6

Transformers

TOPICS DISCUSSED

- Applications of transformers
- Basic principle of transformers
- Constructional details
- EMF equation
- Transformer on no load and on load
- Phasor diagrams
- Circuit parameters
- Equivalent circuit
- Losses and efficiency
- Regulation
- All-day efficiency
- Basic tests on transformers

6.1 INTRODUCTION

Electricity is transmitted from the place of generation to the place of its use through electrical transmission lines which are taken overhead using transmission towers. The voltage level of the power to be transmitted is raised to higher values, say from 11 kV to 220 kV to reduce the cost of transmission. High-voltage transmission reduces the size of transmission line conductors thereby reducing the weight of the conducting material used. Since power is the product of voltage and current, for the same power if voltage is increased, the magnitude of current will decrease. For transmitting at this reduced current, the size of the line conductors will reduce, and hence the cost gets reduced. The power house wherefrom electricity is transmitted through transmission lines is called the 'sending end' whereas the other end of the transmission lines where the electricity is received for use is called the 'receiving end'. At the sending end the voltage level is increased using step-up transformers before, connecting to the transmission lines, while at the receiving end the voltage level is lowered before the distribution of electricity for use. The voltage level is raised for reducing the cost of transmission while it is again lowered before supplying to consumers, for safety reasons. Consumers use electricity at 230 V or at 400 V.

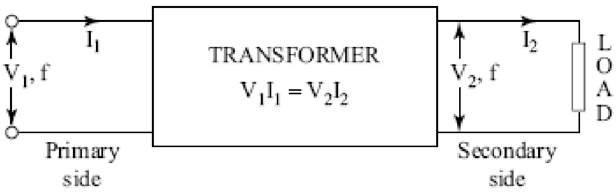


Figure 6.1 Block diagramatic representation of a transformer

A device known as transformer which either raises or lowers the voltage level of electrical power is always used at both the ends of the transmission lines. When voltage is raised from lower level to higher level, the device used is called a step-up transformer. When voltage is lowered from a high level to a low level, the transformer used is called a step-down transformer.

The frequency of the alternating voltage on both sides of the transformer will not change. Whatever the frequency of the input voltage is, the same will be the frequency of the output voltage.

With this introduction, we may define a transformer as a device which raises or lowers the voltage level of any electrical power input without changing the frequency. The block diagramatic representation of a transformer has been shown in Fig. 6.1.

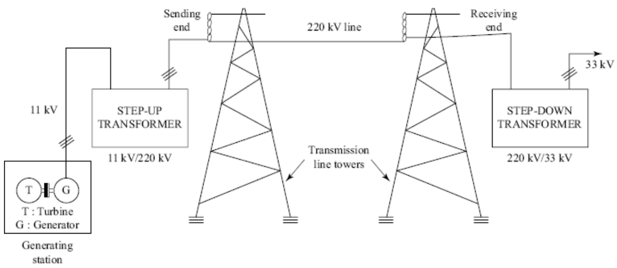
6.2 APPLICATIONS OF TRANSFORMERS

Volt–ampere rating of the transformer is the same whether calculated on the low-voltage side or at the high-voltage side. It must be noted that a transformer does not generate any electricity. It only transforms and transfers electrical power from one circuit to the other at different voltage levels. Depending upon the requirement, transformers are made for various voltage and current ratings.

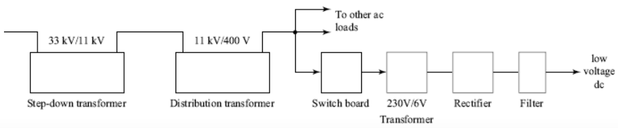
rated at, say, 11 kV/220 kV and several MVAs (mega volt ampers) as their power ratings.

