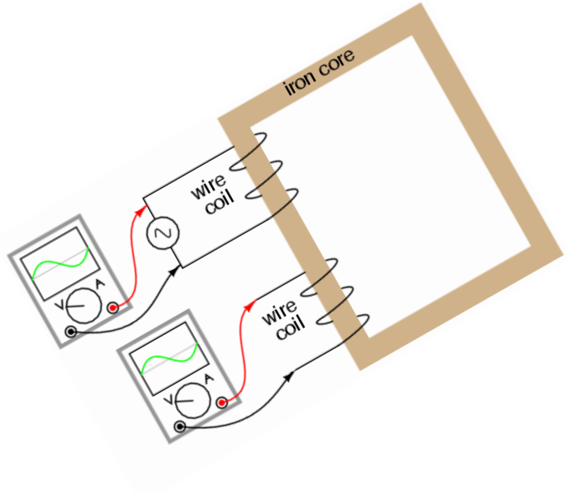
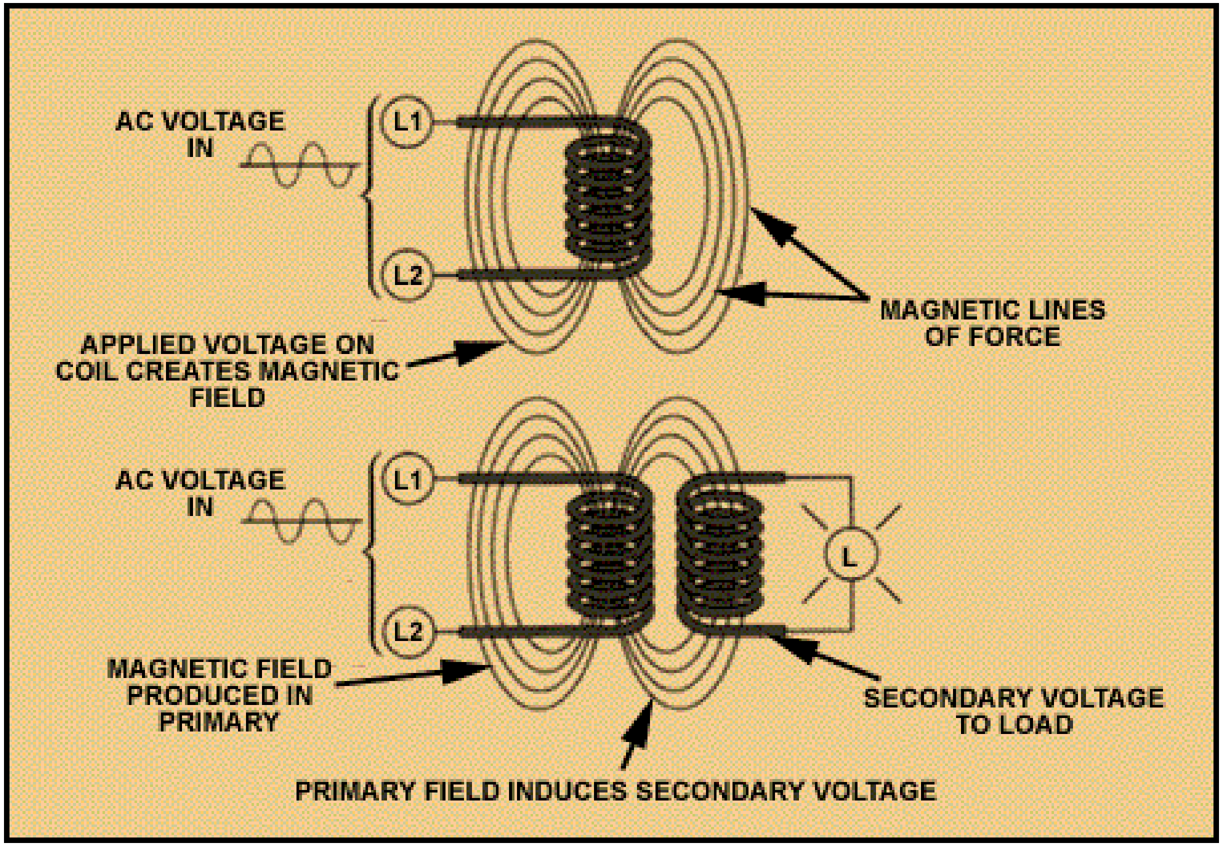
6.0 TRANSFORMERS

A **transformer** is a device that transfers electrical energy from one circuit to another through inductively coupled conductors

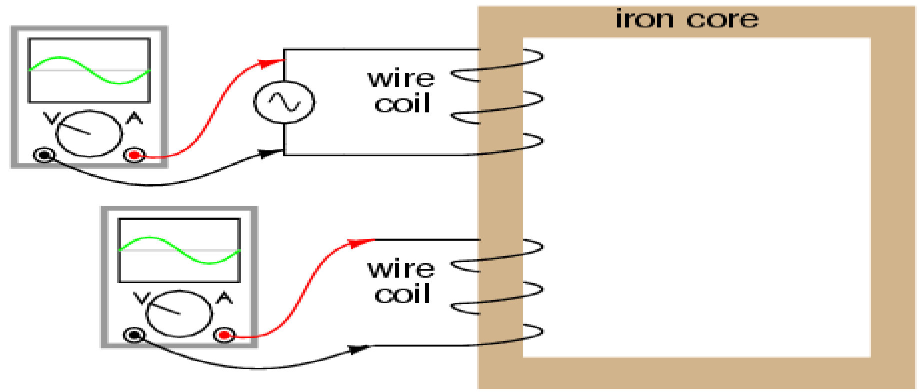


6.1 UNDERSTAND MUTUAL INDUACTANCE



- When two coils are placed close to each other, a changing electromagnetic field produced by the current in one coil will cause an induced voltage in the second coil because of the *mutual inductance.*
- *Mutual inductance* is established by the inductance of each coil and by the amount of coupling between the two coils.

How Induction Works in a Transformer



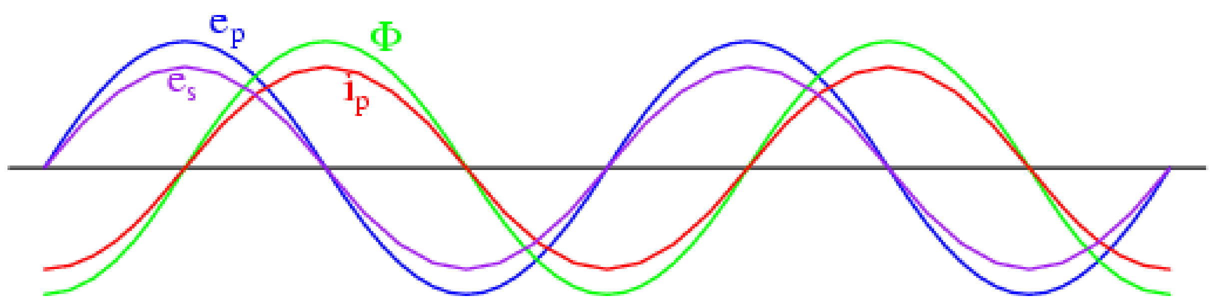
Ferromagnetic core with primary coil (AC driven) and secondary coil.

e_p = primary coil voltage

i_p = primary coil current

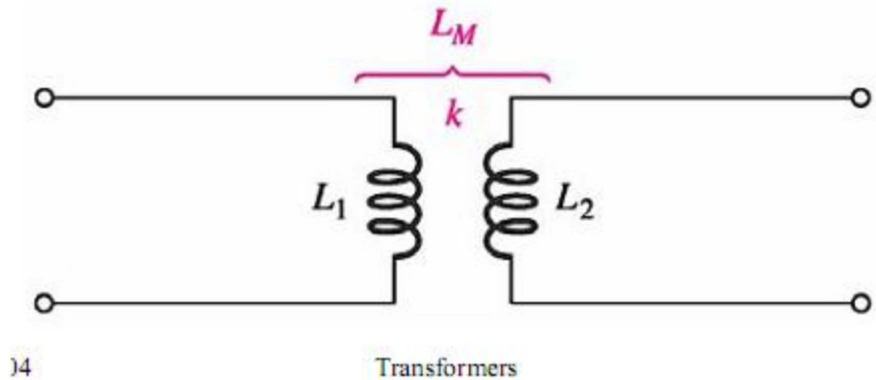
Φ = magnetic flux

e_s = secondary coil voltage



- If this secondary coil experiences the same magnetic flux change as the primary and has the same number of turns around the core, a voltage of equal magnitude and phase to the applied voltage will be induced along its length.

