EEE/ETI3105
ELECTRICAL MACHINES I

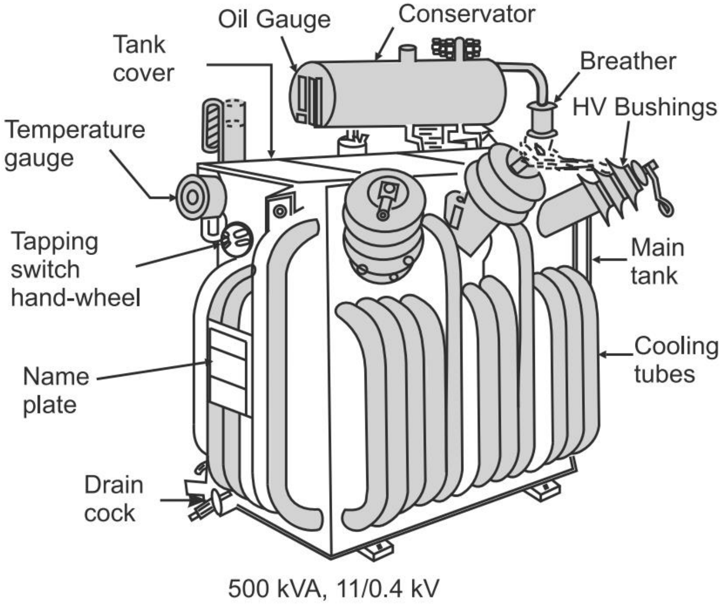
LECTURE 2: TRANSFORMERS

Introduction to Transformers

- The transformer is probably one of the most useful electrical devices ever invented.
- It can change the magnitude of alternating voltage or current from one value to another.
- This useful property of transformer is mainly responsible for the widespread use of alternating currents rather than direct currents i.e., electric power is generated, transmitted and distributed in the form of alternating current.
- Transformers have no moving parts, rugged and durable in construction, thus requiring very little attention.
- They also have a very high efficiency-as high as 99%.
- *A transformer is a static piece of equipment used either for raising or lowering the voltage at the same frequency of an a.c. supply with a corresponding decrease or increase in current.*

Introduction

- Usually electric power is generated between 11 - 33 kV. The voltage level is raised to 220 kV, 400 kV or 750 kV by employing step-up transformers for transmitting the power to long distances. Then to feed different areas, as per their need, the voltage level is lowered down to 132kV, 66 kV, 33 kV or 11 kV by employing step-down transformers. Ultimately for utilization of electrical power, the voltage is stepped down to 400/230 V for safety reasons.
- Thus, transformer plays an important role in the power system. The pictorial view of a power transformer is shown in Fig. (b). The important accessories are labelled on it:



(i) Oil immersed air natural cooled transformer

(ii) Single-phase transformer

Application of a Transformer

- Main applications of the transformers are given below:
  - To change the level of ac voltage and current in electric power systems.
  - As impedance-matching device for maximum power transfer in low-power electronic and control circuits.
  - As a coupling device is electronic circuits
  - To isolate one circuit from another, since primary and secondary are not electrically connected.
  - To measure voltage and currents; these are known as instrument transformers.

Application of a Transformer

- Transformers are extensively used in AC power systems because of the following reasons:
  - Electric energy can be generated at the most economic level (11–33 kV)
  - Stepping up the generated voltage to high voltage, extra high voltage EHV (voltage above 230kV), or to even ultra high voltage UHV (750 kV and above) to suit the power transmission requirement to minimise losses and increase transmission capacity of lines.
  - The transmission voltage is stepped down in many stages for distribution and utilisation for domestic, commercial and industrial consumers.

