Lecture Notes
ME 269

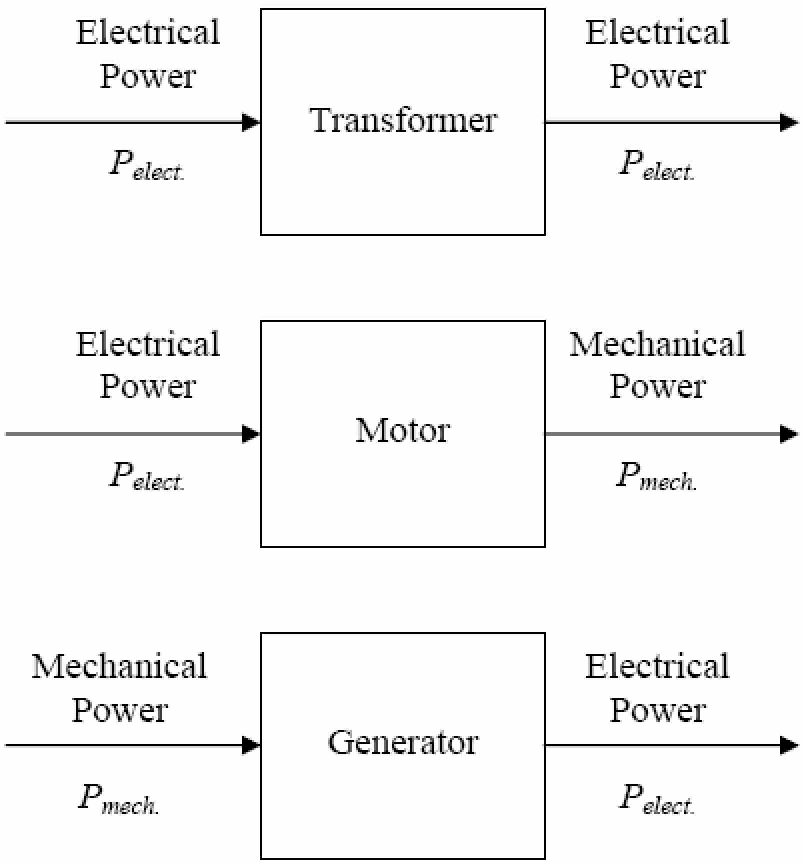
Chapter 7

Transformers

Ali Naderian

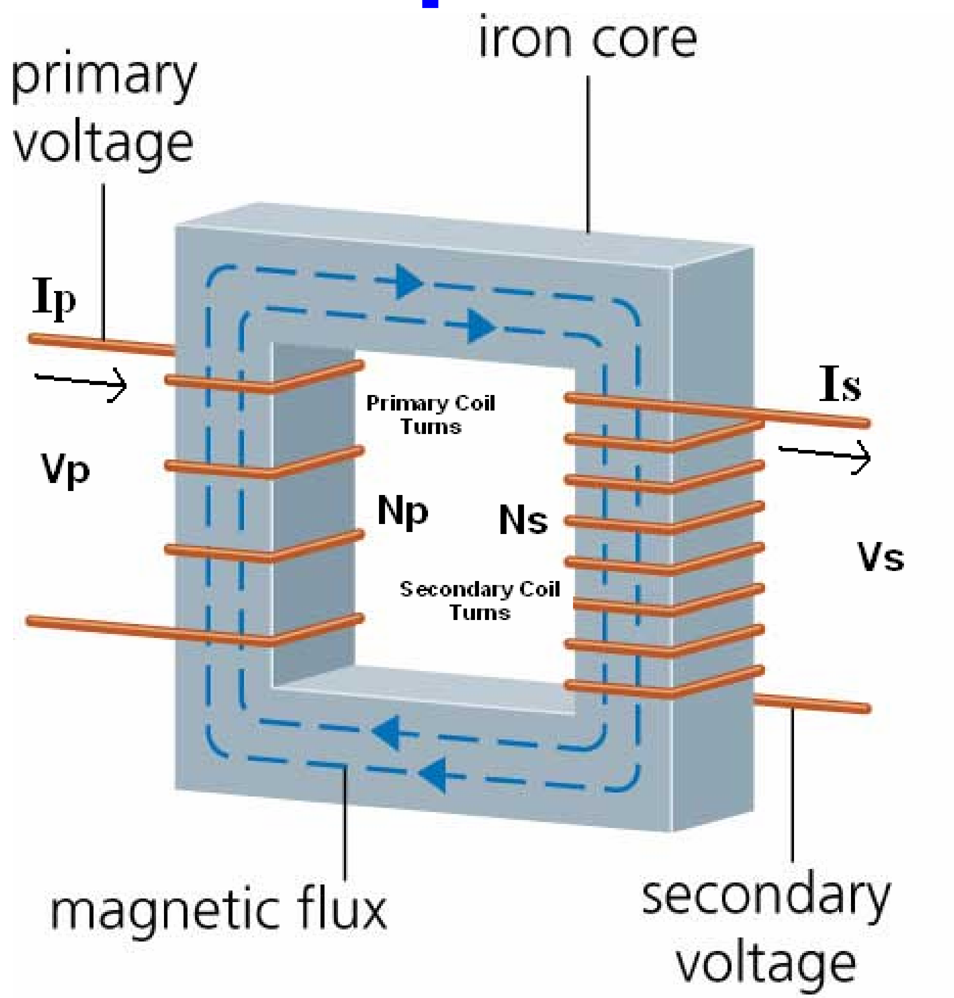
Transformer

- A transformer is a stationary electric machine which transfers electrical energy (power) from one voltage level to another voltage level.
- Unlike in rotating machines, there is no electrical to mechanical energy conversion .
- A transformer is a static device and all currents and voltages are AC.
- The transfer of energy takes place through the magnetic field.