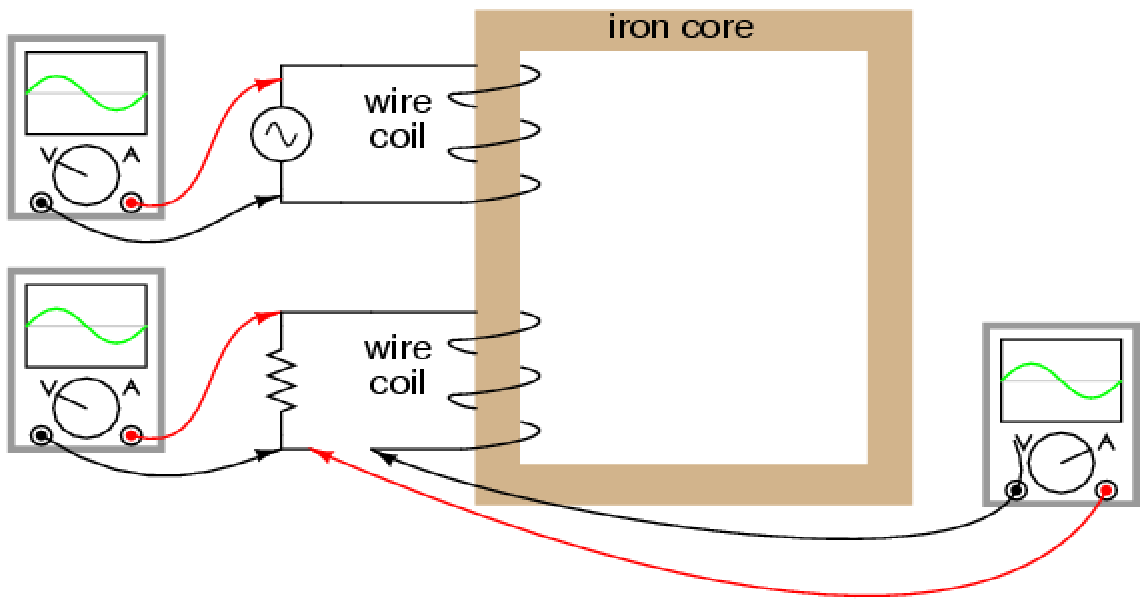
- Like normal (self-) inductance, it is measured in the unit of Henrys, but unlike normal inductance it is symbolized by the capital letter "M" rather than the letter "L":



•The mutual inductance between two coils (L_1 and L_2) may be expressed mathematically as:

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

No current will exist in the secondary coil, since it is open-circuited. However, if we connect a load resistor to it, an alternating current will go through the coil, in-phase with the induced voltage



Resistive load on secondary has voltage and current in-phase.

6.1.1 DISCUSS MAGNETIC COUPLING:

- Two conductors are referred to as **mutual-inductively coupled** or **magnetically coupled** when they are configured such that change in current flow through one wire induces a voltage across the ends of the other wire through electromagnetic induction.

- The amount of inductive coupling between two conductors is measured by their mutual inductance.

- The coupling between two wires can be increased by winding them into coils and placing them close together on a common axis, so the magnetic field of one coil passes through the other coil.

6.1.2 DEFINE ELECTRICAL ISOLATION:

Transformers also provide an extremely useful feature called *isolation*:

- Which is the ability to couple one circuit to another without the use of direct wire connections.

- By being able to transfer power from one circuit to another without the use of interconnecting conductors between the two circuits, transformers provide the useful feature of *electrical isolation*.

6.1.3 DEFINE COEFFICIENT OF COUPLING:

- The coefficient of coupling (k) between two coils is the ratio of the lines of force (flux) produced by one coil linking the second coil ($\varphi 1\text{-}2$) to the total flux produced by the first coil ($\varphi 1$)

- The COEFFICIENT OF COUPLING of a transformer is dependent on the portion of the total flux lines that cuts both primary and secondary windings.

- The coefficient of coupling depends on the physical closeness of the coils and the type of core material on which they are wound

- Construction and core shape are also factors influencing coefficient of coupling

Eg:

- If 80 percent of the lines set up by the primary cut the secondary, there is 80 percent coupling, or a coefficient of coupling(K) is 0.8.

- Ideally, all the flux lines generated by the primary should cut the secondary, and all the lines of the flux generated by the secondary should cut the primary. The coefficient of coupling would then be one (unity), and maximum energy would be transferred from the primary to the secondary.

- If none of the flux from one coil cuts the turns of the other coil, the coefficient of coupling is zero.

- The amount of coupling between the primary and secondary has a direct bearing on the mutual inductance.

$$M = K\sqrt{L_1 \; L_2},$$

** where K is the coefficient of coupling

- *Example:*

What is the mutual inductance of a transformer whose primary has16 h of inductance and whose secondary has 4h, if the coupling between the two coils is 75 percent?

Solution:

$$M = K\sqrt{L_1 \; L_2}$$

$$M = 0.75\sqrt{16 \times 4}$$

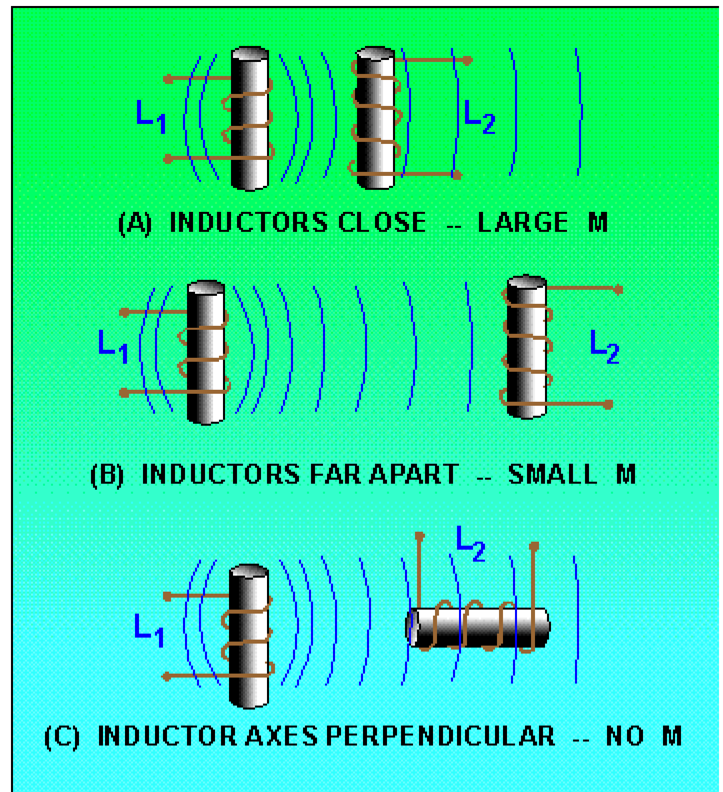
$$M = 6 \text{ h}$$

The mutual inductance(M) of the transformer is 6 h.

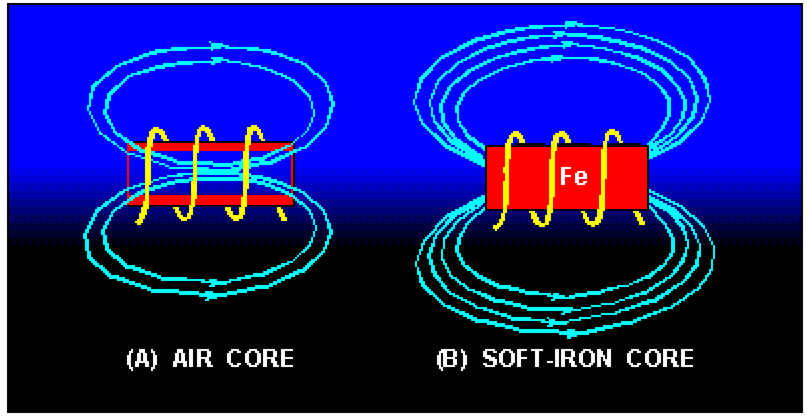
6.1.4 IDENTIFY THE FACTORS THAT AFFECT MUTUAL INDUCTANCE:

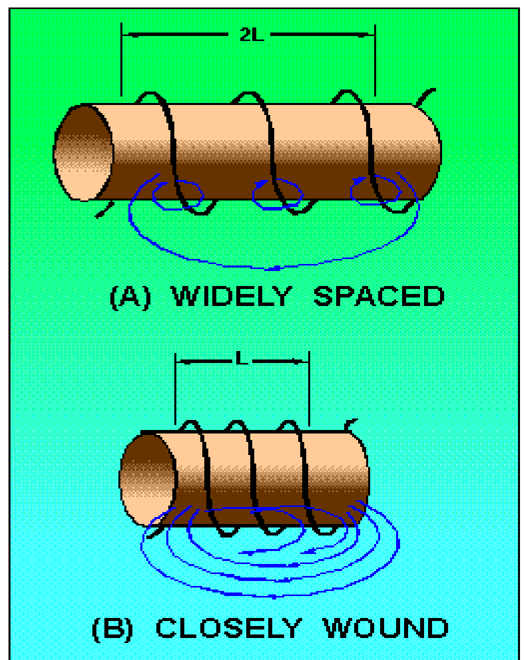
- The amount of mutual inductance depends upon several factors:

- The relative position of the axes of the two coils;
- The permeability of the cores,
- The physical dimensions of the two coils,
- The number of turns in each coil,
- The distance between the coils.