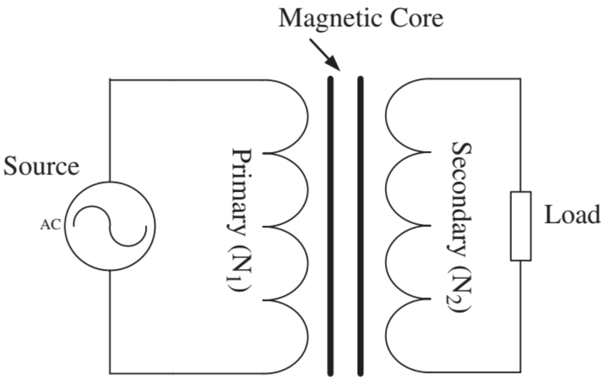
Classification of Transformers

- Transformers are classified according to various parameters such a
- **a) According to the number of phases**
  - Single-phase
  - Three-phase
  - Multiphase
- **b) According to the operation**
  - Step-up
  - Step-down
- **c) According to the construction**
  - Core type
  - Shell type
- **d) According to the number of windings**
  - Single-winding (Auto transformer)
  - Two-winding
  - Three-winding (Tertiary winding)
- **e) According to the use**
  - Power Transformer
  - Distribution Transformer

Classification Based on Number of Phases

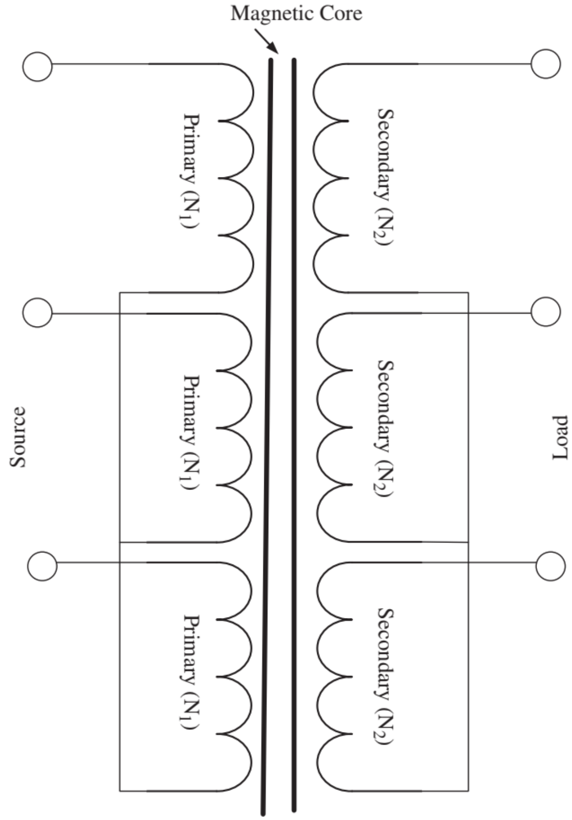
Single-Phase Transformers

- Single-phase transformers are used for single-phase ac input and single-phase ac output.
- There is one primary winding with N_1 number of turns and one secondary winding with N_2 number of turns as shown in Figure.



Three-Phase Transformers

- Three-phase transformers have three-phase input and three-phase output.
- There are three primary and three secondary windings.
- The primary and secondary windings are connected in either star and/or delta connection (shown in Figure with star connected primary and star connected secondary).
- These transformers are used throughout the power system in generation, transmission, and distribution.



Classification Based on Operation

Step-Up Transformers

- In this transformer, the output voltage is more than the input voltage while the output current is less than the input current.

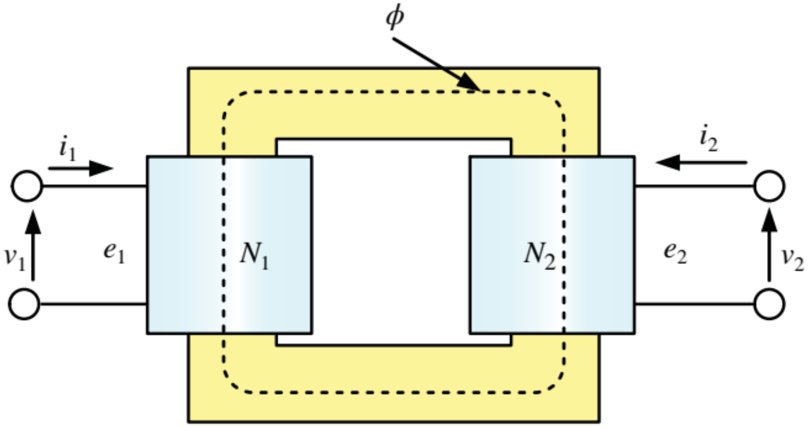
Step-Down Transformers

- In this transformer, the output voltage is less than the input voltage while the output current is more than the input current.

