The induced torque τ_{ind}

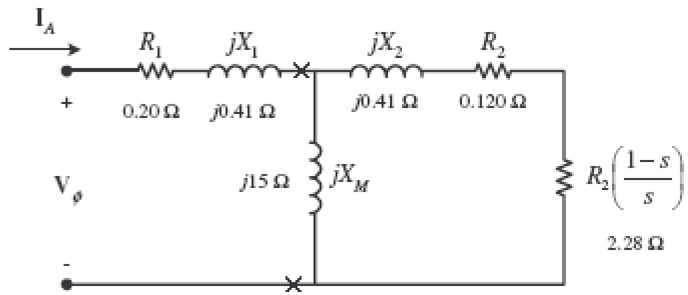
(f) The load torque τ_{load}

(g) The overall machine efficiency

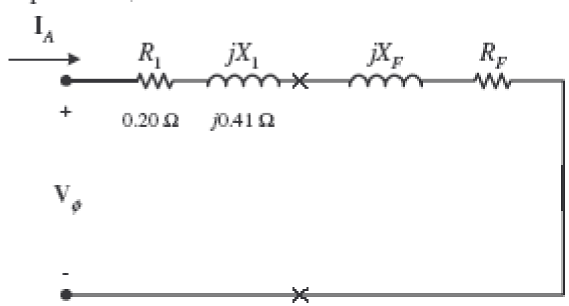
(h) The motor speed in revolutions per minute and radians per second

Solution to Problem 7-7 (pp.468–469)

SOLUTION The equivalent circuit of this induction motor is shown below:



(a) The easiest way to find the line current (or armature current) is to get the equivalent impedance Z_F of the rotor circuit in parallel with jX_M, and then calculate the current as the phase voltage divided by the sum of the series impedances, as shown below.



The equivalent impedance of the rotor circuit in parallel with jX_M is:

$$Z_F = \frac{1}{\dfrac{1}{jX_M} + \dfrac{1}{Z_2}} = \frac{1}{\dfrac{1}{j15\ \Omega} + \dfrac{1}{2.40 + j0.41}} = 2.220 + j0.745 = 2.34\angle 18.5^\circ\ \Omega$$

The phase voltage is $208/\sqrt{3}$ = 120 V, so line current I_L is

Solution to Problem 7-7 (pp.468-469) – Cont'd

$$I_L = I_A = \frac{V_\phi}{R_1 + jX_1 + R_F + jX_F} = \frac{120\angle 0^\circ \text{ V}}{0.20\ \Omega\ + j0.41\ \Omega + \ 2.22\ \Omega + j0.745\ \Omega}$$

$$I_L = I_A = 44.8\angle -25.5^\circ \text{ A}$$

(b) The stator copper losses are

$$P_{\text{SCL}} = 3I_A^{\,2}R_1 = 3(44.8\text{ A})^2(0.20\ \Omega) = 1205\text{ W}$$

(c) The air gap power is $P_{\text{AG}} = 3I_2^{\,2}\frac{R_2}{s} = 3I_A^{\,2}R_F$

(Note that $3I_A^{\,2}R_F$ is equal to $3I_2^{\,2}\frac{R_2}{s}$, since the only resistance in the original rotor circuit was R_2/s, and the resistance in the Thevenin equivalent circuit is R_F. The power consumed by the Thevenin equivalent circuit must be the same as the power consumed by the original circuit.)

$$P_{\text{AG}} = 3I_2^{\,2}\frac{R_2}{s} = 3I_A^{\,2}R_F = 3(44.8\text{ A})^2(2.220\ \Omega) = 13.4\text{ kW}$$

(d) The power converted from electrical to mechanical form is

$$P_{\text{conv}} = (1-s)P_{\text{AG}} = (1-0.05)(13.4\text{ kW}) = 12.73\text{ kW}$$

(e) The induced torque in the motor is

$$\tau_{\text{ind}} = \frac{P_{\text{AG}}}{\omega_{\text{sync}}} = \frac{13.4\text{ kW}}{(3600\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 35.5\text{ N}\cdot\text{m}$$

Solution to Problem 7-7 (pp.468-469) - Cont'd

(f) The output power of this motor is

$$P_{\text{OUT}} = P_{\text{conv}} - P_{\text{mech}} - P_{\text{core}} - P_{\text{misc}} = 12.73\text{ kW} - 250\text{ W} - 180\text{ W} - 0\text{ W} = 12.3\text{ kW}$$

The output speed is

$$n_m = (1-s)\, n_{\text{sync}} = (1-0.05)(3600\text{ r/min}) = 3420\text{ r/min}$$

Therefore the load torque is

$$\tau_{\text{load}} = \frac{P_{\text{OUT}}}{\omega_m} = \frac{12.3\text{ kW}}{(3420\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right)} = 34.3\text{ N}\cdot\text{m}$$

(g) The overall efficiency is

$$\eta = \frac{P_{\text{OUT}}}{P_{\text{IN}}} \times 100\% = \frac{P_{\text{OUT}}}{3V_\phi I_A \cos\theta} \times 100\%$$

$$\eta = \frac{12.3\text{ kW}}{3(120\text{ V})(44.8\text{ A})\cos 25.5^\circ} \times 100\% = 84.5\%$$

(h) The motor speed in revolutions per minute is 3420 r/min. The motor speed in radians per second is

$$\omega_m = (3420\text{ r/min})\left(\frac{2\pi\text{ rad}}{1\text{ r}}\right)\left(\frac{1\text{ min}}{60\text{ s}}\right) = 358\text{ rad/s}$$

Problem 7–19 (p.470)

A 460-V, four-pole, 50-hp, 60-Hz, Y-connected three-phase induction motor develops its full-load induced torque at 3.8 percent slip when operating at 60 Hz and 460 V. The per-phase circuit model impedances of the motor are

$$R_1 = 0.33\ \Omega \qquad X_M = 30\ \Omega$$

$$X_1 = 0.42\ \Omega \qquad X_2 = 0.42\ \Omega$$

Mechanical, core, and stray losses may be neglected in this problem.

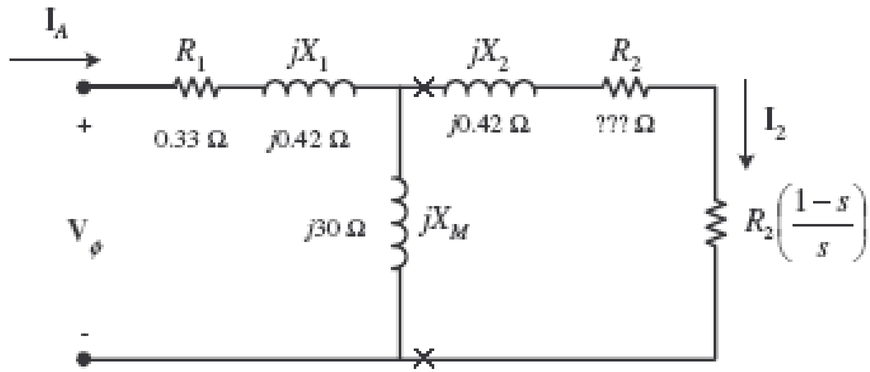
(a) Find the value of the rotor resistance R_2.

(b) Find τ_{max}, s_{max}, and the rotor speed at maximum torque for this motor.

(c) Find the starting torque of this motor.

Solution to Problem 7-19 (pp.470)

SOLUTION The equivalent circuit for this motor is



The Thevenin equivalent of the input circuit is:

$$Z_{TH} = \frac{jX_M(R_1 + jX_1)}{R_1 + j(X_1 + X_M)} = \frac{(j30\ \Omega)(0.33\ \Omega\ +\ j0.42\ \Omega)}{0.33\ \Omega\ +\ j(0.42\ \Omega + 30\ \Omega)} = 0.321 + j0.418\ \Omega = 0.527\angle 52.5°\ \Omega$$

$$\mathbf{V}_{TH} = \frac{jX_M}{R_1 + j(X_1 + X_M)}\mathbf{V}_\phi = \frac{(j30\ \Omega)}{0.33\ \Omega\ +\ j(0.42\ \Omega + 30\ \Omega)}(265.6\angle 0°\ \text{V}) = 262\angle 0.6°\ \text{V}$$

Solution to Problem 7-19 (pp.470) – Cont'd

(a) If losses are neglected, the induced torque in a motor is equal to its load torque. At full load, the output power of this motor is 50 hp and its slip is 3.8%, so the induced torque is

$$n_m = (1 - 0.038)(1800 \text{ r/min}) = 1732 \text{ r/min}$$

$$\tau_{\text{ind}} = \tau_{\text{load}} = \frac{(50 \text{ hp})(746 \text{ W/hp})}{(1732 \text{ r/min})\left(\dfrac{2\pi \text{ rad}}{1 \text{ r}}\right)\left(\dfrac{1 \text{ min}}{60 \text{ s}}\right)} = 205.7 \text{ N}\cdot\text{m}$$

The induced torque is given by the equation

$$\tau_{\text{ind}} = \frac{3V_{\text{TH}}^2 R_2 / s}{\omega_{\text{sync}} \left[(R_{\text{TH}} + R_2 / s)^2 + (X_{\text{TH}} + X_2)^2\right]}$$

Substituting known values and solving for R_2 / s yields

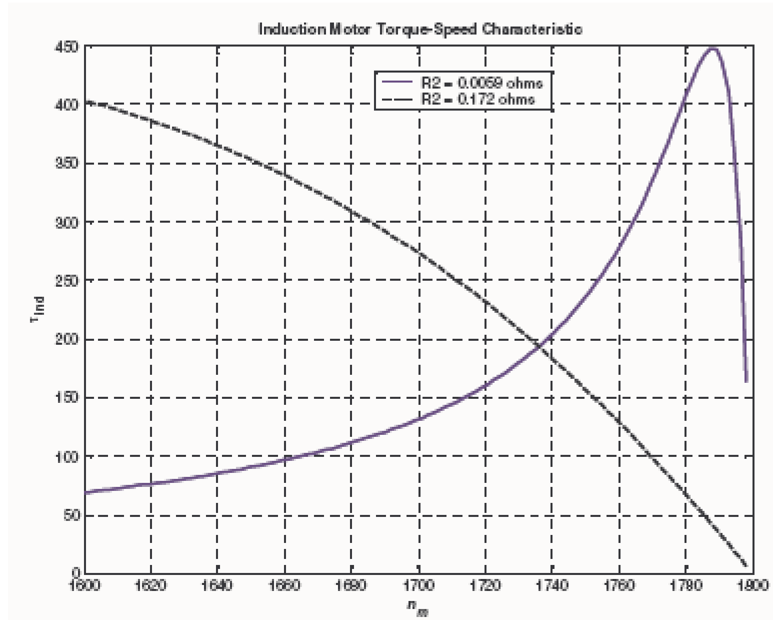
$$205.7 \text{ N}\cdot\text{m} = \frac{3(262 \text{ V})^2 R_2 / s}{(188.5 \text{ rad/s})\left[(0.321 + R_2 / s)^2 + (0.418 + 0.42)^2\right]}$$

$$38,774 = \frac{205,932 \ \ R_2 / s}{(0.321 + R_2 / s)^2 + 0.702}$$

$$(0.321 + R_2 / s)^2 + 0.702 = 5.311 \ \ R_2 / s$$

$$0.103 + 0.642 R_2 / s + (R_2 / s)^2 + 0.702 = 5.311 \ \ R_2 / s$$

Solution to Problem 7-19 (pp.470) – Cont'd



$$\frac{R_2}{s}^2 - 4.669\,\frac{R_2}{s} + 0.702 = 0$$

$$\frac{R_2}{s} = 0.156, \quad 4.513$$

$$R_2 = 0.0059\ \Omega,\ 0.172\ \Omega$$

These two solutions represent two situations in which the torque-speed curve would go through this specific torque-speed point. The two curves are plotted below. As you can see, only the 0.172 Ω solution is realistic, since the 0.0059 Ω solution passes through this torque-speed point at an unstable location on the back side of the torque-speed curve.

Solution to Problem 7-19 (pp.470) – Cont'd

(b) The slip at pullout torque can be found by calculating the Thevenin equivalent of the input circuit from the rotor back to the power supply, and then using that with the rotor circuit model. The Thevenin equivalent of the input circuit was calculate in part *(a)*. The slip at pullout torque is

$$s_{max} = \frac{R_2}{\sqrt{R_{TH}{}^2 + \left(X_{TH} + X_2\right)^2}}$$

$$s_{max} = \frac{0.172\ \Omega}{\sqrt{(0.321\ \Omega)^2 + (0.418\ \Omega\ + 0.420\ \Omega)^2}} = 0.192$$

The rotor speed a maximum torque is

$$n_{pullout} = (1 - s)\ n_{sync} = (1 - 0.192)(1800\ \text{r/min}) = 1454\ \text{r/min}$$

and the pullout torque of the motor is

$$\tau_{max} = \frac{3V_{TH}^2}{2\omega_{sync}\ \ R_{TH} + \sqrt{R_{TH}^2 + \left(X_{TH} + X_2\right)^2}}$$

$$\tau_{max} = \frac{3(262\ \text{V})^2}{2(188.5\ \text{rad/s})\ \ 0.321\ \Omega + \sqrt{(0.321\ \Omega)^2 + (0.418\ \Omega\ + 0.420\ \Omega)^2}}$$

$$\tau_{max} = 448\ \text{N} \cdot \text{m}$$

(c) The starting torque of this motor is the torque at slip $s = 1$. It is

$$\tau_{ind} = \frac{3V_{TH}^2 R_2 / s}{\omega_{sync}\ \ \left(R_{TH} + R_2 / s\right)^2 + \left(X_{TH} + X_2\right)^2}$$

$$\tau_{ind} = \frac{3(262\ \text{V})^2 (0.172\ \Omega)}{(188.5\ \text{rad/s})\ \ (0.321 + 0.172\ \Omega)^2 + (0.418 + 0.420)^2} = 199\ \text{N} \cdot \text{m}$$

