EE 101
Electrical Sciences

Department of Electronics & Electrical Engineering

Lectures 15-16

Transformers

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INTRODUCTION

- It is one of the most common component in electrical systems and it is primarily used to change the voltage level from one level to another as required.
- The simplest transformer consists of two coils wound on a common magnetic core which are coupled by a common magnetic field as shown schematically in Figure 4.1.

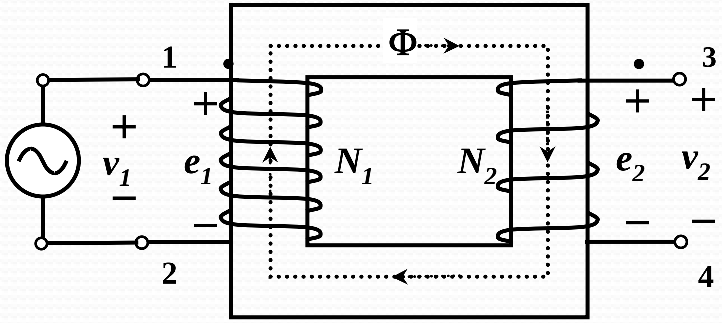


Figure 4.1 Basic features of a transformer

- The two coils are generally referred to as, (i) the primary winding, and (ii) the secondary winding. A time varying current produced by a time varying voltage connected one winding establishes a time varying flux in the coil. The flux links the secondary winding inducing a voltage in the secondary winding. When the transformer is used to obtain a higher output voltage than the input it is called a ‘Step up transformer’, and when the output voltage desired is lower than the input voltage it is termed “Step down transformer”.

IDEAL TRANSFORMER

It is simpler to understand the operating principle of transformers under ideal conditions. The ideal condition assumptions are:

- The windings have negligible resistance which implies that there are no copper losses in the windings and there are no voltage drops.
- All the flux created in the core is confined the core and therefore the same flux links both the windings.
- The permeability of the core is infinitely high, which implies that a vanishingly small mmf (current) is required to set up the flux φ in the core.
- The core does not incur any hysteresis or eddy current loss.

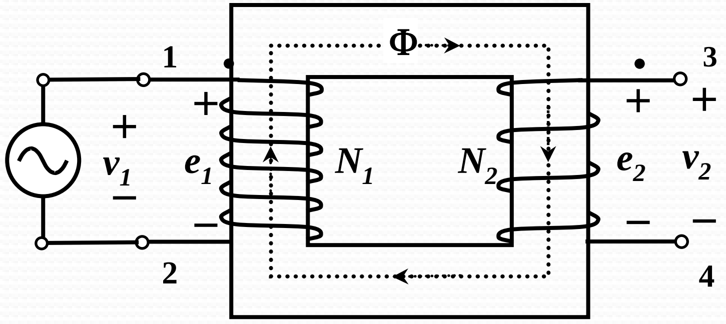


Figure 4.1 Basic features of a transformer

IDEAL TRANSFORMER RELATIONSHIPS

- Consider an ideal transformer with these properties as shown in Figure 4.3, where the flux φ created in the core links both the coils.
- If the number of turns in the two windings be N_1 and N_2, then Faraday's Law applied to the two windings gives,

$$v_1 = e_1 = N_1 \frac{d\varphi}{dt}$$

$$v_2 = e_2 = N_2 \frac{d\varphi}{dt}$$

$$\frac{v_1}{v_2} = \frac{e_1}{e_2} = \frac{N_1}{N_2} = a \text{ (say)}$$

a, is called the turns ratio.

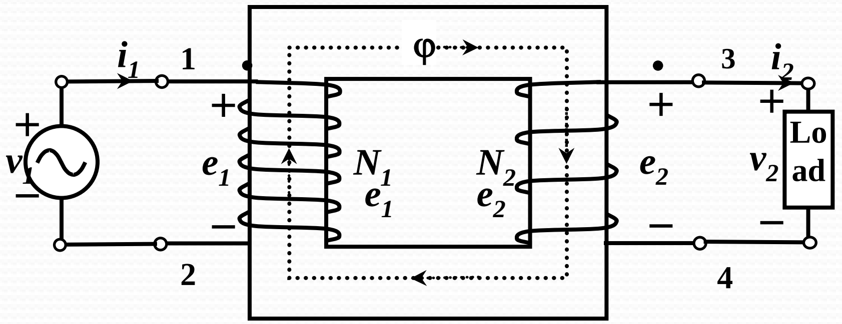


Figure 4.3 Schematic of an ideal transformer

- As the core material is ideal, the total mmf required to create the flux would be vanishingly small, so that

$$N_1 i_1 - N_2 i_2 = 0 \quad \Rightarrow \quad N_1 i_1 = N_2 i_2 \quad \Rightarrow \quad \frac{i_2}{i_1} = \frac{N_1}{N_2} = a$$

IDEAL TRANSFORMER RELATONSHIPS

- Expressing these equations in effective or RMS quantities,

$$\frac{V_1}{V_2} = a, \quad \frac{I_2}{I_1} = a, \quad \text{and,} \quad V_1 I_1^* = V_2 I_2^* \quad (\text{also } V_1 I_1 = V_2 I_2)$$

- Therefore an ideal transformer connected to a source on one side and a load on the other side can be schematically represented as shown in Figure 4.4, where,

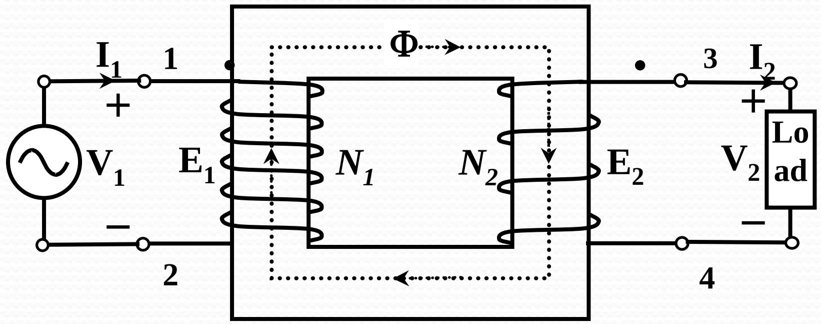
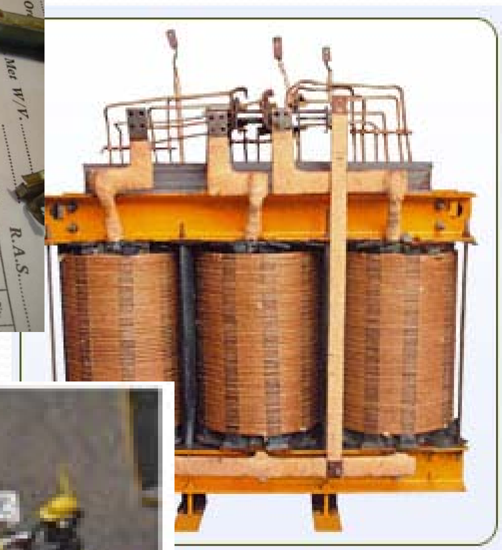


Figure 4.4 Polarity analysis (dot convention)

CONSTRUCTION

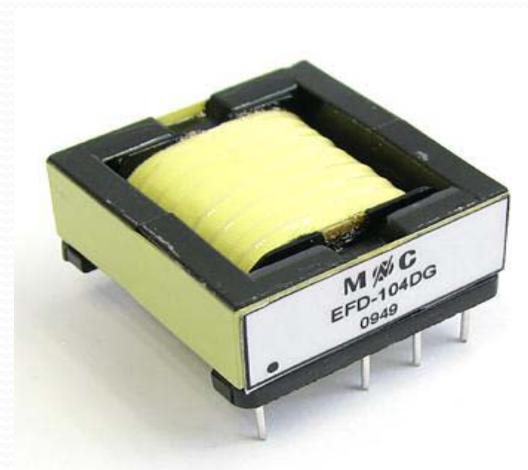
- *Core*: Laminated Silicon Steel,
  Shell type or Core type, etc.
- *Coils*: Disk, Drum, etc.