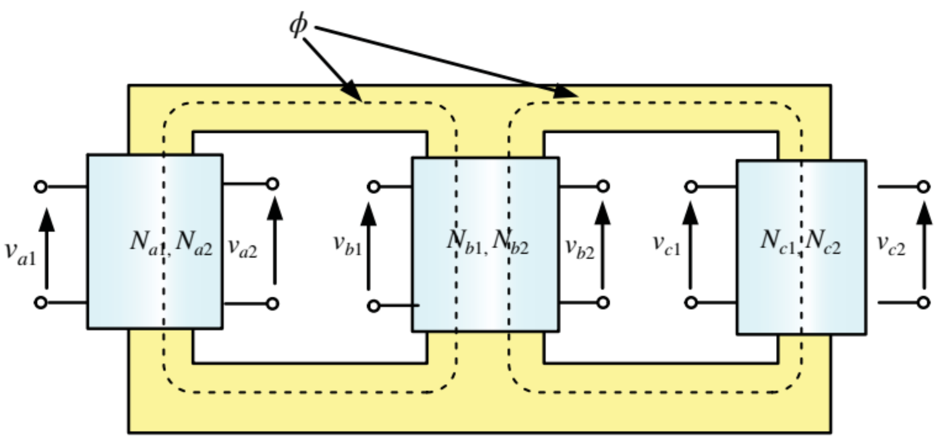
Classification Based on Construction

Core-Type Transformers

- In this type of transformer, windings are put on the outer limb of the core and thus the windings are exposed and maintenance is easier. A core-type single-phase transformer is shown in Fig (a) where primary winding has N_1 number of turns and secondary winding has N_2 number of turns. A three-phase core-type transformer is shown in Fig (b).
- Six windings are places on the transformer limbs. Both primary and secondary windings are placed on the same limb for each phase.



(a) Single-phase core type of transformer construction.

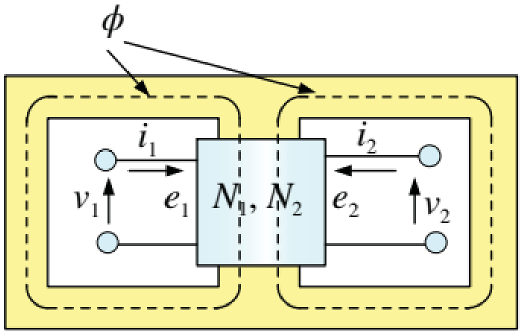


(b) Three-phase core-type transformer construction.

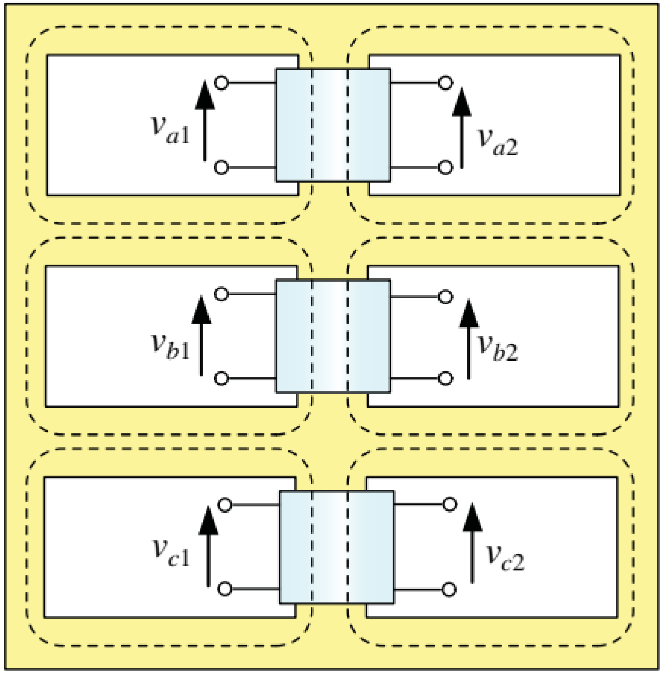
Classification Based on Operation

Shell-Type Transformers

- In this type of transformer, windings are put on the central limb of the core and thus the windings are not easily accessible and maintenance is difficult, but the leakage reactance is lower than the core type and consequently, the voltage regulation is better.
- A single-phase shell type of transformer is shown in Fig (a). Both primary (N_1) and secondary winding (N_2) are placed one over the other. A three-phase shell type of transformer is shown in Fig (b).