Transformers

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Govt Polytechnic Jhajjar

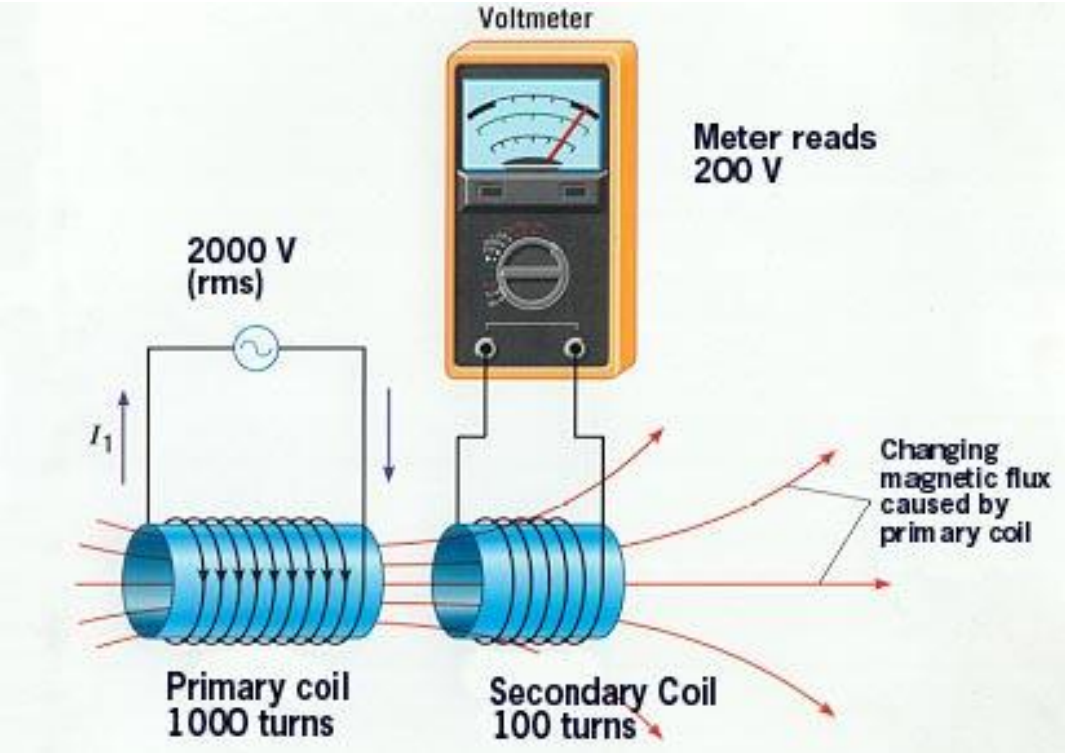
Transformer

An A.C. device used to change high voltage low current A.C. into low voltage high current A.C. and vice-versa without changing the frequency

In brief,

1. Transfers electric power from one circuit to another
2. It does so without a change of frequency
3. It accomplishes this by electromagnetic induction
4. Where the two electric circuits are in mutual inductive influence of each other.

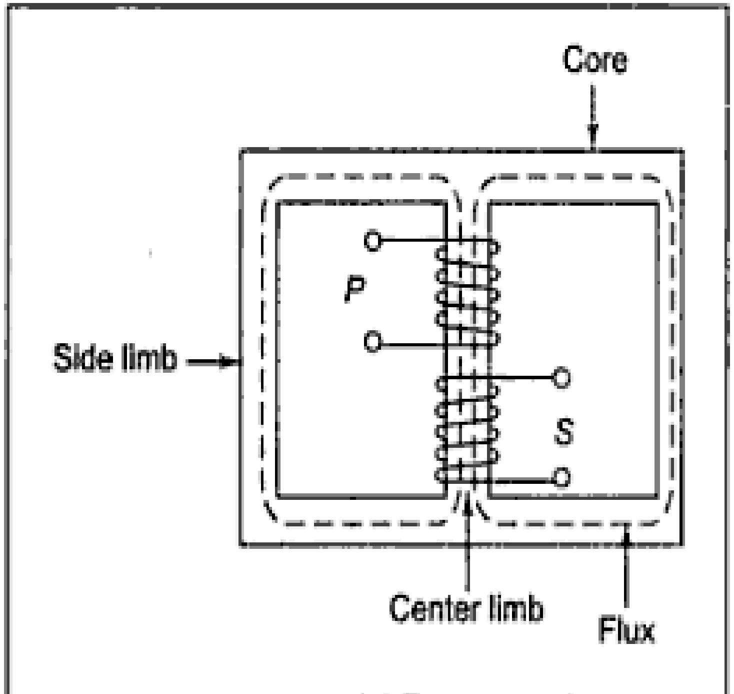
Principle of operation



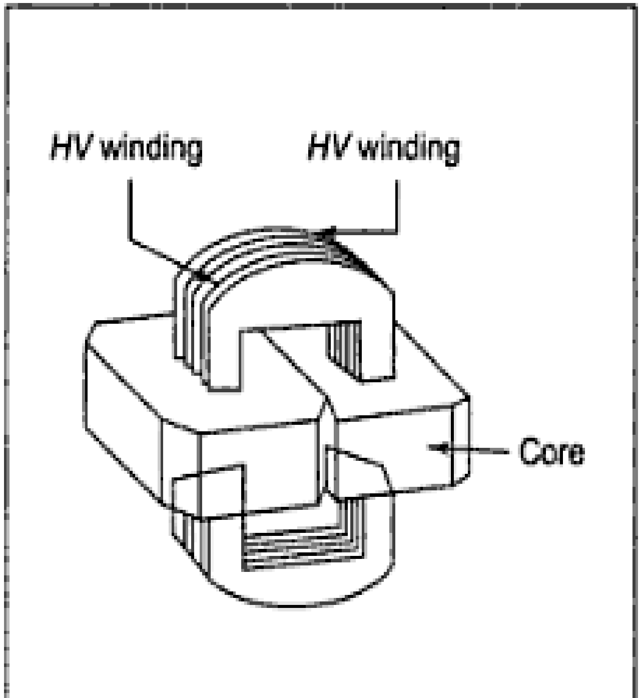
It is based on principle of MUTUAL INDUCTION.

According to which an e.m.f. is induced in a coil when current in the neighbouring coil changes.

Constructional detail : Shell type



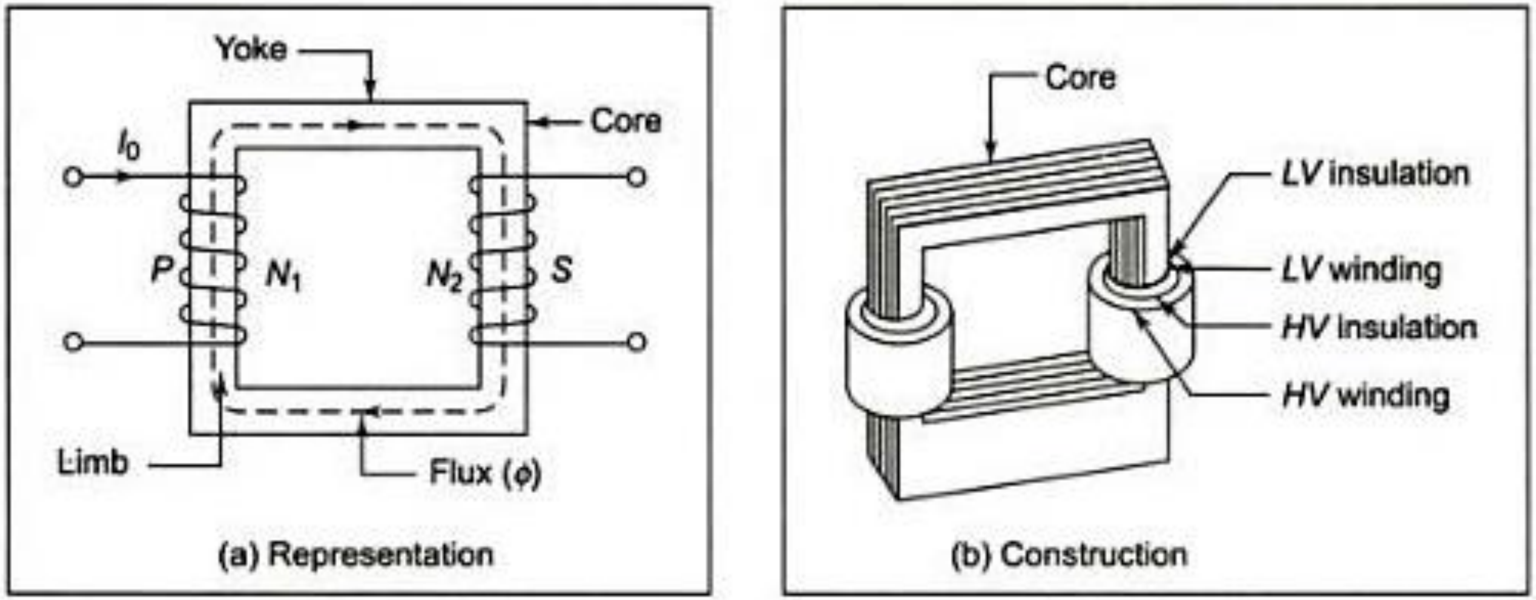
(a) Representation



(b) Construction

- Windings are wrapped around the center leg of a laminated core.

Core type

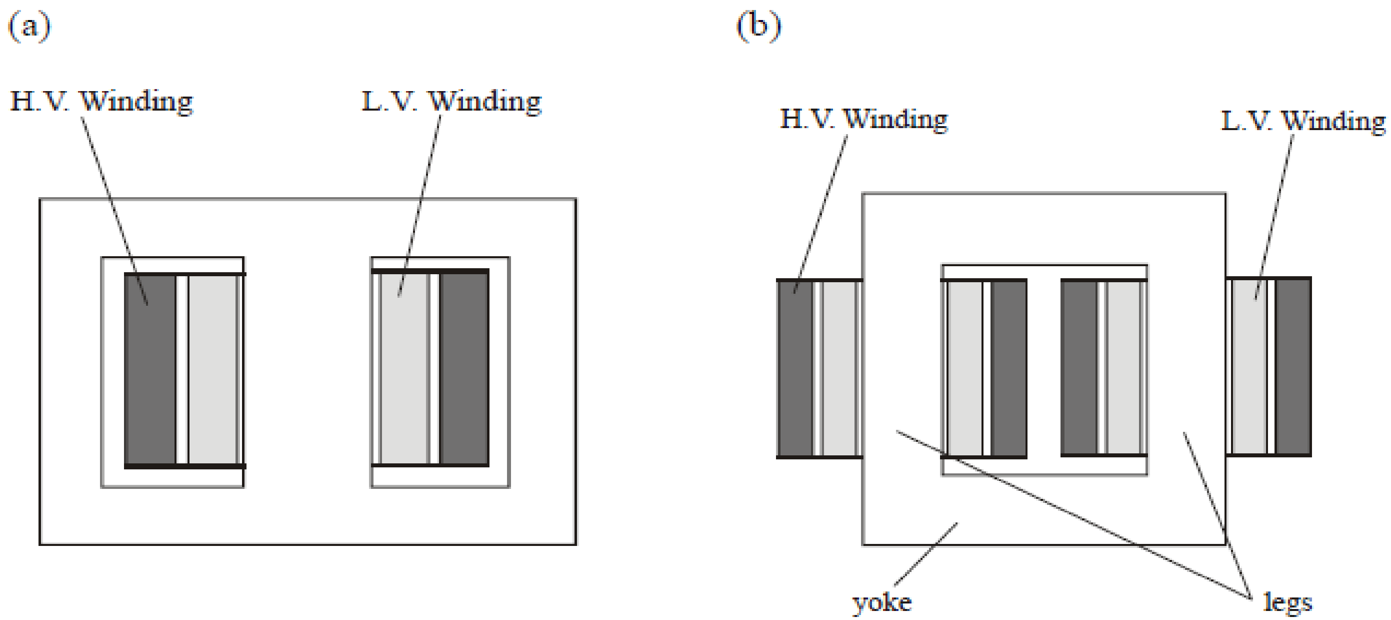


(a) Representation

(b) Construction

- Windings are wrapped around two sides of a laminated square core.

