Ministry of Higher Education and Scientific Research

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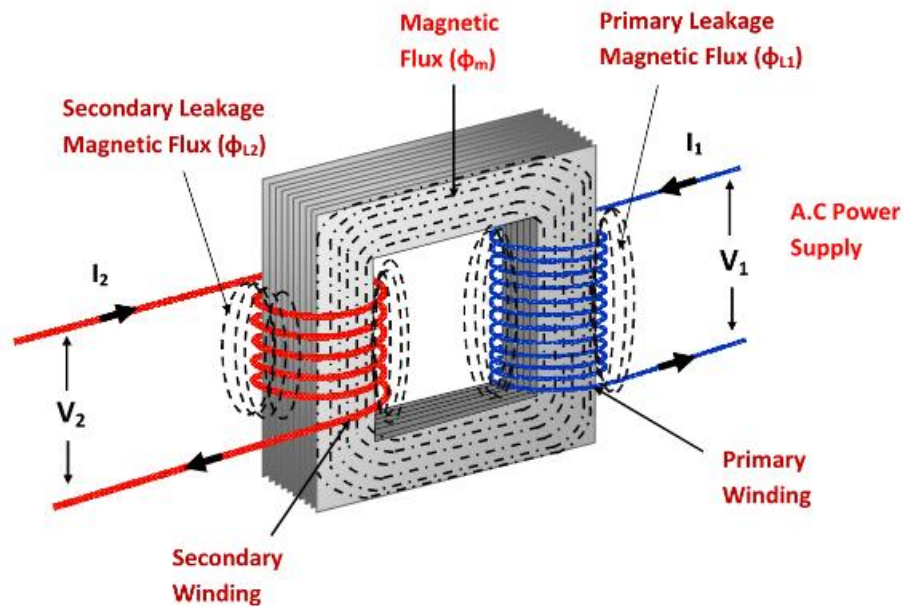
Electrical Machines

Second year

Lecture 1 and Lecture 2

Single Phase Transformers

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1. Introduction

A transformer is a device which converts magnetic energy into electrical energy. It consists of two electrical coils called as a primary winding and secondary winding. The primary winding of a transformer receives power, while the secondary winding delivers power. A magnetic iron circuit called "core" is commonly used to wrap around these coils. Though these two coils are electrically isolated, they are magnetically linked.

An electric current when passed through the primary of a transformer then a magnetic field is created, which induces a voltage across the secondary of a transformer. Based on the type of application, the single-phase transformer is used to either step-up or step-down the voltage at the output. This transformer is typically a power transformer with high-efficiency and low losses.

A transformer is a static machine.

2. Transformer Construction

There are three components of a Transformer:

1- Iron Core

2- Primary Winding

3- Secondary Winding

2.1 Core

The core of the transformer is rectangular in shape and laminated. During the transformer construction, it has to be designed in such a way that there are fewer core losses during the operation of the Transformer. Core losses and iron losses are a combination of all the losses that happen inside the core.

The alternating flux produces certain currents known as Eddy currents. These currents use electrical energy and cause certain losses, known by the name of eddy current losses of the Transformer. The core must be manufactured as a group of laminations. These successive laminations are electrically insulated to reduce eddy currents. The insulation layer is made up of Varnish, which offers high resistance to eddy currents.

2.2 Windings

There are two windings on the transformer i.e. Primary Winding and Secondary Winding. The Primary Winding is connected to the input terminal and is responsible for generating a self-induced EMF. The Secondary Winding is connected to the output load. These windings are placed on the core and are electrically insulated from each other and the core for proper functioning and reduction in losses.

These coils have different numbers of turns compared to each other. The Primary Winding of the Transformer has N_1 turns. Similarly, the Secondary Winding of the Transformer has N_2 turns. Depending upon the operation of the transformer, $N_1 < N_2$, $N_1 > N_2$, and $N1 = N_2$.

3. Types of transformers

Transformers can be classified on different basis, like types of construction, types of cooling etc. **On the basis of their purpose.**

1. Step up transformer: Voltage increases (with subsequent decrease in current) at secondary.

2. Step down transformer: Voltage decreases (with subsequent increase in current) at secondary.

On the basis of type of supply

1- Single phase transformer

2- Three phase transformers

On the basis of their use

1- Power transformer: Used in transmission network, high rating

2- Distribution transformer: Used in distribution network, comparatively lower rating than that of power transformers.

3- Instrument transformer: Used in relay and protection purpose in different instruments in industries

▪ Current transformer (CT)

▪ Potential transformer (PT)

On the basis of construction, transformers can be classified into two types as;

1- Core type transformer.