Single-phase shell type of transformer



Three-phase shell-type transformer construction.

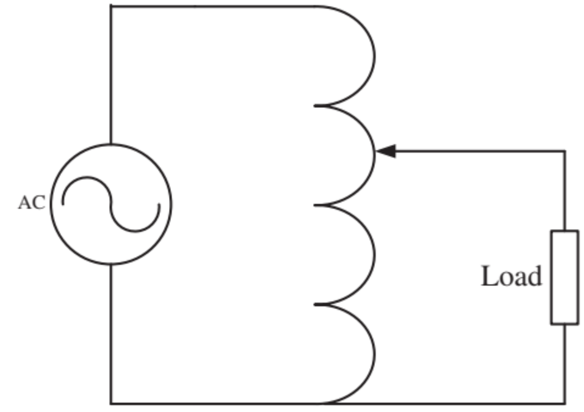
Comparison between Core-type and Shell type Transformers:

Sr. No.	*Core-type transformer*	*Shell-type transformer*
1.	The windings surround a considerable portion of the core.	The *core* surrounds considerable portion of the windings.
2.	Windings are of *form*-wound, and are of cylindrical-type.	Winding are of *sandwich-type*. The coils are first wound in the form of pancakes, and complete winding consists of stacked discs.
3.	More suitable for *high voltage* transformers.	More suitable and economical for *low voltage* transformers.
4.	Mean length of coil turn is *shorter*.	Mean length of coil turn is *longer*.
5.	Core has *two limbs* to carry the windings.	Core has *three or more limbs* but the central limb carries the windings.

Classification Based on Number of Windings

Single-Winding Transformer

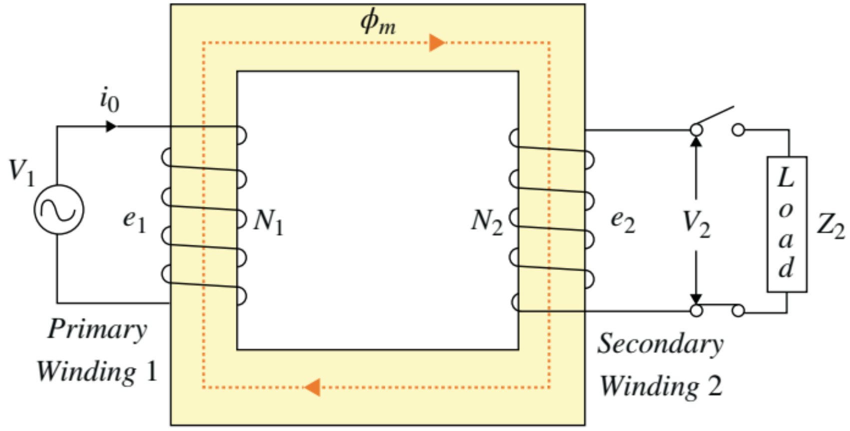
Transformers having only one winding are termed as 'Autotransformers' as shown in Fig. It has a slider on one end to provide variable output voltage. This transformer is used as a variable voltage supply. It transforms energy from one circuit to the other via induction as well as conduction since there is no electrical isolation between primary and secondary.



Basic autotransformer.

Two-Winding Transformer

This type of transformer has two separate windings called primary and secondary as shown in Fig.