CONSTRUCTION

The basic features of a simple transformer are seen in the following pictures where the main components are:

- *Tank*: Oil, Cooling System (radiator, fans, etc), Breather, etc.
- *Connections*: Bushings or Cable head
- Miscellaneous: tap changers, protection gear, etc.



TRANSFORMER POLARITY: DOT CONVENTION

- The polarity of the transformer windings depends on the winding directions, which cannot be seen real transformers, where they will be hidden in the tank. To overcome this problem, terminals of similar polarity, are marked by similar "dots" outside the transformer body.
- The practice of marking the terminals is known as "***Dot-convention***".
- The dot convention provides two very useful rules:
  - The terminals marked by similar "dots" will have the same polarity.
  - It should also be seen from the above analysis that, if the current enters the dotted terminal of transformer winding on one side, the current has to come out of the dotted terminal on the other side.
- With these two rules, it is no longer necessary to include the core or the directions of the two windings in order to find the polarity of transformer terminals. Then the transformer can be represented by a much simpler representation as shown.

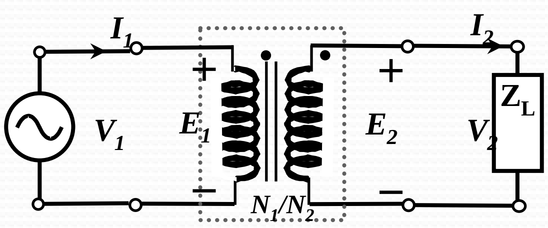


Figure 4.5 Schematic diagram of a transformer with polarity dots

REFERRING AND REFERRED VALUES

- Consider the ideal transformer of Figure 4.6
- For a voltage V_2 in the secondary side of the transformer, the primary voltage will be: $V_1 = aV_2 \;= V_2'$ (say)
- And, for a current I_2 in the secondary side the current in the primary will be: $I_1 = I_2/a \;= I_2'$ (say)

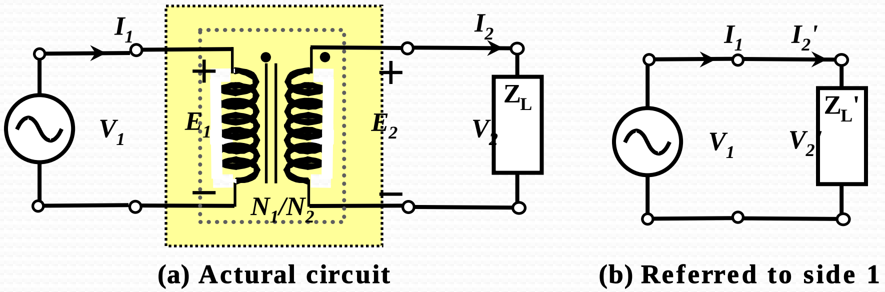


Figure 4.6 Referring in transformer circuits

- V_2', and I_2' are called the referred values of V_2 and I_2 referred to the primary side.
- If Z_2 be the load impedance on the secondary side, then, in the primary side the impedance will appear to be:

$$Z_1 = \frac{V_1}{I_1} = \frac{aV_2}{I_2/a} = a^2\frac{V_2}{I_2} = a^2 Z_2 = Z_2' \text{ (say)}$$

Z_2' is the referred value to Z_2 referred to the primary side.

REFERRING AND REFERRED VALUES

- Transformer circuit of Figure 4.6(a) can be analyzed by using a simpler circuit shown in Figure 4.6 (b) which does not contain any transformer per se. This process of simplifying the circuit is called "*referring*" and Figure 4.5 (b) called the circuit of Figure 4.5 (a) referred to side 1 (primary).

$$V_1 = aV_2 \quad = V_2' \text{ (say)}$$

$$I_1 = I_2/a \quad = I_2'$$

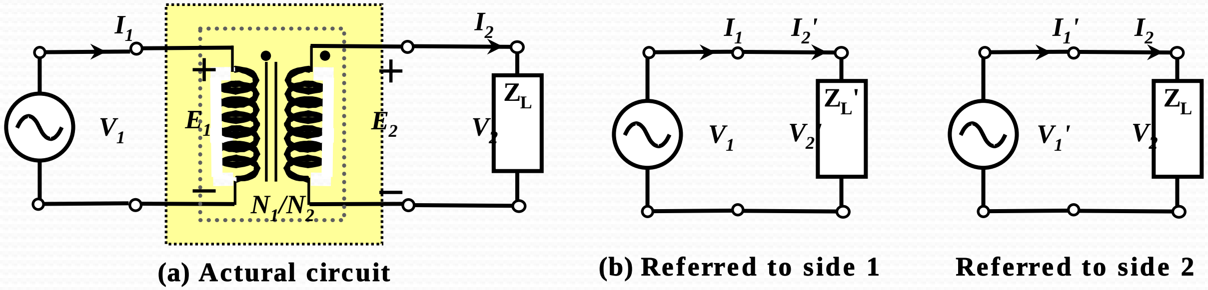


Figure 4.6 Referring in transformer circuits

- Similarly, the transformer circuit referred to the secondary side can be drawn as shown in Figure 4.6 (c), which can be used to analyze the transformer circuit.

EXAMPLE

An ideal transformer has 150 turns on the primary and 750 turns on the secondary. The primary is connected to a 240-V 50 Hz source. The load connected at the secondary side has an impedance of 240+j180 Ω.

Draw the schematic diagram of the transformer circuit and determine, (a) the turns-ratio, (b) the secondary voltage, (c) the power supplied to the load, (d) the current on the primary side, and (e) flux in the core.

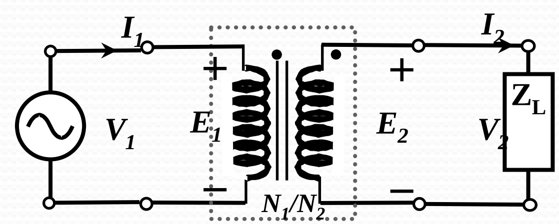


Figure 4.7(a). Schematic diagram of the transformer

Solution: The schematic circuit diagram is shown in Figure 4.7 (a):

The turns ratio, $a = 150/750 = 0.2$

Since, $V_1 = 240$ V, $\Rightarrow$ $V_2 = V_1/a = 240/0.2 = 1200$ V

Let $V_2 = 1200\angle 0^\circ$ V, Then $I_2 = V_2/Z_2 = 1200\angle 0^\circ/(240+j180)$

$= 1200\angle 0^\circ/(300\angle 36.87^\circ) = 4\angle -36.87^\circ$ A

Therefore power supplied, $= V_2\, I_2 \cos\varphi = 1200\times 4\times 0.8 = 3840$ W

Since, $I_2 = 4$ A, $\Rightarrow$ $I_1 = I_2/a = 4/0.2 = 20$ A

EXAMPLE (Cont'd)

Draw the transformer circuit referred to the primary and find the input current to the transformer.

