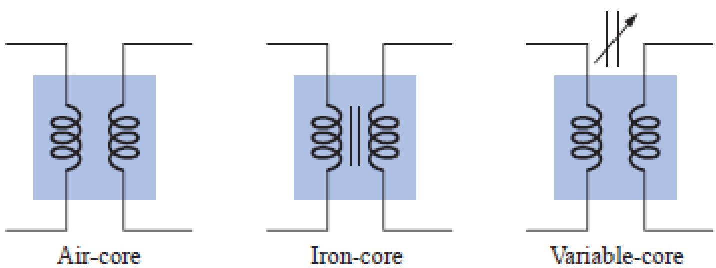
Transformer:

A *transformer* is a device that changes the voltage level of ac electric power through the action of a magnetic field. It consists of two or more coils of wire wrapped around a common ferromagnetic core. These coils are (usually) not directly connected or conductively coupled. The only connection between the coils is the common magnetic flux present within the core (magnetically coupled).

One of the transformer windings is connected to a source of ac electric power, and the remaining winding supplies electric power to loads. The transformer winding connected to the power source is called the *primary winding* or *input winding,* and the winding connected to the loads is called the *secondary winding* or *output winding.* If the secondary voltage is higher, it is known as step-up operation and if the secondary voltage is lower, it is known as step-down operation. Sometimes there is a third winding on the transformer, it is called the *tertiary winding*.

Construction of Transformers

Transformers are available in many different shapes and sizes. Some of the more common types include the power transformer, audio transformer, IF (intermediate-frequency) transformer, and RF (radio frequency) transformer. Each is designed to fulfill a particular requirement in a specific area of application. Size of a transformer decreases with the increase in operating frequency.



Transformer symbols.

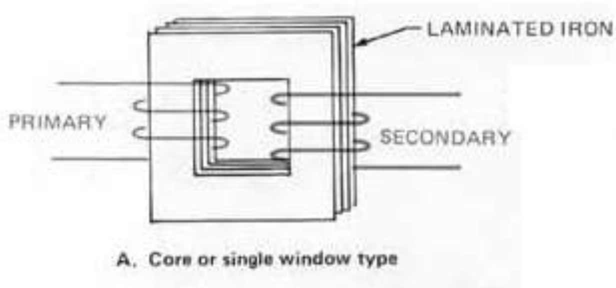
Power transformer: In case of power transformers, the core is made of laminated sheets of ferromagnetic material separated by an insulator (varnish or oxide coating) to reduce the eddy current losses. The sheets themselves will also contain a small percentage of silicon to increase the electrical resistivity of the material and further reduce the eddy current losses.

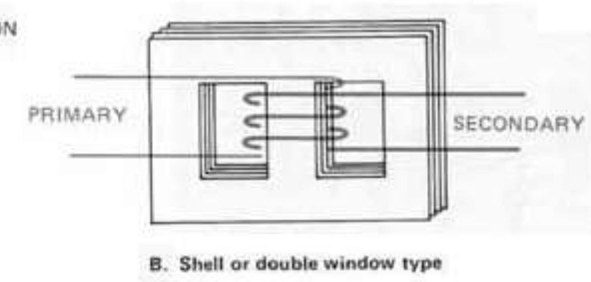
Types of cores for power transformer:

i) **Core Form:** A simple rectangular laminated piece of steel with the transformer windings wrapped around two sides of the rectangle.

ii) **Shell Form:** A three legged laminated core with the windings wrapped around the centre leg. The primary and secondary windings are wrapped one on top of the other with the low-voltage winding innermost. It serves two purposes:

- It simplifies the problem of insulating the high-voltage winding from the core.
- It results in much less leakage flux





Cooling: Heat generation in transformer is mainly due to its copper loss and partially to its core loss. It is essential to control the temperature within permissible limit to ensure the long life of transformer by reducing thermal degradation of its insulation system. Cooling is provided by air convection, forced air, insulating liquids, or gas (SF_6, C_2F_6, etc.)

Power transformers are given a variety of different names, depending on their use in power systems.

- Unit transformers – Usually located at the output of a generator. Its function is to step up the voltage level so that long distance transmission of power is possible.
- Substation transformers – Located at main distribution or secondary level transmission substations. Its function is to lower the voltage levels for 1st level distribution purposes.
- Distribution Transformers – Located at small distribution substation. It lowers the voltage levels for 2nd level distribution purposes.

Air-core Transformer: Due to non-linearity in ferromagnetic core (due to core saturation, power loss in the form of eddy current and hysteresis) electromagnetic field does not change uniformly and output signal gets distorted. To maintain the quality of signal in high frequency application like signal transmission, air core transformer is introduced. Here iron core of transformer is absent and the flux is linked with the windings through air. In addition to the noise-free operation, an air core transformer is quite light weight due to absence of heavy weight iron core. That is why this type of transformer is most suitable for portable, light weight electronic devices and high frequency devices. Air core transformers are generally used in radio transmitter and communication devices etc.

Principle of Operation:

A current-carrying wire produces a magnetic field in the area around it. If the current is time-varying, the resulting magnetic field will be time-varying as well. A time-changing magnetic field induces a voltage in a coil of wire if it passes through that coil; this is known as electromagnetic induction.

The magnitude of the flux is directly proportional to the current. Therefore for a sinusoidal input, the magnitude of the flux will vary as a sinusoid as well.

The sinusoidal time-varying flux that links both coils can be expressed as

$$\emptyset_M(t) = \Phi_{\max} \sin\omega t$$

The induced voltage across the primary due to a sinusoidal input can be determined by Faraday's law:

$$e_p(t) = N_p \frac{d\emptyset_p(t)}{dt} = N_p \frac{d\emptyset_M(t)}{dt} = N_p \frac{d}{dt}\Phi_{\max} \sin\omega t = \omega N_p \Phi_{\max} \cos\omega t$$

Effective value of e_p is given by,

$$E_p = \frac{\omega N_p \Phi_m}{\sqrt{2}} = \frac{2\pi f N_p \Phi_m}{\sqrt{2}} = 4.44 f N_p \Phi_{\max}$$

Similarly, effective value of the induced voltage across the secondary

$$E_s = 4.44 f N_s \Phi_{\max}$$

Ideal Transformer:

An *ideal transformer* is a lossless device with an input winding and an output winding.

$$v_p(t) i_p(t) = v_s(t) i_s(t)$$

The transformer has N_p turns of wire on its primary side and N_s turns of wire on its secondary sides. The relationship between the primary and secondary voltage is as follows:

$$\frac{v_p(t)}{v_s(t)} = \frac{N_p}{N_s} = a$$

where *a* is the turns ratio of the transformer.