2- Shell type transformer.

3.1 Core type transformer

In core type transformer, windings are cylindrical former wound, mounted on the core limbs as shown in the Figure1. The cylindrical coils have different layers and each layer is insulated from each other. Materials like paper, cloth or mica can be used for insulation. Low voltage windings are placed nearer to the core, as they are easier to insulate.
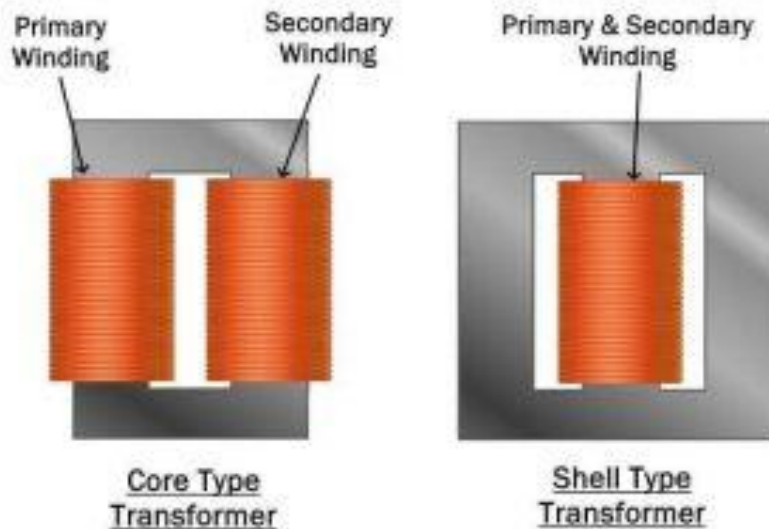
Fig 1. Shell and Core type.

3.2 Shell type transformer

The coils are former wound and mounted in layers stacked with insulation between them. A shell type transformer may have simple rectangular form or it may have a distributed form.

4. Working principle of transformer

The **basic principle behind working of a transformer** is the phenomenon of mutual induction between two windings linked by common magnetic flux. The figure shows the simplest form of a transformer. Basically a transformer consists of two inductive coils; primary winding and secondary winding. The coils are electrically separated but magnetically linked to each other. When, primary winding is connected to a source of alternating voltage, alternating magnetic flux is produced around the winding. The core provides magnetic path for the flux, to get linked with the secondary winding. Most of the flux gets linked with the secondary winding which is called as 'useful flux' or main 'flux', and the flux which does not get linked with secondary winding is called as 'leakage flux'. As the flux produced is alternating (the direction of it is continuously changing), EMF gets induced in the secondary winding according to Faraday's law of electromagnetic induction. This emf is called 'mutually induced emf', and the frequency of

mutually induced emf is same as that of supplied emf. If the secondary winding is closed circuit, then mutually induced current flows through it, and hence the electrical energy is transferred from one circuit (primary) to another circuit (secondary).
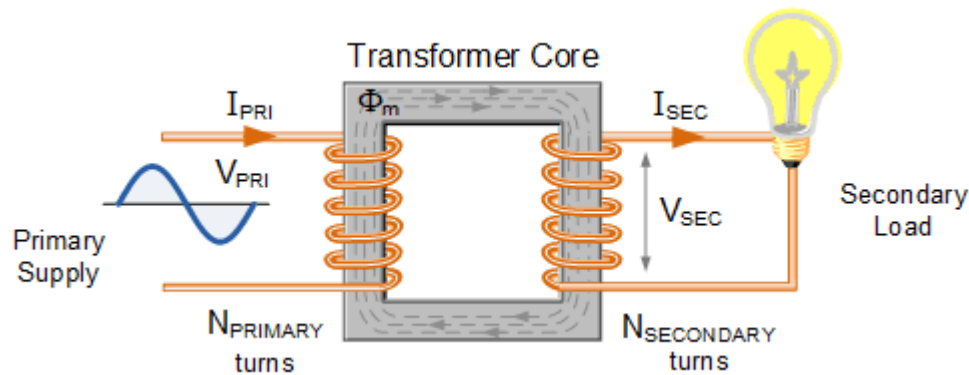

Fig 2. Single phase transformer.

5. Elementary Theory of an Ideal Transformer

An ideal transformer is one which has no losses, i.e. its windings have no ohmic resistance and there is no magnetic leakage. In other words, an ideal transformer consists of two coils which are purely inductive and wound on a loss-free core.