permeability of the cores





distance between the coils

6.2 UNDERSTAND THE CONSTRUCTION AND THE OPERATION OF A TRANSFORMER

6.2.1 SKETCH PARTS OF A BASIC TRANSFORMER:

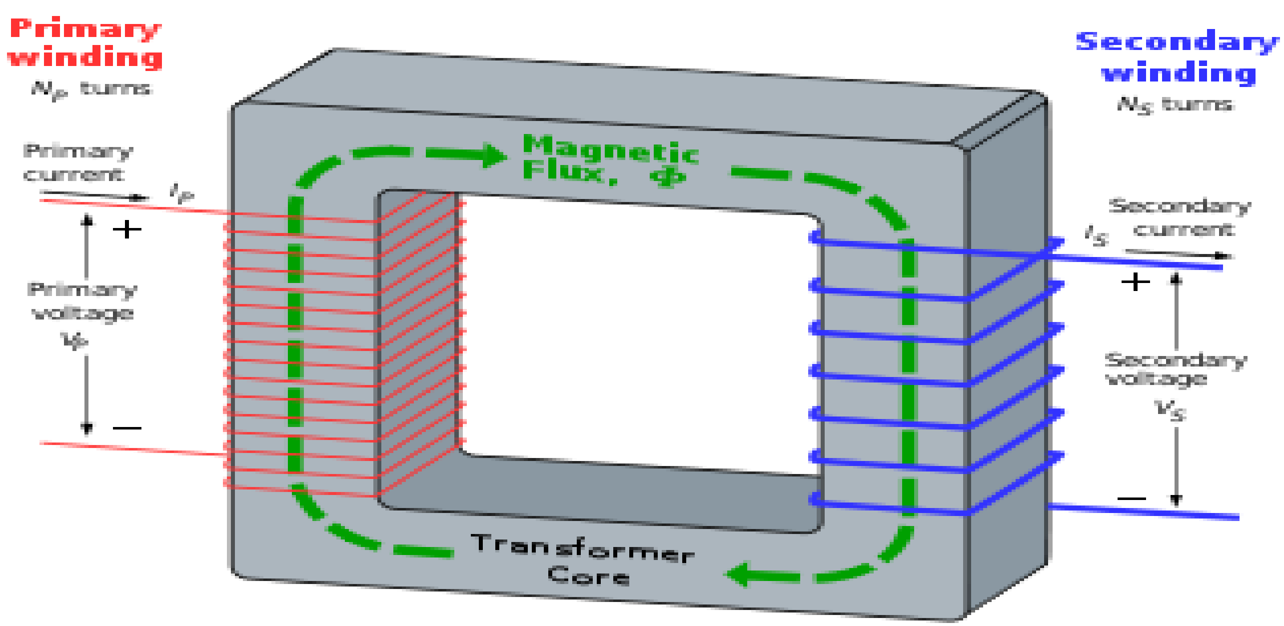
- The principle parts of a transformer and their functions are:

  1) The CORE, which provides a path for the magnetic lines of flux.

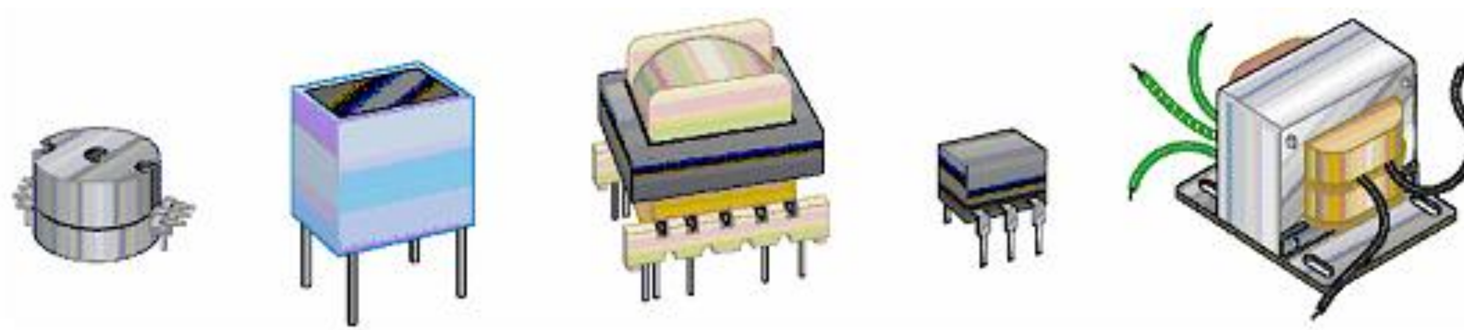
  2) The PRIMARY WINDING, which receives energy from the ac source.

  3) The SECONDARY WINDING, which receives energy from the primary winding and delivers it to the load.

  4) The ENCLOSURE, which protects the above components from dirt, moisture, and mechanical damage.



TRANSFORMER ENCLOSURE

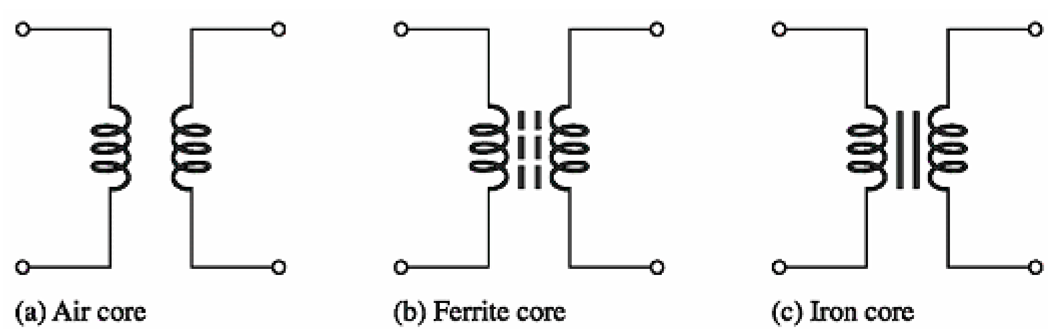


6.2.2 EXPLAIN THE IMPORTANCE OF THE CORE MATERIAL:

- The composition of a transformer core depends on such factors as voltage, current, frequency, size limitations and construction costs.

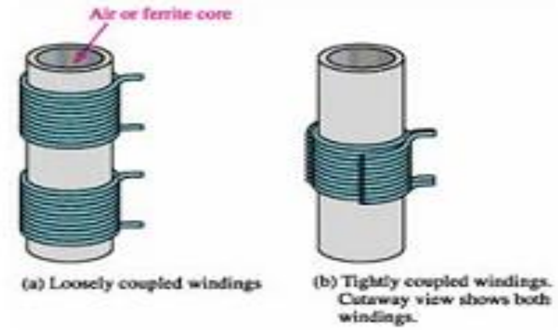
- Typical core materials are: air, ferrite, and iron

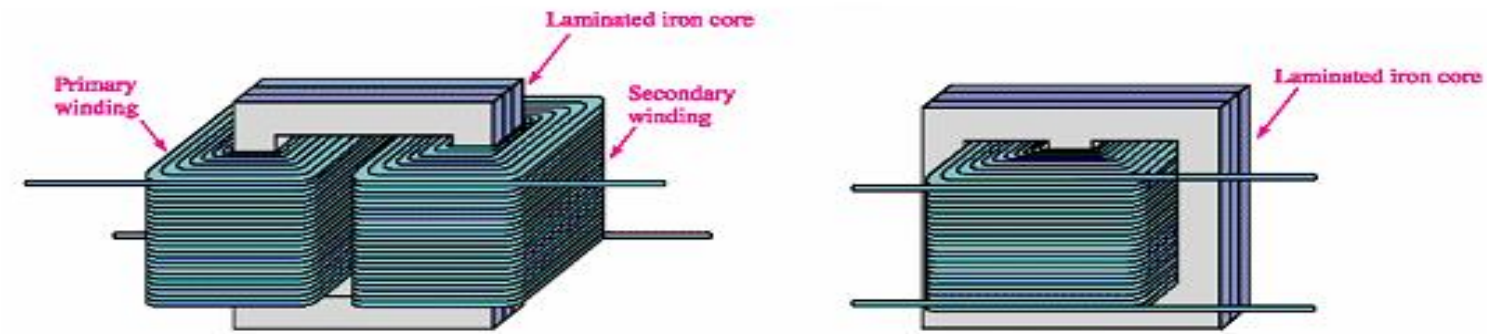
- **Air and ferrite cores** are used at high frequencies (above 20 kHz).
- **Iron cores** are used for low frequency (below 20 kHz) and power applications.
- A **soft-iron-core** transformer is very useful where the transformer must be physically small, yet efficient.



SYMBOL OF CORE MATERIAL

Examples of Transformers with Different Cores





(a) Core type has each winding on a separate leg.

(b) Shell type has both windings on the same leg.

- The iron-core transformer provides better power transfer than does the air-core transformer.

- A transformer whose core is constructed of laminated sheets of steel dissipates heat readily; thus it provides for the efficient transfer of power.

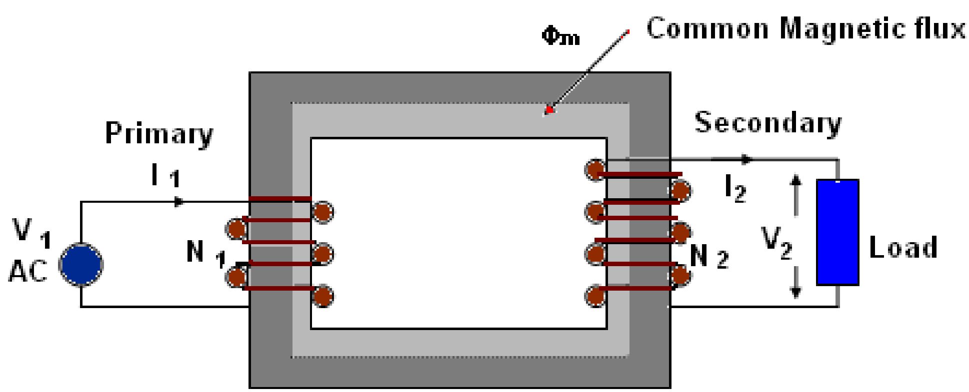
- The purpose of the laminations is to reduce certain losses.

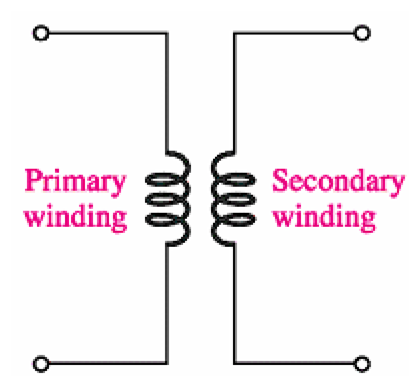
- The most efficient transformer core is one that offers the best path for the most lines of flux with the least loss in magnetic and electrical energy.