Transformer Principles

- It has 2 electric circuits called *primary* and *secondary.*
- A magnetic circuit provides the link between primary and secondary.
- When an AC voltage is applied to the primary winding (Vp)of the transformer, an AC current will result (Ip). Ip sets up a time-varying magnetic flux φ in the core.
- A voltage is induced to the secondary circuit (Vs) according to the Farday's law.

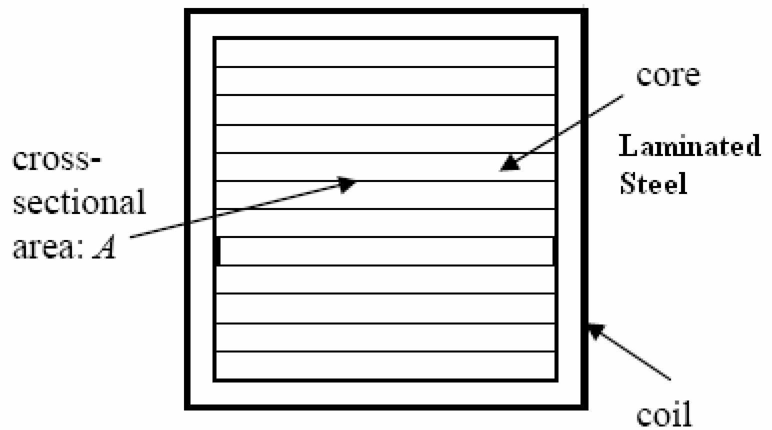


Transformer Core Types

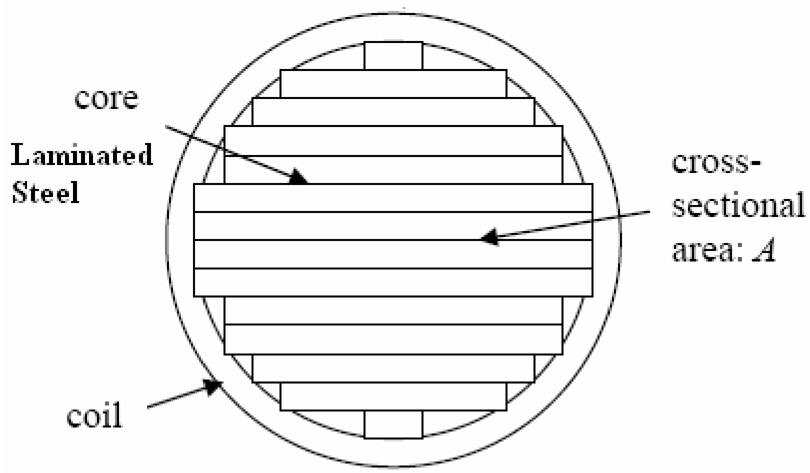
- The magnetic (iron) core is made of thin laminated steel.
- The reason of using laminated steel is to minimizing the eddy current loss by reducing thickness (t):

$$Pe = kh\,(Bmax\ t\,f)^{2}$$

- 2 common cross section of core is square or rectangular) for small transformers and circular (stepped) for the large and 3 phase transformers.



(a) Square core



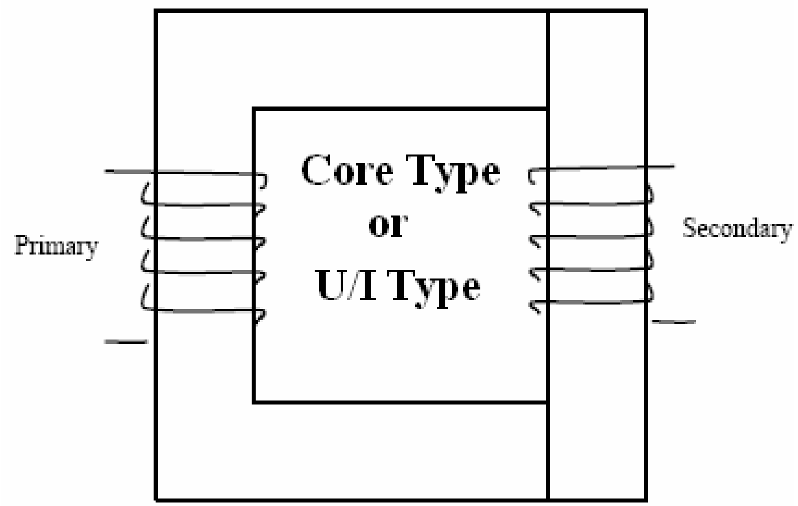
(b) Stepped core

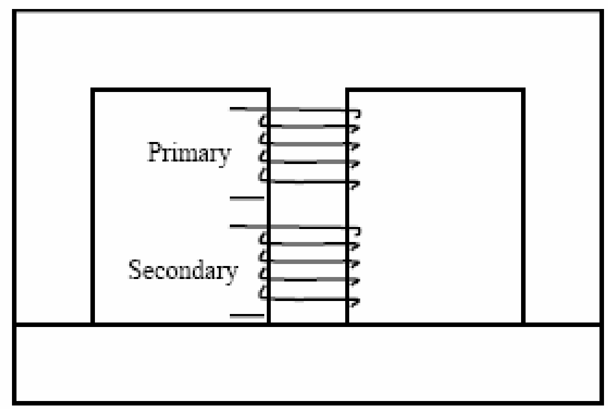
Transformer Construction

2 Type of Transformers:

- **1- Core (U/I) Type:** is constructed from a stack of U- and I-shaped laminations. In a core-type transformer, the primary and secondary windings are wound on two different legs of the core.