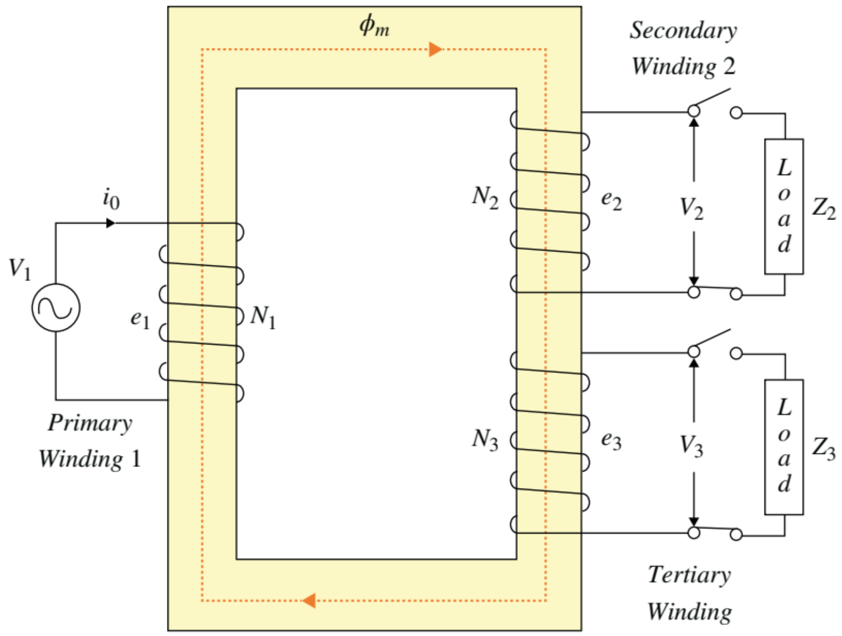
Two winding transformer.

Classification Based on Number of Windings

Three-Winding Transformer

This is a special type of transformer having three windings namely primary, secondary and tertiary.

This transformer is used for special applications where two different voltage levels are required such as in substations for auxiliary loads.



Three winding transformer.

Classification Based on Application

Power Transformer

- The transformer used in power plant and grid substations for high voltage step up and step down are called power transformers. The generated voltage in the power plant (11–33 kV) is stepped-up to transmission voltage level (132, 220, and 400 kV). The same transmission voltage is then stepped down by power transformers to 66 and 33 kV in the grid substations.
- The power transformer is used to further step down 33–11 kV in the substation.

Distribution Transformer

- This type of transformer is used for low-voltage distribution network to connect to the users. The 11 kV is stepped down to 440 V three-phase using distribution transformer to supply to the residential users

Classification Based on Application

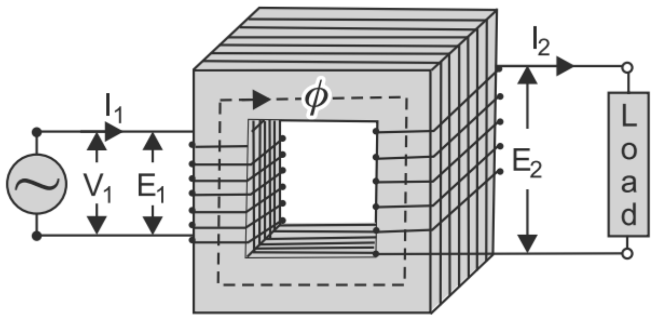
- **Instrument Transformers:** To measure high voltages and currents in power system potential transformer (P.T.) and current transformer (C.T.) are used, respectively. The potential transformers are used to decrease the voltage and current transformers are used to decrease the current up to measurable value. These are also used with protective devices.
- **Testing transformers:** These transformers are used to step up voltage to a very high value for carrying out the tests under high voltage, e.g., for testing the dielectric strength of transformer oil.
- **Special purpose transformer:** The transformers may be designed to serve special purposes, these may be used with furnaces, rectifiers, welding sets etc.
- **Auto-transformers:** These are single winding transformers used to step down the voltages for starting of large three-phase squirrel cage induction motors.