- The equivalent circuit shown in Figure 4.7 (b), where
- The turns ratio, $a = 150/750 = 0.2$, $V_1 = 240$ V, and
- $Z_2' = a^2 Z_2 = 0.2^2 \times (240 + j180)$ $= 12\angle{-36.87^\circ}\ \Omega$
- Therefore, $I_1 = V_1/Z_2'$ $= 240\angle 0^\circ / 12\angle{-36.87^\circ}$ $= 20$ A

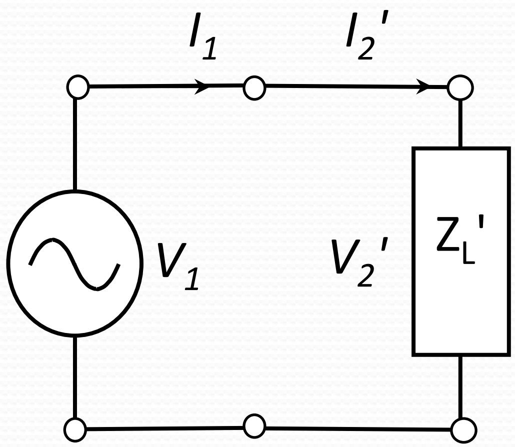


Figure 4.7(b) Transformer circuit referred to primary

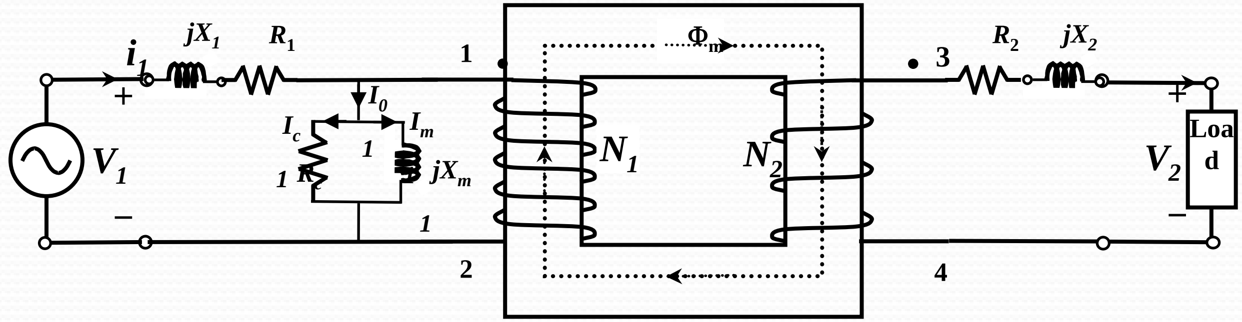
PRACTICAL (NON-IDEAL) TRANSFORMER

- **Winding Resistances:**

  The windings have small but non-zero resistances. These are represented externally.

- **Leakage Flux:**

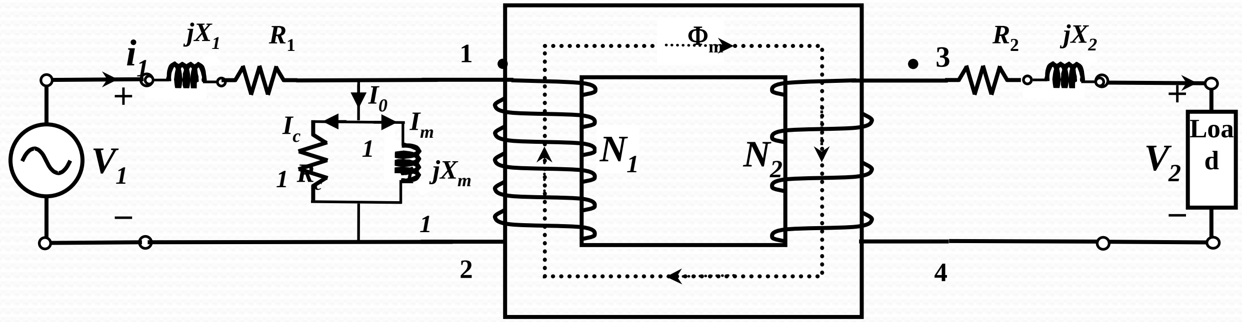
  All the flux do not link both the windings, each has small but non zero leakage flux which links only itself. These are represented by small inductances externally.



(a) Exact equivalent circuit with magnetic circuit
(Representation of transformer parameters externally)

PRACTICAL (NON-IDEAL) TRANSFORMER

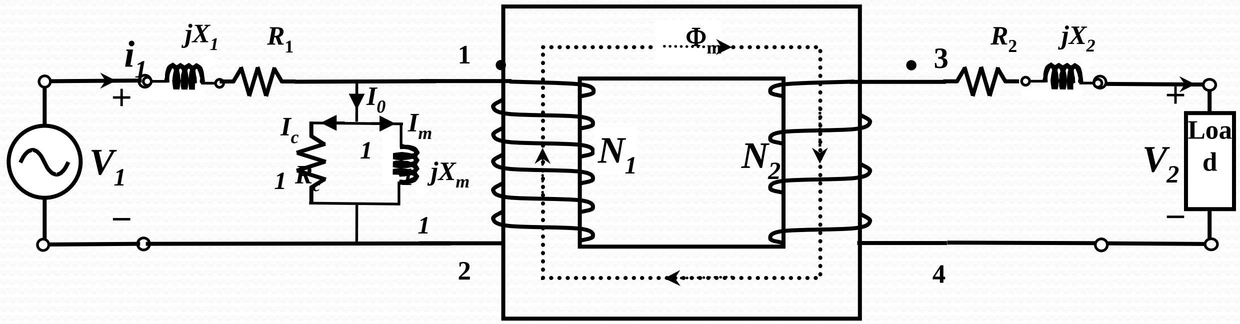
- **No load Current:**
  - a small current to establish the mutual flux in the core, which is accounted for by the mutual inductance, and
  - the current required to supply the core losses consisting of hysteresis and eddy current losses are represented by the resistance connected across the winding.



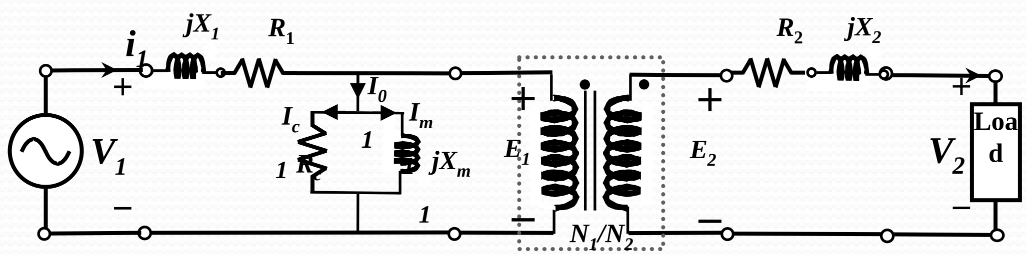
(a) Exact equivalent circuit with magnetic circuit
(Representation of transformer parameters externally)

EQUIVALENT CIRCUIT OF PRACTICAL TRANSFORMER

Representing all non-ideal features externally leaves the transformer ideal and it can be represented by the equivalent circuit shown below.



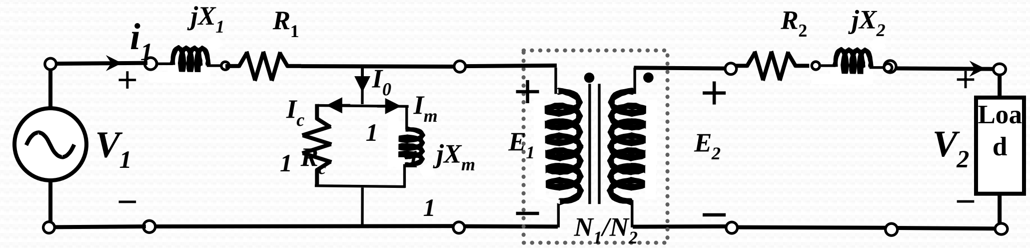
(a) Exact equivalent circuit with magnetic circuit



(b) Exact equivalent circuit without core

Figure 4.11. Exact equivalent circuits of a transformer

PROCEDURE TO ANALYZE EQUIVALENT CIRCUIT



- Start with: $V_2\angle 0°$ as the reference
- Calculate $I_2\angle -\theta_2$

  I_2 can usually be found from the information about the load. Lagging pf assumed here and, $\theta_2 = \cos^{-1}$pf.
- The following relationships can then be sequentially utilized to calculate other circuit quantities.