- **2- Shell Type:** A shell-type transformer is constructed from a stack of E- and I-shaped laminations. In a shell-type transformer, the primary and secondary windings are wound on the same leg of the core, as concentric windings, one on top of the other one.

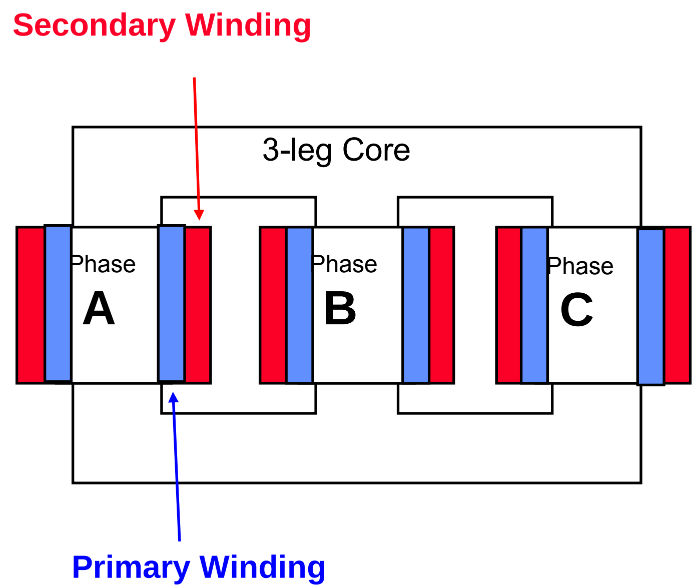




Shell Type or E/I type

3 Phase Transformer

- The three phase transformer iron core has three legs.
- A phase winding is placed in each leg.
- So, each leg has 2 sets of winding : Primary and Secondary. They are placed on top of each other and insulated by layers or tubes.



- **All the 3 legs have the same primary coil turns ($N_{pA}=N_{pB}=N_{pC}$). The 3 secondary winding have aslo the same coil turns($N_{sA}=N_{sB}=N_{sC}$). Otherwise the induced voltage is unbalanced.**

Ideal Transformer

- **Induced Voltages:**

  The induced emf in primary winding is:

  $$E_p = 4.44\ N_p\ \Phi_m\ f,$$

  where N_p is the number of winding turns in primary winding, Φ_m, the maximum (peak) flux, and f the frequency of the supply voltage.

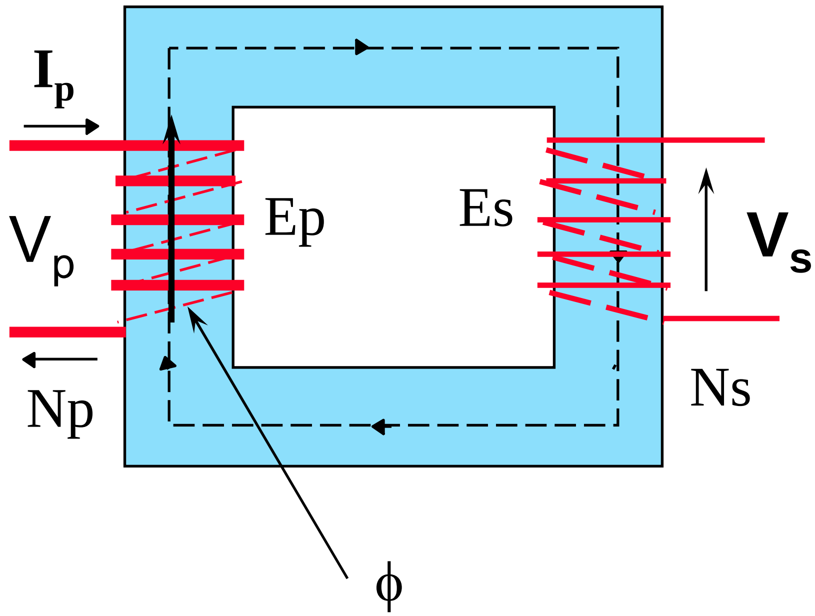
- Similarly, the induced emf in secondary winding:

  $$E_s = 4.44\ N_s\ \Phi_m\ f,$$

- where N_s is the number of winding turns in secondary winding.

- **Turns Ratio, a** = $E_p/E_s = N_p/N_s$

Voltage generation



Ideal Transformer

- **If the transformer is ideal,**

  Pin=Pout

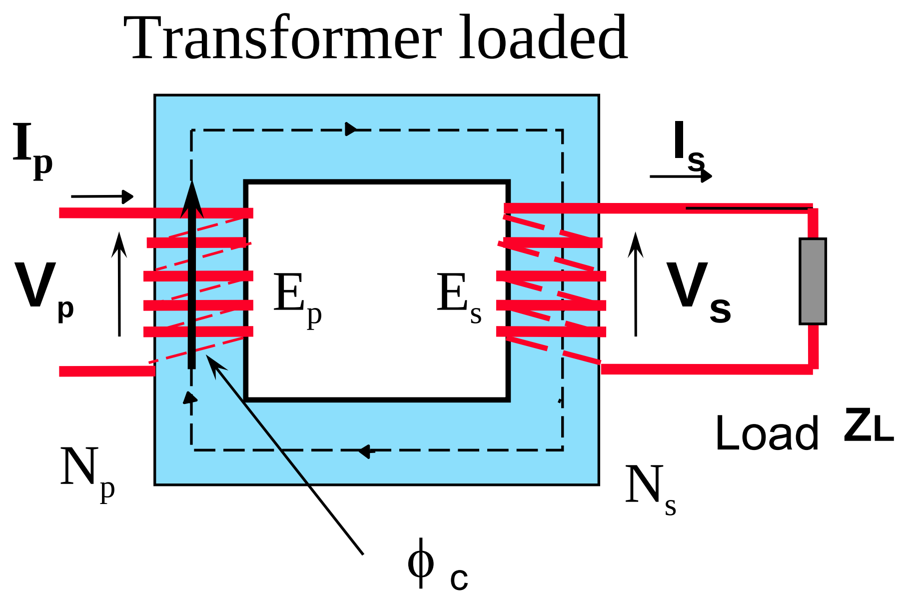
  (Input power = Output power).