6.2.3 DEFINE PRIMARY WINDING AND SECONDARY WINDING:

- The *primary winding* is the winding which receives the energy@ source; it is not always the high-voltage winding.

- The unpowered inductor in a transformer is called the *secondary winding.*
- The *secondary winding* is the output winding where the load is connected.





Schematic symbol

6.2.4 DEFINE TURN RATIO:

- Turns ratio (n) is defined as the ratio of the number of turns in the secondary winding (NSEC) to the number of turns in the primary winding (NPRI)

$$n = \frac{N_{SEC}}{N_{PRI}}$$

- The ratio between output voltage and input voltage is the same as the ratio of the number of turns between the two windings.

$$\frac{\text{Voltage (input)}}{\text{Voltage (output)}} = \frac{\text{Number of Primary Turns}}{\text{Number of Secondary Turns}}$$

$$\frac{E_S}{E_P} = \frac{N_S}{N_P}$$

Where:

N_P = number of turns in the primary

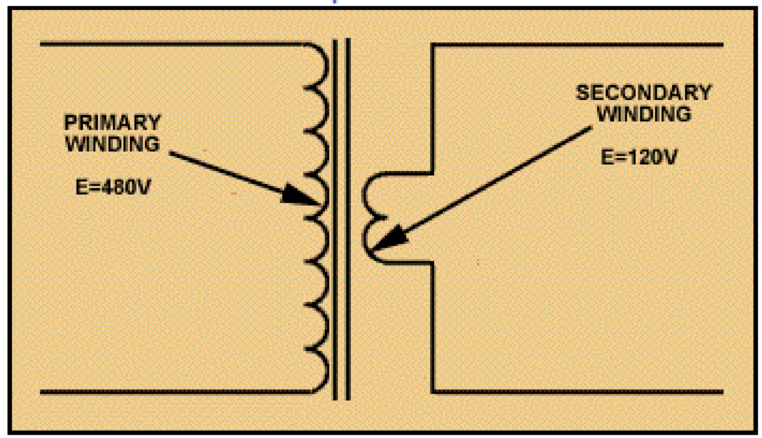
E_P = voltage applied to the primary

E_S = voltage induced in the secondary

N_S = number of turns in the secondary

Example:

Turns Ratio Example



- Transformer Primary Voltage: 480 volts
- Transformer Secondary Voltage: 120 volts

$$\frac{480 \text{ volts}}{120 \text{ volts}} = \frac{4 \text{ (4 Primary Turns)}}{1 \text{ (1Secondary turn)}}$$

This transformer has four primary turns for every one secondary turn. Turns ratio is written as 4 to 1, or 4:1.

Example.

- A transformer has 200 turns in the primary, 50 turns in the secondary, and 120 volts applied to the primary (E_p). What is the voltage across the secondary (E_s)?

Given:

$$N_P = 200 \text{ turns}$$
$$N_S = 50 \text{ turns}$$
$$E_P = 120 \text{ volts}$$
$$E_S = ? \text{ volts}$$

Solution:

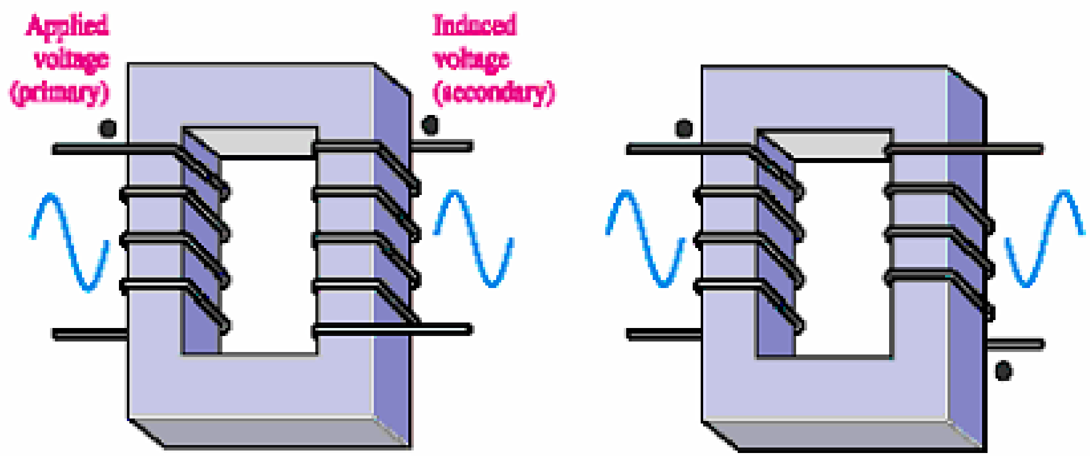
$$E_S = \frac{E_P N_S}{N_P}$$

Substitution:

$$E_S = \frac{120 \text{ volts} \times 50 \text{ turns}}{200 \text{ turns}}$$
$$E_S = 30 \text{ volts}$$

6.2.5 DETERMINE HOW THE DIRECTION OF WINDINGS AFFECTS VOLTAGE POLARITIES:

- The direction of the windings determines the polarity of the voltage across the secondary winding with respect to the voltage across the primary.
- The secondary voltage of a simple transformer may be either in phase or out of phase with the primary voltage.
- Phase dots are used to indicate polarities

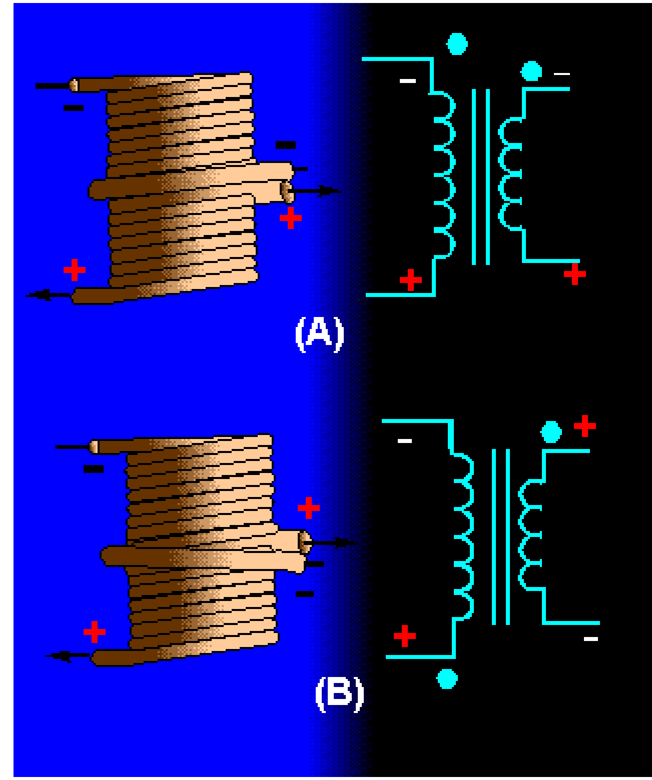


(a) The primary and secondary voltages are in phase when the windings are in the same effective direction around the magnetic path.

(b) The primary and secondary voltages are 180° out of phase when the windings are in the opposite direction.

In part (A) of the figure:

- Both the primary and secondary windings are wound from top to bottom in a clockwise direction,
- When constructed in this manner, the top lead of the primary and the top lead of the secondary have the SAME polarity.
- This is indicated by the dots on the transformer symbol.



Instantaneous polarity depends on direction of winding.

Part (B) of the figure:

• Illustrates a transformer in which the primary and secondary are wound in opposite directions.

• The primary is wound in a clockwise direction from top to bottom, while the secondary is wound in a counterclockwise direction.

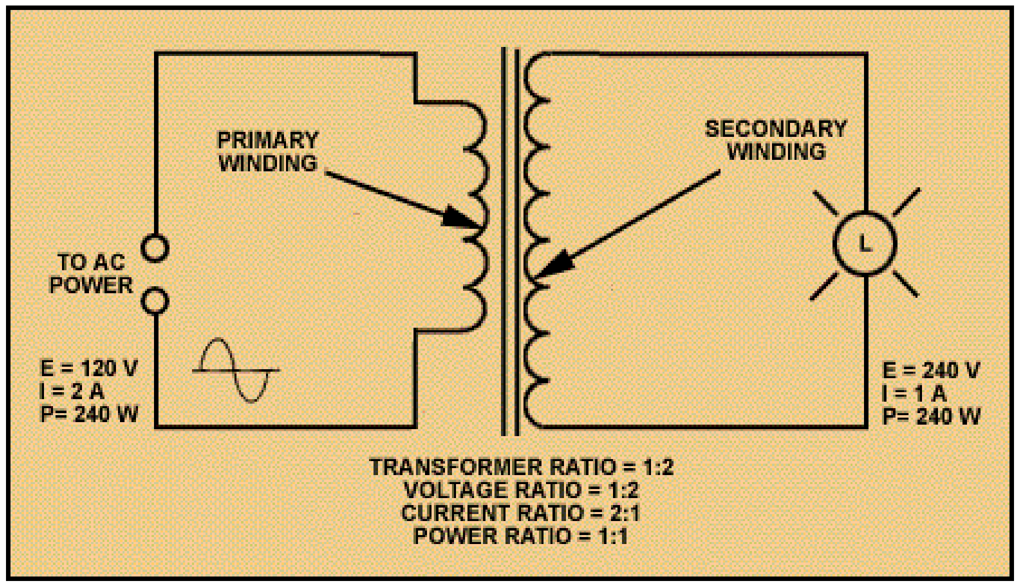
•Notice that the top leads of the primary and secondary have OPPOSITE polarities.