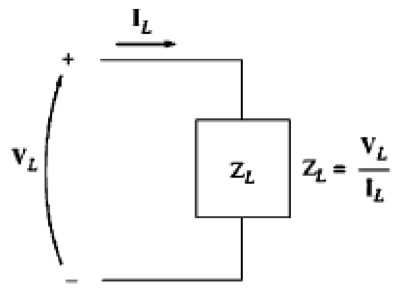
The relationship between primary and secondary current is:

$$\frac{i_p(t)}{i_s(t)} = \frac{N_s}{N_p} = \frac{1}{a}$$

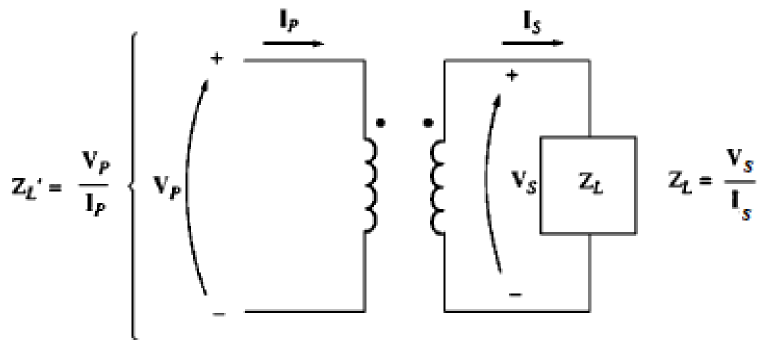
In terms of phasor quantities:

$$\frac{\boldsymbol{V}_p}{\boldsymbol{V}_s} = \frac{\boldsymbol{I}_s}{\boldsymbol{I}_p} = a$$

Impedance Transformation:



Definition of impedance.



Impedance scaling through a transformer.

$$Z_L = \frac{\boldsymbol{V}_s}{\boldsymbol{I}_s}$$

$$Z_L{}' = \frac{\boldsymbol{V}_p}{\boldsymbol{I}_p} = \frac{a\,\boldsymbol{V}_s}{\boldsymbol{I}_s/a} = a^2\frac{\boldsymbol{V}_s}{\boldsymbol{I}_s}$$

$$Z_L{}' = a^2\,Z_L$$

DOT Convention:

In real transformers, to determine the polarity of the secondary terminals, it is required to open the transformer casing and examine the orientation of its windings. To avoid this transformers utilize the *dot convention.* The dots appearing at one end of each winding tell the polarity of the voltage and current on the secondary side of the transformer.

- If the primary *voltage* is positive at the dotted end of the winding with respect to the undotted end, then the secondary voltage will be positive at the dotted end also.
- If the primary *current* of the transformer flows *into* the dotted end of the primary winding, the secondary current will flow *out* of the dotted end of the secondary winding.

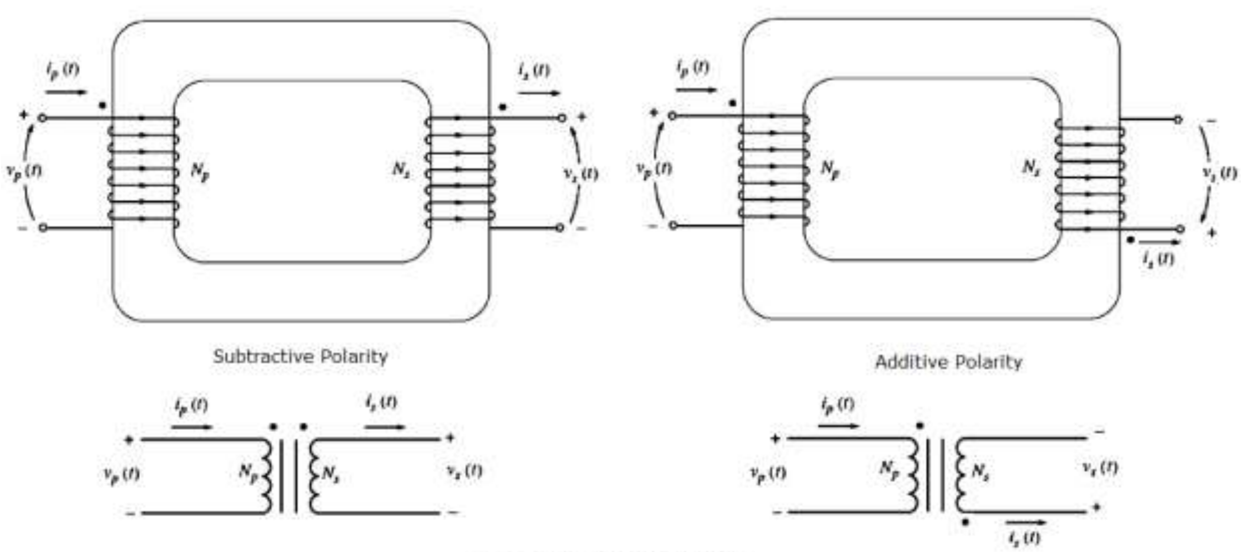


Illustration of Dot Convention

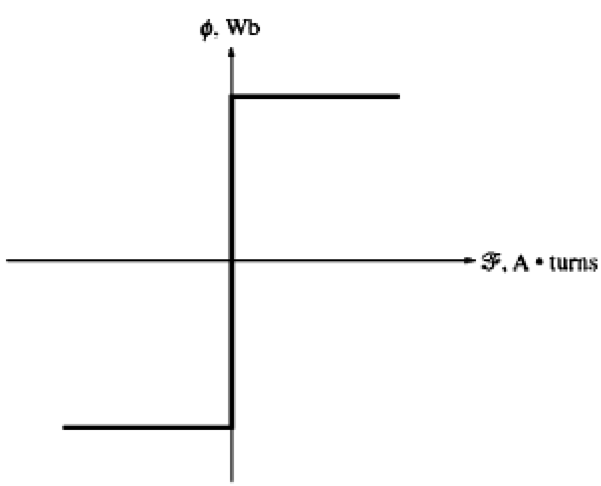
Subtractive Polarity: In this connection, the terminals with the same instantaneous polarity are opposite to each other. If an accidental contact between any two adjacent terminals occurs, the voltage across the other terminals will be the difference between the high and low voltages

Additive Polarity: Accidental contact between adjacent terminals of opposite windings will result in a voltage across the other ends equal to the sum of high and low voltages.