$$E_2 = V_2 + I_2(R_2 + jX_2) = E_2\angle\theta_{E2}$$

Turns ratio: $a = N_1/N_2 = (\text{Rated } V_1)/(\text{Rated } V_2)$

$$E_1 = aE_2 = aE_2\angle\theta_{E2}, \quad \text{and} \quad I_p = I_2/a = (I_2/a)\angle -\theta_2$$

$$I_c = \frac{E_1}{R_c} = \frac{E_1}{R_c}\angle\theta_{E2}; \quad I_m = \frac{E_1}{jX_m} = \frac{E_1}{X_m}\angle(\theta_{E2} - 90^\circ); \quad I_1 = I_p + I_c + I_m = I_1\angle\theta_{I1}$$

$$V_1 = E_1 + I_1(R_1 + jX_1) = V_1\angle\theta_{V1}$$

- Note that the input power factor is: $\cos\theta_1$.

  where, $\theta_1 = (\theta_{V1} - \theta_{I1})$

EXAMPLE

- A 25 kVA, 1150/230-V, 50 Hz transformer has the following parameters:

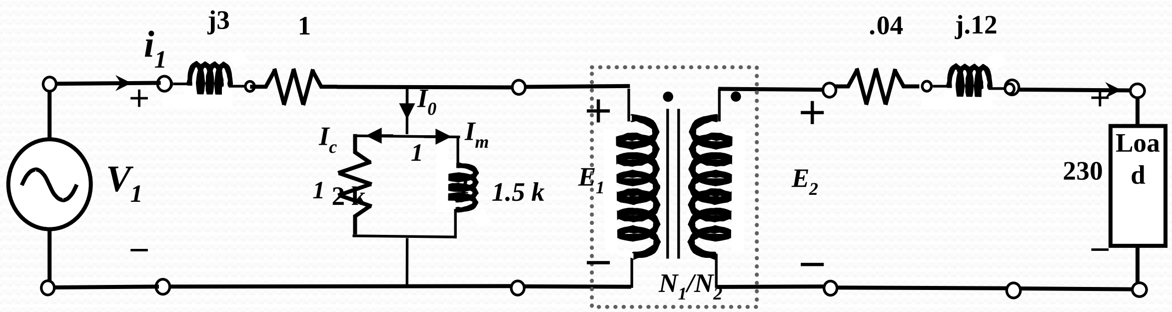
  R_1= 1 Ω, R_2=0.04 Ω, X_1=3 Ω, X_2=0.12 Ω, R_{c1}=2 kΩ, X_{m1}=1.5 kΩ

  Draw the actual equivalent circuit of the transformer.

  If the transformer delivers a load of 20 kVA at 0.8 pf (lag) at load terminal voltage of 230 V, determine:(i) the input current, (ii) the input voltage, (iii) the total copper loss, (iv) the core loss, and (v) the input power.

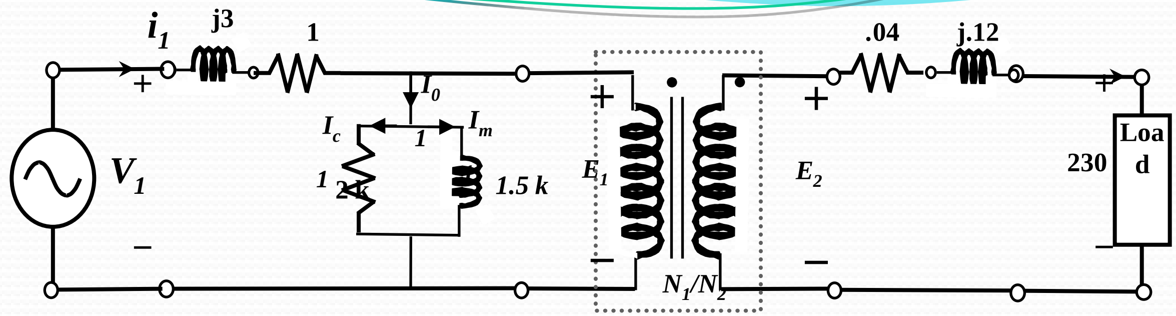
- **Solution**

  The equivalent circuit is as shown, with the parameters shown.



Exact equivalent circuit for Example

EXAMPLE



Exact equivalent circuit for Example

- V_2 = 230V (**rated value**), Let $V_2 = 230\angle 0°$ V **reference**
- Load S=20 kVA, $\Rightarrow$ $S=20\times 23\angle 36.87°$ kVA, **$\cos^{-1}0.8=36.87°$**
- Load current I_2 $= (S/V_2)^* = 20\times 1000\angle{-36.87°}/230\angle 0°$

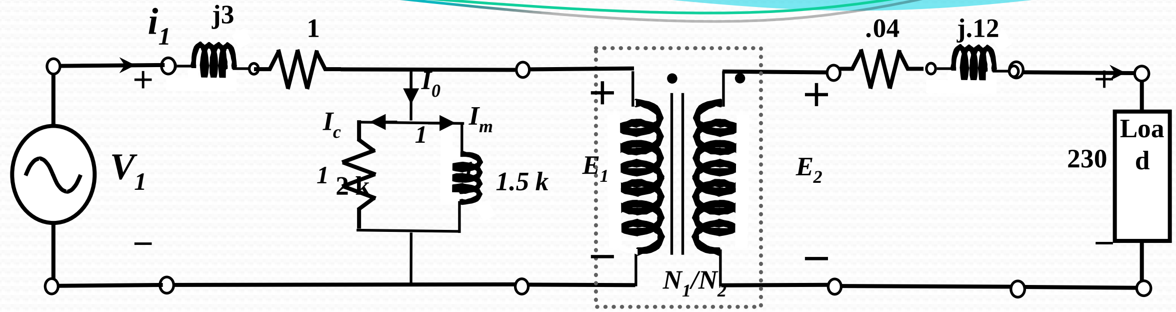
$$= 86.96\angle{-36.87°}\ \text{A}$$

$$E_2 = V_2 + I_2(R_2 + jX_2) = 230\angle 0^\circ + 86.96\ {-36.87} \times (0.04 + j0.12) = 239.12\angle 1.5^\circ$$

- Turns ratio a= 1150/230=5
- Therefore, $E_1 = aE_2 = 1195.61\angle 1.5^\circ$ V, $I_p = I_2/a = 17.39\angle -36.87^\circ$ A

  and $I_c = \dfrac{E_1}{R_c} = \dfrac{1195.61\angle 1.5^\circ}{2000} = 0.60\angle 1.5^\circ$ A
- Then, $I_m = \dfrac{E_1}{jX_m} = \dfrac{1195.61\angle 1.5^\circ}{j1500} = 0.797\angle -88.5^\circ$ A

EXAMPLE



Exact equivalent circuit for Example

- Then,

$$I_1 = I_p + I_c + I_m$$

$$= 17.39\angle -36.87^\circ + 0.60\angle 1.5^\circ + 0.797\angle -88.5^\circ = 18.35\angle -37.65^\circ \text{ A}$$

$$V_1 = E_1 + I_1(R_1 + jX_1) = 1195.61\angle 1.5^\circ + 18.35\angle -37.65^\circ \times (1 + j3)\left[0,1\right] = 1245\angle 2.92^\circ \text{ V}$$

- Now the required quantities can be listed or calculated as:

  the input current: $I_1 = 18.35$ A

  the input voltage: $V_1 = 1245$ V

  the total copper loss: $= I_1^{\,2}R_1 + I_2^{\,2}R_2 = 18.35^2 \times 1 + 86.96^2 \times 0.04 = 639.2$ W

- the core loss: $= E_1^{\,2} / R_c = 1195.61^2 / 2000 = 714.7$ W

  alternatively, core loss $= I_c^{\,2}R_c = 0.6^2 \times 2000 = 720$ W

- the input power: $= V_1 I_1 \cos\varphi = 1245 \times 18.35 \times \cos(2.92^\circ + 37.65^\circ) = 17353.9$ W

  or, input power = output + core loss + copper loss

EXACT EQUIVALENT CIRCUIT REFERRED TO THE PRIMARY

- The equivalent circuit can be simplified referring all the parameters to one side of the transformer.
- The equivalent circuit can be referred to the primary side by making the following transformations on the secondary quantities:

$Z_2 \rightarrow Z_2' = a^2 Z_2$

$(R_2' = a^2 R_2,$

$X_2' = a^2 X_2,$

$Z_L' = a^2 Z_L)$

$V_2 \rightarrow V_2' = aV_2,$

$I_2 \rightarrow I_2' = (1/a)\, I_2$

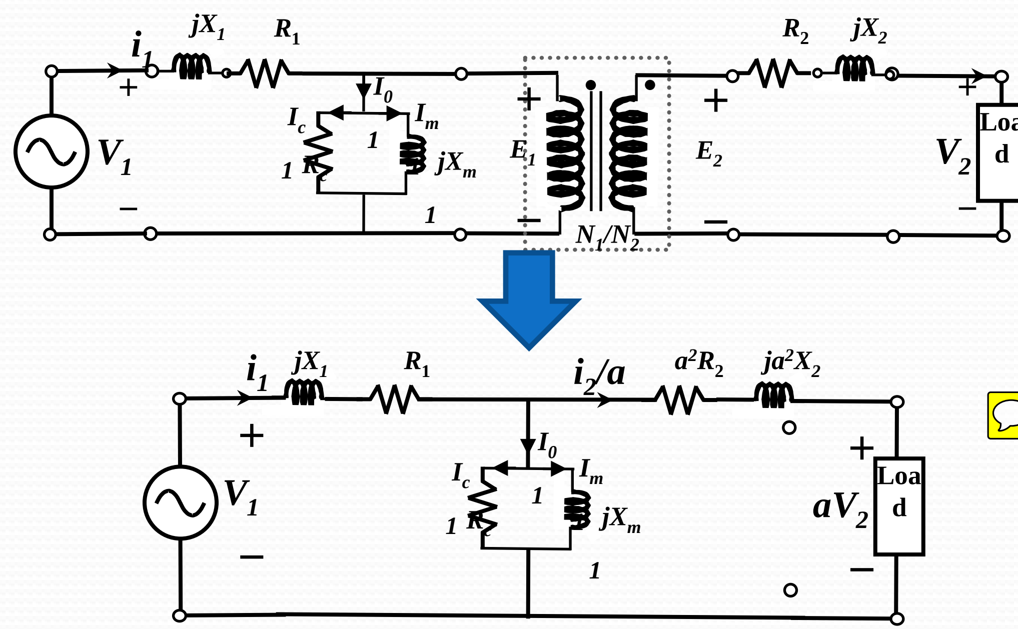


Figure 4.13 Exact equivalent circuit referred to the primary side

EXACT EQUIVALENT CIRCUIT REFERRED TO THE SECONDARY

- The equivalent circuit can be referred to the secondary side by making the following transformations on the primary quantities:

$Z_1 \rightarrow Z_1' = (1/a^2)\, Z_1$

$R_1 \rightarrow R_1' = R_1/a^2,$

$X_1 \rightarrow X_1' = X_1/a^2,$

$R_{c1} \rightarrow R_{c1}' = R_{c1}/a^2,$

$X_m \rightarrow X_m' = X_m/a^2$

$I_1 \rightarrow I_1' = a\, I_1,$

$I_\Phi \rightarrow I_\Phi' = a\, I_\Phi,$

$I_{c1} \rightarrow I_{c1}' = a\, I_{c1}$

$I_m \rightarrow I_m' = a\, I_m$

$V_1 \rightarrow V_1' = V_1/a$

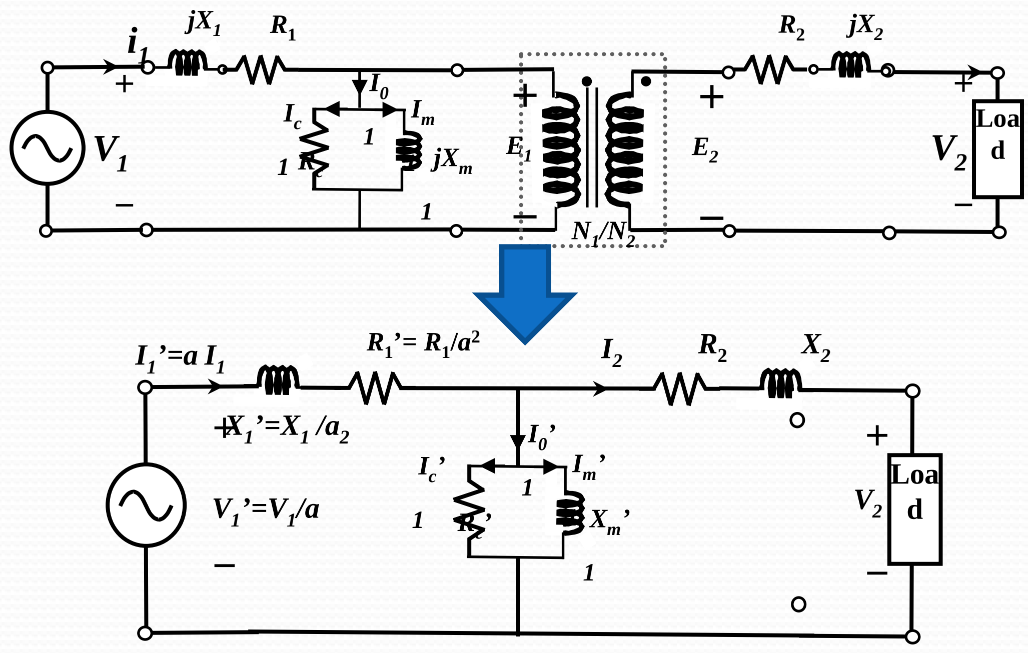


Figure 4.14 Exact equivalent circuit referred to the secondary side

- Both these equivalent circuits can be used to analyze transformer circuits

TRANSFORMER PARAMETER VALUES

- The general nature of the transformer performance depends on the values of the parameters R_1, X_1, R_2, X_2, X_m and R_c. An understanding of the relative sizes of these parameters is very useful in the comprehension of transformer problems.
- *Series Components*

  R_1 and R_2 represent the resistances of the copper coils, and therefore these are usually very small. X_1 and X_2 represent the reactances arising from the leakage fluxes, which are very small. Therefore their magnitudes are also very small. The losses and the voltage drops in these series parameters are usually very small, and often ignorable.
- *Shunt components*

  I_m represents the current drawn to set up the flux in the core, and I_c represents the current that accounts for the core loss. Since very good magnetic material is used in transformers, both these currents are very small, often ignorable. And the corresponding shunt impedances R_{c1} and X_{m1} are very large often taken as infinity and ignored from the circuit.

APPROXIMATE EQUIVALENT CIRCUIT REFERRED TO THE PRIMARY

- Because of the relative values of the series and the shunt components, it introduces very small error if we move the shunt branch from the middle position to either side.
- Such simplified circuits obtained by arbitrarily moving the shunt branches to either side of the transformer terminals are called the approximate equivalent circuits .
- In doing so, the circuit is further simplified because the series parameters in the approximate equivalent circuit can be combined as:

$$R_{e1} = R_1 + a^2 R_2, \quad \text{and}$$
$$X_{e1} = X_1 + a^2 X_2$$

- These combined values are called the total effective resistance and reactance respectively.