Sectional view of transformers

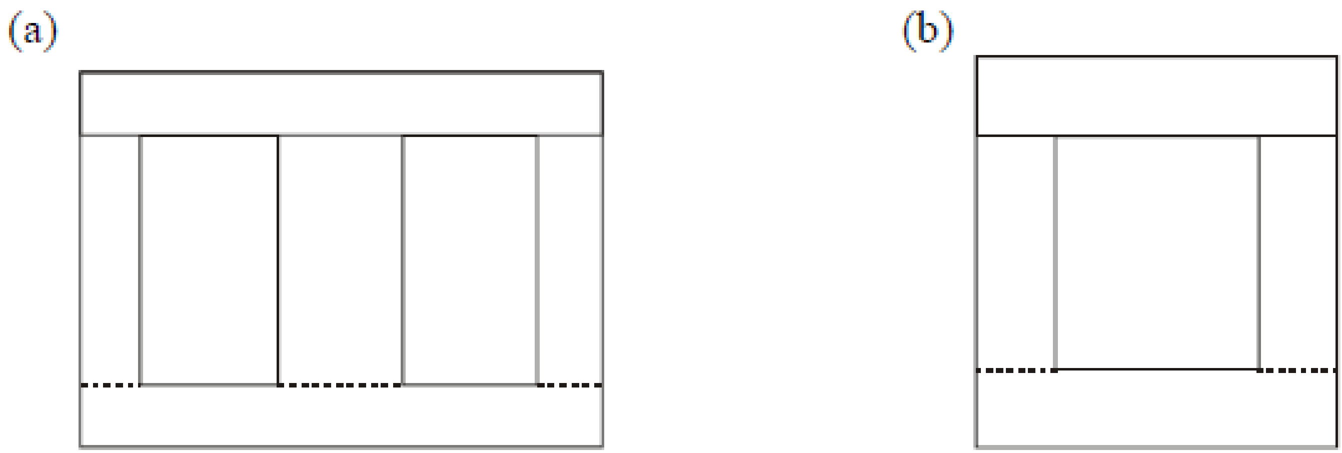


(a) Shell-type transformer, (b) core-type transformer

Note:

High voltage conductors are smaller cross section conductors than the low voltage coils

Construction of transformer from stampings



(a) Shell-type transformer, (b) core-type transformer

Core type

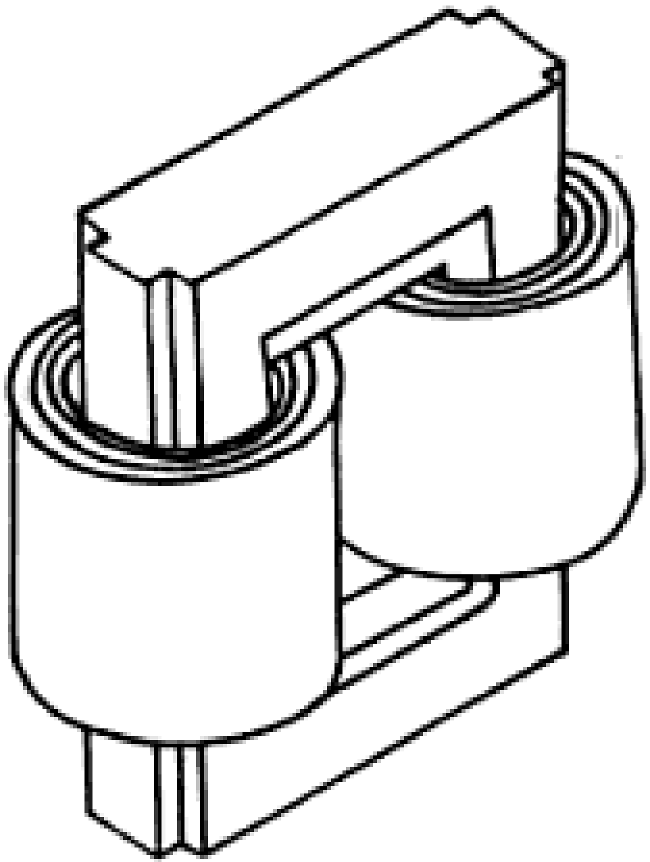


Fig1: Coil and laminations of core type transformer

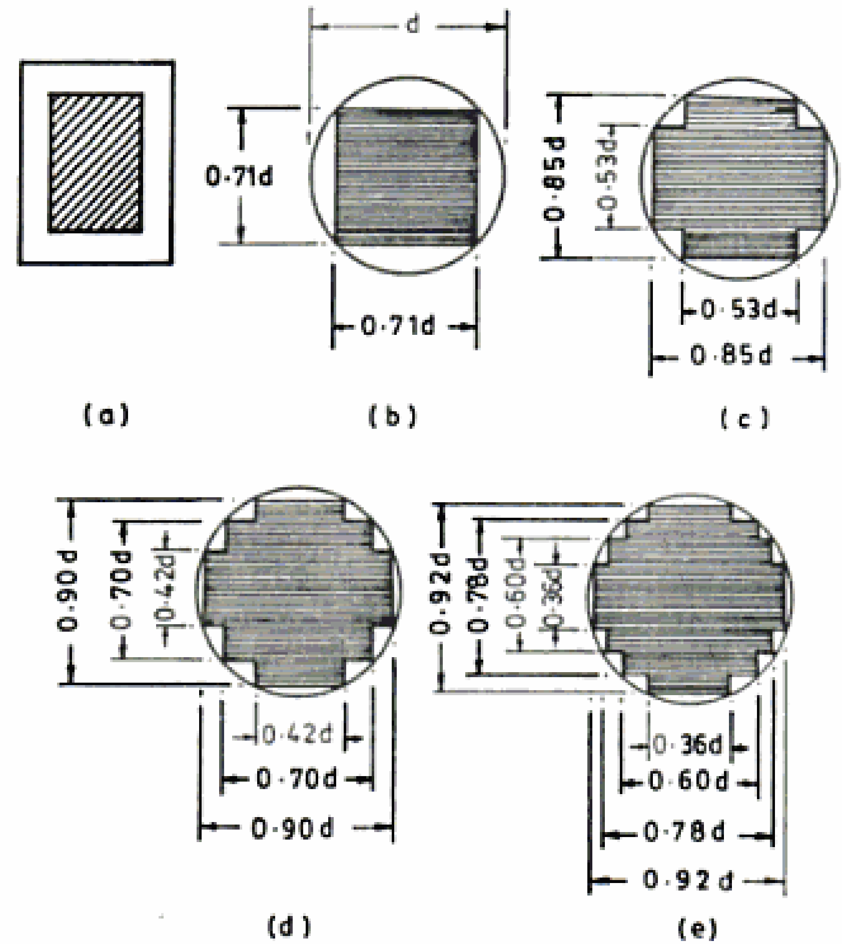


Fig2: Various types of cores

Shell type

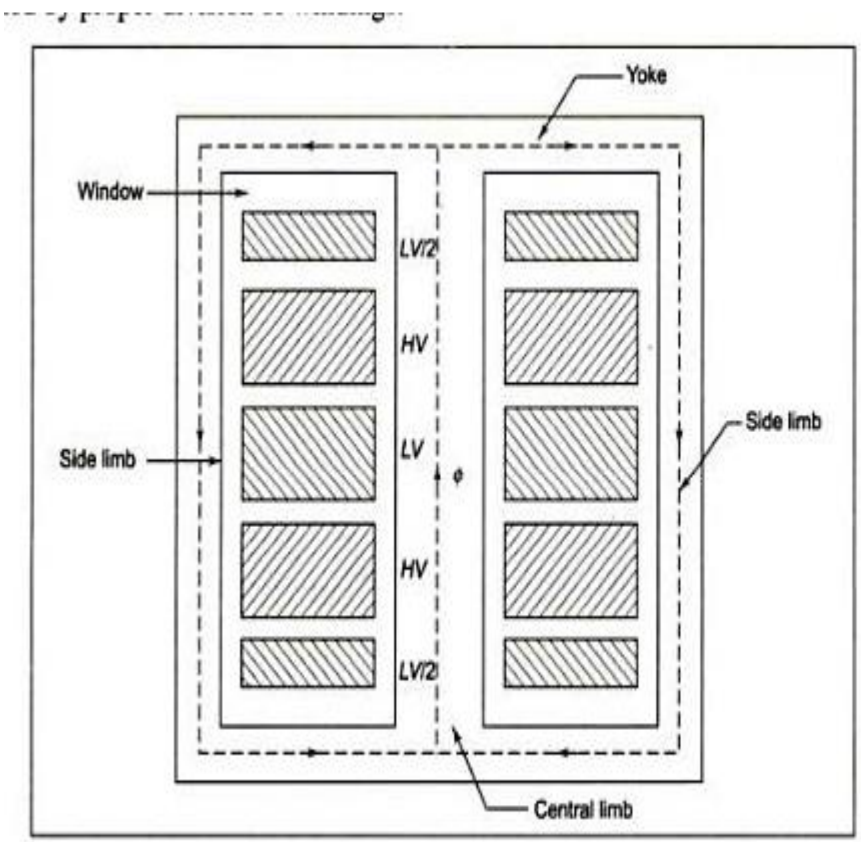
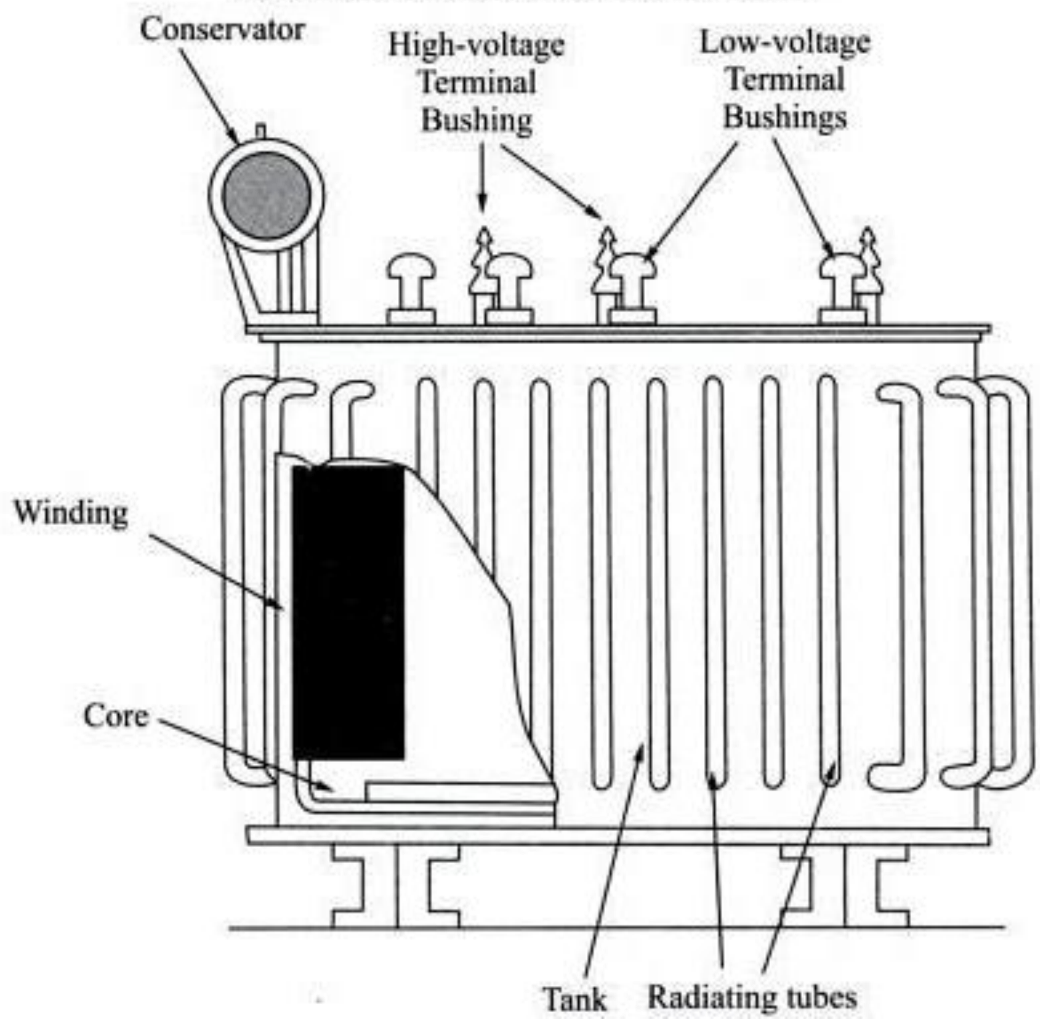


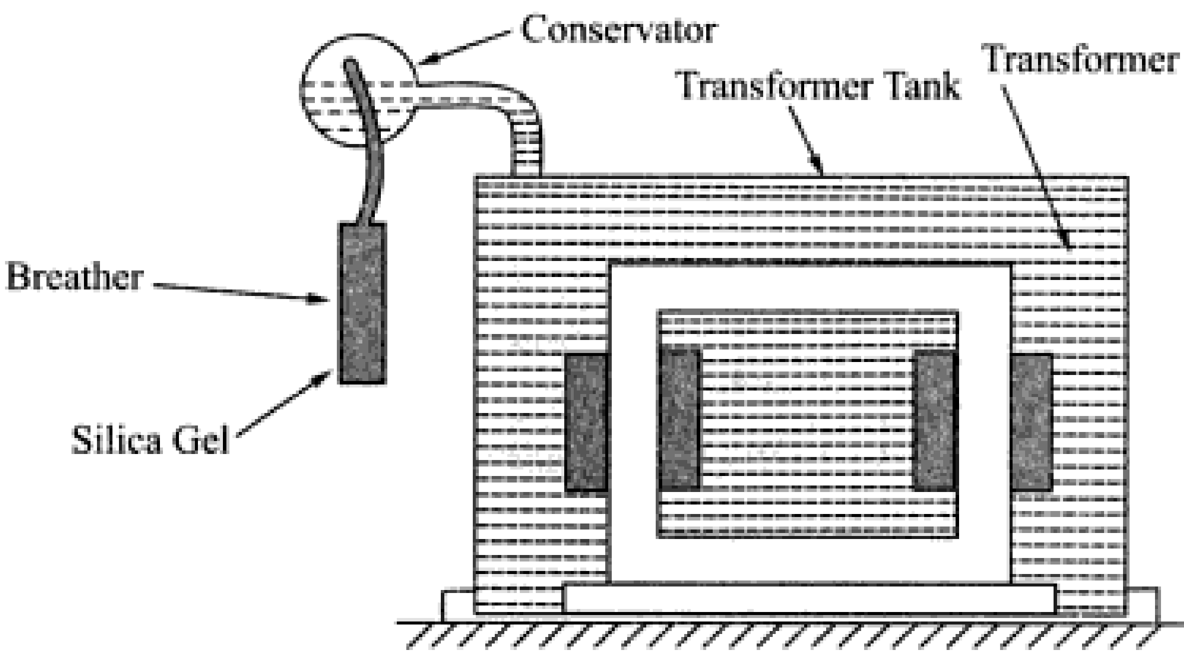
Fig: Sandwich windings

- The HV and LV windings are split into no. of sections
- Where HV winding lies between two LV windings
- In sandwich coils leakage can be controlled

Cut view of transformer

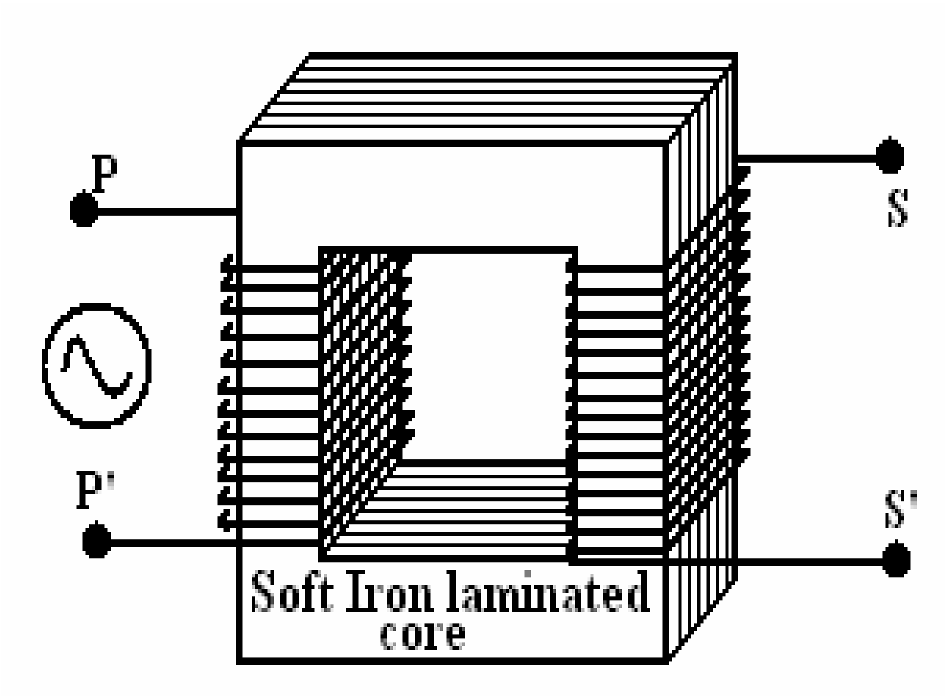


Transformer with conservator and breather



Working of a transformer

1. When current in the primary coil changes being alternating in nature, a changing magnetic field is produced
2. This changing magnetic field gets associated with the secondary through the soft iron core
3. Hence magnetic flux linked with the secondary coil changes.
4. Which induces e.m.f. in the secondary.