Smaller transformers are used in lowering the voltage level for the purpose of distribution of electricity to consumers. The transformer which feeds electricity to your house will have specifications like 11 kV/400 V, 50 Hz, 500 kVA. Here, the voltage is being reduced to 400 V or 230 V at the user end for safe supply to residences. These are called *distribution transformers*. Supply of power at high voltage to residences may lead to chances of fatal accidents and other problems. Equipment to be used also have to be manufactured for higher voltage ratings. Insulation of wires used in house wiring will have to be sustaining for higher voltages. Therefore, electricity is supplied at residences at 230 V for single-phase appliances and at 400 V for three-phase equipment. Very small transformers are used in many electrical and electronic equipment, and gadgets to lower the voltage level from 230 V on one side to, say, 6 V or 3 V, on the other side. For example, if you are to construct a battery eliminator for your transistor radio, or your tape recorder, you need to get 6 V dc supply from the available 230 V ac supply. A transformer is required to step down the voltage and then a diode rectifier and filter are required to get the steady 6 V dc output. Fig. 6.2 shows the use of transformers of different voltage ratings.

Electricity is generated in the power house when a turbine (T) rotates a generator (G). The generation voltage is 11 kV which is stepped up to 220 kV by a step-up transformer. The output of the transformer is connected to the high-voltage transmission line. At the receiving end of the transmission line, a step-down transformer is used to bring the voltage level again to a lower level. The power received is further stepped-down to lower voltage by use of distribution transformers and is connected to the load of the consumer, i.e., to industry, commercial buildings, and residential houses. Fig. 6.2 (b) shows the use of distribution transformers for supply to various kinds of electrical loads including low-voltage dc supply after rectification. Thus, we have seen that transformers of different voltage levels and power capacity are used for transmission, distribution, and utilization of electricity. Transformers are, therefore, seen as one of the most important components of the whole power system network.



(a) Single-line diagram of the power transmission system (only one line has been shown)



(b) Block-diagramatic representation of the distribution of electricity for end use

Transformers work on the principle of electromagnetic induction. To understand the principle of working of a transformer, one small experiment can be performed as explained below. We will need one battery, one single-way and one two-way switch, two coils, and a PMMC-type dc low-range center zero voltmeter. The connections are as shown in Fig. 6.3. In Fig. 6.3 (a), when the switch S is turned on and off quickly, the voltmeter neddle will get deflected. In Fig. 6.3 (b), a two-way switch is used. When the switch is quickly turned on and off, the current through coil 1 will flow in opposite directions every time the switch is operated. There will be voltage induced in the second coil as would be indicated by the deflection of the needle of the voltmeter in opposite directions.

Operation of the two-way switch in opposite directions changes the polarity of supply voltage to coil 1. The frequency of change of polarity will depend upon how quickly the switch is repeatedly operated. This is equivalent to connecting an ac supply of certain frequency to coil 1, which has been shown in Fig. 6.3 (c).

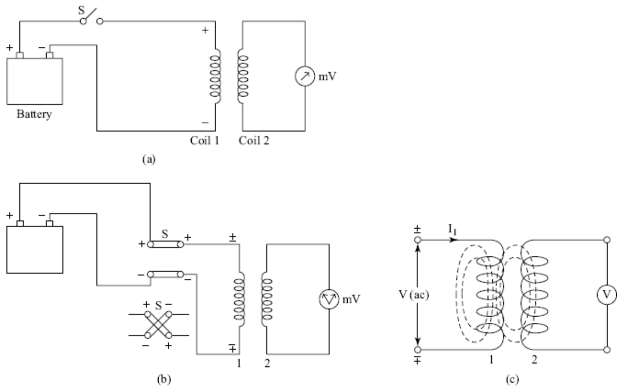


Figure 6.3 Principle of electromagnetic induction: (a) changing current in coil 1 produces EMF in coil 2; (b) changing current flowing in reverse direction in coil 1 produces alternating voltage in the second coil; (c) alternating voltage applied to coil 1 induces alternating EMF in the second coil

Voltage is induced in the second coil due to changes of current flowing in the first coil. When current flows through the first coil a flux is produced around the coil. If current is changing, the flux produced will also change. If the second coil is placed near the first coil, there will be a changing linkage of the flux by the coils. This will induce EMF in both the coils. The magnitude of EMF induced will depend upon the rate of change of the flux linkage and the number of turns of the coil.