It may, however, be noted that it is impossible to realize such a transformer in practice, yet for convenience, we will first analyze such a transformer and then an actual transformer. Consider an ideal transformer [Fig. 3(a)] whose secondary is open and whose primary is connected to a sinusoidal alternating voltage V_1. Under this condition, the primary draws current from the source to build up a counter electromotive force equal and opposite to the applied voltage.

Since the primary coil is purely inductive and there is no output, the primary draws the magnetizing current I_μ only. The function of this current is merely to magnetize the core, it is small in magnitude and lags V_1 by 90°. This alternating current I_μ produces an alternating flux f which is proportional to the current and hence is in phase with it. This changing flux is linked with both the windings. fore, it produces self-induced emf in the primary. This self-induced emf

e_1 is, at any instant, equal to and in opposition to V_1. It is also known as counter emf of the primary.
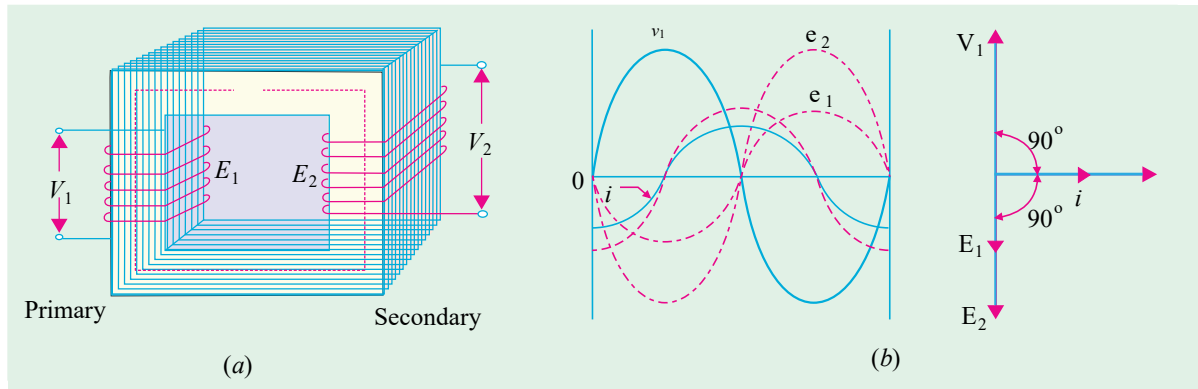

Fig 3. Single phase transformer.

Similarly in the secondary winding, an induced emf e_2 is produced which is known as mutually induced emf. The emf is in phase opposition with V_1 and its magnitude is proportional to the rate of change of flux and the number of secondary turns. Figure 3(b) shows the vectorial representations of the above quantities.

6. E.M.F. Equation of a Transformer

Let N_1 = Number of turns in primary , N_2 = Number of turns in secondary

ϕ_m is Maximum flux in the core in Weber , B_m = Flux density in weber/ m² (Tesla)

A = Net cross-sectional area of core in m², f = Frequency of ac input in Hz

V_1 = Instantaneous value of applied voltage in primary winding in volts.

V_{1m} = Maximum value of applied voltage in volts.

The instantaneous value of counter electromotive force e1 is

$$e_1 = -N_1 \frac{d\phi}{dt}$$

the counter emf e_1 is equal and opposite to applied voltage V_1, i.e.

$$v_1 = N_1 \frac{d\phi}{dt}$$

If the applied voltage is sinusoidal, that is

$$v_1 = v_{1m} \sin 2\pi f t$$

Then

$$\phi = \phi_m \sin 2\pi f t$$

$$e_1 = -N_1 \phi_m \, 2\pi f \times \cos 2\pi f t$$

These equations are expressed as vectors as shown in Fig. 2.2(b), where V_1 and E_1 are the rms values of v_1 and e_1. To obtain the rms value of counter emf e_1, divide its maximum value given above by $\sqrt{2}$.

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

The cosine term has no significance except to derive the instantaneous values.

$$E_1 = 4.44 N_1 \phi_m f$$

$$E_1 = 4.44 N_1 B_m A f$$

Similarly rms value of emf induced in secondary is,

$$E_2 = 4.44 N_2 B_m A f$$

7. Voltage Transformation Ratio (K)

The ratio K is defined as the division of the secondary emf over the emf of the primary side.

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K$$

This constant is known as voltage transformation ratio.

1- If $N_2 > N_1$, i.e., K > 1, then the transformation is called as step-up transformer.

2- If $N_1 > N_2$, i.e., K < 1, then the transformation is called as step-down transformer.