Single Phase Transformer

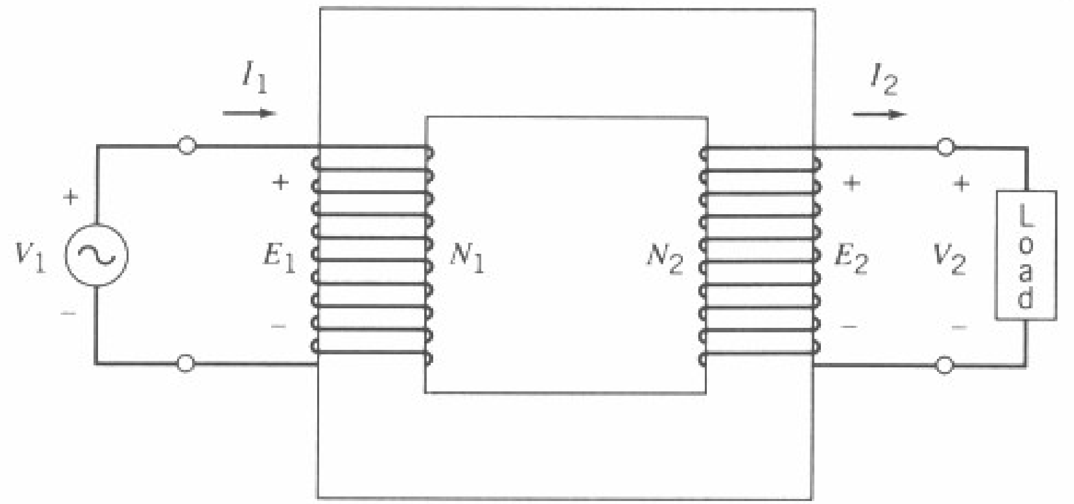


FIGURE 4.8 A transformer circuit.

- A single phase transformer
  - Two or more winding, coupled by a common magnetic core

Ideal Transformers

- **Zero leakage flux:**

  -Fluxes produced by the primary and secondary currents are confined within the core

- **The windings have no resistance:**

  - Induced voltages equal applied voltages

- **The core has infinite permeability**

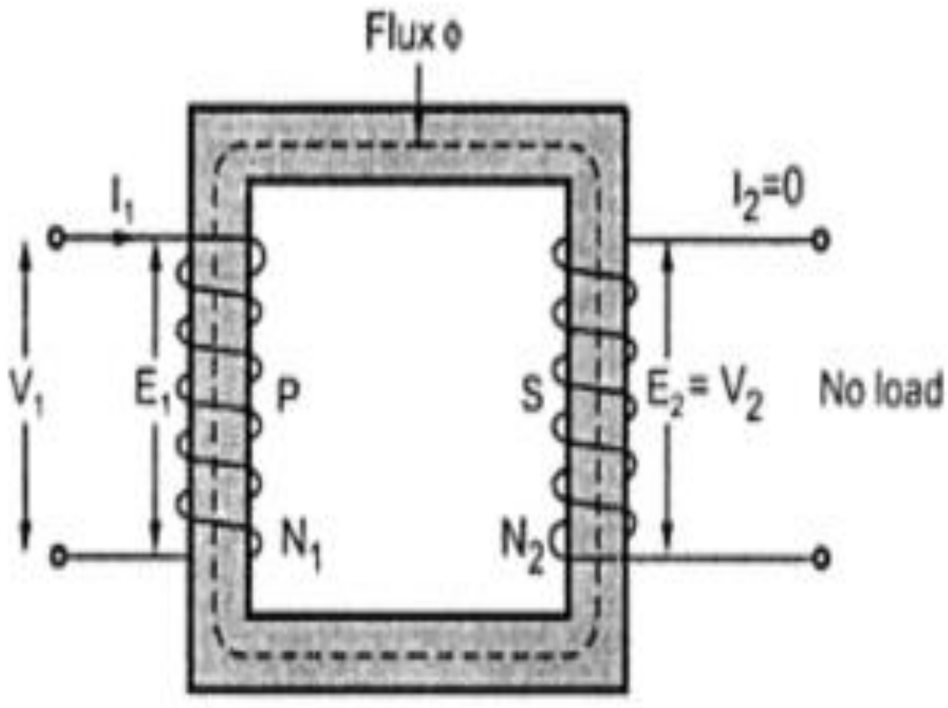
  - Reluctance of the core is zero

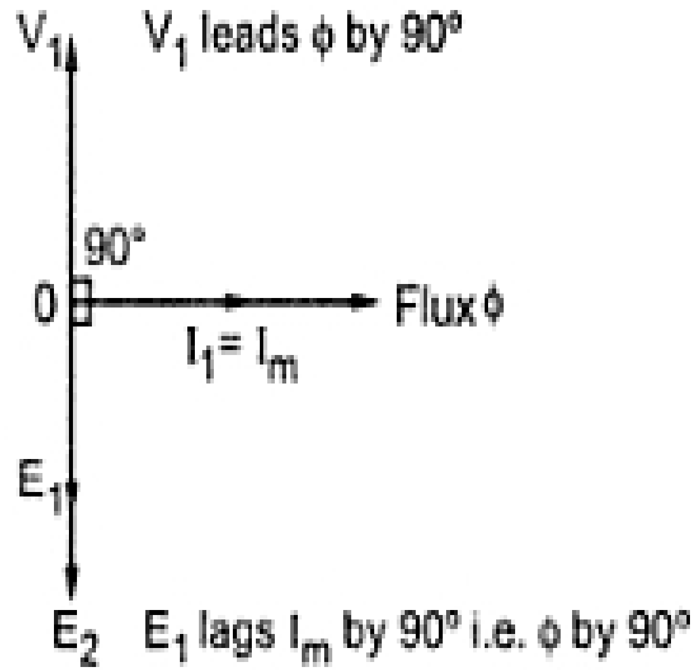
  - Negligible current is required to establish magnetic flux

- **Loss-less magnetic core**

  - No hysteresis or eddy currents

Ideal transformer





V_1 – supply voltage ; I_1- noload input current ;

V_{2-} output voltgae; I_2- output current

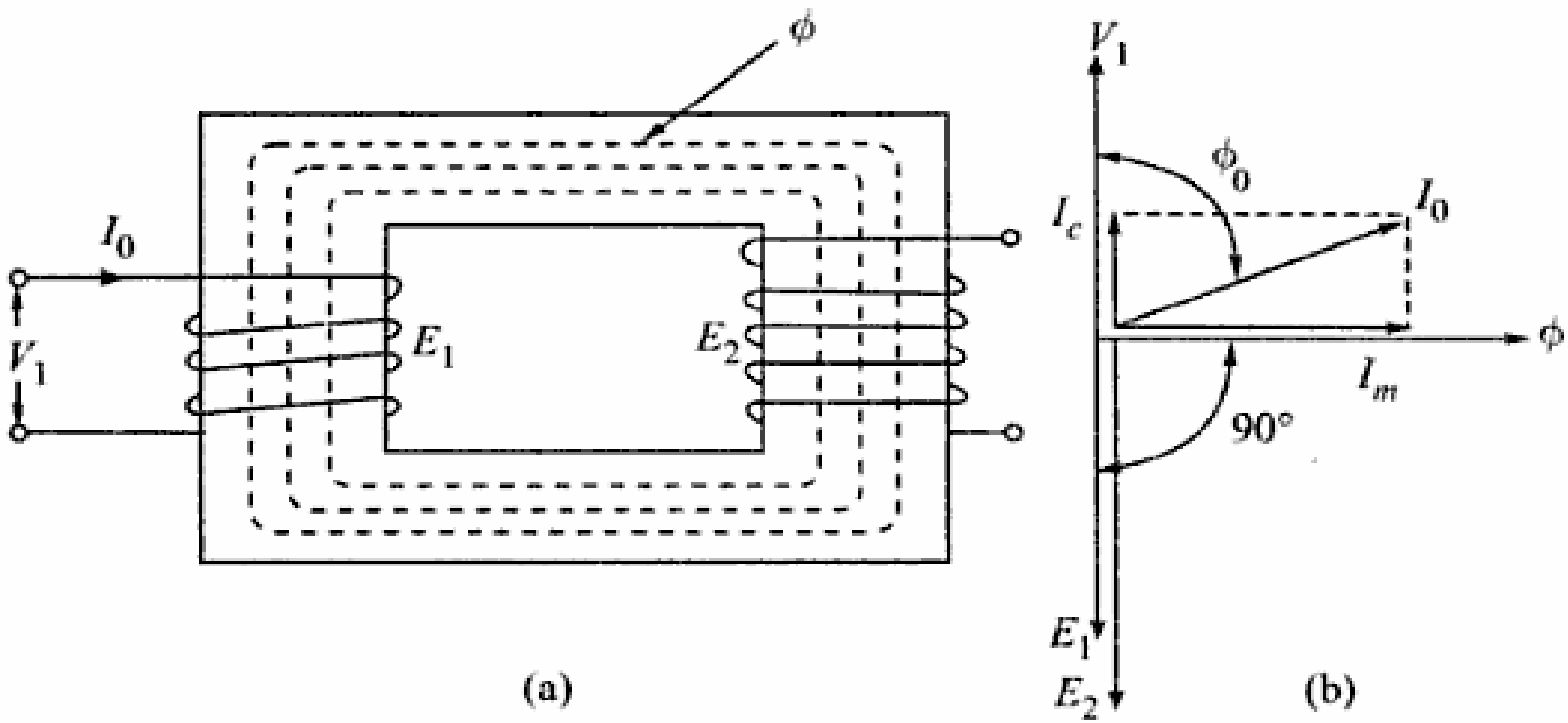
I_m- magnetising current;

E_1-self induced emf ; E_2- mutually induced emf

EMF equation of a transformer

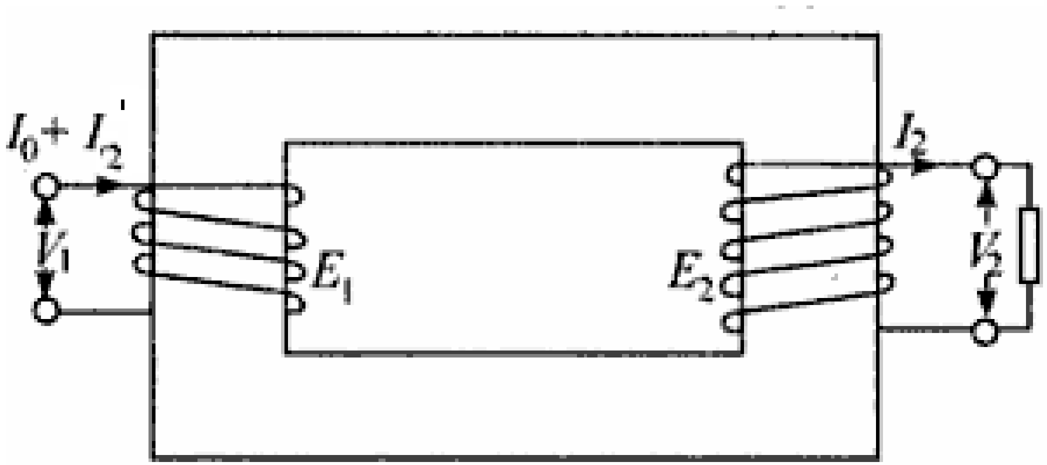
- Worked out on board /
- Refer pdf file: emf-equation-of-tranformer