6.3.1 Basic Principle

The basic principle of the transformer is that EMF is induced in a coil due to the rate of change of flux linkage by it as has been shown in Fig. 6.3 (c).

through the core, and hence through the windings. Since it is necessary to produce more flux by using small current, the reluctance of the flux path must be low. Iron has high permeability, i.e., low reluctance. Use of iron as the core material for the windings improves the magnetic coupling between the windings, which is essential for the transfer of power from one circuit to the other efficiently.

By changing the ratio of the number of turns of the coils the magnitude of the induced EMF in the second coil can be changed, e.g. if the number of turns of the second coil is less than the first coil, EMF induced will be less. The frequency of the induced EMF in the two coils will be the same as that of the frequency of power supply to the first coil. Now, it should be possible to connect an electrical load across the second coil, and power will be delivered to the load. Thus, when electrical supply is connected to the primary circuit or the winding, power gets transferred to the second circuit via the magnetic circuit. This device, called transformer, is based on the same principle of magnetic coupling of two coils. The constructional details of a transformer is described as follows.

6.3.2 Constructional Details

Fig. 6.4 (a) shows the outside view of a transformer. It may be noted that the transformer is placed inside an iron tank filled with oil. The tank has some radiating tubes and fins so that oil inside the tank gets circulated and the heat from the transformer is radiated to the atmosphere. The transformer consists of a core made up of a magnetic material around which two coils are placed. One coil is connected to supply voltage as shown in Fig. 6.4 (b). This coil is called the primary winding. The other coil is called the secondary winding. Supply is taken from the secondary winding by connecting any electrical load like fan, tube light, electrical motors, etc.

The transformer core is made up of thin sheets called laminations. The laminated silicon steel sheets are cut into proper size from a big sheet and are placed one above the other to form the core of required width and cross section. The laminated sheets are tightly fastened to form the core. If the laminations are not tightly fastened, they will vibrate in the magnetic field and give rise to humming noise. This magnetic vibration of laminations is known as magnetostriction which is not desirable. The core is made up of a magnetic material using thin laminated sheets instead of a solid one. This is done to reduce power loss in the core due to circulating current flowing in the core and producing undesirable heating of the core as well as of the windings which are wound on the core. The reason for circulating current in the core is explained below. When an alternating voltage is applied across the primary winding, an alternating current I_0 will flow through the winding. This current will produce an alternating flux which will link (i.e., pass through) both the primary and secondary windings. The flux will close their path through the magnetic material, i.e., the core material. EMFs will be induced in the both the windings due to change of flux linkage as induced EMF, e is expressed as

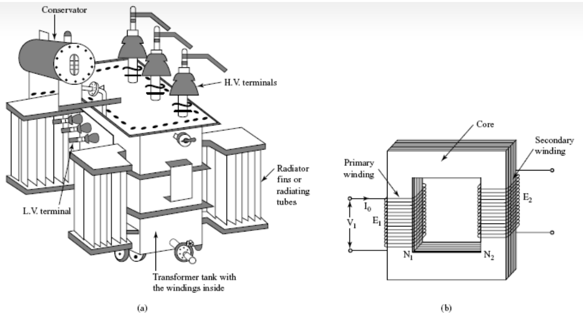


Figure 6.4 Constructional details of a transformer. (a) Outside view of a transformer; (b) view of core and windings

$$e = -N\frac{d\phi}{dt} \tag{6.1}$$

where, N is the number of turns of the winding, and ϕ is the flux produced.

EMF will also be induced in the core material when the material is being subjected to an alternating magnetic field. Due to this induced EMF in the core, a circulating current, called eddy current will flow across the core cross section. If the core is laminated and the laminated sheets are varnished with varnish insulation, the eddy current will get reduced, and hence there will be reduced eddy current loss. To reduce the eddy current loss in the core it is, therefore, made up of thin laminated silicon steel sheets.