- Assuming the power factor to be same on both sides,

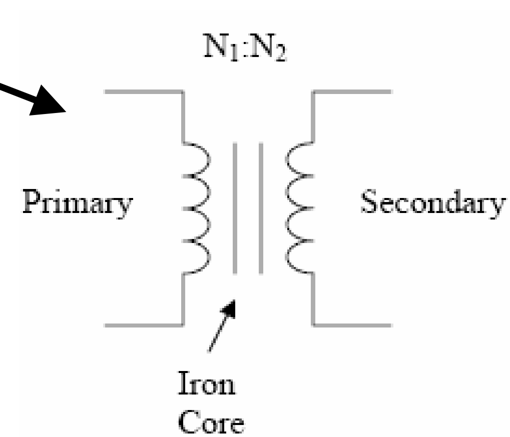
$$V_p I_p = V_s I_s$$

Hence, $N_p/N_s = V_p/V_s = I_s/I_p = a$

Note that in transformers, subscripts “1” and “p” are used interchangeably for the primary-side quantities. Also, subscripts “2” and “s” are used interchangeably for the secondary-side quantities.

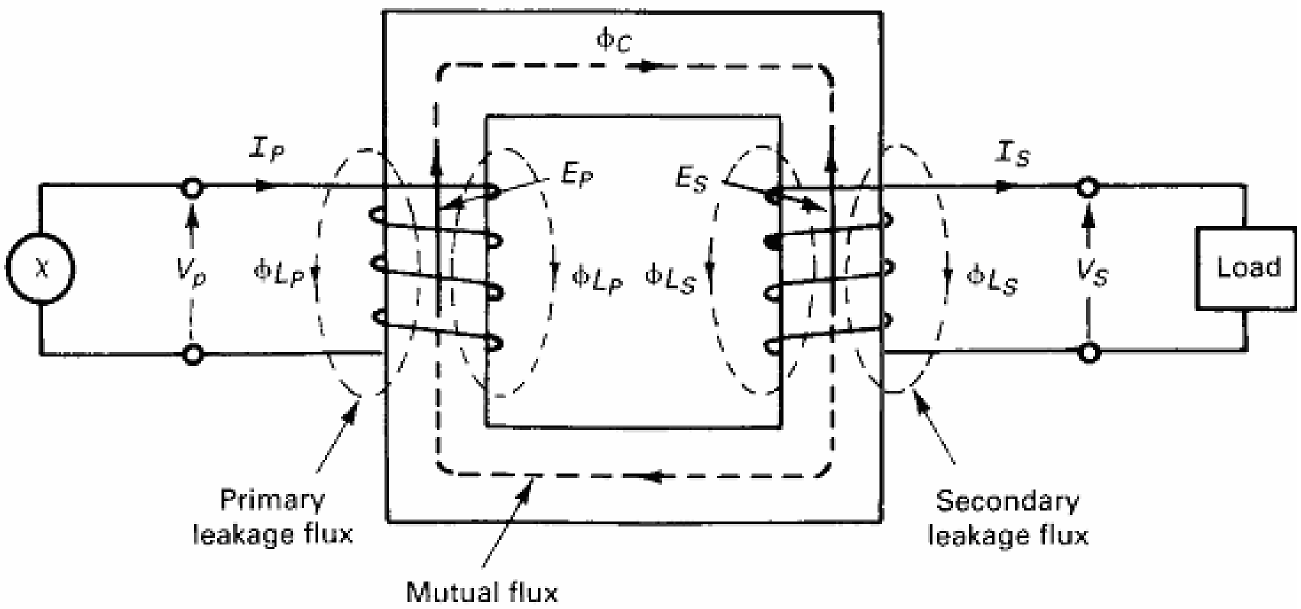


Symbol Circuit Of a transformer



Real Transformer

- **<u>Leakage Flux</u>: Not all of the flux produced by the primary current links the winding, but there is leakage of some flux into air surrounding the primary. Similarly, not all of the flux produced by the secondary current (load current) links the secondary, rather there is loss of flux due to leakage. These effects are modelled as leakage reactance in the equivalent circuit representation.**