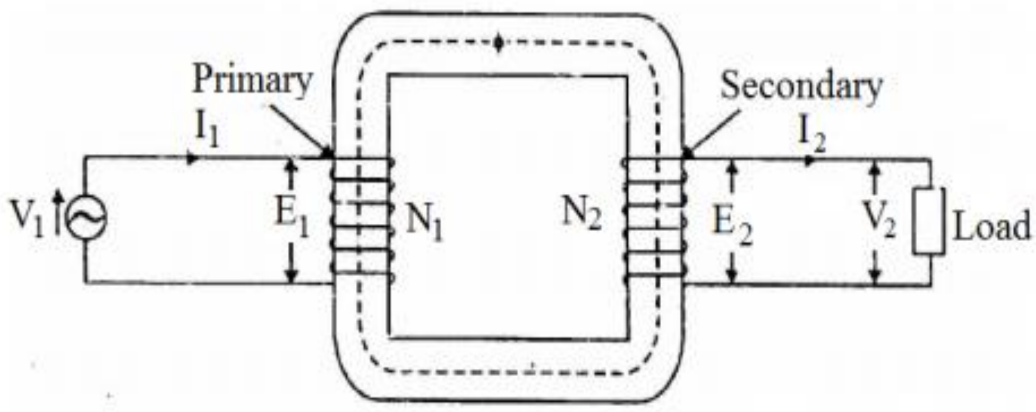
Classification Based on Application

- **Isolation transformer:** These transformers are used only to isolate (electrically) the electronic circuits from the main electrical lines, therefore, their transformation ratio is usually one.
- **Impedance matching transformer:** These transformers are used at the output stage of the amplifier for impedance matching to obtain maximum output from the amplifiers.

Working Principle of a two winding Transformer

- It essentially consists of two windings, the primary and secondary, wound on a common laminated magnetic core as shown in Figure below.





- The winding connected to the a.c. source is called primary winding (or primary) and the one connected to load is called secondary winding (or secondary).
- The alternating voltage V_1 whose magnitude is to be changed is applied to the primary.

- Depending upon the number of turns of the primary (N_1) and secondary (N_2), an alternating e.m.f. E_2 is induced in the secondary.
- This induced e.m.f. E_2 in the secondary causes a secondary current I_2.
- The change in flux, $d\Phi/dt$ is common for both windings.
- Consequently, terminal voltage V_2 will appear across the load.
- If $V_2 > V_1$, it is called a **step up-transformer**.
- On the other hand, if $V_2 < V_1$, it is called a **step-down transformer**.

Working principle

- Once AC supply of voltage V_1 is given to primary winding, an alternating flux is set-up in the magnetic core which links with the primary and secondary winding. Consequently, self-induced emf E_1 and mutually-induced emf E_2 are induced in primary and secondary, according to Faraday's laws respectively.
- These induced emf's are developed in phase opposition to V_1 as per Lenz's law. The self-induced emf in the primary is also called back emf since it acts in opposite direction to the applied voltage.
- Thus $$E_1 = -N_1 \frac{d\phi}{dt} \quad \text{and} \quad E_2 = -N_2 \frac{d\phi}{dt}$$

$$\therefore \quad \frac{E_2}{E_1} = \frac{N_2}{N_1}$$

- Although, there is no electrical connection between primary and secondary winding, still electric power is transferred from one circuit (primary side) to the other circuit (secondary side).
- It is all because of magnetic coupling, i.e., the alternating flux which is set-up in the core linking with both the windings.
- The magnitude of induced emf in a coil depends upon rate of change of flux linkages i.e., $e \alpha N$. since, the rate of change of flux for both the winding is the same, the magnitude of induced emf in primary and secondary will depend upon their number of turns, i.e., primary induced emf $E_1 \alpha N_1$ and secondary induced emf E_2 v αN_2.
- When $N_2 > N_1$, the transformer is called a step-up transformer, on the other hand, when $N_2 < N_1$ the transformer is called step-down transformer

Facts to note about transformers

i. The transformer action is based on the laws of electromagnetic induction.

ii. There is no electrical connection between the primary and secondary.

iii. The a.c. power is transferred from primary to secondary through magnetic flux.

iv. There is no change in frequency i.e., output power has the same frequency as the input power.

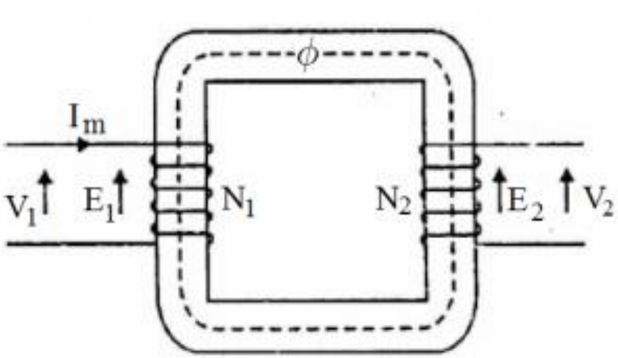
v. The losses that occur in a transformer are:

  - core losses-eddy current and hysteresis losses
  - copper losses-in the resistance of the windings

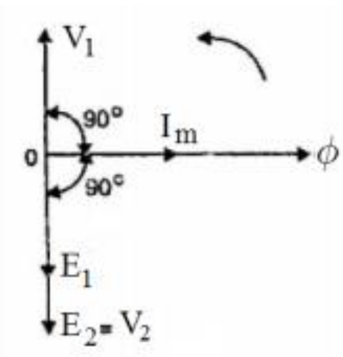
- In practice, these losses are very small so that output power is nearly equal to the input primary power.
- Meaning, a transformer has very high efficiency.

An Ideal Transformer : Theory

- A transformer with the following characteristics is called an Ideal transformer.:
    1. The primary and secondary windings have no resistance.
    2. There is no leakage flux. All the flux produced by primary winding links with the secondary winding.
    3. There is no core/iron loss.
    4. Permeability of the core material is infinite. Therefore, the exciting current required to establish flux in the core is negligible.
- Although ideal transformer cannot be physically realized, yet its study provides a very powerful tool in the analysis of a practical transformer.
- In fact, practical transformers have properties that approach very close to an ideal transformer.
- Consider an ideal transformer on no load i.e., secondary is open-circuited as shown in Fig (a) with its phasor diagram on Fig (b).



(a)



(b)

- The primary of an ideal transformer is simply a coil of pure inductance.
- When an alternating voltage V_1 is applied to the primary, it draws a small magnetizing current (I_m) which lags behind the applied voltage by 90^0 (Being a purely inductive circuit).
- This alternating current I_m produces an alternating flux (Φ) which is proportional to and in phase with it.
- The alternating flux (Φ) links both the windings and induces e.m.f. E_1 in the primary and e.m.f. E_2 in the secondary.
- The primary e.m.f. E_1 is equal to and in opposition to V_1 (Lenz's law).
- Both e.m.f.s E_1 and E_2 lag behind flux (Φ) by 90^0 and their magnitudes depend upon the number of primary and secondary turns.
- Since flux (Φ) is common to both the windings, it has been taken as the reference phasor.
- As will be later seen the primary e.m.f. E_1 and secondary e.m.f. E_2 lag behind the flux (Φ) by 90^0.
- Note that E_1 and E_2 are in phase. But, E_1 is equal to V_1 and 180^0 out of phase with it.

E.M.F. Equation of a Transformer

- When an alternating voltage V_1 of frequency f is applied to the primary of a transformer, the sinusoidal flux (Φ) produced by the primary can be represented as:

$$\Phi = \Phi_m \, Sin(wt)$$

The instantaneous e.m.f. e_1 induced in the primary is;

$$e_1 = -N_1 \frac{d\phi}{dt} = -N_1 \frac{d}{dt}(\phi_m \sin \omega t) \quad = -\omega N_1 \phi_m \cos \omega t$$

$$= -2\pi f N_1 \phi_m \cos \omega t \quad = 2\pi f N_1 \phi_m \sin(\omega t - 90^0) \qquad ....(i)$$

It is clear from the above equation from that e.m.f. E_1 induced in the primary lags behind the flux ϕ by 90^0 and it has a maximum value of;

$$E_{m1} = 2\pi f N_1 \phi_m$$

- The r.m.s. value E_1 of the primary e.m.f. is:

$$E_1 = \frac{E_{m1}}{\sqrt{2}} = \frac{2\pi\, f\, N_1\, \phi_m}{\sqrt{2}}$$

$$E_1 = 4.44\, f\, N_1\, \phi_m$$

- Similarly to value of E_2

$$E_2 = 4.44\, f\, N_2\, \phi_m$$

- In an ideal transformer, $E_1 = V_1$ and $E_2 = V_2$

Voltage Transformation Ratio (K)

- From the induced E.M.F equations, we have;

$$\frac{E_2}{E_1} = \frac{4.44 f N_2 \phi_m}{4.44 f N_1 \phi_m} = \frac{N_2}{N_1} = K$$

- The constant K is called voltage transformation ratio.