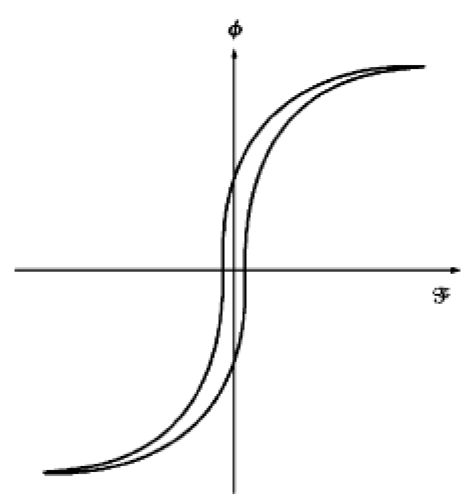
Real Transformer:

Ideal transformers may never exist due to the fact that there are losses associated to the operation of transformers. The differences between a real transformer and an ideal transformer are:

- In an ideal transformer, the resistance of the transformer windings is assumed to be zero. Whereas, real transformers have nonzero winding resistance that results in power loss (known as Cu loss).
- In an ideal transformer, the leakage flux in the core is assumed to be zero, implying that all the flux in the core couples both windings. In a real transformer leakage flux is present in both primary and secondary coils.
- When secondary terminals are open, there is no current flow in the secondary coil. If the transformer is ideal, current in the primary coil is zero as well. However, in a real transformer there is a current flow in the primary coil, when no load in the secondary. This is known as exciting current.
- In a real transformer, power losses occur in the ferromagnetic core in the form hysteresis loss and eddy current loss. Whereas, in an ideal transformer, the core must have no hysteresis or eddy currents.
- The permeability of the core is infinite; it requires no exciting current to maintain the flux. In an ideal transformer, the net magnetomotive force is zero. $F_{net} = N_p i_p - N_s i_s = 0$. The resulting magnetization curve must have the shape shown below.



The magnetization curve of an ideal transformer.



The hysteresis curve of the transformer.

Equivalent Circuit of a Real Transformer:

To analyze the performance of a real transformer, the non-ideal factors are to be considered. The equivalent circuit will take into account all the major imperfections in a real transformer.

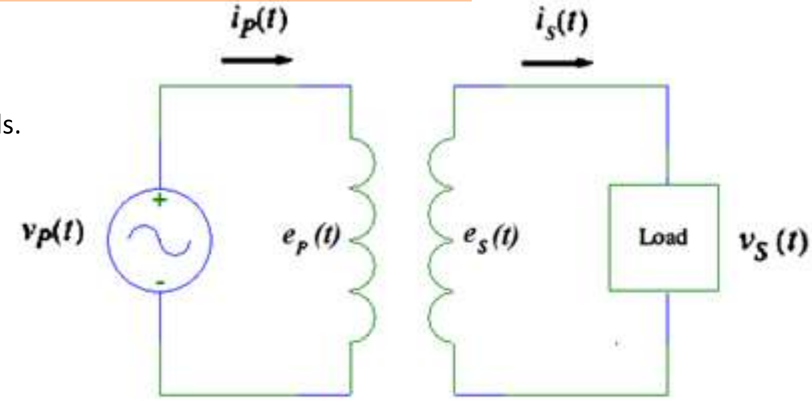
Leakage Flux:

For an ideal transformer, same flux links both coils.

$v_p(t) = e_p(t)$

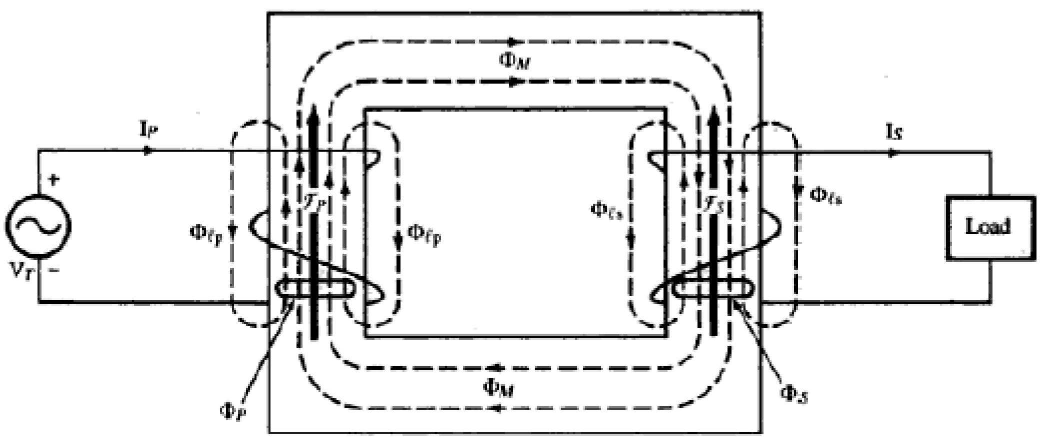
$v_s(t) = e_s(t)$

$\frac{v_p(t)}{v_s(t)} = \frac{e_p(t)}{e_s(t)} = a$



However, in a real transformer due to leakage flux, there will be some voltage drops and voltage ratio, $\frac{v_p(t)}{v_s(t)}$ will be different than turns ratio, a.

The portion of the flux that goes through one of the transformer coils but not the other one is called leakage flux. The following figure depicts various flux components in a loaded transformer.



$$\emptyset_p = \emptyset_M + \emptyset_{lp} \qquad\qquad \emptyset_s = \emptyset_M - \emptyset_{ls}$$

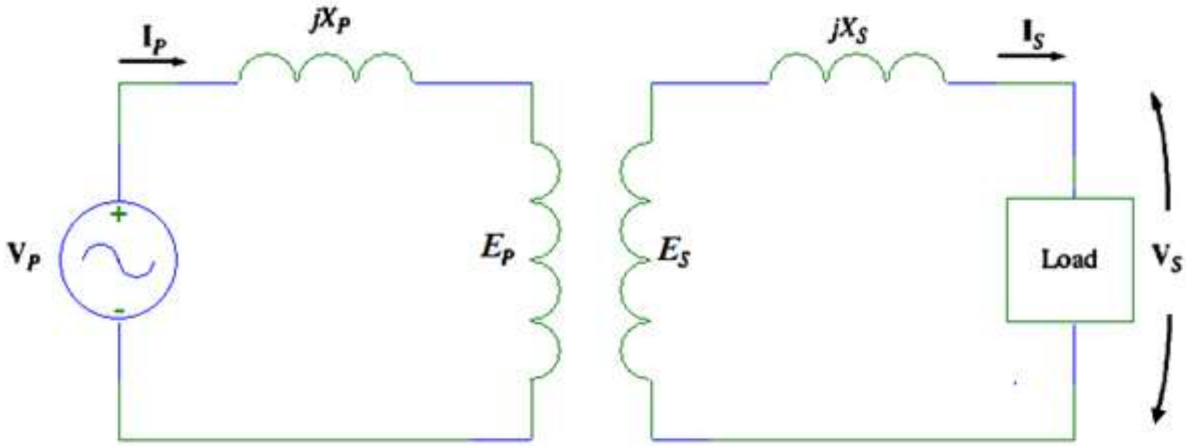
$$v_p(t) = N_p \frac{d\emptyset_p}{dt} \qquad\qquad v_s(t) = N_s \frac{d\emptyset_s}{dt}$$

$$v_p(t) = N_p \frac{d\emptyset_M}{dt} + N_p \frac{d\emptyset_{lp}}{dt} \qquad\qquad v_s(t) = N_s \frac{d\emptyset_M}{dt} - N_s \frac{d\emptyset_{ls}}{dt}$$

$$v_p(t) = e_p(t) + e_{lp}(t) \qquad\qquad v_s(t) = e_s(t) - e_{ls}(t)$$

$$e_{lp}(t) = N_p \frac{d\emptyset_{lp}}{dt} = N_p \frac{d\emptyset_{lp}}{di_p} \frac{di_p}{dt} = L_p \frac{di_p}{dt} \qquad\qquad e_{ls}(t) = N_s \frac{d\emptyset_{ls}}{dt} = N_s \frac{d\emptyset_{ls}}{di_s} \frac{di_s}{dt} = L_s \frac{di_s}{dt}$$

Therefore the **leakage element may be modeled as an inductance** connected together in series with the primary and secondary circuit respectively.