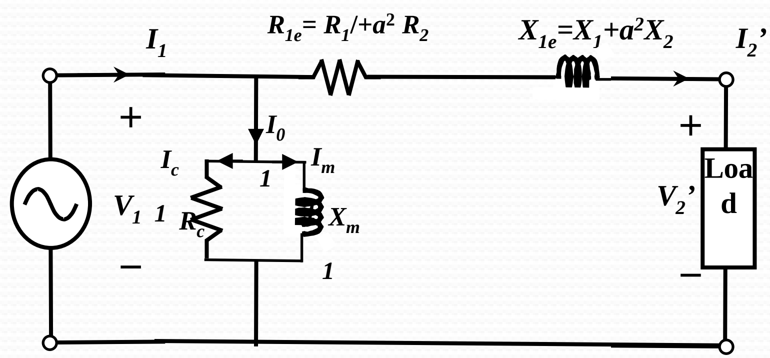


Figure 4.15 Approximate equivalent circuit referred to primary

APPROXIMATE EQUIVALENT CIRCUIT REFERRED TO THE SECONDARY

- Similarly, the approximate equivalent circuit referred to the secondary side may be formed as shown in the following Figure 4.16.
- The total effective resistance and the total effective reactance respectively referred to the secondary side (side 2) of the transformer may be obtained by combining the parameters as follows:

$$R_{e2} = R_1 / a^2 + R_2, \text{ and}$$

$$X_{e2} = X_1 / a^2 + X_2$$

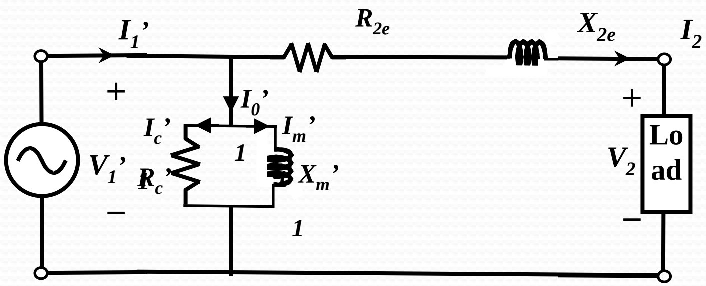


Figure 4.16 Approximate equivalent circuit referred to the secondary

EXAMPLE

A 25 kVA, 1150/230-V, 50 Hz transformer has the following parameters:

R_1= 1 Ω, R_2=0.04 Ω, X_1=3 Ω, X_2=0.12 Ω, R_{c1}=2.0 kΩ, and X_{m1}=1.5 kΩ

If the transformer supplies 20 kVA load at 0.8 pf (lag) and the load terminal voltage is 230 V, calculate the input voltage using the approximate equivalent circuit referred to the primary.

Solution

a=2300/230 = 5, and the circuit is as shown, where,

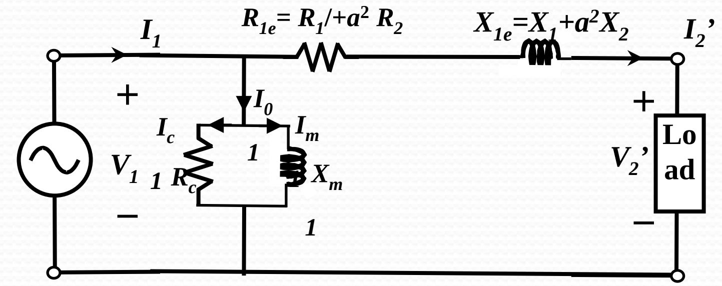


Figure 4.17 Approximate equivalent circuit for Example 4.3

$R_{e1} = 1 + 5^2 \times 0.04 = 2\ \Omega$ and,

$X_{e1} = 3 + 5^2 \times 0.12 = 6\ \Omega$

As before, $V_2 = 230\angle 0°$ V, $I_2 = 86.96\angle -36.87°$ A, so that

$V_2' = aV_2 = 5 \times 230\angle 0° = 1150\angle 0°$ V,

$I_p = I_2' = I_2/a = 86.96\angle -36.87°/5 = 17.39\angle -36.87°$A $\qquad 1245\angle 2.92^{\circ}$

$$V_1 = V_2' + I_2' \times (R_{e1} + jX_{e1}) = 1150\angle 0^{\circ} + 17.39\angle -36.87^{\circ} \times (2 + j6) = 1242\angle 2.89^{\circ}\ \text{V}$$

Compare this with the value obtained by the exact method (1245∠2.92° V).

EXAMPLE

A 25 kVA, 1150/230-V, 50 Hz transformer has the following parameters:

R_1= 1 Ω, R_2=0.04 Ω, X_1=3 Ω, X_2=0.12 Ω, R_{c1}=2.0 kΩ, and X_{m1}=1.5 kΩ

Calculate the input voltage to the transformer if it needs to supply a load of 25 kVA at a voltage of 230 V at power factors of 0.8 pf lag, and 0.8 lead respectively.

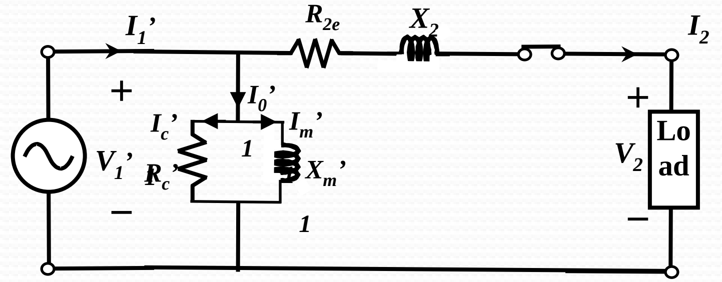


Figure 4.20 Approximate equivalent circuit for Example 4.4

Solution

Consider the approx. eq. circuit as shown, where, a = 1150/230 = 5,

$$R_{e2} = 1/5^2 + 0.04 = 0.08\ \Omega, \text{ and } \quad X_{e2} = 3/5^2 + 0.12 = 0.24\ \Omega$$

Let, V_2 = 230∠0° V,

At 25 kVA load, I_2 = 25×1000/230 = 108.7 A, and

For lagging pf, $\varphi = \cos^{-1} 0.8 = 36.87°$, so that, $I_2 = 108.7\angle -36.87°$ A

and $\quad \mathrm{V}_1' = \mathrm{V}_2 + \mathrm{I}_2 \mathrm{Z}_{2e} = 230\angle 0° + 108.7\angle -36.87°(0.08 + j0.24) = 253.1\angle 3.55°$ V

Input voltage : $\quad V_1 = \mathrm{a}V_1' = 5 \times 253.1 = 1265.5$ V

LOSSES AND EFFICIENCY

- Transformer is very common equipment in power systems and elsewhere. So, it is imperative that they should exhibit high efficiency.
- The losses in transformers consist of:
  - the magnetic losses – core losses, and
  - the copper losses.
- The magnetic core losses (P_c) consist of two components: the *hysteresis loss* and the *eddy current loss*. As the flux and the flux density remain practically constant in a transformer, both these components of the magnetic losses remain practically constant. Therefore, these losses are also called fixed losses. These are together represented by the loss in R_c in the equivalent circuit.
- The copper losses P_{cu} (also known as I^2R loss) occur in the primary and the secondary windings. These losses depend on the currents in the windings and therefore on the load supplied by the transformer.

LOSSES AND EFFICIENCY

- The power flow diagram for a transformer is shown in Figure 4.24 and the input power can be expressed as: $P_{in} = P_o + P_c + P_{cu}$

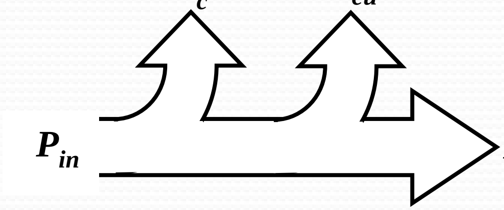


Figure 4.24 Power flow in transformers

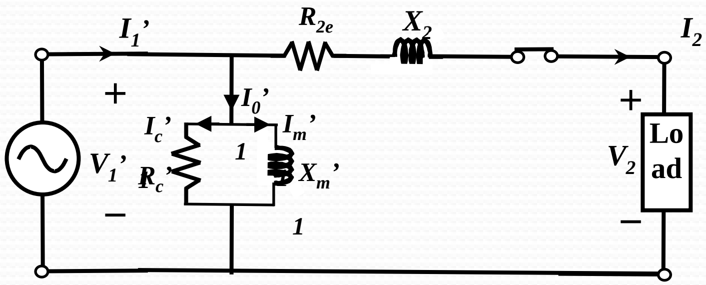


Figure 4.25 Approximate equivalent circuit

- Referring to the approx. eq. circuit as shown,
  - Output = $P_o = V_2 I_2 \cos\varphi$, and
  - the efficiency can be expressed as:

$$\eta = \frac{P_{output}}{P_{input}} = \frac{P_{output}}{P_{input} + Cu\ loss + Core\ \mathrm{loss}} = \frac{V_2 I_2 \cos\varphi}{V_2 I_2 \cos\varphi + I_2^2 R_{e2} + P_c}$$

- Note that the efficiency depends on the power factor in addition to the load itself.
- Different types of transformers have different efficiency characteristics and requirements.