Phasor diagram: Transformer on No-load



(a) Transformer on no-load (b) Phasor diagram of a transformer on no-load

Transformer on load assuming no voltage drop in the winding



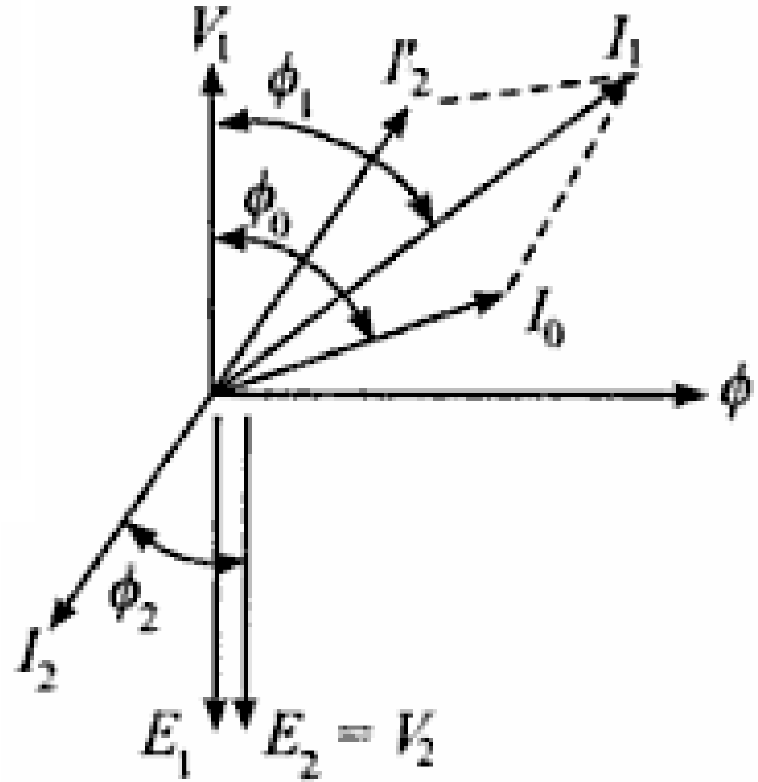


Fig shows the Phasor diagram of a transformer on load by assuming

1. No voltage drop in the winding
2. Equal no. of primary and secondary turns

Transformer on load

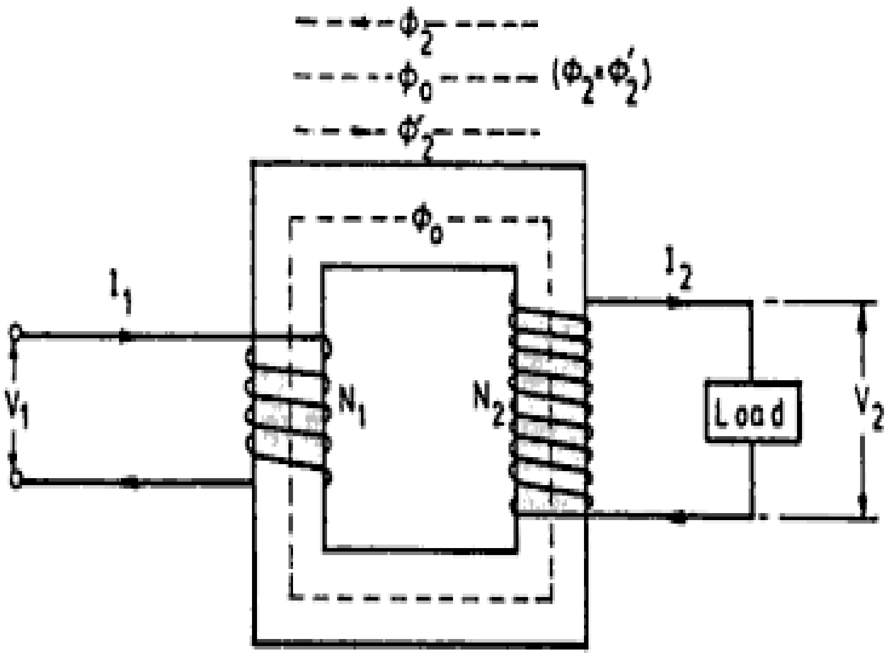


Fig. a: Ideal transformer on load

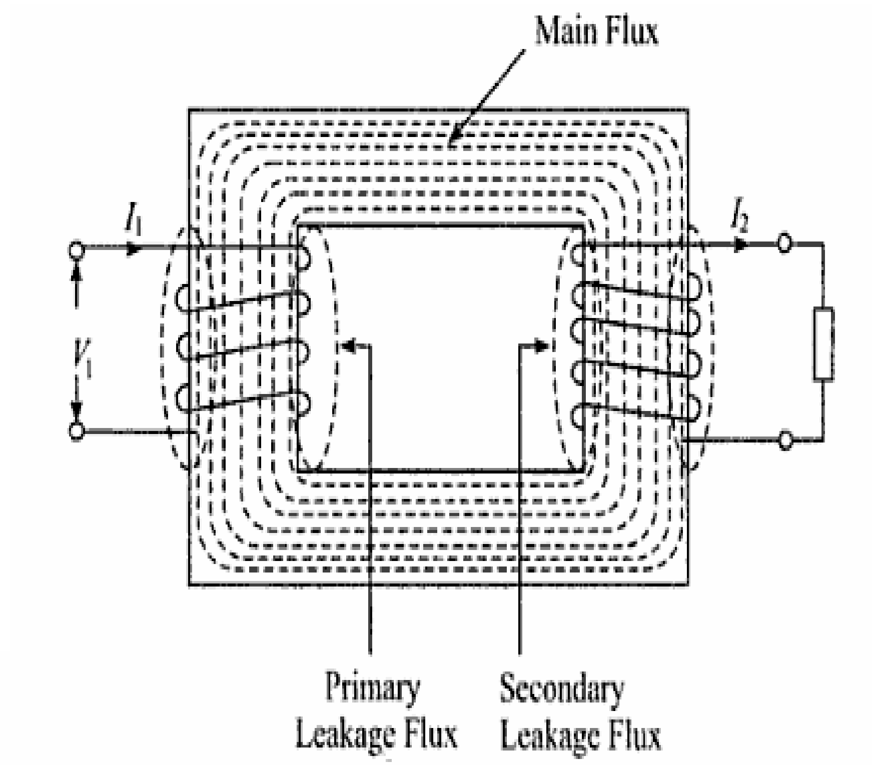
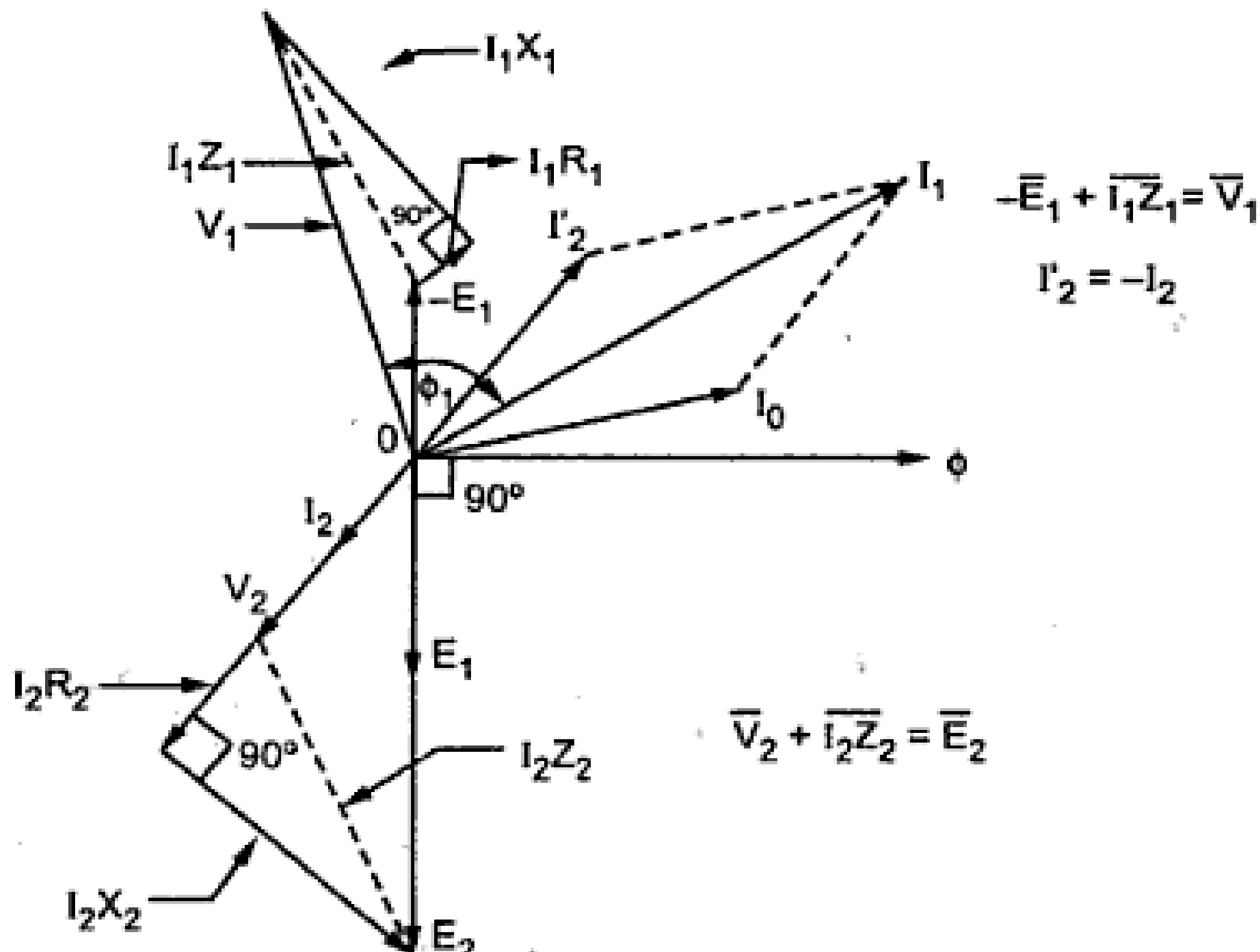
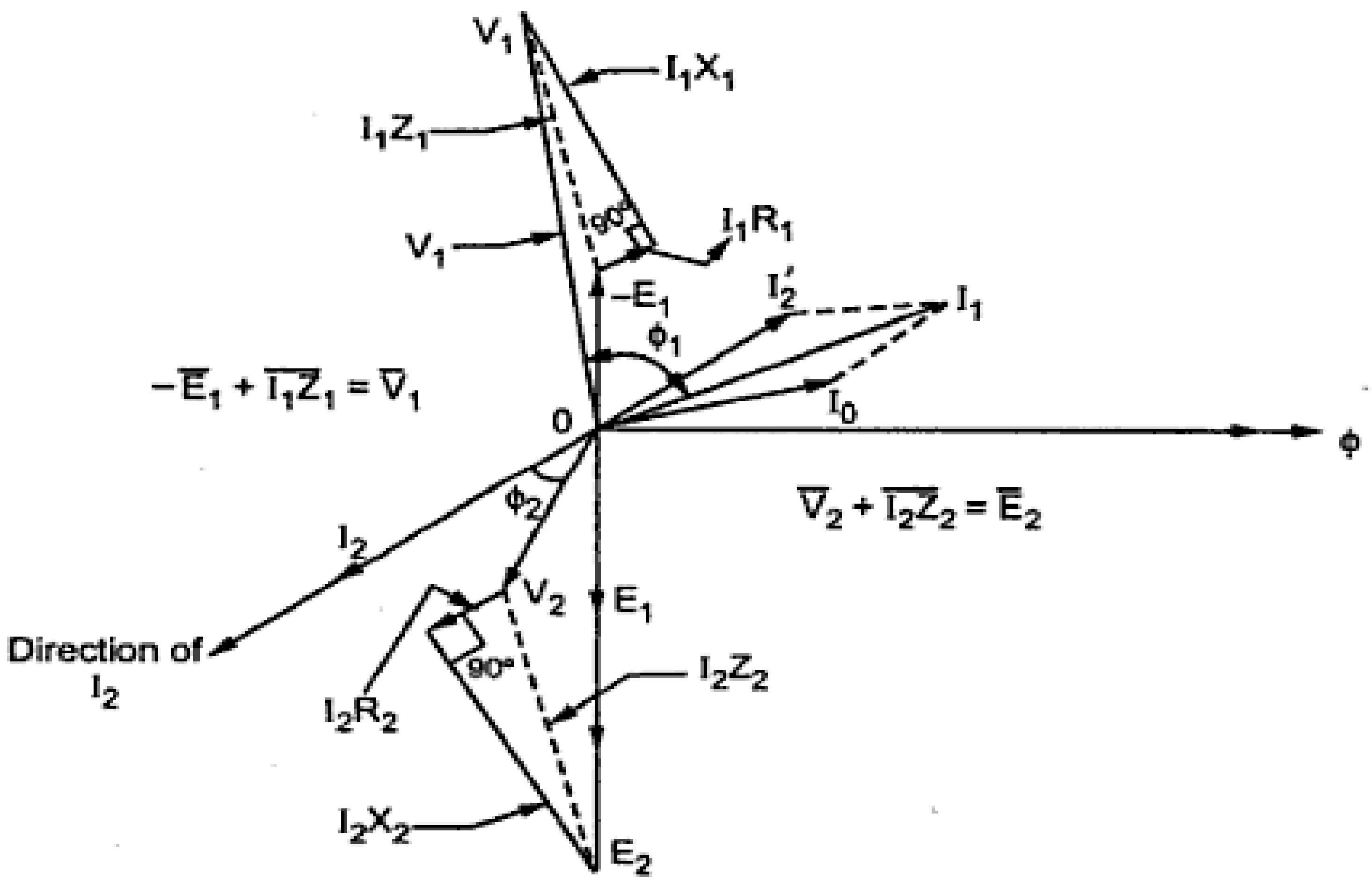