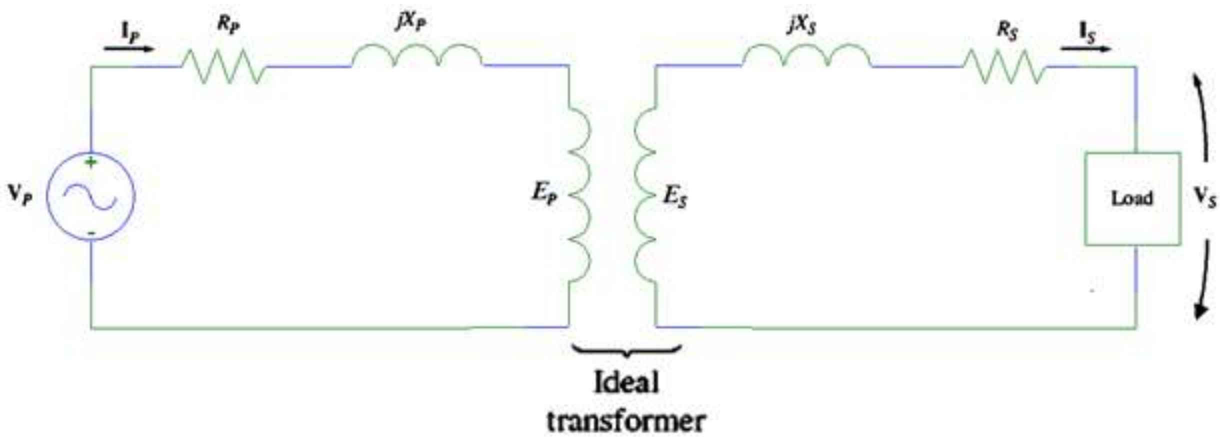
In terms of phasor quantities,

$$\boldsymbol{V}_p = \boldsymbol{E}_p + j\boldsymbol{I}_p X_p \qquad \boldsymbol{V}_s = \boldsymbol{E}_s - j\boldsymbol{I}_s X_s$$

Where X_p and X_s are leakage reactances of primary and secondary coil.

Copper Loss:

Copper losses are resistive power losses due to nonzero winding resistance of the coils. These losses are modeled by placing a resistor R_P in the primary circuit and a resistor R_S in the secondary circuit.



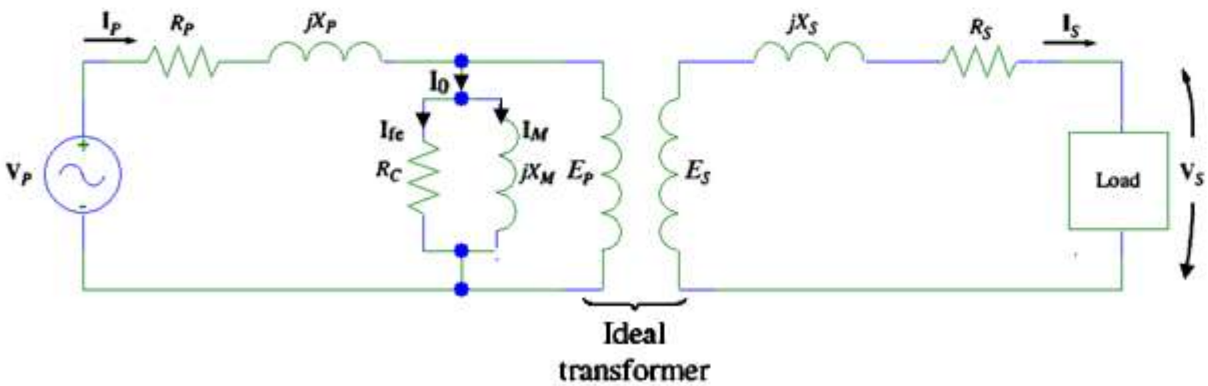
$$\boldsymbol{V}_p = \boldsymbol{E}_p + \boldsymbol{I}_p R_p + j\boldsymbol{I}_p X_p \qquad \boldsymbol{V}_s = \boldsymbol{E}_s - j\boldsymbol{I}_s X_s - \boldsymbol{I}_s R_s$$

Where R_p and R_s are winding resistances of primary and secondary coil

Exciting Current:

Exciting current flows in the primary circuit, even when *the secondary circuit is open circuited.* To accommodate this current, a parallel branch (no-load branch) is to be included in the equivalent circuit. Exciting current consists of two components:

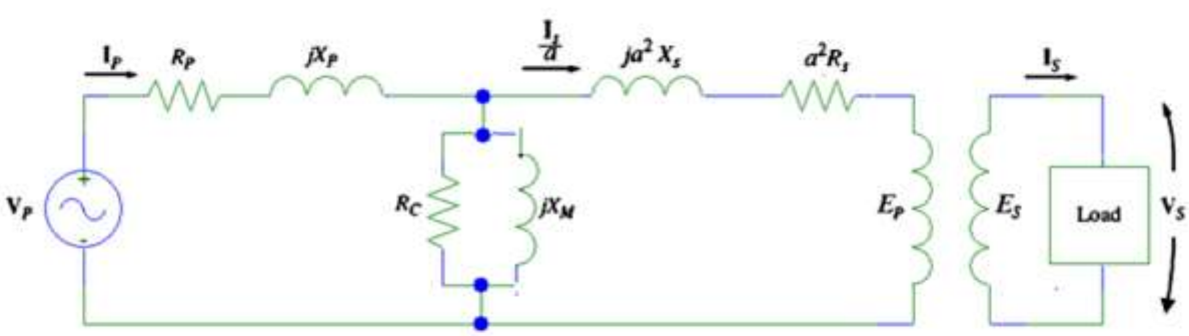
- The magnetization current *I_m*, which is the current required to produce the flux in the transformer core. The magnetization current I_m is proportional (in the unsaturated region) to the voltage applied to the core and lagging the applied voltage by 90°. Therefore, the magnetizing current can be modeled as reactance X_m across the primary voltage source.
- The *core-loss current I_{fe}* which is the current required to make up for hysteresis and eddy current losses. The core loss current I_{fe} is proportional to the voltage applied to the core and also in phase with the applied voltage. Therefore, the core-loss current can be modeled as a resistance R_C across the primary voltage source.