8. Electrical Power in a Transformer

Another one of the transformer basics parameters is its power rating. The power rating of a transformer is obtained by simply multiplying the current by the voltage to obtain a rating in **Volt-amperes**, (VA). Small single phase transformers may be rated in volt-amperes only, but much larger power transformers are rated in units of **Kilo volt-amperes**, (kVA) where 1 kilo volt-ampere is equal to 1,000 volt-amperes, and units of **Mega volt-amperes**, (MVA) where 1 mega volt-ampere is equal to 1 million volt-amperes.

In an ideal transformer (ignoring any losses), the power available in the secondary winding will be the same as the power in the primary winding, they are constant wattage devices and do not change the power only the voltage to current ratio. Thus, in an ideal transformer the **Power Ratio** is equal to one (unity) as the voltage, V multiplied by the current, I will remain constant.

That is the electric power at one voltage/current level on the primary is "transformed" into electric power, at the same frequency, to the same voltage/current level on the secondary side. Although the transformer can step-up (or step-down) voltage, it cannot step-up power. Thus, when a transformer steps-up a voltage, it steps-down the current and vice-versa, so that the output power is always at the same value as the input power. Then we can say that primary power equals secondary power, ($P_1 = P_2$).

9. Transformer Efficiency

The transformer's efficiency has a direct effect on its performance and aging. In general, the efficiency of a transformer is in the range of 95 – 99 %. The efficiency of large power transformers

with very low losses can be as high as 99.7%. The output and input of a transformer are not measured under loaded conditions when the wattmeter readings inevitably suffer errors of 1 – 2%.

The copper losses depend on the currents through the transformer primary and secondary windings and the core losses depend on the transformer rated voltage. Therefore, transformer efficiency plays an important role in operating it under constant voltage and frequency conditions. The temperature rise of the transformer due to heat generated has an effect on the life of transformer oil properties and decides the reasonable type of cooling method. The rating of the equipment is limited by the temperature rise. The **transformer' efficiency** is simply shown as

$$\eta = \frac{Output\ Power}{Input\ Power} \times 100\%$$

For a practical transformer, the input power is given by,

Input power = Output power + Losses

Therefore, the transformer efficiency can also be calculated using the following expression:-

$$\eta = \frac{Output\ Power}{Output\ Power\ +\ Losses} \times 100\%$$

Examples 1: The maximum flux density in the core of a 250/3000-volts, 50-Hz single phase transformer is 1.2 Wb/m². If the e.m.f. per turn is 8 volt, determine

1- Primary and secondary turns

2- Area of the core.

Solution

$E_1 = N_1 \times e.\,m.\,f/turn$

N_1= 250/8 = 32; N_2 = 3000/8 = 375

1- We may use $E_2 = 4.44 N_2 B_m A f$

$$3000 = 4.44 \times 50 \times 375 \times 1.2 \times A \implies A = 0.03 \, m^2.$$

Example 2: A single-phase transformer has 400 primary and 1000 secondary turns. The net cross-sectional area of the core is 60 cm². If the primary winding be connected to a 50-Hz supply at 520 V, calculate

    1- Peak value of flux density in the core

    2- Voltage induced in the secondary winding.

Solution

    1- $K = \dfrac{N_2}{N_1} = \dfrac{1000}{400} = 2.5$

    $\dfrac{E_2}{E_1} = K \implies E_2 = KE_1 = 2.5 \times 520 = 1300 \, V$

    2- $E_1 = 4.44 N_1 B_m A f \implies 520 = 4.44 \times 50 \times 400 \times B_m \times (60 \times 10^{-4})$

$$B_m = 0.976 \, \text{Wb/m}^2$$

Example 3: The Secondary of a 500 kVA, 4400/500 V, 50 Hz, single-phase transformer has 500 turns. Determine

    1- e.m.f Per Turn.

    2- Primary turns.

    3- Secondary full load current.

    4- Maximum flux.

    5- Gross cross-sectional area of the core for flux density of 1.2 tesla.

Solution

VA = 500 kVA , $E_1 = 4400 \, V$, $E_2 = 500 \, V$, $f = 50 \, Hz$, $N_2 = 500$, $B_m = 1.2 \, T$

1- $\dfrac{E_2}{N_2} = \dfrac{500}{500} = \mathbf{1}$ V/turn

2- $\dfrac{E_1}{N_1} = 1 = \dfrac{4400}{N_1} \implies N_1 = \mathbf{4400}$

3- Secondary full load current $I_2 = \dfrac{kVA}{V_2} = \dfrac{500 \times 1000}{500} = \mathbf{1000\ A}$

4- Maximum flux, $\phi_m = \dfrac{E_2}{4.44 \times N_2 \times f} = \dfrac{500}{4.44 \times 500 \times 50} = \mathbf{4.5\ mWb}$