Fig. b: Main flux and leakage flux in a transformer

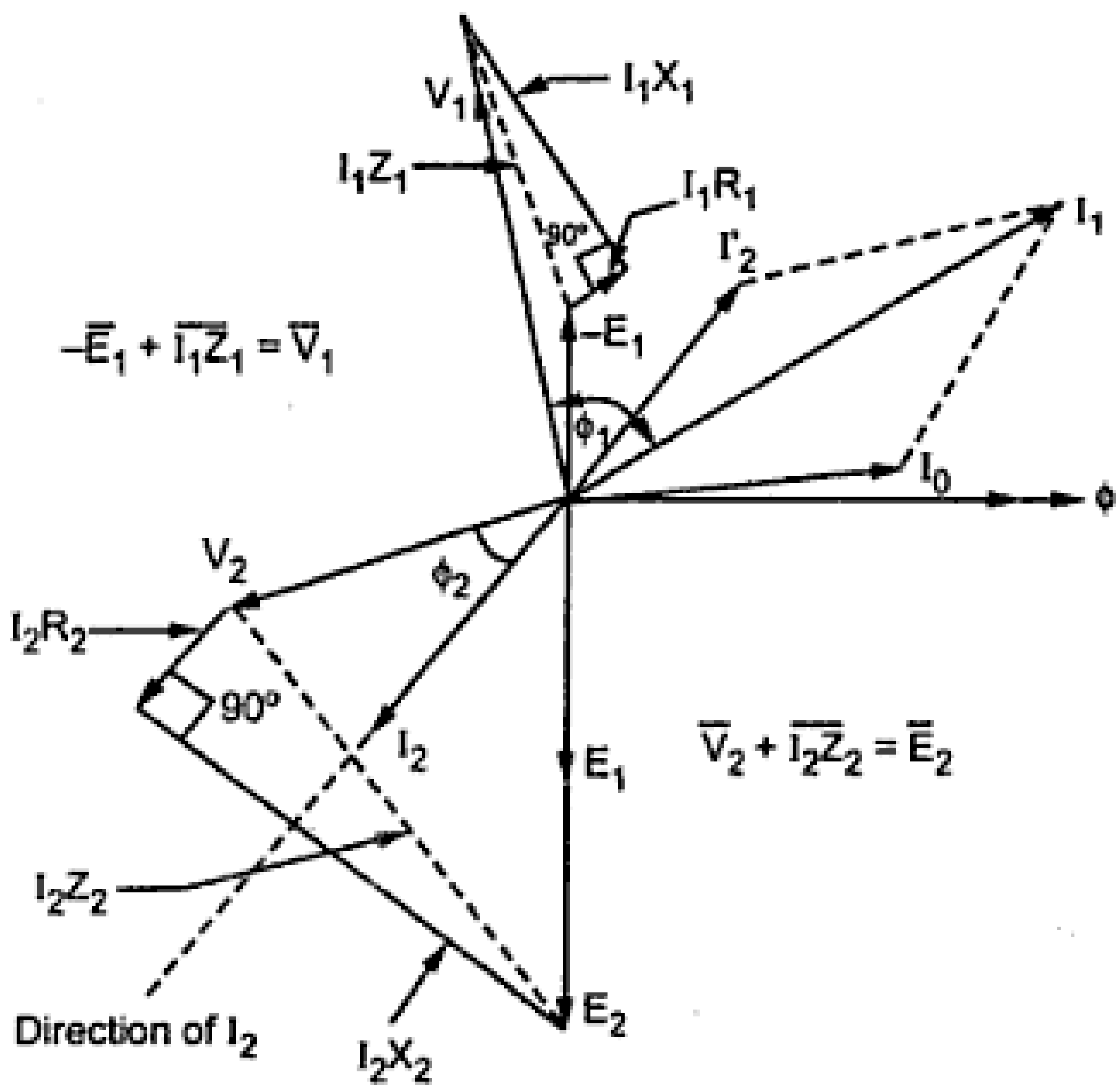
Phasor diagram of transformer with UPF load



Phasor diagram of transformer with lagging p.f load

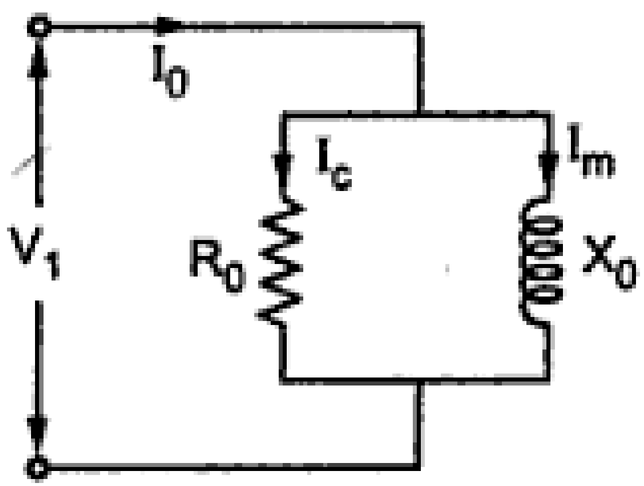


Phasor diagram of transformer with leading p.f load



Equivalent circuit of a transformer

No load equivalent circuit:



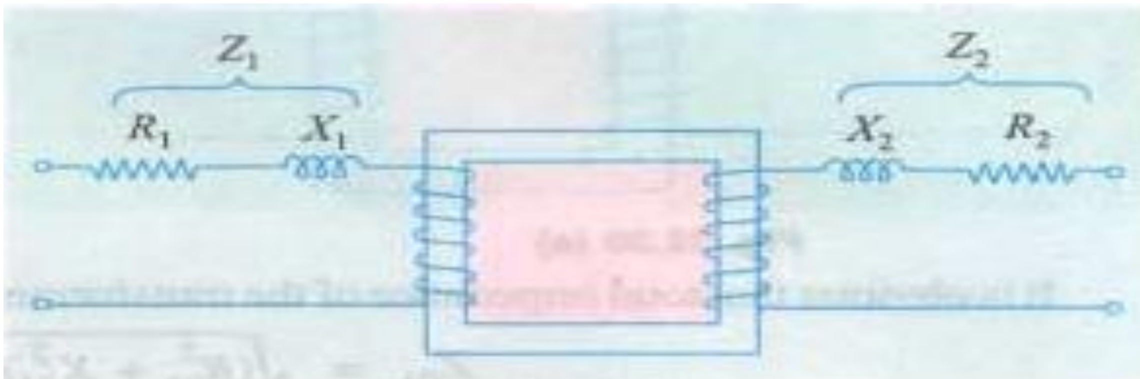
$$R_0 = \frac{V_1}{I_c}$$

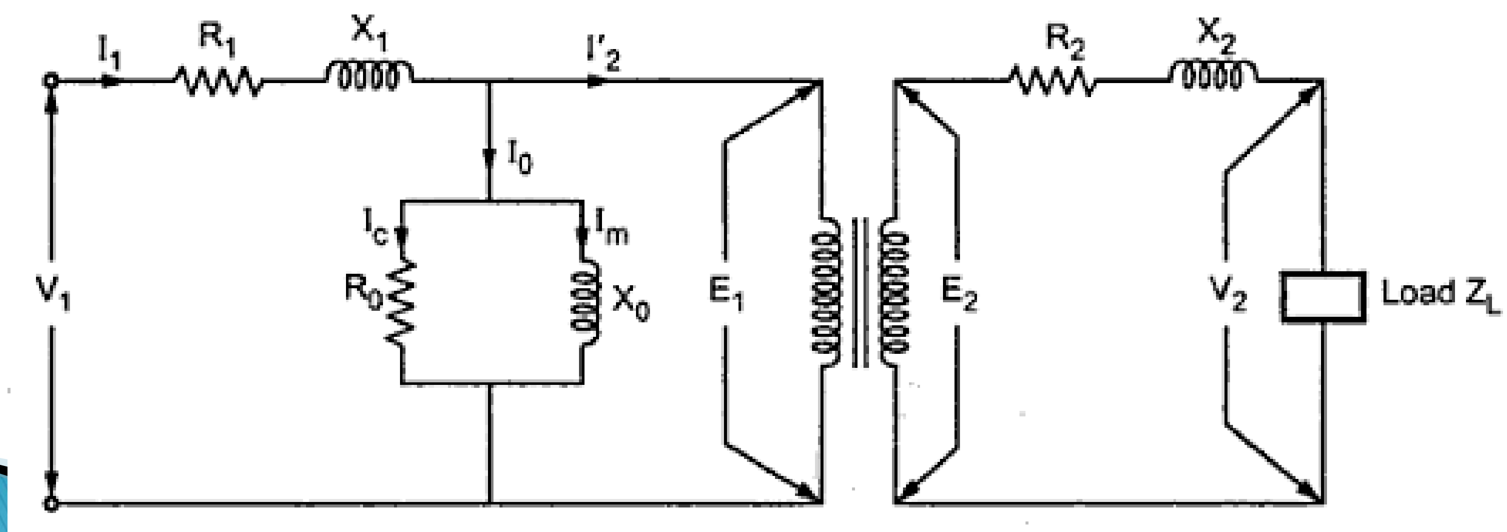
$$X_0 = \frac{V_1}{I_m}$$

$I_m = I_0 \sin \phi_0$ = Magnetising component

$I_c = I_0 \cos \phi_0$ = Active component

Equivalent circuit parameters referred to primary and secondary sides respectively





Contd.,

- The effect of circuit parameters shouldn't be changed while transferring the parameters from one side to another side
- It can be proved that a resistance of R_2 in sec. is equivalent to R_2/k^2 will be denoted as R_2'(ie. Equivalent sec. resistance w.r.t primary) which would have caused the same loss as R_2 in secondary,

$$I_1^2 R_2' = I_2^2 R_2$$

$$R_2' = \left(\frac{I_2}{I_1} \right)^2 R_2$$

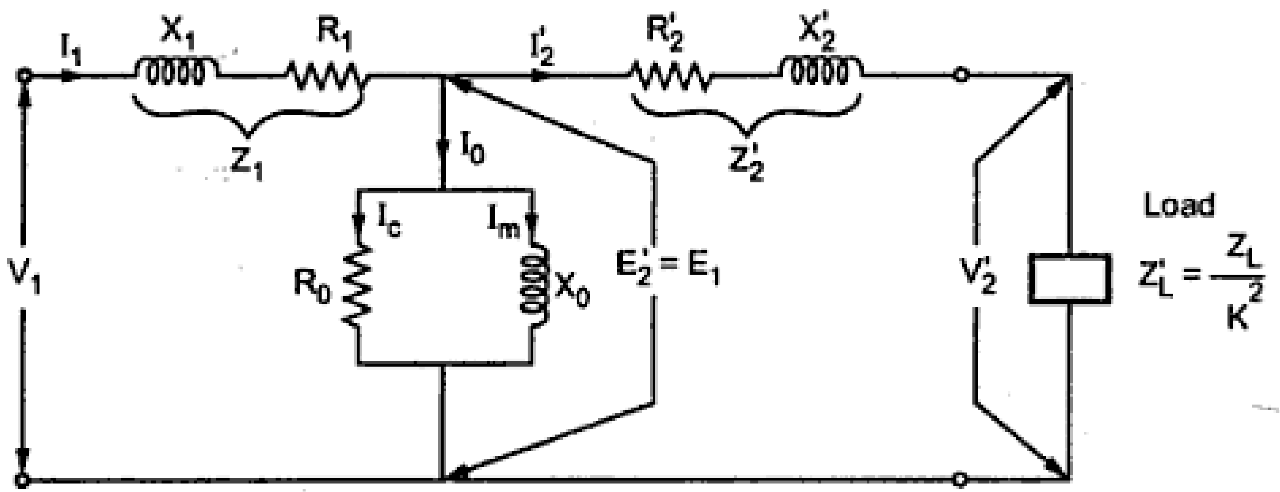
$$= \frac{R_2}{k^2}$$

Transferring secondary parameters to primary side

$$R_2' = \frac{R_2}{K^2}, \qquad X_2' = \frac{X_2}{K^2}, \qquad Z_2' = \frac{Z_2}{K^2}$$

While $$E_2' = \frac{E_2}{K}, \qquad I_2' = KI_2$$

where $$K = \frac{N_2}{N_1}$$



Exact equivalent circuit referred to primary

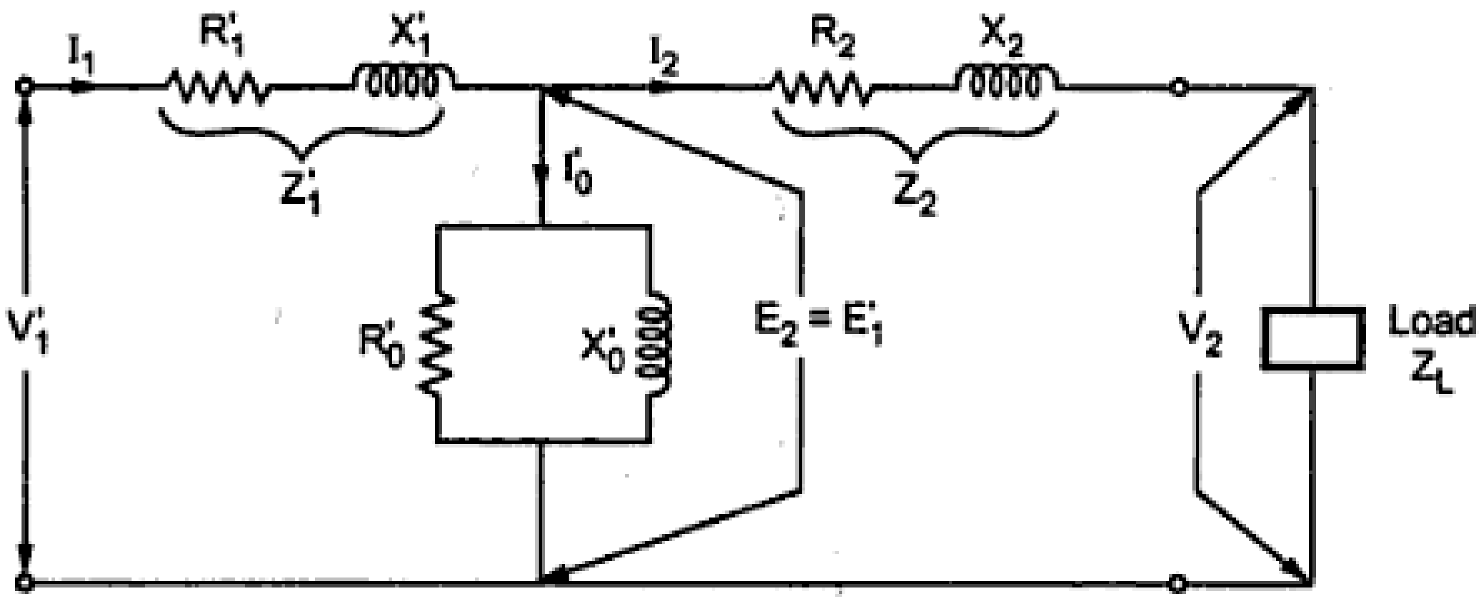
Equivalent circuit referred to secondary side