Instead of iron, the core is made up of laminated silicon steel sheets. When a certain percentage of silicon is added to steel, the hysteresis loss in the core gets reduced. Hysteresis loss occurs due to orientation of the magnetic dipoles of the magnetic material when the material is subjected to the alternating magnetic field.

The windings of the transformer are made up of insulated copper wires. The cross-sectional area of the winding wires will depend upon the requirement of current-carrying capacity, and the number of turns are calculated according to the voltage ratio of primary and secondary windings. The core and the winding assembly are placed inside a tank filled with transformer oil for the purpose of providing insulation to the windings and also for cooling purpose. Transformer oil used is mineral oil having high dielectric strength. The tank is provided with radiating tubes so that heated oil gets circulated through the tubes and heat produced in the transformer is radiated to the atmosphere through the oil circulating from the tank through the radiating tubes.

Heat is produced in the transformer due to I^2R loss in the windings and hysteresis and eddy current loss in the core. The I^2R loss in the windings will depend upon the magnitude of current flow through the windings when the transformer is supplying some electrical load. The core loss which is the sum of hysteresis loss and eddy curthe core loss will remain constant. That is why the core loss is called constant loss. The I^2R loss which is also called copper loss is a variable loss, as it varies with the magnitude of load current.

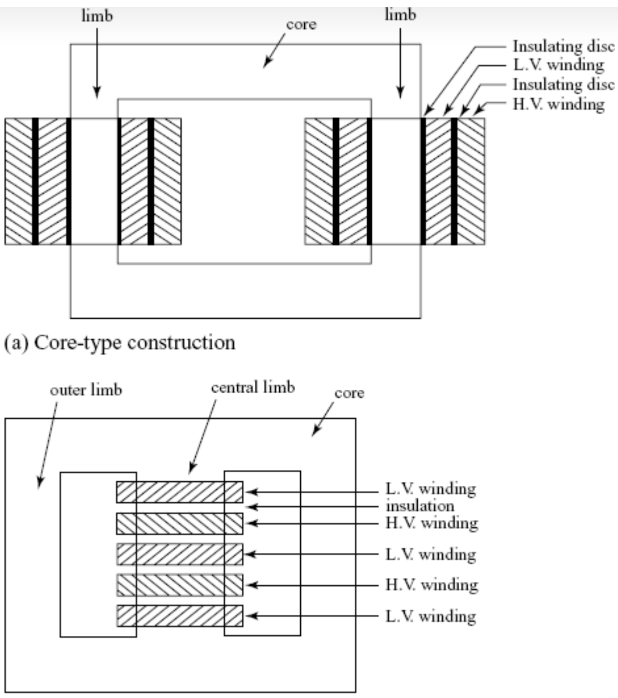
These losses will overheat the transformer unless the heat generated is radiated out to the atmosphere. If a transformer gets too overheated, its insulation strength will reduce and ultimately there may be short circuit inside the transformer damaging it completely.

Transformers are manufactured as single-phase transformers and as three-phase transformers. In three-phase transformers three separate windings are made for both primary and secondary sides. The windings are connected either in star or in delta. Terminal connections are brought out through low voltage (L.V.) terminals and high voltage (H.V.) terminals. A conservator tank fitted with a breather is placed above the tank. The conservator is connected to the transformer tank with a pipe and carries transformer oil. The empty space above the level of oil in the conservator is provided to allow the expansion of oil in the tank due to heating and for the removal of gas formed.