The no-load branch consists of a resistance, R_C (core-loss resistance) in parallel with an inductive reactance, X_M (magnetizing reactance).

To analyze practical circuits containing transformers, it is normally necessary to convert the entire circuit to an equivalent circuit at a single voltage level.

Impedances of the secondary side can be reflected to the primary side (muliplying by square of the turns ratio) and thus equivalent circuit referred to the primary circuit can be obtained.

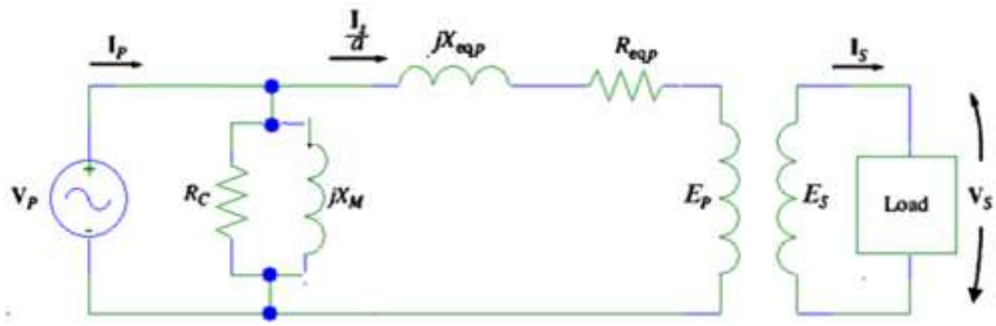


Equivalent circuit referred to primary side

The circuit can be further simplified by combining the impedance of the primary side and the reflected impedance of the secondary side.

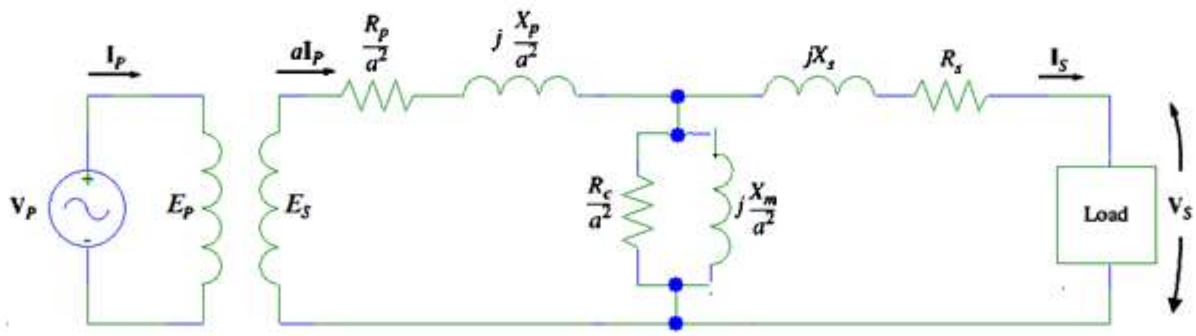
$$R_{eq,p} = R_p + a^2 R_s$$

$$X_{eq,p} = X_p + a^2 X_s$$

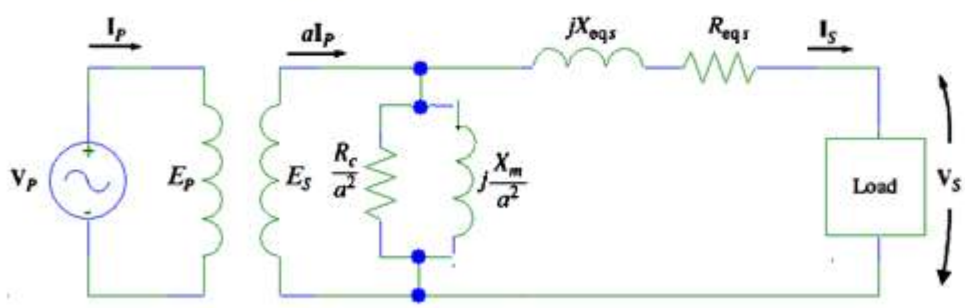


Approximate equivalent circuit referred to primary side

Alternatively, impedances of the primary side can be reflected to the secondary side (dividing by square of the turns ratio) and hence combined to form a equivalent resistance and reactance.



Equivalent circuit referred to secondary side



Approximate equivalent circuit referred to secondary side

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

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

Voltage Regulation:

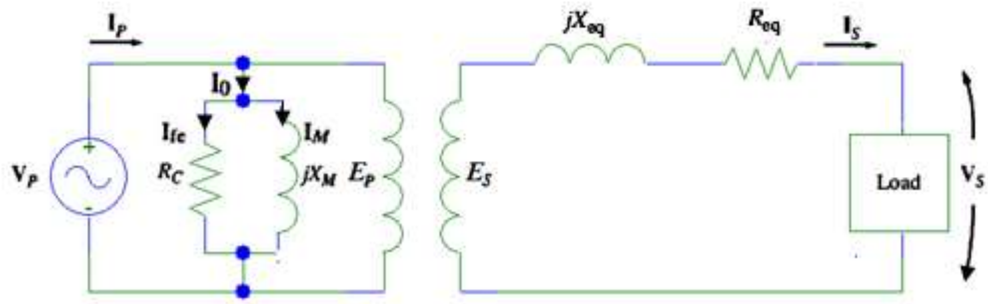
Because a real transformer has series impedances within it, the output voltage of a transformer varies with the load even if the input voltage remains constant. To conveniently compare transformers in this respect, it is customary to define a quantity called *voltage regulation* (VR). *Full-load voltage regulation* is a quantity that compares the output voltage of the transformer at no load with the output voltage at full load.