- Transferring primary side parameters to secondary side

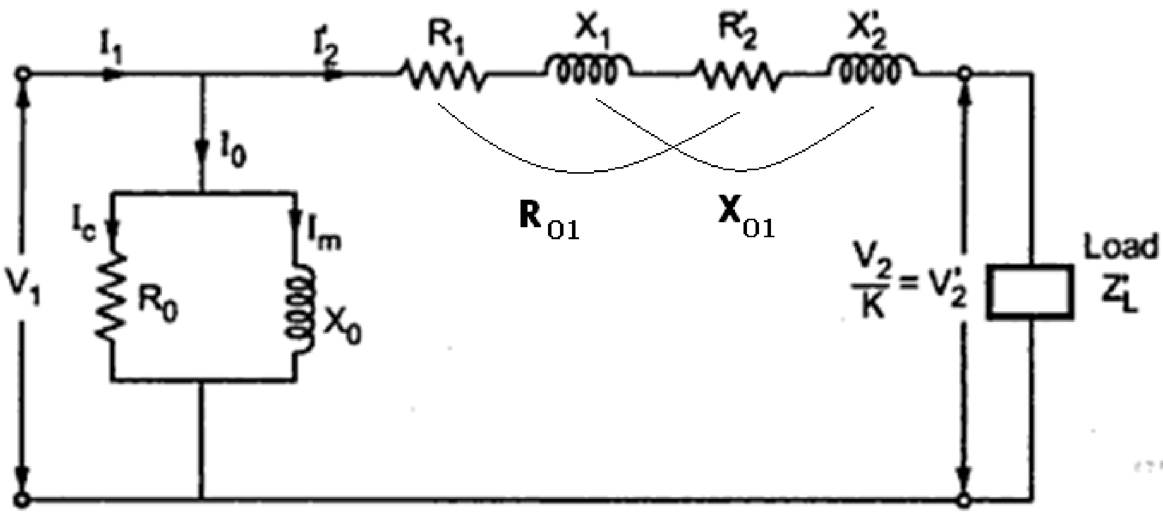
$$R_1' = K^2 R_1, \quad X_1' = K^2 X_1, \quad Z_1' = K^2 Z_1$$

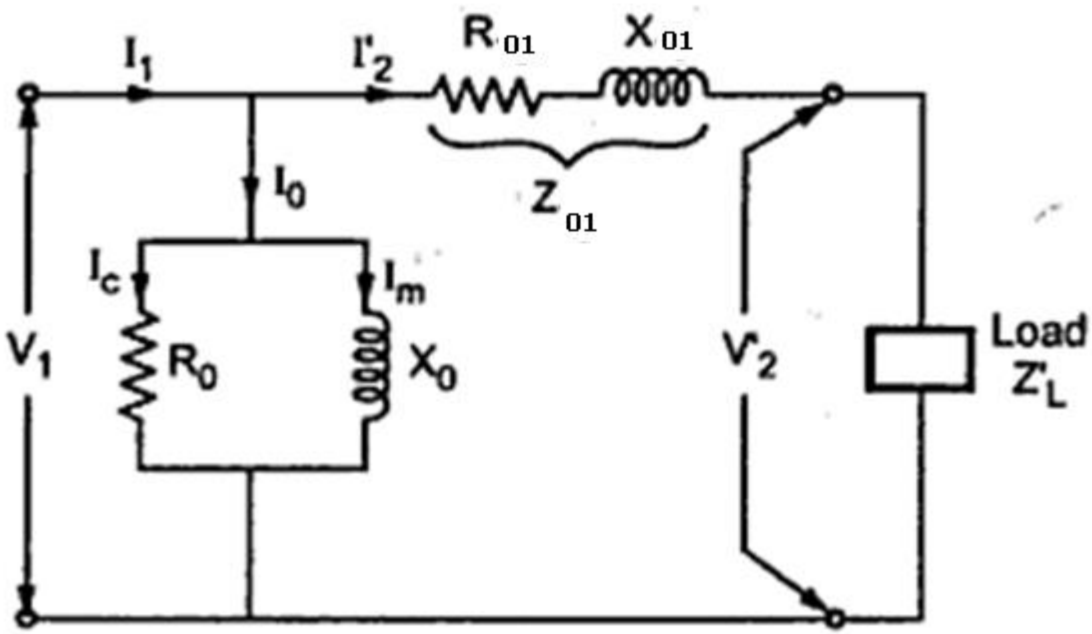
$$E_1' = K E_1, \quad I_1' = \frac{I_1}{K}, \quad I_0' = \frac{I_0}{K}$$

Similarly exciting circuit parameters are also transferred to secondary as R_o' and X_o'



equivalent circuit w.r.t primary





where

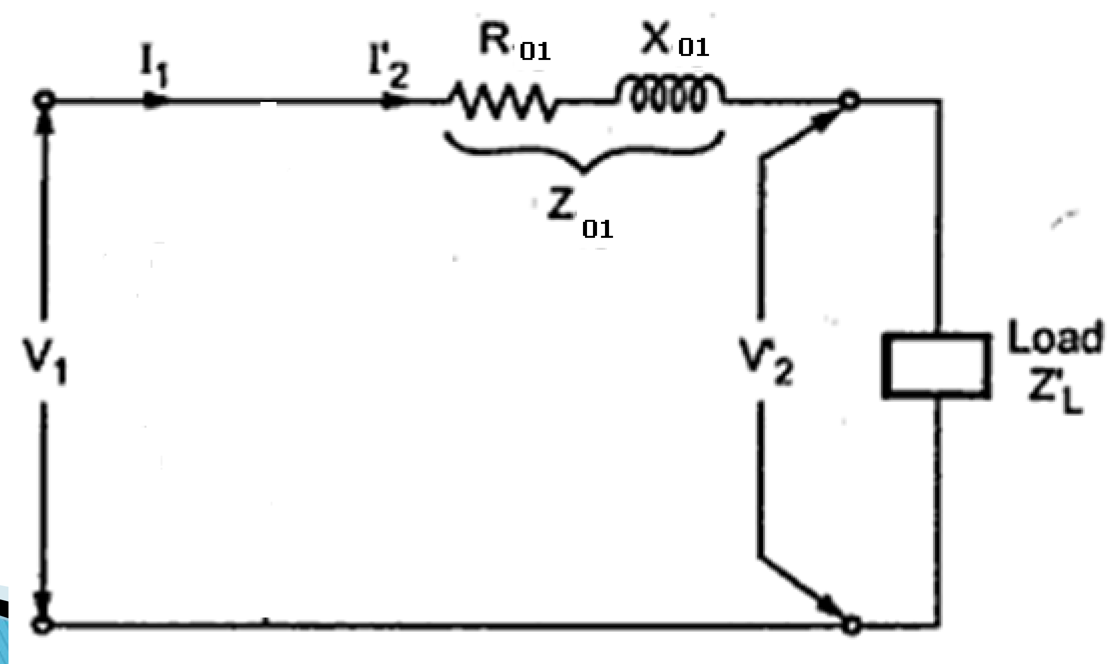
$$R_{01} = R_1 + R_2' = R_1 + \frac{R_2}{K^2}$$

$$X_{01} = X_1 + X_2' = X_1 + \frac{X_2}{K^2}$$

$$Z_{01} = R_{01} + j\,X_{01}$$

Approximate equivalent circuit

- Since the noload current is 1% of the full load current, the nolad circuit can be neglected

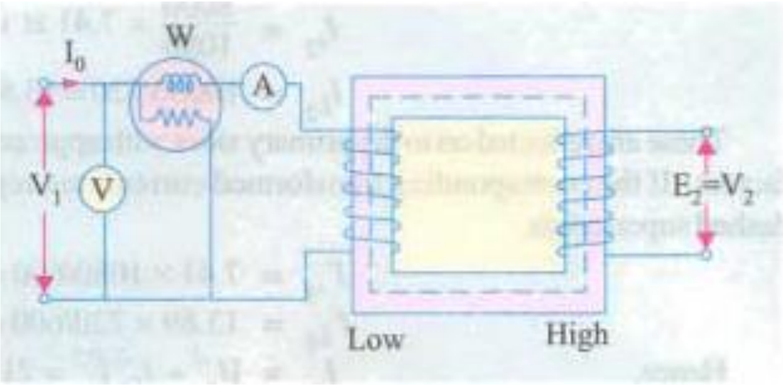


Transformer Tests

- The performance of a transformer can be calculated on the basis of equivalent circuit
- The four main parameters of equivalent circuit are:
  - R_{01} as referred to primary (or secondary R_{02})
  - the equivalent leakage reactance X_{01} as referred to primary (or secondary X_{02})
  - Magnetising susceptance B_0 (or reactance X_0)
  - core loss conductance G_0 (or resistance R_0)
- The above constants can be easily determined by two tests
  - Oper circuit test (O.C test / No load test)
  - Short circuit test (S.C test/Impedance test)
- These tests are economical and convenient
  - these tests furnish the result without actually loading the transformer

Open–circuit Test

In Open Circuit Test the transformer's ***secondary winding is open-circuited***, and its ***primary winding is connected to a full-rated line voltage***.



$$\text{Core loss} = W_{oc} = V_0 I_0 \cos\phi_0$$

$$\cos\phi_0 = \frac{W_{oc}}{V_0 I_0}$$

$$\mathrm{I_c}\, or\ \mathrm{I_w} = I_0 \cos\phi_0$$

$$\mathrm{I_m}\, or\ \mathrm{I}_\mu = I_0 \sin\phi_0 = \sqrt{I_0^2 - I_w^2}$$

$$\mathrm{I_0 = V_0 Y_0}; \quad \therefore \mathrm{Y_o} = \frac{I_0}{V_0}$$

$$R_0 = \frac{V_0}{I_w} \qquad X_0 = \frac{V_0}{I\mu} \qquad G_0 = \frac{I_w}{V_0} \qquad B_0 = \frac{I\mu}{V_0}$$

$$\mathrm{W_{oc} = V_0^2 G_0}; \quad \therefore \text{Exciting conductance } \mathrm{G_0} = \frac{\mathrm{W_{oc}}}{\mathrm{V_0^2}}$$

$$\& \quad \text{Exciting susceptance } \mathrm{B_0} = \sqrt{Y_0^2 - G_0^2}$$

- Usually conducted on H.V side
- To find

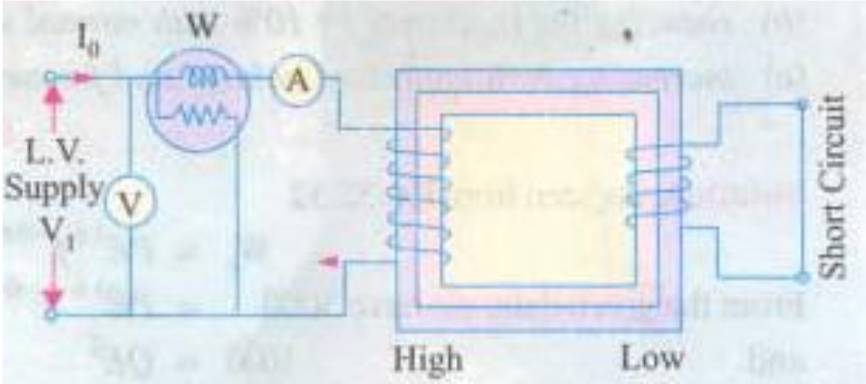
  (i) No load loss or core loss

  (ii) No load current I_o which is helpful in finding G_o (or R_o) and B_o (or X_o)

Short–circuit Test

In Short Circuit Test the ***secondary terminals are short circuited***, and the ***primary terminals are connected to a fairly low-voltage source***

The input voltage is adjusted until the current in the short circuited windings is equal to its rated value. The input voltage, current and power is measured.



- Usually conducted on L.V side
- To find

  (i) Full load copper loss – to pre determine the efficiency

  (ii) Z_{01} or Z_{02}; X_{01} or X_{02}; R_{01} or R_{02} - to predetermine the voltage regulation

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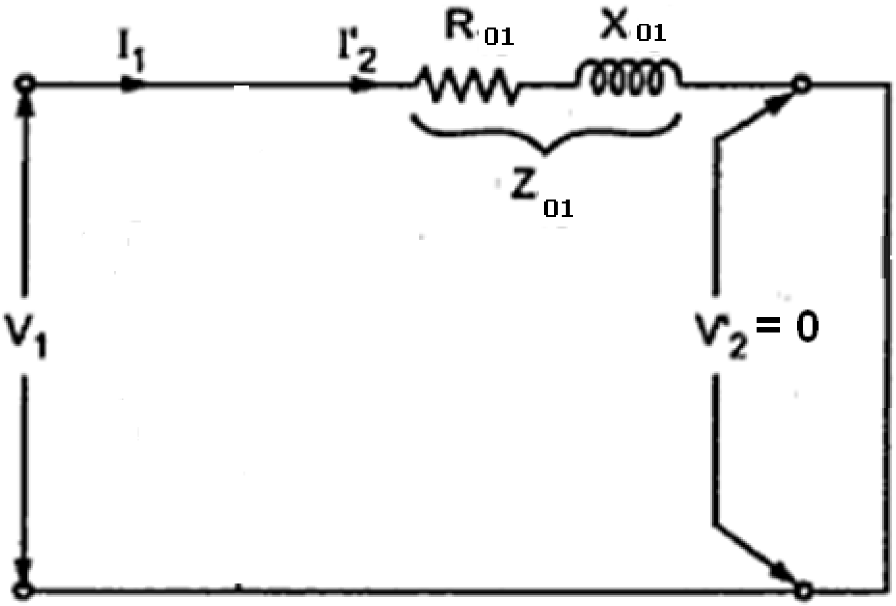


$$\text{Full load cu loss} = W_{sc} = I_{sc}^2 R_{01}$$

$$R_{01} = \frac{W_{sc}}{I_{sc}^2}$$

$$Z_{01} = \frac{V_{sc}}{I_{sc}}$$

$$\therefore X_{01} = \sqrt{Z_{01}^2 - R_{01}^2}$$

Transformer Voltage Regulation and Efficiency

The output voltage of a transformer varies with the load even if the input voltage remains constant. This is because a real transformer has series impedance within it. Full load Voltage Regulation is a quantity that compares the output voltage at no load with the output voltage at full load, defined by this equation:

$$\text{At noload } k = \frac{V_s}{V_p}$$

$$\text{Regulation up} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,fl}} \times 100\%$$

$$\text{Regulation up} = \frac{(V_P / k) - V_{S,fl}}{V_{S,fl}} \, x \, 100\%$$

$$\text{Regulation down} = \frac{V_{S,nl} - V_{S,fl}}{V_{S,nl}} \times 100\%$$

$$\text{Regulation down} = \frac{(V_P / k) - V_{S,fl}}{V_{S,nl}} \, x \, 100\%$$

Ideal transformer, VR = 0%.