Equivalent Circuit of a Real Transformer

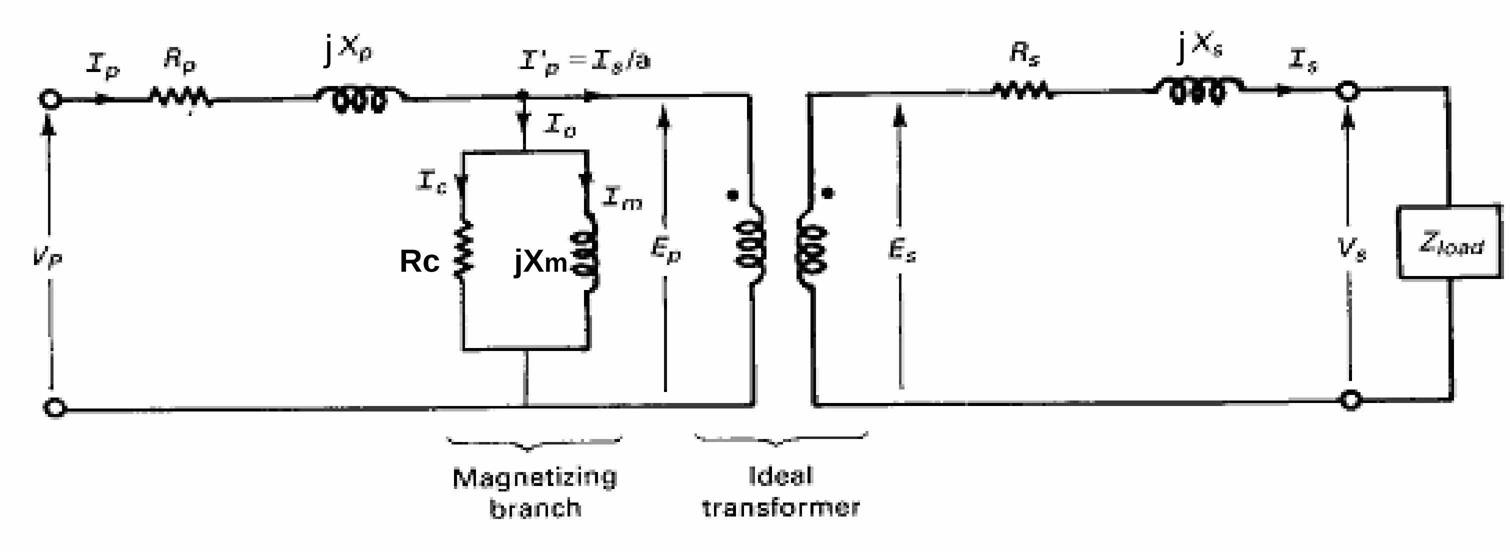
Equivalent Circuit of a Two-winding, 1-phase, Transformer:

R_c :core loss component, This resistance models the active loss of the core

X_m : magnetization component, This reactance models the reactive loss of the core

R_p and X_p are resistance and reactance of the primary winding

R_s and X_s are resistance and reactance of the secondary winding



Real Transformer

- **Impedance Transfer:**

  To model a transformer, it is important to understand how impedance are transferred from one side to another, that is primary to secondary or secondary to primary. Impedance transfer helps to calculate the current/voltage easier and get ride of the ratio for the rest of the calculation.

- Looking into the circuit from source side, let us define the impedance as $Z_{in} = V_p/I_p$
- Looking into the circuit from load side (neglecting the load itself), let us define the impedance as $Z_L = V_s/I_s$
- Relating V_p/I_p in terms of V_s/I_s using the turns ration, a,

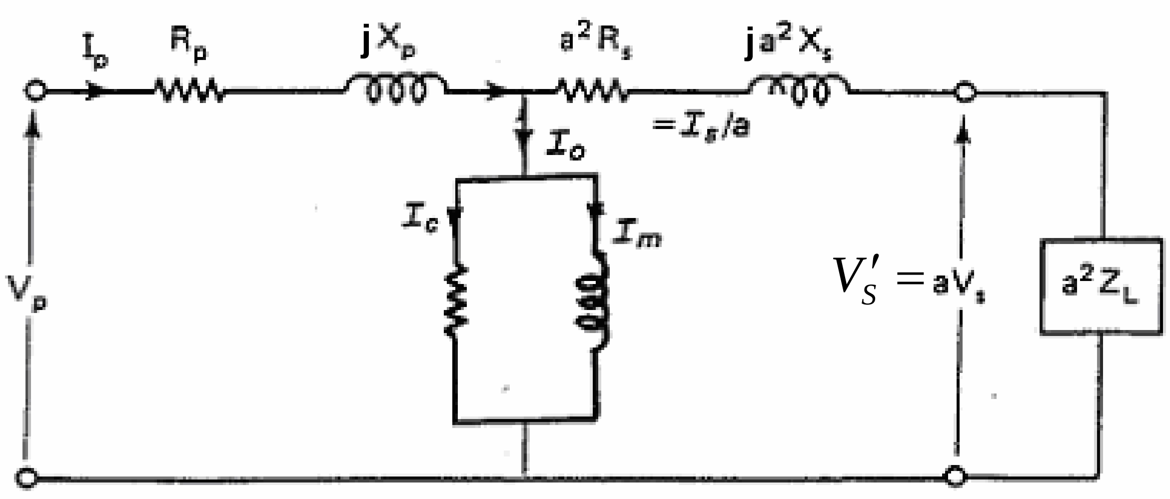
$$[V_p/I_p] = a^2 [V_s/I_s]$$

$$Z_{in} = a^2 Z_L$$

Hence, in general, any impedance transferred from secondary side to primary side must be multiplied by the square of the turns-ratio, a^2.

Real Transformer

Equivalent Circuit - seen from primary side



Secondary parameters transferred to primary

The terminal voltage (Vp, Vs) is not constant and changes depends on the load current.