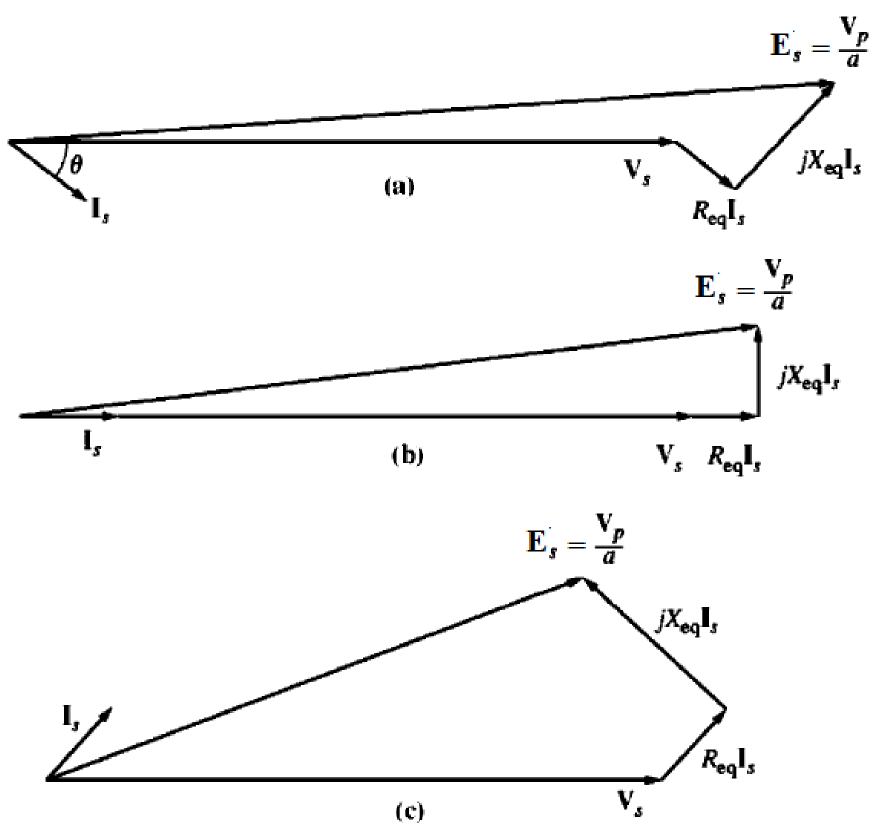
$$VR = \frac{V_{nl} - V_{fl}}{V_{fl}}$$

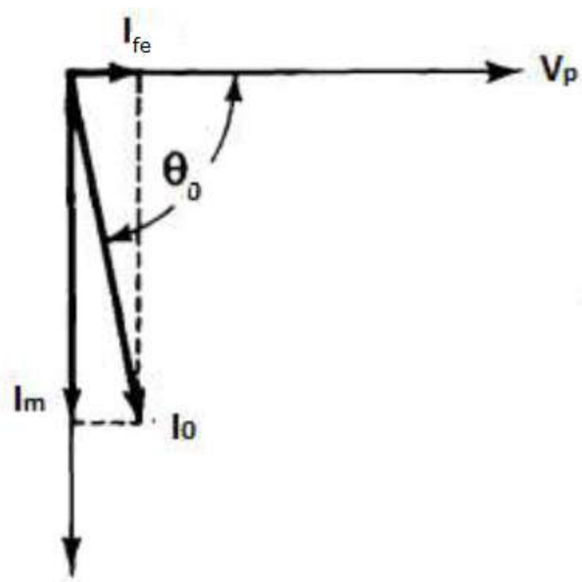
Usually it is a good practice to have as small a voltage regulation as possible. For an ideal transformer, VR = 0 percent. It is not always a good idea to have a low-voltage regulation, though-sometimes high-impedance and high-voltage regulation transformers are deliberately used to reduce the fault currents in a circuit.

Transformer Phasor Diagram:

$$\boldsymbol{E}_s = \boldsymbol{V}_s + \boldsymbol{I}_s R_{eq} + j\boldsymbol{I}_s X_{eq}$$







Phasor Diagram of the transformer while operating at no load

Phasor diagram of a transformer operating at a (a) lagging, (b) unity and (c) leading power factor

From the phasor diagrams, it is evident that voltage regulation is positive for lagging and unity power factor, whereas negative for leading power factor.

Efficiency:

Transformers are also compared and judged on their efficiencies. The efficiency of a device is defined by the equation

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{loss}} = \frac{P_{out}}{P_{out} + P_{core} + P_{Cu}} = \frac{V_s I_s cos\theta_s}{V_s I_s cos\theta_s + P_{core} + P_{Cu}}$$

An ideal transformer has zero copper loss and zero core loss. Therefore, efficiency of an ideal transformer is unity (100%). In case of real transformers, efficiency is commonly above 95% and in some cases can be as high as 99%.

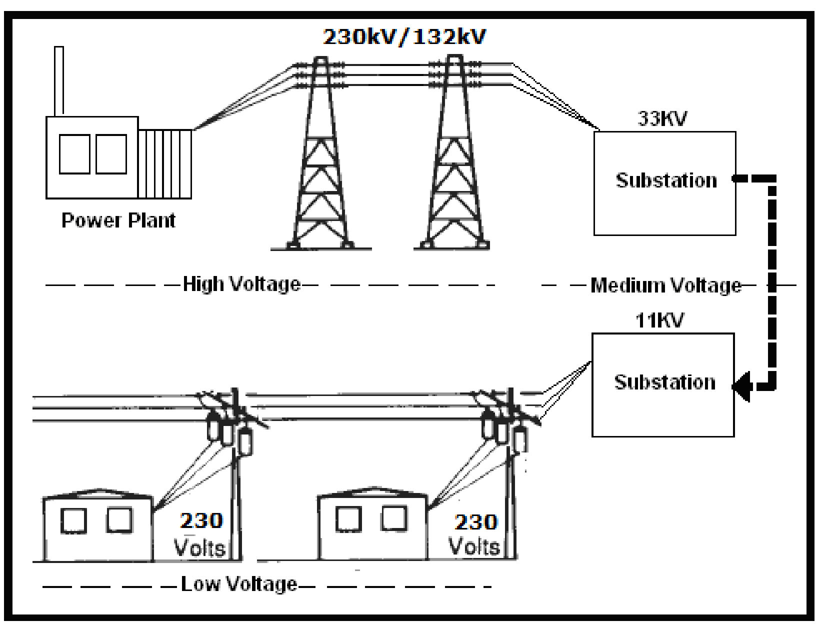
Applications of Transformer:

Power Transformer: Transformer plays an integral part in power distribution systems. The main purpose of using transformers is to reduce power loss and voltage drop in transmission line. Since the power loss is proportional to the square of line current, by rise of line voltage at the transmission end can significantly lower the power loss. Besides, the smaller current reduces the required conductor size, producing considerable cost savings. Without the transformer, the majority of the power generated would be lost on the transmission line and long-distance transmission would not be possible.

In a modern power system, electric power is generated at voltages of 12 to 25 kV. Transformers step up the voltage to between 110 kV and nearly 1000 kV for transmission over long distances at very low losses. Transformers then step down the voltage to the 12- to 34.5-kV range for local distribution and finally permit the power to be used safely in homes, offices, and factories at voltages as low as 120 V.

In Bangladesh, electric power is generated at voltages around 13 kV. It is then stepped up to 132 kV or 230 kV and transmitted through national grid. It is then stepped down in successive stages to 33 kV, 11 KV and finally to 400 V.