•This is indicated by the dots being placed on opposite ends of the transformer symbol.

6.3 UNDERSTAND HOW TRANSFORMER INCREASES AND DECREASES VOLTAGE

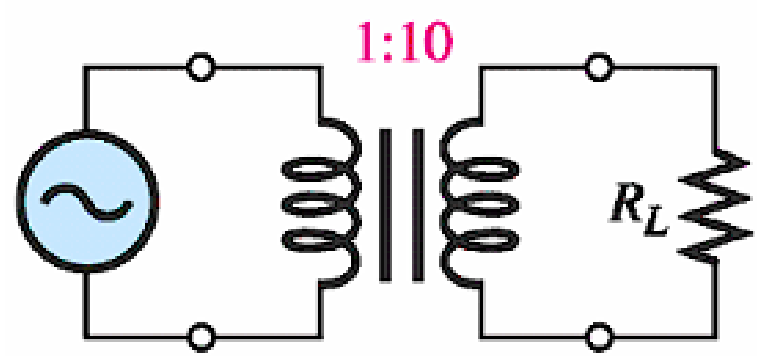
6.3.1 EXPLAIN HOW A STEP UP TRANSFORMER WORKS:

- **Step-Up Transformer** : The primary winding of a step-up transformer has fewer turns than the secondary winding, with the resultant secondary voltage being higher than the primary.



6.3.2 IDENTIFY A STEP UP TRANSFORMER BY ITS TURNS RATIO:

- If there are fewer turns in the primary winding than in the secondary winding, the secondary voltage will be higher than the secondary circuit.



6.3.3 STATE THE RELATIONSHIP BETWEEN PROMARY AND SECONDARY VOLATGES AND THE TURN RATIO:

- The ratio of secondary voltage (VSEC) to primary voltage (VPRI) is equal to the ratio of the number of turns in the secondary winding (NSEC) to the number of turns in the primary winding (NPRI)

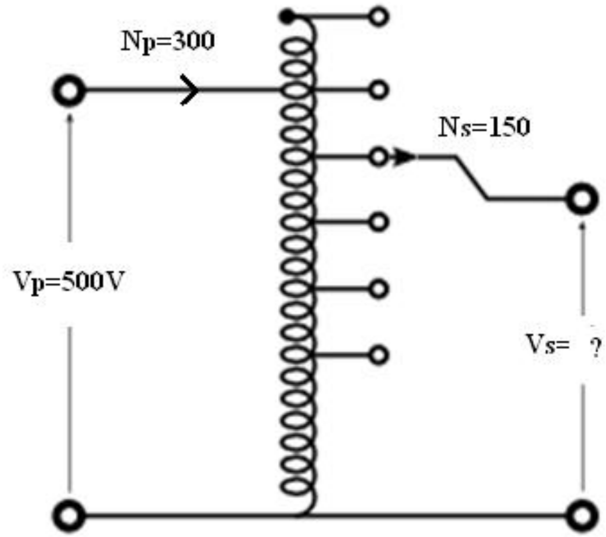
$$\frac{V_{SEC}}{V_{PRI}} = \frac{N_{SEC}}{N_{PRI}}$$

$$V_{SEC} = V_{PRI}\left(\frac{N_{SEC}}{N_{PRI}}\right)$$

Example:

- An autotransformer has a primary voltage;500V, 300 turns primary winding and 150 turns secondary winding. Using suitable diagram, calculate the value of secondary voltage.

Solution:



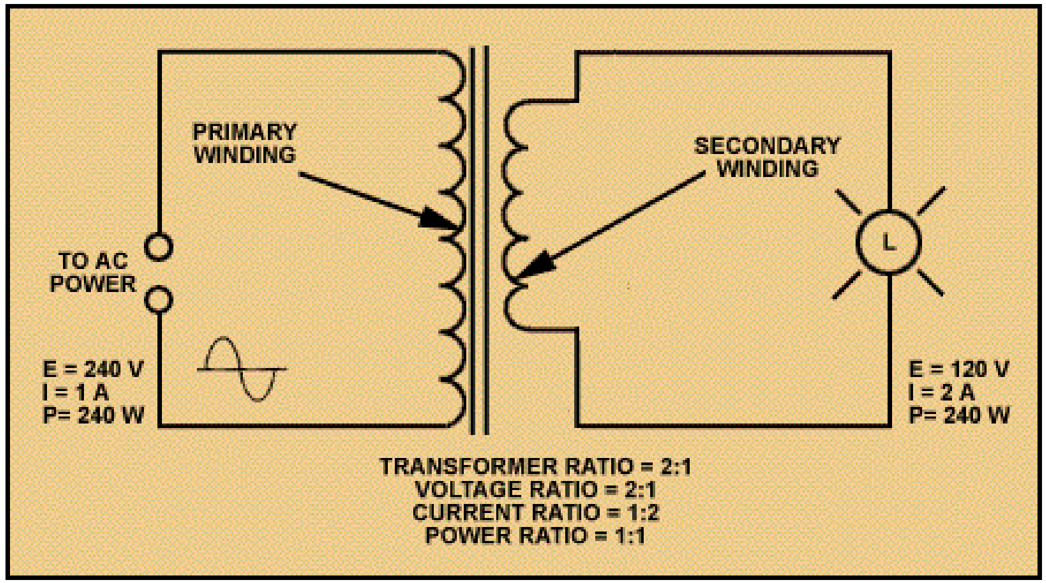
$$\frac{V_{SEC}}{V_{PRI}} = \frac{N_{SEC}}{N_{PRI}}$$

$$V_{SEC} = V_{PRI}\left(\frac{N_{SEC}}{N_{PRI}}\right)$$

Vsec = 500V (150/300) = 250V

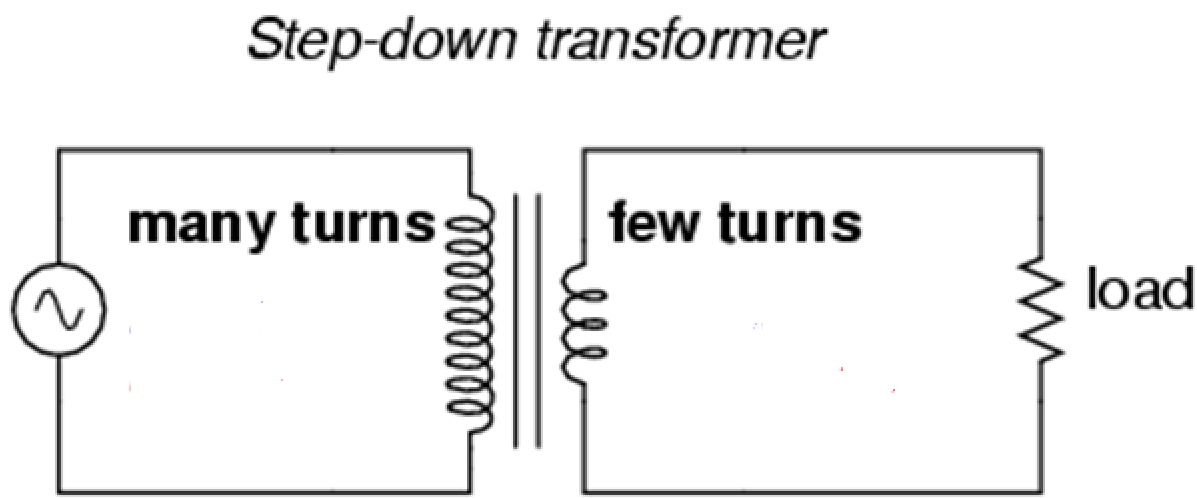
6.3.4 EXPLAIN HOW A STEP DOWN TRANSFORMER WORKS:

- **Step-Down Transformer** : The primary winding of a step-down transformer has more turns than the secondary winding, so the secondary voltage is lower than the primary



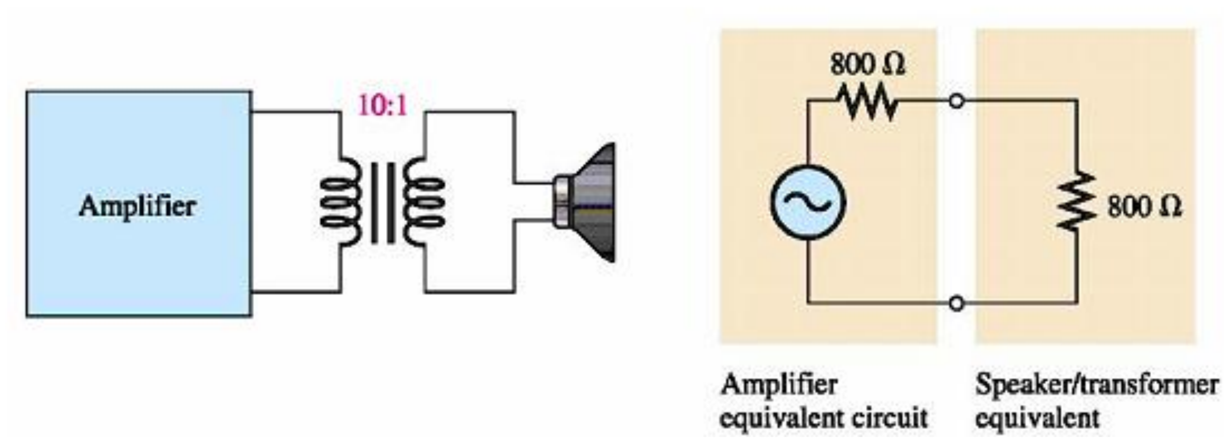
6.3.5 IDENTIFY A STEP DOWN TRANSFORMER BY ITS TURNS RATIO:

- This is a step-down transformer, as evidenced by the high turn count of the primary winding and the low turn count of the secondary.
- The amount by which the voltage is stepped down depends on the turns ratio
- The turns ratio of a step-down transformer is always less than 1



6.3.6 DESCRIBE DC ISOLATION

- A transformer does not pass dc, therefore a transformer can be used to keep the dc voltage on the output of an amplifier stage from affecting the bias of the next amplifier.
- The ac signal is coupled through the transformer between amplifier stages



6.4 UNDERSTAND THE EFFECT OF A RESISTIVE LOAD ACROSS THE SECONDARY WINDING

CURRENT:

- When a load resistor is connected to the secondary winding, there is a current through the resulting secondary circuit because of the voltage induced in the secondary coil
- This secondary current results in a primary current

$I_{sec} = (N_{pri}/N_{sec})I_{pri}$

Where;

$$\frac{V_P}{V_S} = \frac{N_P}{N_S} = \frac{I_S}{I_P} = k\ (transformer\ ratio)$$

$$\text{Voltage transformation ratio} = \frac{N_{secondary}}{N_{primary}}$$

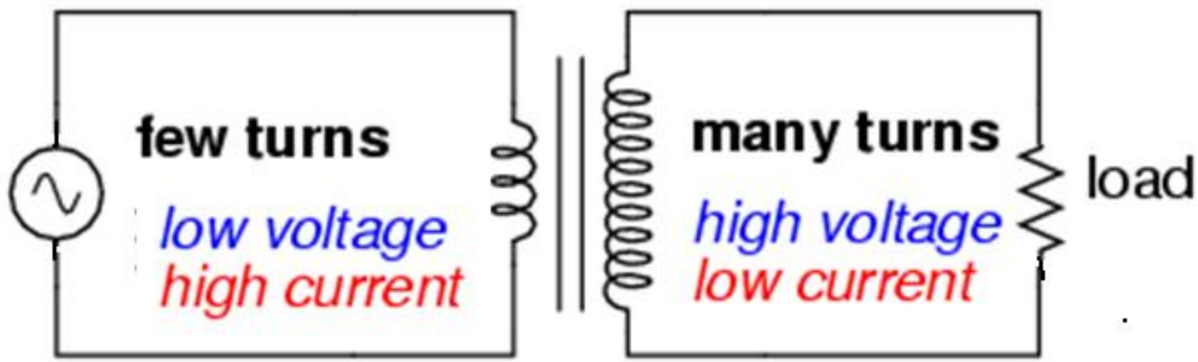
$$\text{Current transformation ratio} = \frac{N_{primary}}{N_{secondary}}$$

Where,

N = number of turns in winding

6.4.1 DETERMINE THE CURRENT DELIVERED BY THE SECONDARY WHEN A STEP UP TRANSFORMER IS LOADED:

Step-Up Transformer

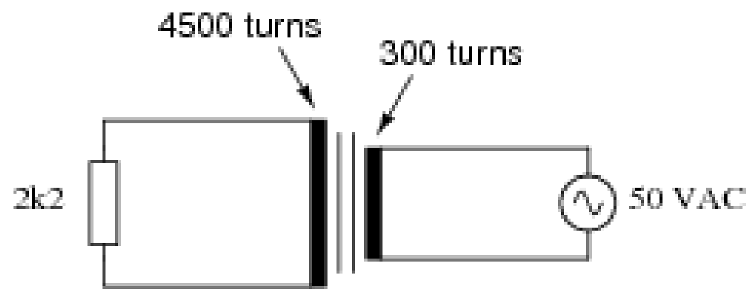


Where;

$$I_P > I_S$$

Example:

Calculate all voltages and all currents in this circuit, given the component values and the number of turns in each of the transformer's windings:



Solution:

$V_P = 50V$

$V_S = ?$

$N_P = 300$

$N_S = 4500$

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

$$\frac{N_P}{N_S} = \frac{V_P}{V_S}$$

$$\frac{300}{4500} = \frac{50}{V_S} \qquad \therefore V_S = 750V$$

$ohm\ law: V = IR$

$\therefore V_S = I_S R_S$

$750V = I_S \times 2.2k\Omega$

$\therefore I_S = 340.91mA$

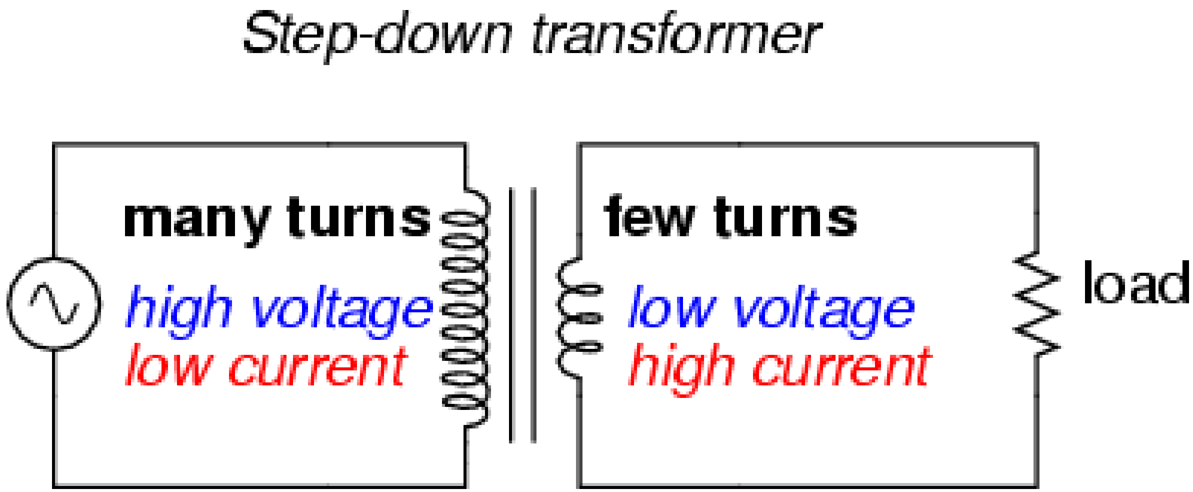
$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

$$\frac{300}{4500} = \frac{340.91mA}{I_P}$$

$\therefore I_P = 5.114A$

$\therefore I_P > I_S$

6.4.2 DETERMINE THE CURRENT DELIVERED BY THE SECONDARY WHEN A STEP DOWN TRANSFORMER IS LOADED:



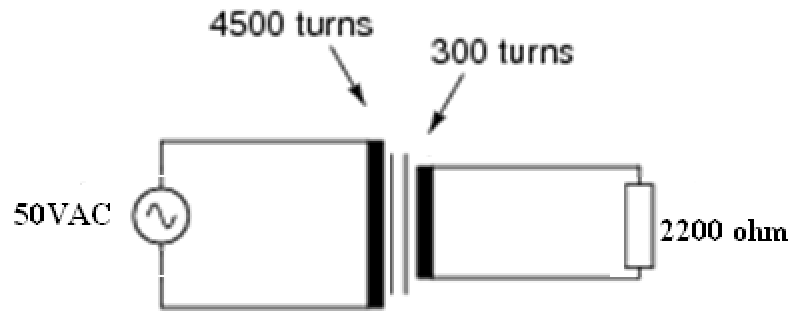
Where;

$$I_P < I_S$$

DETERMINE THE CURRENT DELIVERED BY THE SECONDARY WHEN A STEP DOWN TRANSFORMER IS LOADED

Example:

Calculate all voltages and all currents in this circuit, given the component values and the number of turns in each of the transformer's windings:



Solution:

$V_P = 50V$

$V_S = ?$

$N_P = 4500$

$N_S = 300$

$$\frac{N_P}{N_S} = \frac{V_P}{V_S} = \frac{I_S}{I_P}$$

$$\frac{N_P}{N_S} = \frac{V_P}{V_S}$$

$$\frac{4500}{300} = \frac{50}{V_S} \qquad \therefore V_S = 3.33$$

$$ohm\ law: V = IR$$

$$\therefore V_S = I_S R_S$$

$$3.33V = I_S \times 2.2k\Omega$$

$$\therefore I_S = 1.515mA$$

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

$$\frac{4500}{300} = \frac{1.515mA}{I_P}$$

$$\therefore I_P = 0.1mA$$

$$\therefore I_P < I_S$$

6.4.3 CALCULATE POWER IN A TRANSFORMER

- For an ideal transformer, the power delivered in the secondary equals the power in the primary
- In a real transformer, some power is dissipated in the transformer, so primary power is always greater than secondary power
- In an ideal transformer, power transfer is not related to the turns ratio

$$P_{pri} = V_{pri} I_{pri} = V_{sec} I_{sec} = P_{sec}$$

6.5 UNDERSTAND A NON-IDEAL TRANSFORMER

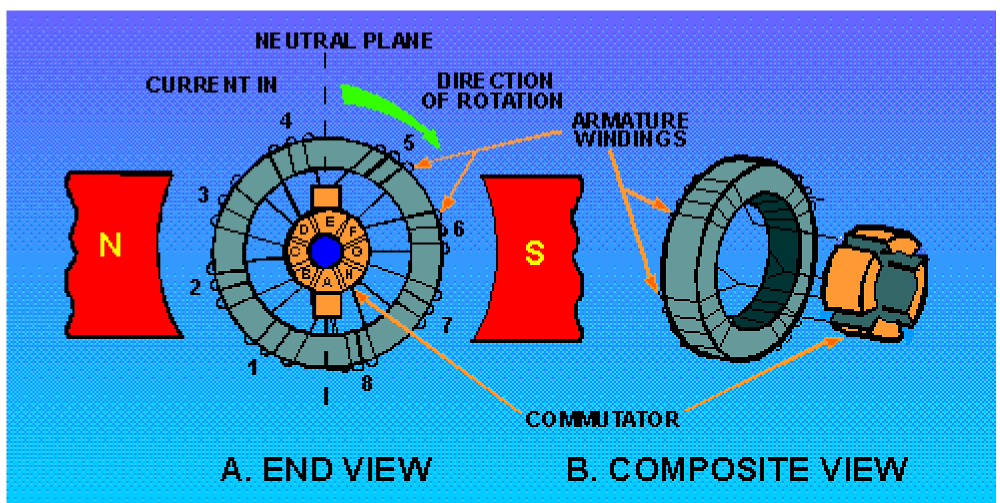
• A *nonideal* (or *actual*) transformer differs from an ideal transformer in that the former has hysteresis and eddy-current (core) losses, and has resistive ($i^2 R$) losses in its primary and secondary windings.