Example 1

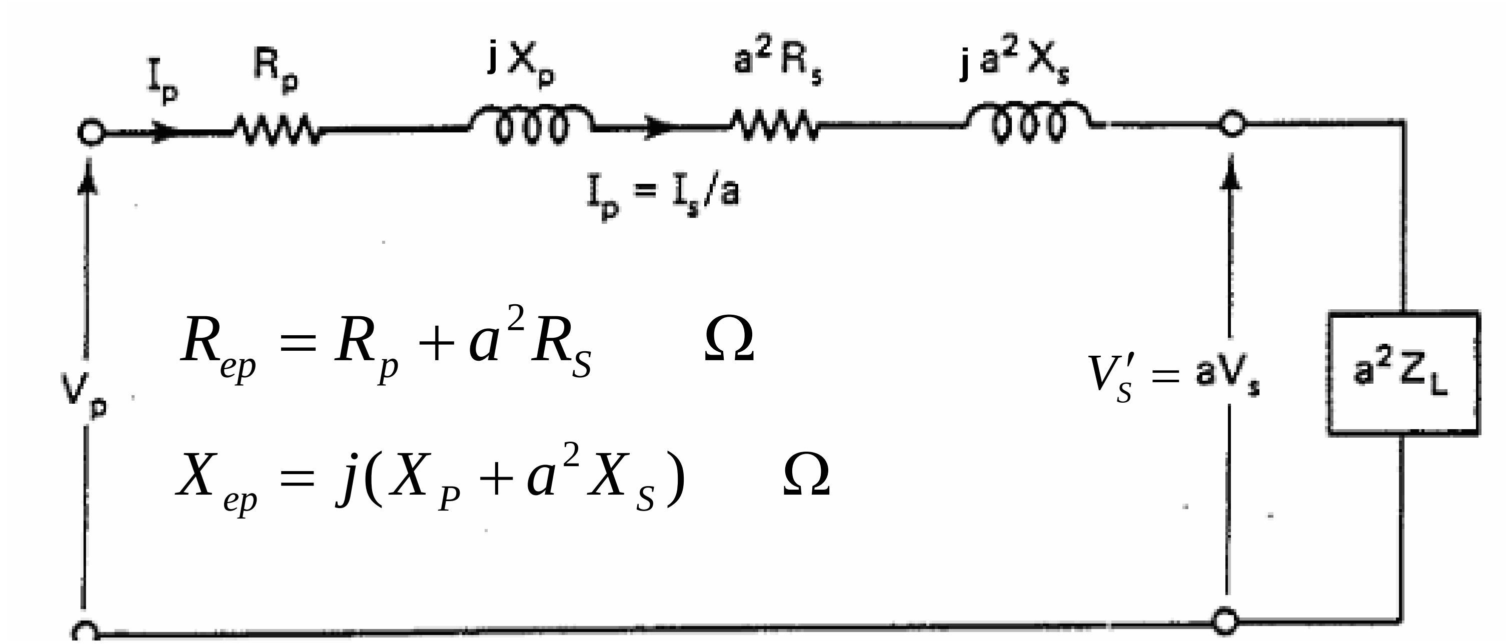
- A Single phase 20 KVA, 2400 / 240 V, 60 Hz transformer has the following parameters:

Rp = 0.8 Ω, Xp= 3 Ω, Rs = 0.008 Ω, Xs = 0.03 Ω, R_s = 0.04 Ω and X_s = 0.08 Ω, Xm= 400 Ω, Rc=1500 Ω

The transformer delivers 20 kW at 0.8 pf lagging to a load on the low voltage side. Find the equivalent circuit referred to the primary and draw the equivalent circuit and phasor diagram.

Approximate circuit
Neglecting Core Loss

Approximate Simplified Equivalent Circuit - seen from primary side



KVL : $V_p = (R_{ep} + jX_{ep} + a^2 Z_L) I_P$

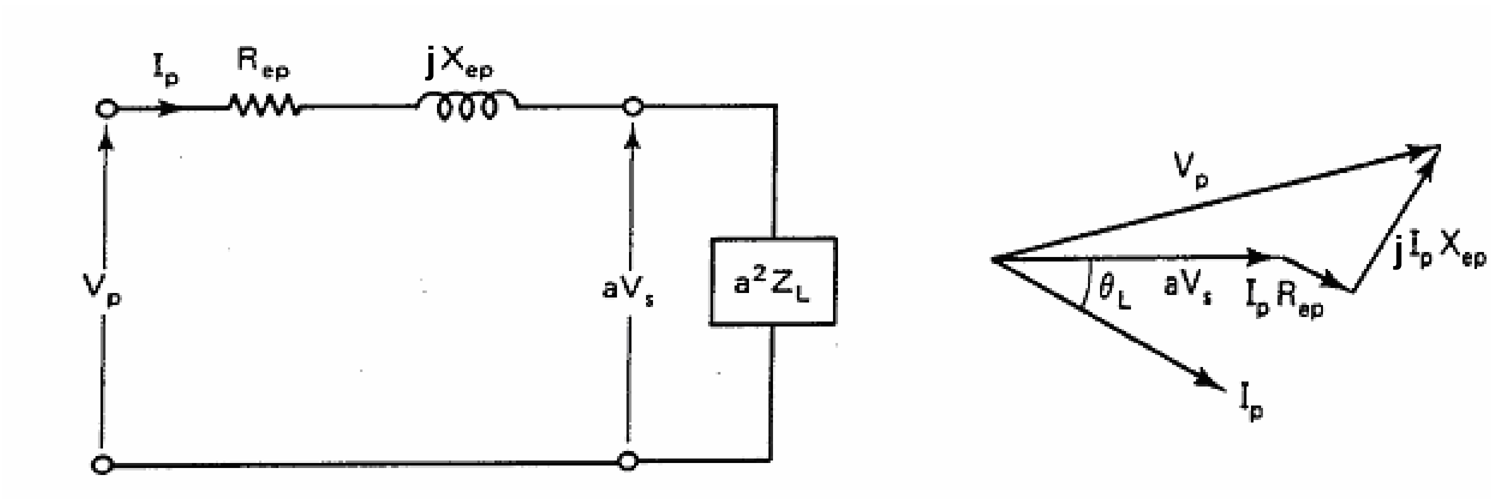
Equivalent Circuit

In this model, the parameters from secondary are transferred to primary side.