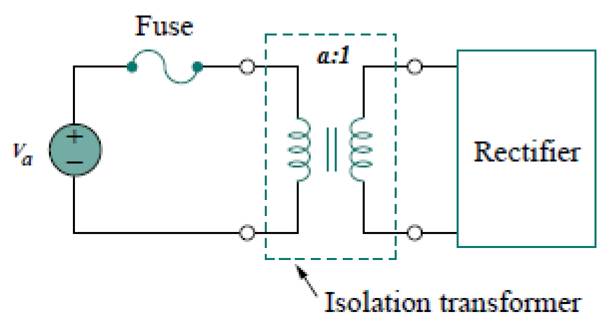
Residential users are given connections at 230V (1-phase) whereas for industrial consumers 3-phase supply is provided at 11 kV or 33 kV.



Isolation Transformer:

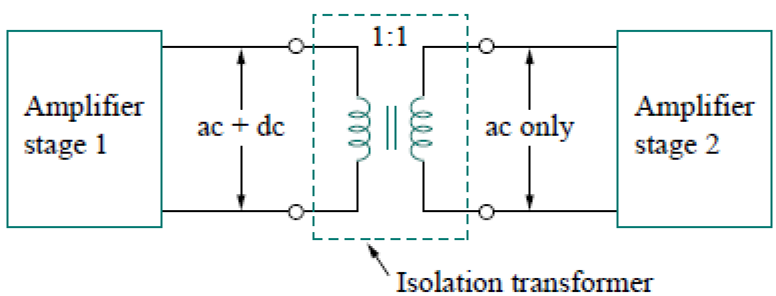
Electrical isolation is said to exist between two devices when there is no physical connection between them. In a transformer, energy is transferred by magnetic coupling, without electrical connection between the primary circuit and secondary circuit.

First, consider the circuit shown below. A rectifier is an electronic circuit that converts an ac supply to a dc supply. A transformer is often used to couple the ac supply to the rectifier. The transformer serves two purposes. First, it steps up or steps down the voltage. Second, it provides electrical isolation between the ac power supply and the rectifier, thereby reducing the risk of shock hazard in handling the electronic device.



A transformer used to isolate an ac supply from a rectifier.

A transformer is often used to couple two stages of an amplifier, to prevent any dc voltage in one stage from affecting the dc bias of the next stage. Biasing is the application of a dc voltage to a transistor amplifier or any other electronic device in order to produce a desired mode of operation. Each amplifier stage is biased separately to operate in a particular mode; the desired mode of operation will be compromised without a transformer providing dc isolation.

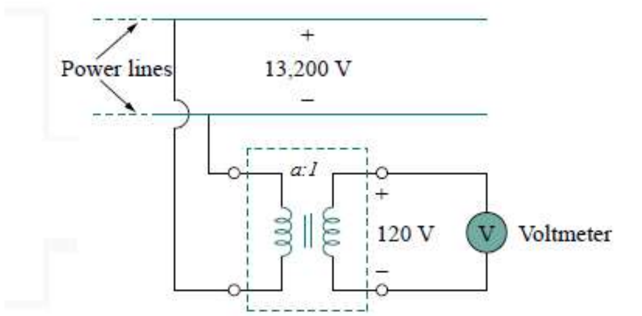


A transformer providing dc isolation between two amplifier stages.

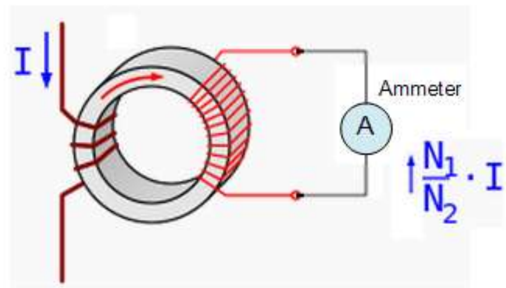
As shown in the figure above, only the ac signal is coupled through the transformer from one stage to the next. Transformers are used in radio and TV receivers to couple stages of high-frequency amplifiers. When the sole purpose of a transformer is to provide isolation, its turns ratio *a* is made unity. Thus, an isolation transformer has *a* = 1.

Instrument Transformer:

Generators in the power plant produce voltage in the range of 13.2 kV and then this voltage is raised to 230 kV or 132 kV for long distance transmission. It is obviously not safe to connect a voltmeter directly to such high-voltage lines. A transformer can be used both to electrically isolate the line power from the voltmeter and to step down the voltage to a safe level, as shown in the figure below. This transformer is called potential transformer or voltage transformer. Similarly, current transformers can be used to measure high line currents.



A potential transformer being used to sample and measure a high voltage

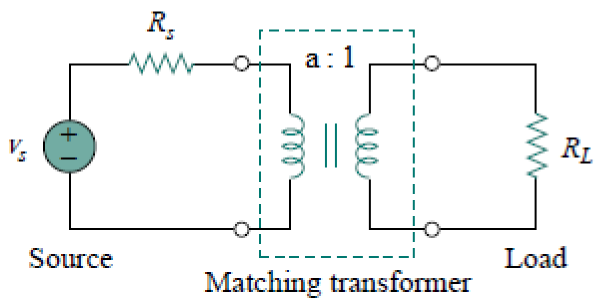


Current transformer being used to sample and measure a high current

Impedance Matching Transformer:

For maximum power transfer, the load resistance R_L must be matched with the source resistance R_S . In most cases, the two resistances are not matched; both are fixed and cannot be altered. However, an iron core transformer can be used to match the load resistance to the source resistance. This is called *impedance matching*.

For example, to connect a loudspeaker to an audio power amplifier requires a transformer, because the resistance of the speaker is very small compared to the internal resistance of the amplifier.



Transformer being used as a matching device.

The ideal transformer reflects its load back to the primary with a scaling factor of a^2.

Turns ratio of the desired matching transformer can be determined using the relation: $R_S = a^2 R_L$

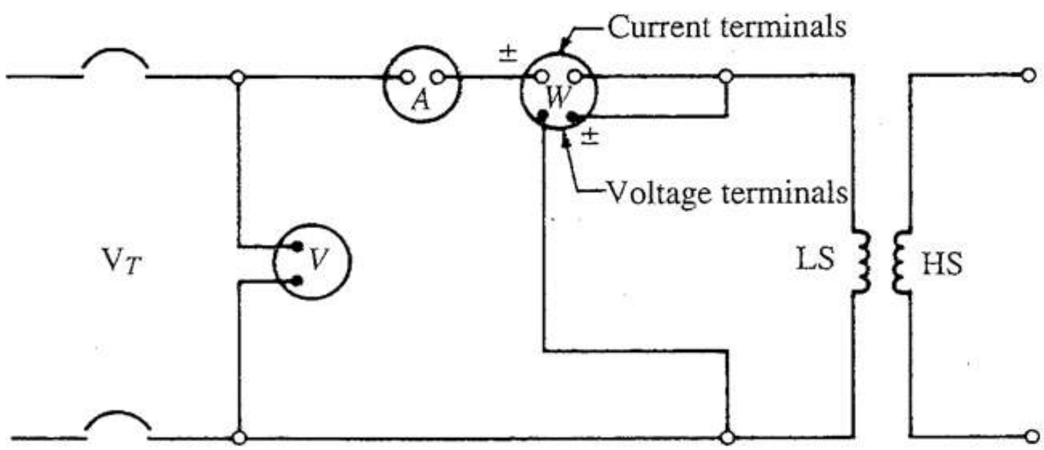
Therefore a step-down transformer ($a > 1$) is needed as the matching device when $R_S > R_L$, and a step-up ($a < 1$) is required when $R_S < R_L$.