•Real transformers have winding resistance, resistance in series with each winding, resulting in less than idea secondary voltage

6.5.1 LIST THE NON IDEAL CHARACTERISTICS

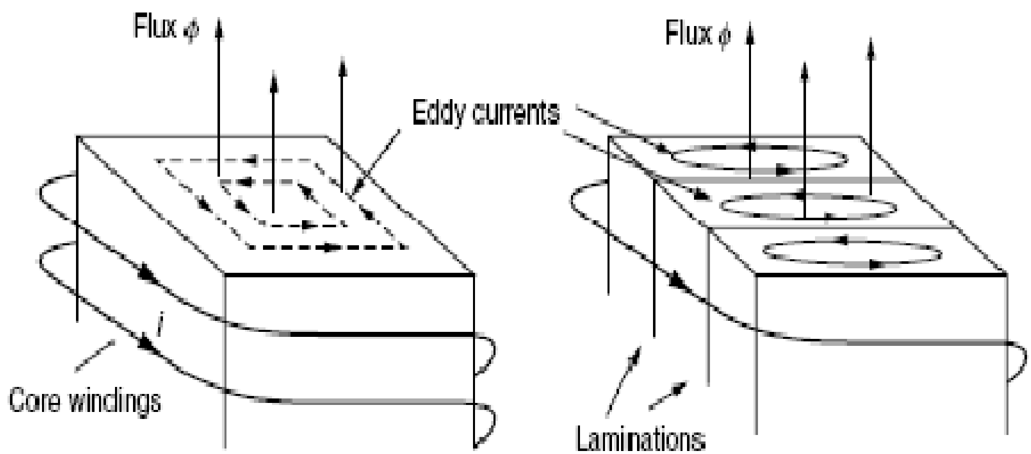
HYSTERESIS LOSSES@CORE LOSS:

- Hysteresis losses are core losses: due to the continuous reversal of the magnetic field due to the changing direction of the primary current.
- Hysteresis loss is a heat loss caused by the magnetic properties of the armature.
- When the armature core is rotating, its magnetic field keeps changing direction. The continuous movement of the magnetic particles, as they try to align themselves with the magnetic field, produces molecular friction. This, in turn, produces heat. This heat is transmitted to the armature windings. The heat causes armature resistances to increase.



EDDY CURRENT:

- Eddy currents: result in more heat losses in the core material.
- Eddy currents are produced when voltage is induced in the core material itself

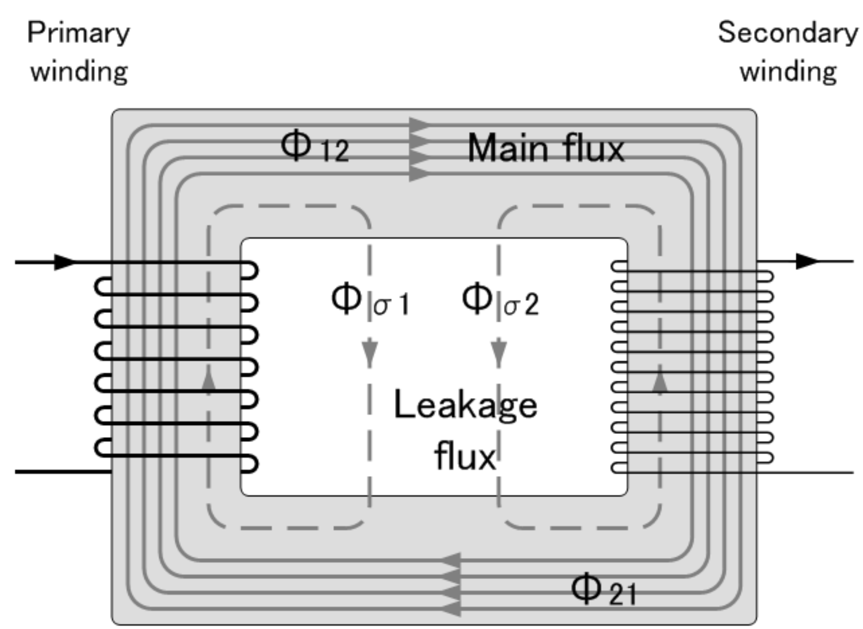


COPPER LOSS:

- Cause by the ac resistance of the copper wire in the primary and secondary windings.
- Because of the length of the wire and its tiny cross sectional area, the ac resistance can be quite high.
- Copper loss can be reduced by increasing the size of the copper wire in the winding.
- Larger wire has less resistance.

LEAKAGE FLUX:

- Lines of flux generated by one winding which do not link with the other winding are called LEAKAGE FLUX.
- Since leakage flux generated by the primary does not cut the secondary, it cannot induce a voltage into the secondary.
- The voltage induced into the secondary is therefore less than it would be if the leakage flux did exist.
- LEAKAGE INDUCTANCE is assumed to drop part of the applied voltage, leaving less voltage across the primary



6.5.2 EXPLAIN POWER RATING OF A TRANSFORMER

- Transformers are typically rated in volt-amperes (VA), primary/ secondary voltage, and operating frequency.

Note:

$$Input\ power = output\ power + losses$$

$$Total\ losses = copper\ loss + iron\ losses$$

Where:

$$\mathbf{P_{pri} = V_{pri} I_{pri} \cos\theta}$$

$$\mathbf{P_{sec} = V_{sec} I_{sec} \cos\theta}$$

6.5.3 DETERMINE EFFICIENCY OF A TRANSFORMER:

$$\eta = \frac{output\ power}{input\ power} = \frac{input\ power - losses}{input\ power}$$

$$\eta = 1 - \frac{losses}{input\ power}$$

- Is usually expresses as a percentage.

@

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Input}} = \frac{P_s}{P_p} \times 100$$

$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power Output} + \text{Copper Loss} + \text{Core Loss}} \times 100$$

$$\text{Efficiency} = \frac{V_s\ I_s \times PF}{(V_s\ I_s \times PF) + \text{Copper Loss} + \text{Core Loss}} \times 100$$

where

PF = power factor of the load

$$Copper\ loss = I_P^2 R_P + I_S^2 R_S$$

Example:

A 200kVA rated transformer has a full load copper loss of 1.5kW & an iron loss of 1kW. Determine the transformer efficiency at full load and o.85 power factor.

Full load output power = IV cos θ = 200 X 0.85 = 170 kW.

Total losses = copper loss + iron loss = 1.5kW + 1kW = 2.5kW

Input power = output power + losses = 170kW + 2.5kW = 172.5kW

$$\eta = 1 - \frac{losses}{input\,power} = 1 - \frac{2.5kW}{172.5kW} = 1 - 0.01449 = 0.9855@\ 98.55\%$$

<u>Example:</u>

A 5:1 stepdown transformer has a fullload secondary current of 20A. A short circuit test for copper loss at full load gives a wattmeter reading of 100 W. If R_P = 0.3W, find R_S and power loss in the secondary

Solution:

Copper Loss = $I^2_P \; R_P + I^2_S \; R_S = 100$ W

To find I_P:

$$\frac{N_P}{N_S} = \frac{I_S}{I_P}$$

$$I_P = \frac{N_S}{N_P} I_S = \frac{1}{5} 20 = 4 \text{ amps}$$

To find R_S:

$$I^2_S \; R_S = 100 - I^2_P \; R_P$$

$$R_S = \frac{100 - I^2_P \; R_P}{I^2_S} = \frac{100 - 0.3(4)^2}{20^2} = 0.24$$

Example:

- A primary and secondary winding of 500kVA transformer have each 0.5Ω and 0.0012Ω resistor. Given a primary voltage 6.6kV and secondary voltage 0.4kV and core loss 3kW. Calculate the transformer efficiency in full load condition.

  Assume the power factor is 0.8.