Voltage regulation of a transformer

$$\text{Voltage regulation} = \frac{\text{no-load voltage} - \text{full-load voltage}}{\text{no-load voltage}}$$

recall $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

Secondary voltage on no-load $V_2 = V_1\left(\frac{N_2}{N_1}\right)$

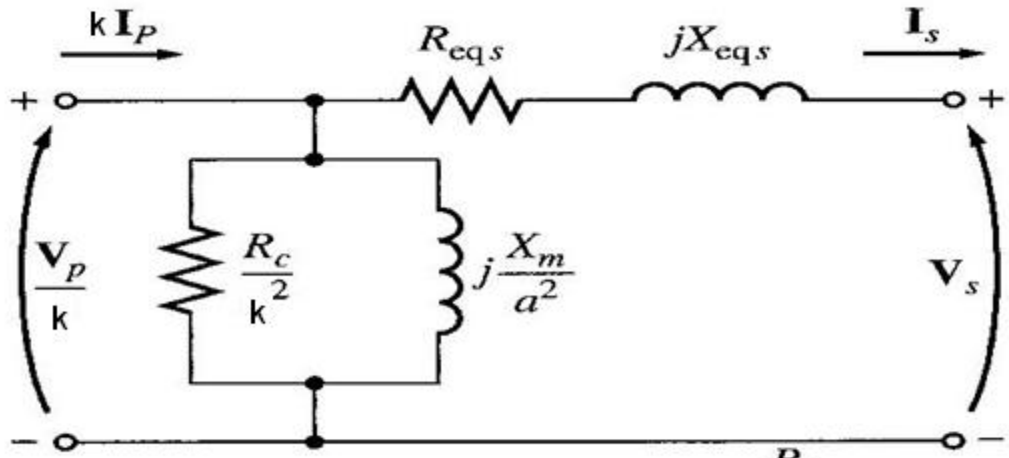
V_2 is a secondary terminal voltage on full load

Substitute we have

$$\text{Voltage regulation} = \frac{V_1\left(\frac{N_2}{N_1}\right) - V_2}{V_1\left(\frac{N_2}{N_1}\right)}$$

Transformer Phasor Diagram

To determine the voltage regulation of a transformer, it is necessary understand the voltage drops within it.



$$R_{eq\,s} = \frac{R_p}{k^2} + R_s$$

$$X_{eq\,s} = \frac{X_p}{k^2} + X_s$$

Transformer Phasor Diagram

Ignoring the excitation of the branch (since the current flow through the branch is considered to be small), more consideration is given to the series impedances (R_{eq} +jX_{eq}).

Voltage Regulation depends on magnitude of the series impedance and the phase angle of the current flowing through the transformer.

Phasor diagrams will determine the effects of these factors on the voltage regulation. A phasor diagram consist of current and voltage vectors.

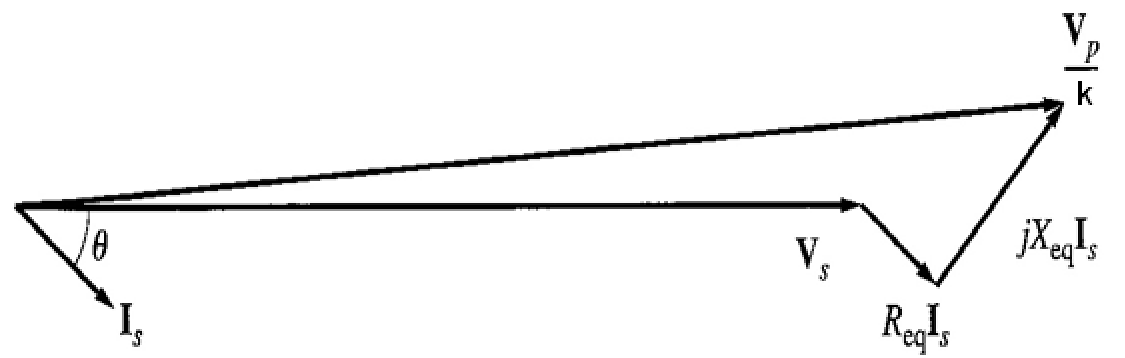
Assume that the reference phasor is the secondary voltage, V_S. Therefore the reference phasor will have 0 degrees in terms of angle.

Based upon the equivalent circuit, apply Kirchoff Voltage Law,

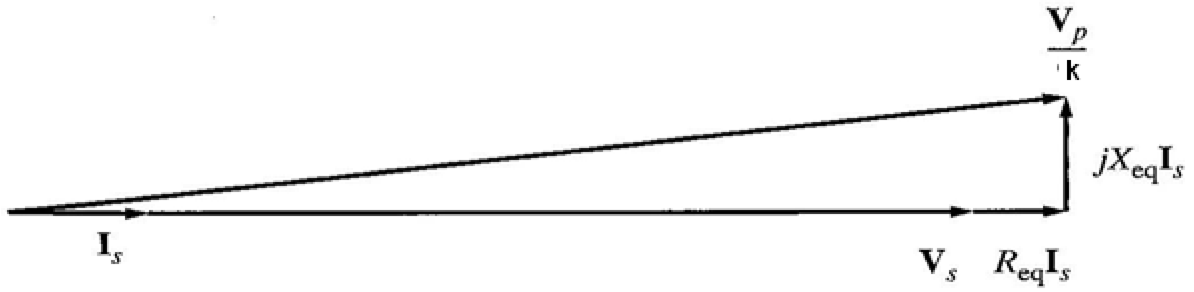
$$\frac{V_P}{k} = V_S + R_{eq} I_S + jX_{eq} I_S$$

Transformer Phasor Diagram

For lagging loads, V_P / a > V_S so the voltage regulation with lagging loads is > 0.



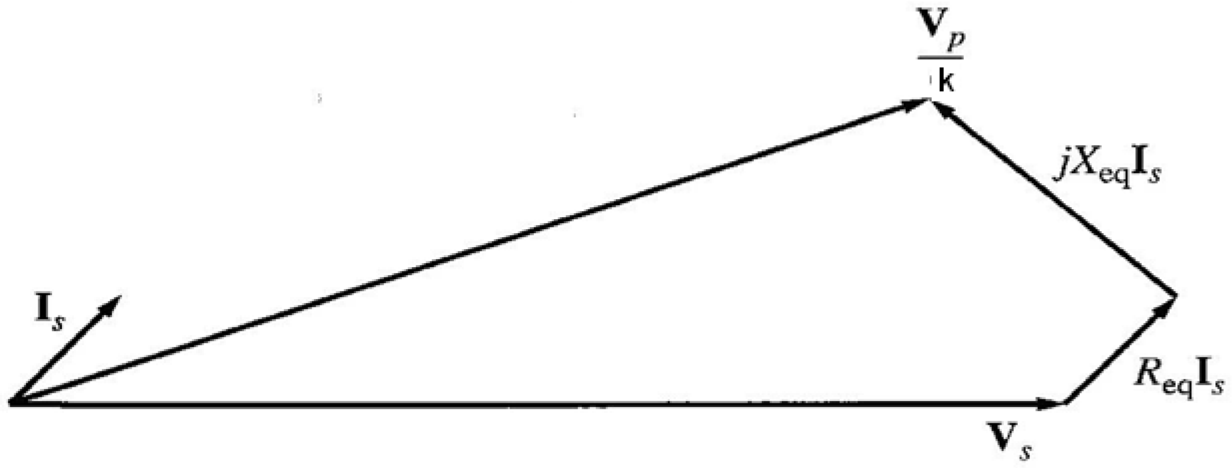
When the power factor is unity, V_S is lower than V_P so VR > 0.



(a)

Transformer Phasor Diagram

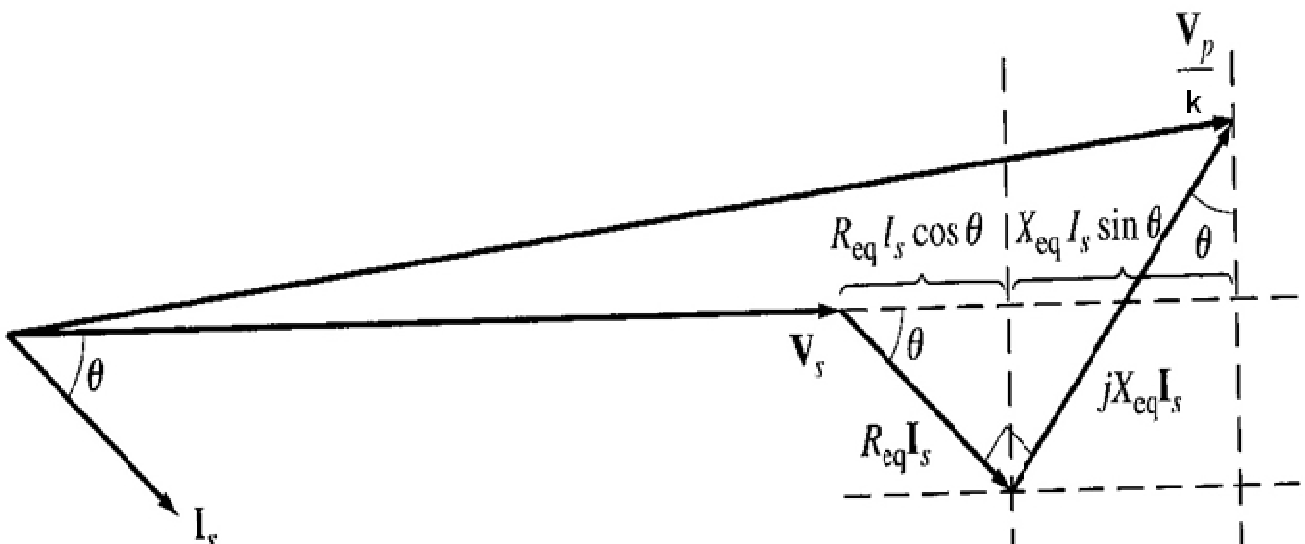
With a leading power factor, V_S is higher than the referred V_P so VR < 0



(b)

Transformer Phasor Diagram

For lagging loads, the vertical components of R_{eq} and X_{eq} will partially cancel each other. Due to that, the angle of V_P/a will be very small, hence we can assume that V_P/k is horizontal. Therefore the approximation will be as follows:



$$\frac{V_p}{k} \approx V_s + R_{eq} I_s \cos\theta + X_{eq} I_s \sin\theta$$

Formula: voltage regulation

In terms of secondary values

$$\% \text{ regulation} = \frac{{}_0\mathrm{V}_2 - V_2}{{}_0\mathrm{V}_2} = \frac{I_2 R_{02} \cos\phi_2 \pm I_2 X_{02} \sin\phi_2}{{}_0\mathrm{V}_2}$$

where '+' for lagging and '-' for leading

In terms of primary values

$$\% \text{ regulation} = \frac{\mathrm{V}_1 - V_2^{'}}{\mathrm{V}_1} = \frac{I_1 R_{01} \cos\phi_1 \pm I_1 X_{01} \sin\phi_1}{\mathrm{V}_1}$$

where '+' for lagging and '-' for leading

Transformer Efficiency

Transformer efficiency is defined as (applies to motors, generators and transformers):

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100\%$$

Types of losses incurred in a transformer:

- Copper I^2R losses
- Hysteresis losses
- Eddy current losses

Therefore, for a transformer, efficiency may be calculated using the following:

$$\eta = \frac{V_S I_S \cos\theta}{P_{Cu} + P_{core} + V_S I_S \cos\theta} x100\%$$

Losses in a transformer

Core or Iron loss:

Hysteresis loss $W_h = \eta B^{1.6}_{max} f V$ watt;

eddy current loss $W_e = \eta B^2_{max} f^2 t^2$ watt

Copper loss:

Total Cu loss $= I_1^2 R_1 + I_2^2 R_2 = I_1^2 R_{01} + I_2^2 R_{02}$.

Condition for maximum efficiency

$$\text{Cu loss} = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02} = W_{cu}$$

$$\text{Iron loss} = \text{Hysteresis loss} + \text{Eddy current loss} = W_h + W_e = W_i$$

Considering primary side,

$$\text{Primary input} = V_1 I_1 \cos\phi_1$$

$$\eta = \frac{V_1 I_1 \cos\phi_1 - \text{losses}}{V_1 I_1 \cos\phi_1} = \frac{V_1 I_1 \cos\phi_1 - I_1^2 R_{01} - W_i}{V_1 I_1 \cos\phi_1}$$

$$= 1 - \frac{I_1 R_{01}}{V_1 \cos\phi_1} - \frac{W_i}{V_1 I_1 \cos\phi_1}$$

Differentiating both sides with respect to I_1, we get

$$\frac{d\eta}{dI_1} = 0 - \frac{R_{01}}{V_1 \cos\phi_1} + \frac{W_i}{V_1 I_1^2 \cos\phi_1}$$

For η to be maximum, $\frac{d\eta}{dI_1} = 0$. Hence, the above equation becomes

$$\frac{R_{01}}{V_1 \cos\phi_1} = \frac{W_i}{V_1 I_1^2 \cos\phi_1} \quad \text{or} \quad W_i = I_1^2 R_{01} \quad \text{or} \quad I_2^2 R_{02}$$

or $\quad$ **Cu loss = Iron loss**

Contd.,

The output current corresponding to maximum efficiency is $I_2 = \sqrt{(W_i/R_{02})}$.

The load at which the two losses are equal = $= \text{Full load} \times \sqrt{\left(\frac{\text{Iron loss}}{\text{F.L. Cu loss}}\right)}$

All day efficiency

$$\text{ordinary commercial efficiency} = \frac{\text{out put in watts}}{\text{input in watts}}$$

$$\eta_{all\ \text{day}} = \frac{\text{output in kWh}}{\text{Input in kWh}} (\ for\ 24\ \text{hours})$$

- All day efficiency is always less than the commercial efficiency