  Thus if $K = 5$ then $E_2 = 5\ E_1$.

  For an ideal transformer;

  1. $E_1 = V_1$ and $E_2 = V_2$ as there is no voltage drop in the windings

  $$\therefore \frac{E_2}{E_1} = \frac{V_2}{V_1} = \frac{N_2}{N_1} = K$$

  2. there are no losses. Therefore, volt-amperes input to the primary are equal to the output volt-amperes i.e.

  $$V_1 I_1 = V_2 I_2 \qquad \text{or} \qquad \frac{I_2}{I_1} = \frac{V_1}{V_2} = \frac{1}{K}$$

- *Hence, currents are in the inverse ratio of voltage transformation ratio.*
- *This simply means that if we raise the voltage, there is a corresponding decrease of current.*

Practice Questions

- **Qn 1.** The primary and secondary of a 25 kVA transformer has 500 and 40 turns, respectively. If the primary is connected to 3000 V, 50 Hz mains, calculate (i) primary and secondary currents at full load; (ii) The secondary emf and (iii) The maximum flux in the core. Neglect magnetic leakage, resistance of the winding and the primary no-load current in relation to the full load current.

- **Qn 2.** A 100 kVA, 3300/200 volt, 50 Hz single phase transformer has 40 turns on the secondary, calculate:

  (i) the values of primary and secondary currents.

  (ii) the number of primary turns.

  (iii) the maximum value of the flux.

If the transformer is to be used on a 25 Hz system, calculate.

(iv) the primary voltage, assuming that the flux is increased by 10%

(v) the kVA rating of the transformer assuming the current density in the windings to be unaltered.

Solution Qn 2

(*i*) Full load primary current, $I_1 = \dfrac{100 \times 1000}{3300} =$ **30.3 A** (*Ans.*)

Full load secondary current, $I_2 = \dfrac{100 \times 1000}{200} =$ **500 A** (*Ans.*)

(*ii*) No. of Primary turns, $N_1 = N_2 \times \dfrac{E_1}{E_2} = 40 \times \dfrac{3300}{200} =$ **660** (*Ans.*)

(*iii*) We know $E_2 = 4.44 f \phi_{max} N_2$ volt

$$200 = 4.44 \times 50 \times \phi_{max} \times 40$$

$$\therefore \quad \phi_{max} = \frac{200}{4.44 \times 50 \times 40} = \mathbf{0.0225\ Wb}\ (Ans.)$$

(*iv*) As the flux is increased by 10% at 25 Hz

$\therefore$ Flux at 25 Hz, $\phi'_m = 0.0225 \times 1.1 = 0.02475$ Wb

$\therefore$ Primary voltage $= 4.44 \times N_1 \times f' \times \phi'_m$ volt

$= 4.44 \times 660 \times 25 \times 0.02475 =$ **1815 volt** (*Ans.*)

(*v*) For the same current density, the full load primary and secondary currents remain unaltered.

$\therefore$ kVA rating of the transformer $= \dfrac{30.3 \times 1815}{1000} =$ **55 kVA** (*Ans.*)

Practice Questions

Qn1. A 2000/200V, 20 kVA transformer has 66 turns in the secondary. Neglecting the losses calculate:

(i) primary turns

(ii) primary and secondary full load currents.

Qn2. A 100kVA, 11/0.44kV, 50Hz single phase transformer has an effective cross sectional area of core 0.02m^2 and has 100 turns in its LV winding. Determine:

(i) the maximum value of flux density,

(ii) the number of turns on the HV winding

(iii) full load current in each winding

Self Assessment

- What essentially is a transformer? What are the broad areas of applications of transformer?
- Why does a transformer have iron core?
- Why is the transformer core laminated?
- Why arcing horns are provided across the transformer bushings?
- What is an ideal transformer?
- Can a transformer work on DC? Justify.
- The secondary of a 100 kVA, 3300/400 V, 50 Hz, one-phase transformer carries 110 turns. Determine the approximate values of the primary and secondary full-load currents, the maximum value of flux in the core and the number of primary turns. How does the core flux vary with load? [Ans. 30.3 A; 250 A; 16.4 mWb; 907]