EXAMPLE

A 25 kVA 1150/230-V transformer has the primary and secondary winding resistances of R_1= 1 Ω, and R_2=0.12 Ω and the shunt (core loss component) resistance referred to the primary side is 2 kΩ.

Calculate the copper loss and the core loss of the transformer at full load (rated conditions). Also, calculate the full load efficiency at 0.8 pf lagging.

Solution

At full load: $I_{2fl} = S_{fl} / V_2 = 25000/230 = 108.7\ \text{A}$

$I_{1fl} = S_{fl} / V_1 = 25000/1150 = 21.74\ \text{A}$

Copper loss at full load $\boxed{\approx I_{1fl}^2 R_1 + I_{2fl}^2 R_2 = 21.74^2 \times 1 + 108.7^2 \times 0.04 =}\ 945.3\ \text{W}$

Core losses at (full load) $P_c \approx 1150^2/2000 = 661.3$ W

At full load and 0.8 pf,

Power output = 25000×0.8 = 20000 W

$$\eta_{fl} = \frac{P_{o-fl}}{P_{o-fl} + P_{cu-fl} + P_c} \times 100 = \frac{20000}{20000 + 945.3 + 661.3} \times 100 = 92.56\ \%$$

TRANSFORMER TESTING:
DETERMINATION OF PARAMETERS

- The values of the transformer parameters, r_e, x_e, r_c and x_m are required to carry out any analysis of transformer problems. These parameters are obtained:
  - From design data,
  - But more commonly by conducting two standard tests

    Open Circuit Test, and

    Short Circuit Test

OPEN CIRCUIT (OC) TEST

- This test is carried out to determine the shunt parameters r_c and x_m of the transformer. The connection diagram of the test set-up is shown in Figure 4.28.

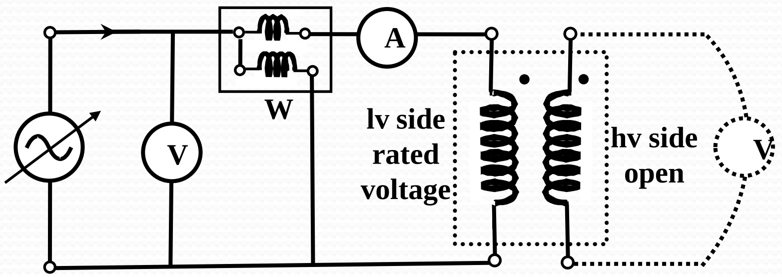
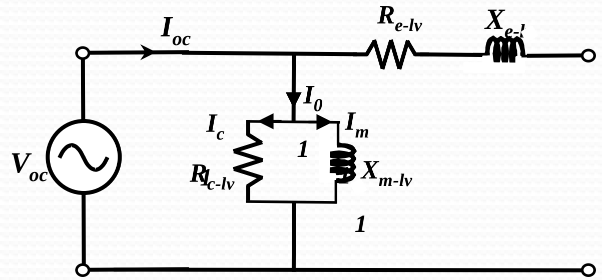


Figure 4.28 Connection diagram for open circuit test

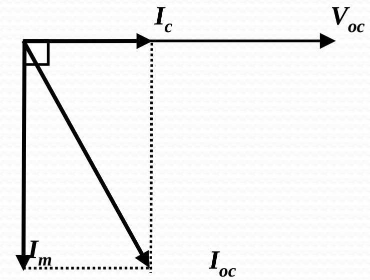
- One winding, usually the high voltage side, is left open. The low voltage side is supplied with rated voltage at rated frequency.
- The wattmeter, the voltmeter, and the ammeter connected as shown in the figure are used to record:
  - The applied rated voltage (V_{oc}) V.
  - The power input (P_{oc}) W, and
  - The current drawn (I_{oc}) A

OPEN CIRCUIT (OC) TEST- COMPUTATION

- The approximate equivalent circuit for the circuit connection during OC test is shown in Figure 4.29 (a). Since the test is conducted on the low voltage side, the parameters obtained will be the effective values referred to the *lv* side.



(a). Approximate equivalent circuit



(b) Vector diagram

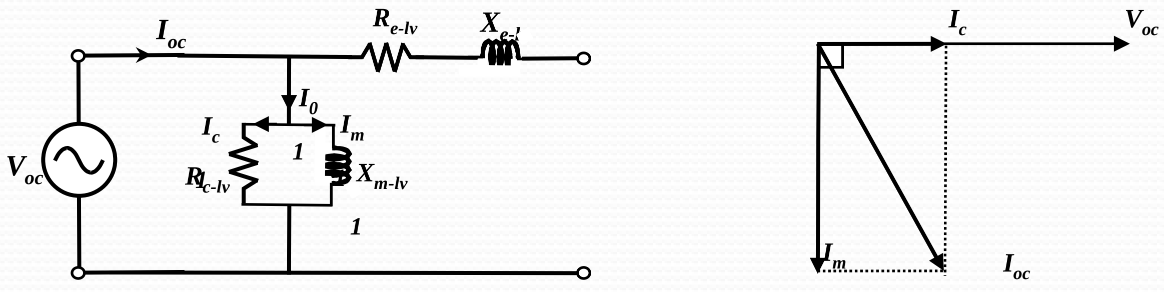
Figure 4.29 Open circuit test

- All the power input during the test is consumed by R_{c-lv}.

$$P_{oc} = \frac{V_{oc}^2}{R_{clv}} \quad \Rightarrow \quad R_{clv} = \frac{V_{oc}^2}{P_{oc}}$$

- Then, $I_c = V_{oc} / R_{clv}$ A
- The vector relationship between the currents, I_c, I_m, and I_{oc} is shown in Figure 4.29 (b).

OPEN CIRCUIT (OC) TEST- COMPUTATION



(a). Approximate equivalent circuit

(b) Vector diagram

Figure 4.29 Open circuit test

- Clearly, $I_{oc}^2 = I_c^2 + I_m^2 \quad \Rightarrow \quad I_m = \sqrt{I_{oc}^2 - I_c^2}$

  Then, $X_{mlv} = V_{oc} / I_m$

- Thus, the simple data collected from the OC test, V_{oc}, P_{oc}, and I_{oc}, can be easily used to calculate the shunt parameters R_{clv} and X_{mlv} of the transformer approximate equivalent circuit.