$R_{ep} = R_p + a^2 R_s$

$X_{ep} = X_p + a^2 X_s$

where, R_{ep} and X_{ep} are equivalent resistance and reactance from primary winding side.



Voltage Regulation

$$\%VR = \frac{V_{NL} - V_{FL}}{V_{NL}} \times 100 =$$

= $(V_p - aV_s) \times 100 / aV_s$

= $(V_p - V'_s) \times 100 / V'_s$

Note: The primary side voltage is always adjusted to meet the load changes; hence, V'_s and V_s are kept constant. There is no source on the secondary side

Efficiency of Transformers

As always, efficiency is defined as power output to power input ratio.

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

$P_{in} = P_{out} + P_{core} + P_{copper}$

P_{copper} represents the copper losses in primary and secondary windings. There are no rotational losses.

Example 2

Example: a 150 kVA, 2400/240 V transformer has the following parameters referred to the primary:

Rep = 0.5 Ω, Xep = 1.5 Ω, the shunt magnetizing branch is very large and can be neglected. At full load, the transformer delivers rated kVA at 0.85 p.f. lagging and the secondary voltage is 240 V. Calculate:

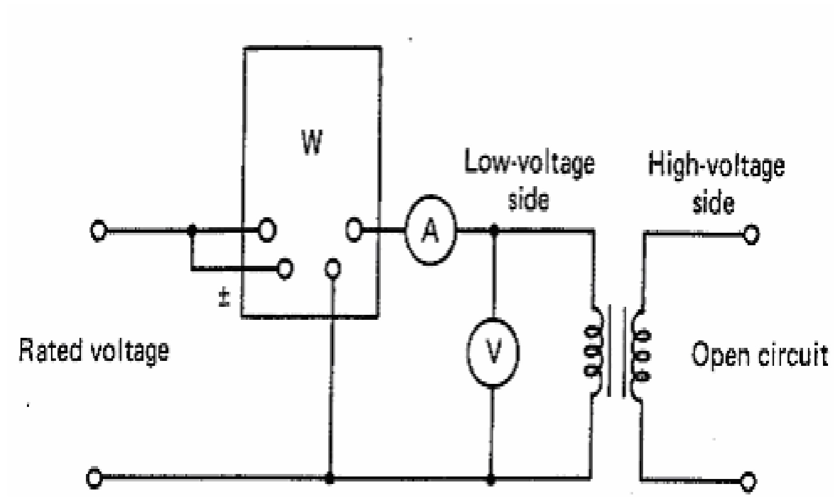
1. The voltage regulation
2. The efficiency assuming core loss = 600 W.

Real Transformer

Equivalent circuit parameters

- **Open Circuit Test:** Secondary (normally the HV winding) is open, that means there is no load across secondary terminals; hence there is no current in the secondary.
- Winding losses are negligible, and the source mainly supplies the core losses, P_{core}.
- **Parameters obtained:** Test is done at rated voltage with secondary open. So, the ammeter reads the no-load current, I_o; the wattmeter reads the core losses, and the voltmeter reads the applied primary voltage.

Open circuit test

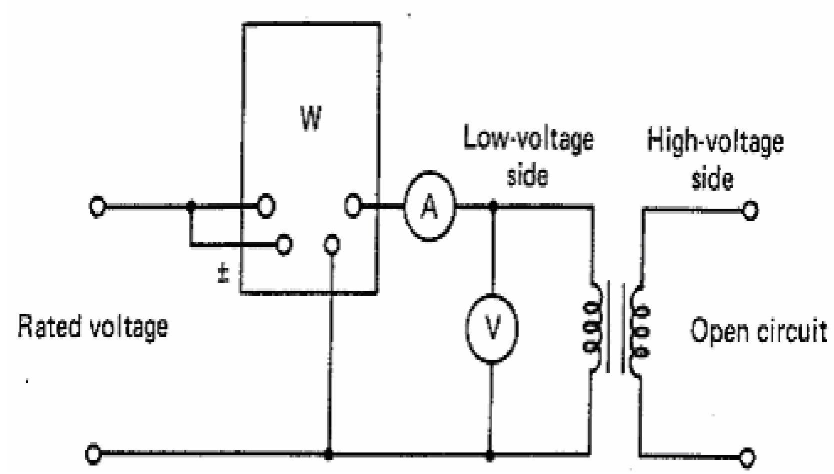


Real Transformer

Equivalent circuit parameters

- Wattmeter reading = P_{oc} = P_{core}
- Hence, $R_{c\,(LV)} = V^2_{(LV)}/P_{oc}$
- Note: The open circuit test was done by energizing the LV (low voltage) side with secondary (HV) open.
- Once, $R_{c(LV)}$ is known, X_m can be found as follows.
- $I_{c(LV)} = V_{(LV)}/R_{c(LV)}$
- But, Ammeter reading = I_o.
- Therefore, $\mathbf{I}_{m(LV)} = \mathbf{I}_o - \mathbf{I}_{c(LV)}$
- $X_m = V_{(LV)}/I_{m(LV)}$