Solution:

$$\eta = \frac{P_O}{P_{IN}} \times 100\% = \frac{P_O}{P_O + P_i + P_{CU}} \times 100\%$$

$$P_O = IV\cos\theta = 500kVA \times 0.8 = 400kVA$$

$$core\ loss, Pi = 3kW$$

$$copper\ loss, Pcu = I_P^2 R_P + I_S^2 R_S$$

$$P_P = I_P V_P$$

$$\therefore I_P = \frac{P_P}{V_P} = \frac{500kVA}{6.6kV} = 75.76A$$

$$\therefore I_S = \frac{P_S}{V_S} = \frac{500kVA}{0.4kV} = 1250A$$

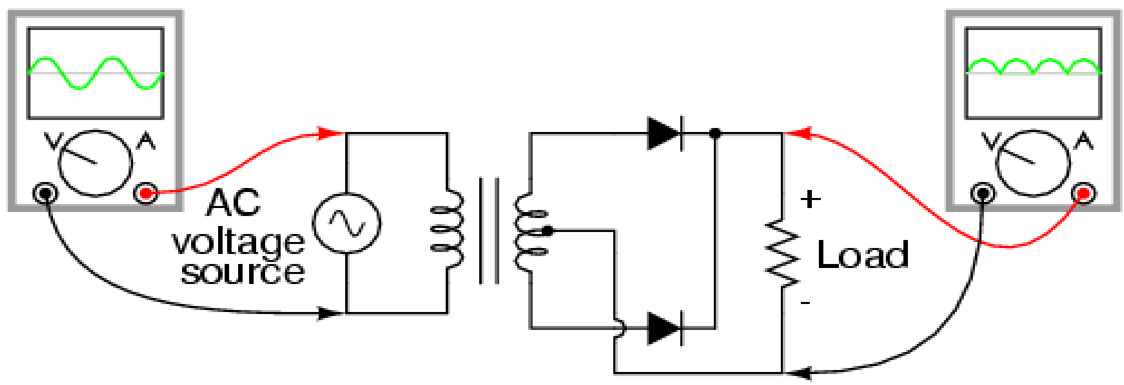
$$\therefore copper\ loss, Pcu = I_P^2 R_P + I_S^2 R_S = [75.76^2 \times 0.5\Omega] + [1250^2 \times 0.0012\Omega] = 4744.79W$$

$$\eta = \frac{P_O}{P_O + P_i + P_{CU}} \times 100\% = \frac{400kVA}{400kVA + 3kW + 4744.79W} \times 100\% = 98.1\%$$

6.6 UNDERSTAND SEVERAL TYPES OF TRANSFORMER

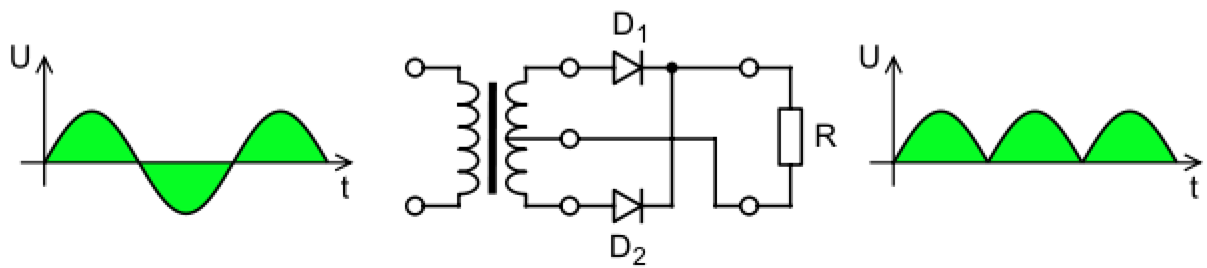
6.6.1 DESCRIBE CENTER TAPPED TRANSFORMER:

- Simply defined as a transformer with a “tap” in the center of the secondary winding.
- This “tap” or additional connection in the middle of the winding can be used with, or instead of, other types of connections at the ends of the windings.
- This scenario provides a variety of winding ratios



Common applications of center-tapped *transformers:*

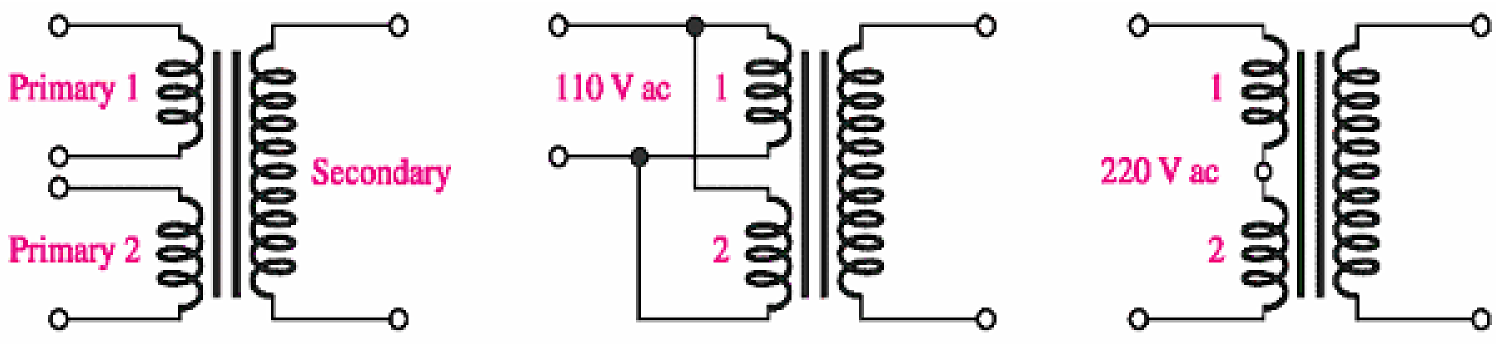
- In a rectifier, a center-tapped transformer and two diodes can form a full-wave rectifier that allows both half-cycles of the AC waveform to contribute to the direct current.



- In an audio power amplifier center-tapped transformers are used to drive push-pull output stages. This allows two devices operating in Class B to combine their output to produce higher audio power with relatively low distortion.
- In analog telecommunications systems center-tapped transformers can be used to provide a DC path around an AC coupled amplifier for signaling purposes.

6.6.2 DESCRIBE MULTIPLE WINDING TRANSFORMER

- Multiple-winding transformers have more than one winding on a common core.
- They are used to operate on, or provide, different operating voltages



(a) Two primary windings

(b) Primary windings in parallel for 110 V ac operation

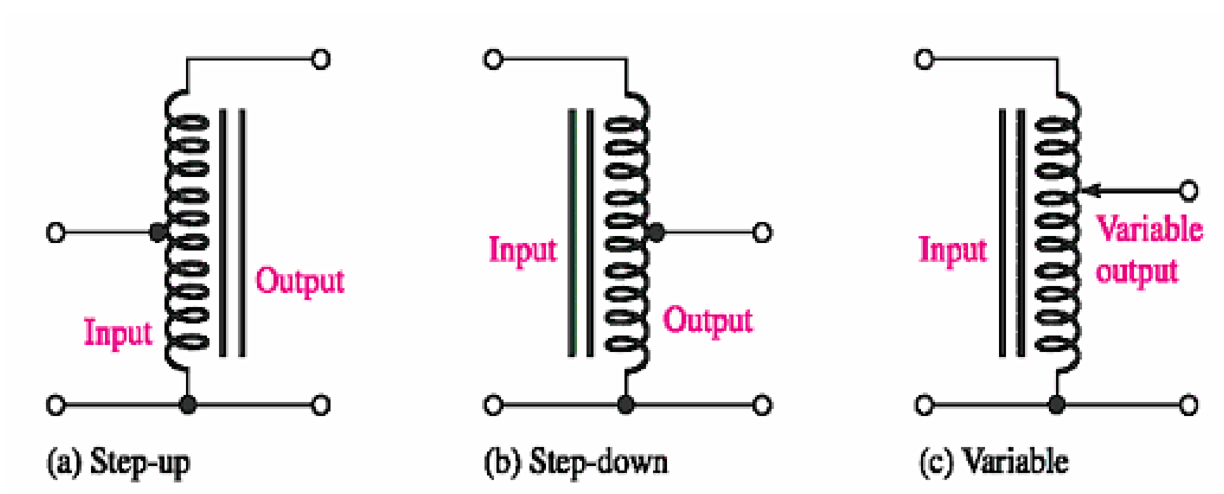
(c) Primary windings in series for 220 V ac operation

6.6.3 DESCRIBE AUTO-TRANSFORMERS:

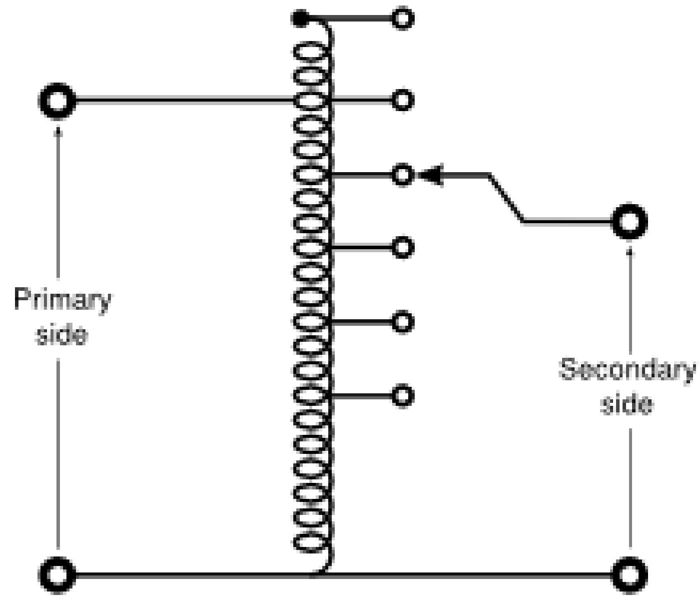
- In an autotransformer, one winding serves as both the primary and the secondary. The winding is tapped at the proper points to achieve the desired turns ratio for stepping up or down the voltage

- An autotransformer can be smaller, lighter and cheaper than a standard dual-winding transformer however the autotransformer does not provide electrical isolation.

- Autotransformers are often used to step up or down between voltages in the 110-117-120 volt range and voltages in the 220-230-240 volt range,



AUTOTRANSFORMER



• As in an **ordinary transformer**, the ratio of secondary to primary voltages is equal to the ratio of the number of turns of the winding they connect to.

• For example, connecting the load between the middle and bottom of the autotransformer will reduce the voltage by 50%.