Transformer Test

If transformer parameters are not readily available from the nameplate or from the manufacturer, they can be approximated from an open-circuit test (also called a no-load test) and a short circuit test.

Open Circuit Test

In the *open-circuit test,* a transformer's secondary winding is open-circuited, and its primary winding is connected to the full-rated line voltage at the rated frequency. The input voltage, input current, and input power to the transformer are measured using a voltmeter, an ammeter and a wattmeter respectively. For safety in testing and instrumentation, the open circuit test is generally made on the low-voltage side. To prevent accidental contact, the high side terminals should be covered with insulating material.



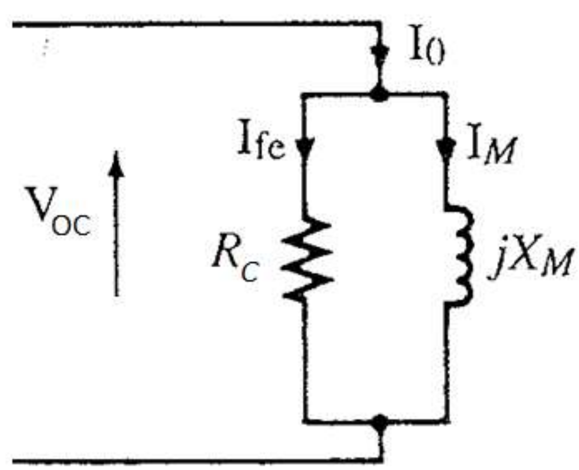
Connection for transformer open-circuit test.

Under the conditions described, all the input current must be flowing through the excitation branch of the transformer. The series elements R_p and X_p are too small in comparison to R_c and X_M to cause a significant voltage drop, so essentially all the input voltage is dropped across the excitation branch. Since the secondary is carrying no load, the copper losses in the secondary are zero, and the copper losses in the primary are negligible. Thus, the wattmeter reading for the open circuit test can be considered as the approximate core loss at rated condition.

$$R_c = \frac{V_{oc}^2}{P_{oc}}$$

$$X_m = \frac{V_{oc}^2}{Q_{oc}} = \frac{V_{oc}^2}{\sqrt{(V_{oc} I_{oc})^2 - P_{oc}^2}}$$

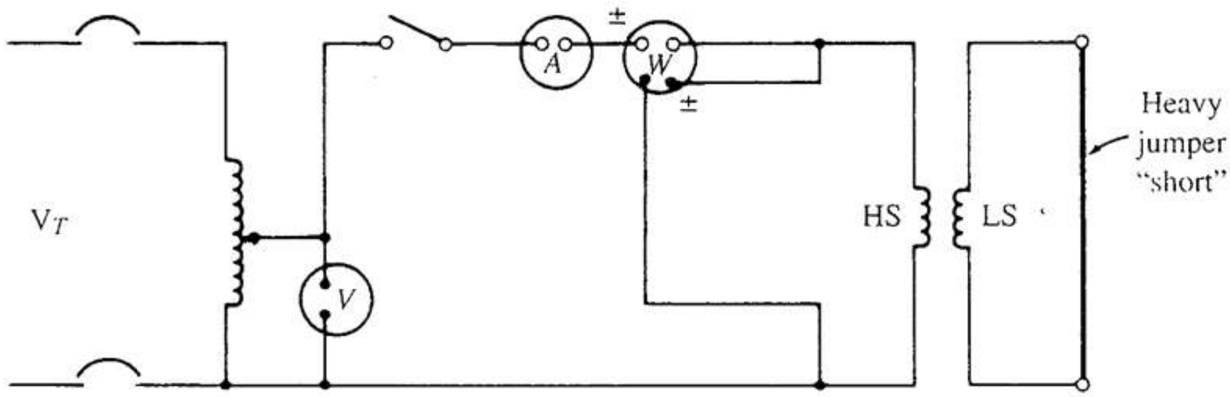
$$P_{core} \approx P_{oc}$$



Equivalent Circuit under open-circuit condition

Short Circuit Test:

In the *short-circuit test,* the secondary terminals of the transformer are short circuited, and the primary terminals are connected to the supply line through an adjustable-voltage autotransformer. The input voltage is adjusted until the current in the short circuited windings is equal to its rated value. Short circuit test can be performed using either winding. For reasons of lower current input and meter sizing, the high voltage winding is preferred.



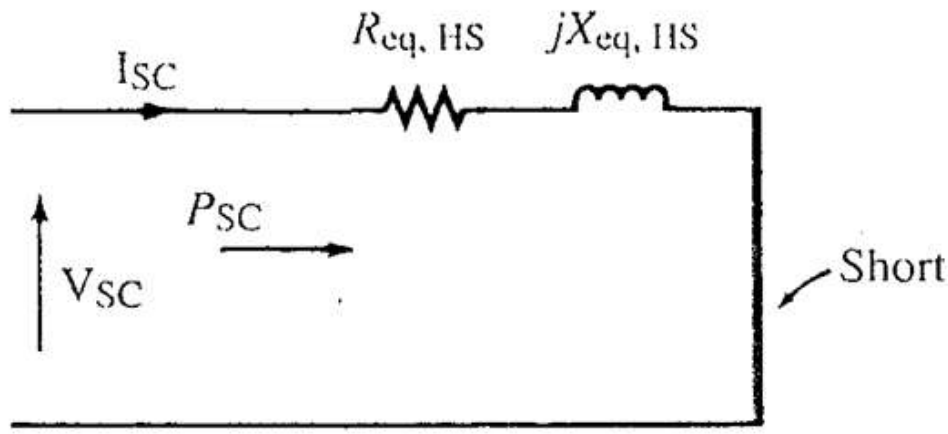
Connection for transformer short-circuit test.

Since the input voltage is so low during the short-circuit test, negligible current flows through the excitation branch. If the excitation current is ignored, then the entire voltage drop in the transformer can be attributed to the series elements in the circuit. Short circuiting the secondary causes the flux density to be reduced to a very low value, making the core losses insignificant. Thus the wattmeter reading for the short circuit test can be considered as an approximate value of copper loss at rated condition.

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2}$$

$$X_{eq} = \frac{Q_{sc}}{I_{sc}^2} = \frac{\sqrt{(V_{sc}I_{sc})^2 - P_{sc}^2}}{I_{sc}^2}$$

$$P_{Cu} \approx P_{sc}$$



Equivalent Circuit of the transformer under short circuit condition