Open circuit test



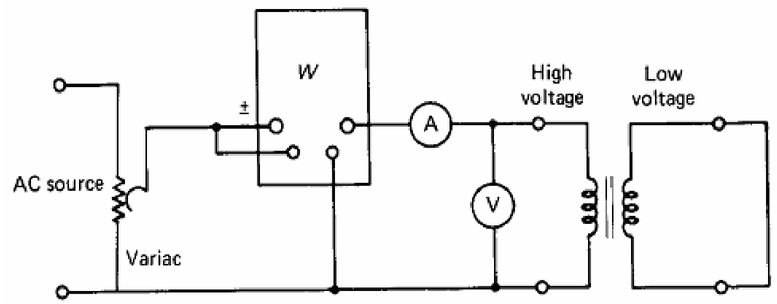
Real Transformer

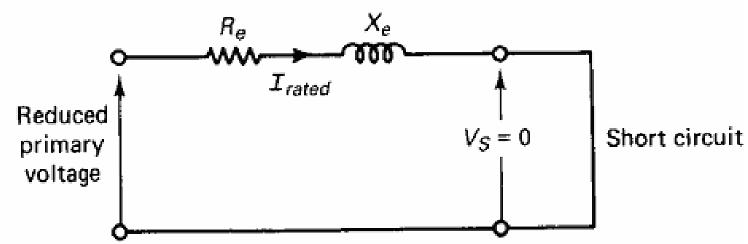
Equivalent circuit parameters

- Secondary (normally the LV winding) is shorted, that means there is no voltage across secondary terminals; but a large current flows in the secondary.

- **Parameters obtained: Test is done at reduced voltage (about 5% of rated voltage) with full-load current in the secondary. So, the ammeter reads the full-load current, Ip; the wattmeter reads the winding losses, and the voltmeter reads the applied primary voltage.**

Short- circuit test



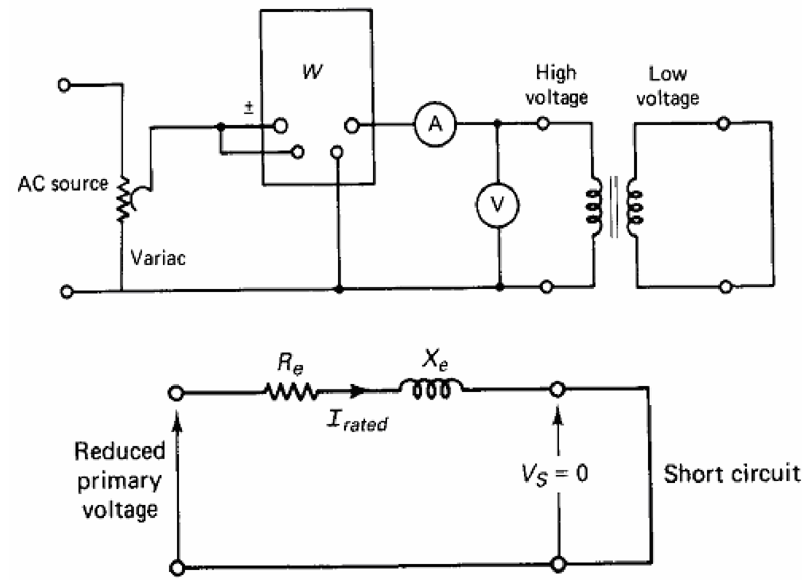


Real Transformer

Equivalent circuit parameters

Short- circuit test

- Core losses are negligible as the applied voltage is << rated voltage.
- $Rep = P_{sc}/I^2_{sc}$
- But, $Z_{ep}(HV) = V_{sc}(HV)/I_{sc}$ hence, $X_{ep}(HV)$ can be obtained



Transformer Types Based on Windings Turns Ratio (a)

Based on the value of the turns-ratio *a*, 3 different types of transformer are commercially available:

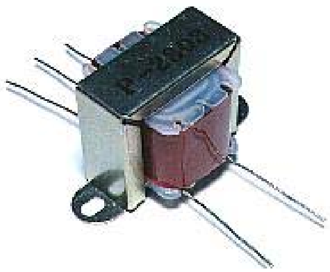
1. $a > 1 \Rightarrow E_s < E_p \Rightarrow$ Step-Down Transformer
2. $a < 1 \Rightarrow E_s > E_p \Rightarrow$ Step-Up Transformer
3. $a = 1 \Rightarrow E_s = E_p \Rightarrow$ Isolation Transformer

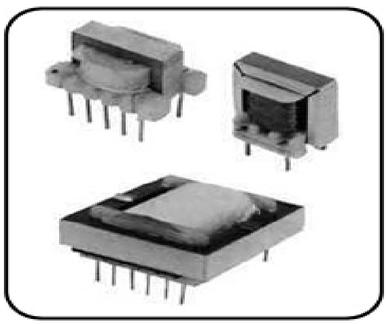
1- Step-down Transformer

Applications :

- **Electrical distribution networks (to reduce the voltage from medium voltage (10,000 V – 30,000 V) to low voltage (110 V or 208 V) for different costumers.**

- **To reduce the plug voltage (110 V) to lower voltages in electronic equipments/ circuits such as radio, phone, lap top, adaptors, … .**





Distribution Transformers used by Hydro companies to deliver the electric energy

2- Step-Up Transformer

- **A step-up transformer is one whose secondary voltage is greater than its primary voltage.**

Applications :

- **Power plants to increase the generated voltage and send it to high voltage transmission lines.**

- **To increase the voltage in order to get higher electrical field (TVs, Radar and Microwaves,**