SHORT CIRCUIT (SC) TEST

- This test is carried out to determine the series parameters r_e, and x_e of the transformer. The connection diagram of the test set-up is shown in Figure 4.30.
- One winding, usually the low voltage side, is short circuited. The high voltage side is supplied with a variable voltage source of the rated frequency. The input voltage is kept low (≈ 5% of rated voltage), at a value to make rated currents flow in the windings under the short circuit test condition.
- The wattmeter, the voltmeter, and the ammeter connected as shown in the figure are used to record:
  - The applied ***reduced*** voltage (V_{sc}) V.
  - The power input (P_{sc}) W, and,
  - The current drawn (I_{sc}) A

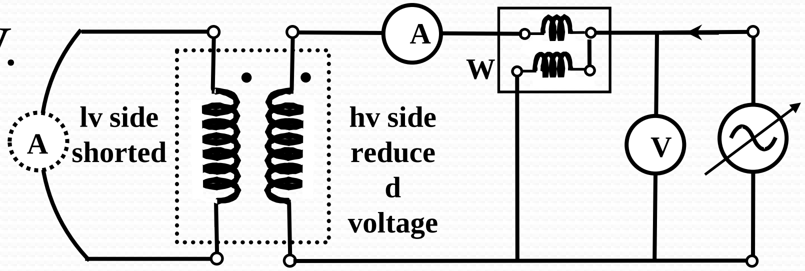


Figure 4.30 Connection diagram for short circuit (SC) test

SHORT CIRCUIT (SC) TEST – COMPUTATION

- The approximate equivalent circuit for the connection during SC test is shown in Figure 4.31. The test is conducted on the high voltage side. So the parameters obtained will be the effective values referred to the hv (H) side.

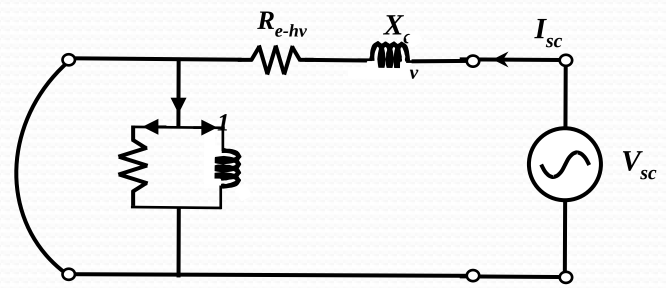


Figure 4.31 Circuit diagram for short circuit test

- All the power input during the test is consumed by R_{ehv}

$$P_{sc} = I_{sc}^2 R_{ehv} \quad \Rightarrow \quad R_{ehv} = \frac{P_{sc}}{I_{sc}^2}$$

- Also, $Z_{ehv} = V_{sc} / I_{sc}$
- then, clearly $Z_{ehv}^2 = R_{ehv}^2 + X_{ehv}^2 \quad \Rightarrow \quad X_{ehv} = \sqrt{Z_{ehv}^2 - R_{ehv}^2}$
- Thus, the simple set of data collected from the SC test, V_{sc}, P_{sc}, and I_{sc}, can be easily used to calculate the total effective values of the series parameters R_{ehv} and X_{ehv} of the transformer equivalent circuit.
- These two tests are generally conduced on two different sides of the transformer. Therefore appropriate adjustments of the parameters are required to use them in the same common circuit.

EXAMPLE

The following test data were collected for a 50 kVA, 50 Hz, 2400/240 V transformer

	Voltage (V)	Current (A)	Power (W)
Open Circuit test	240	3	200
Short Circuit test	120	8	800

Determine the equivalent circuit of the transformer: (i) referred to the high voltage side, and (ii) referred to the low voltage side

Solution

OC test must be done at rated voltage. Therefore, the OC test is conducted on the low voltage side.

Therefore, $V_{oc} = 240$ V, $I_{oc} = 3$ A, and $P_{oc} = 200$ W.

$$P_{oc} = \frac{V_{oc}^2}{R_{cL}} \Rightarrow R_{cL} = \frac{V_{oc}^2}{P_{oc}} = \frac{240^2}{200} = 288$$

$$I_{cL} = \frac{V_{oc}}{R_{cL}} = \frac{240}{288} = 0.833$$

EXAMPLE

Then, $$I_{mL} = \sqrt{I_{oc}^2 - I_{cL}^2} = \sqrt{3^2 - 0.833^2} = 2.88\ \text{A}$$

and, $$X_{mL} = \frac{V_{oc}}{I_{mL}} = \frac{240}{2.88} = 83.3\ \Omega$$

SC test is done on the hv (H) side, and

V_{sc} = 120 V, I_{ac} = 8 A, and P_{sc} = 800 W.

$$R_{eH} = \frac{P_{sc}}{I_{sc}^2} = \frac{800}{8^2} = 12.5\ \Omega$$ and, $$Z_{eH} = V_{sc} / I_{sc} = 120/8 = 15\ \Omega$$

$$X_{eH} = \sqrt{Z_{eH}^2 - R_{eH}^2} = \sqrt{15^2 - 12.5^2} = 8.29\ \Omega$$

Now, the turns ratio of the transformer, a = 2400/240=10, therefore,

$$R_{cL} = 288\ \Omega \quad \Rightarrow \quad R_{cH} = a^2 R_{cL} = 10^2 \times 288 = 28.8\ \text{k}\Omega$$

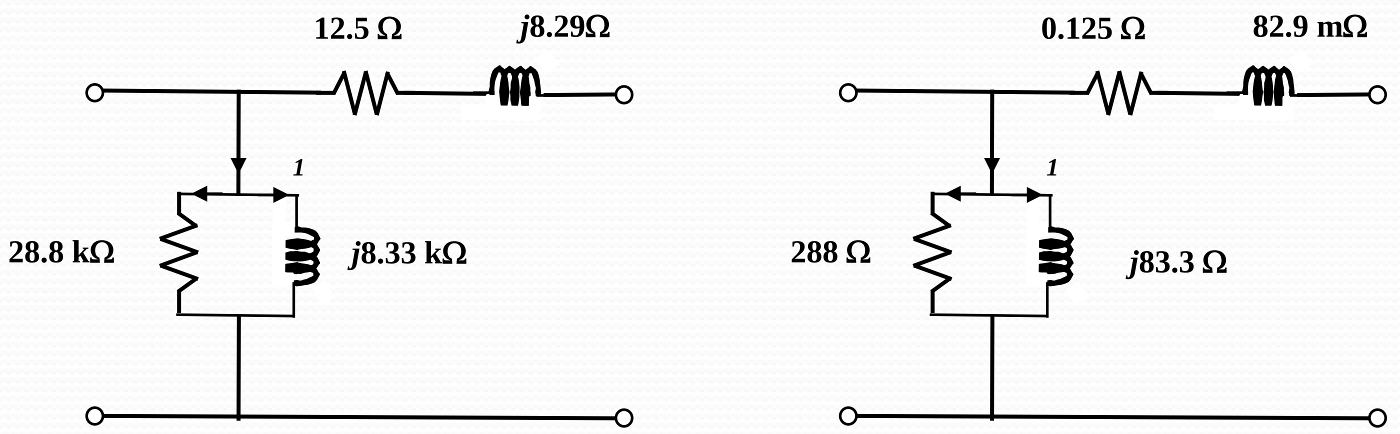
$$X_{mL} = 83.3\ \Omega \quad \Rightarrow \quad X_{mH} = a^2 X_{mL} = 10^2 \times 83.3 = 8.33\ \text{k}\Omega$$

$$R_{eL} = (1/a^2) R_{eH} = 1/10^2 \times 12.5 = 0.125\ \Omega \quad \Leftarrow \quad R_{eH} = 12.5\ \Omega$$

$$X_{eL} = (1/a^2) X_{eH} = 1/10^2 \times 8.29 = 0.0829\ \Omega = 82.9\ \text{m}\Omega \quad \Leftarrow \quad X_{eH} = 8.29\ \Omega$$

EXAMPLE

The approximate equivalent circuits can now be drawn as the following.



(a) Referred to hv side

(b) Referred to lv side

Figure 4.32 Approximate equivalent circuit referred to two sides of the transformer

MISCELLANEOUS

- The general concepts and basic analysis of a transformer has been presented. But there are many different types of transformer which are commonly used in practice; of particular importance are:
  - Auto-transformers
  - Three-phase transformers
- More detailed treatment would be needed to fully understand the concepts, functions, and applications of transformers.
  - Efficiency
  - Voltage Regulation
  - Tap Changers
  - Etc.