6.4 CORE-TYPE AND SHELL-TYPE TRANSFORMERS

There are two types of core constructions, viz core type and shell type. In core-type construction, the primary and secondary windings are placed around the limbs of the transformer core. The windings are made in cylindrical form and are placed around the core limbs. First, the low-voltage winding is placed around the limbs. Over the low-voltage windings are placed the high-voltage windings. The high-voltage winding is placed somewhat away from the core so as to reduce the insulation problem. The windings are insulated from the core through insulating cylindrical disc made of insulating material. The windings are made up of insulated copper wires in two sections or parts and are connected after they are placed in positions to form primary and secondary windings, respectively.

In a shell-type construction, the windings are placed in the central limb. The windings are wound in the form of a number of circular discs, and are placed one above the other. The extreme two discs on the central limb are low-voltage winding sections. These, l.υ sections and h.υ. sections are then connected to form low-voltage- and high-voltage windings. The width of the central limb is twice the width of the outer limbs so that the flux density is the same in all the limbs.



(a) Core-type construction

(b) Shell-type construction

Figure 6.5 Core-type and shell-type transformers

The choice of type of core to be used for transformer construction depends on a number of factors. In power transformers, in general, the core-type construction is preferred while for distribution transformers, the shell-type construction is preferred. The leakage flux and leakage reactance of a transformer depends upon the magnetic coupling between the primary and secondary windings. Voltage regulation and short-circuit impedance depend upon the leakage reactance of a transformer. In the shell-type construction the magnetic coupling is better than in the core-type construction.

6.4.1 Power Transformers and Distribution Transformers

Power transformers are connected at the two ends of the transmission lines to step up or to step down the voltage. A number of such transformers are connected in parallel depending upon the amount of power to be transmitted. They are rated for high voltages, e.g. 11 kV/220 kV, 100 MVA. The size of such transformers is very large. They are installed outdoors in a substation.

Distribution transformers feed electricity to the consumers. They are rated for voltages like 11 kV/400 V. These transformers are generally of pole-mounted type and always remain energized being ready all 24 hours to supply electricity to the consumers. Even if there is no consumption of electricity from a distribution transformer, it has to remain energized all the time. The core losses of such transformers must be low by design. Otherwise, their all-day operating efficiency will be low.

quency of the primary supply voltage which is normally 50 Hz. The magnitude of the EMF induced in the two windings of a transformer will be different if they have different number of turns. Let us now derive the EMF equation. Referring to Fig. 6.6, and considering a sinusoidal input voltage, V_1 at a frequency, f, the flux produced due to current, I_0 is $\phi = \phi_m \sin \omega t$.

The general equation for the instantantaneous value of the EMF induced, e is expressed as

$$e = -N \frac{d\phi}{dt}$$

[Note that the minus sign indicates that the induced EMF opposes the supply voltage according to Lenz's law.]

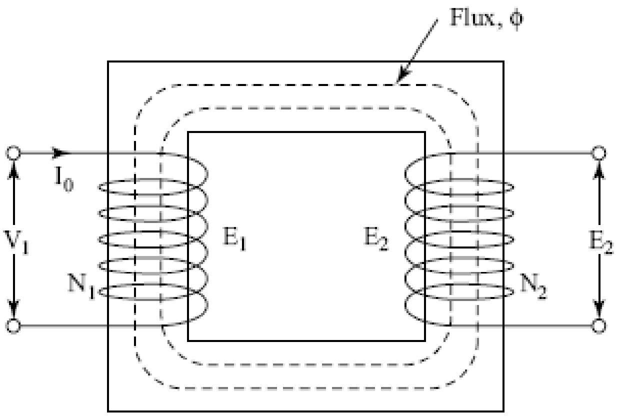


Figure 6.6 Two windings of a transformer wound on a common core

A sinusoidally varying flux is represented as

$$\phi = \phi_m \sin \omega t$$

where ϕ is the instantaneous value, and ϕ_m is the maximum value

Considering $\phi = \phi_m \sin \omega t$,

$$e = -N \frac{d(\phi_m \sin \omega t)}{dt}$$

$$
\begin{aligned}
e &= -N\,\phi_m \omega \cos \omega t \\
&= -N\,\phi_m \omega[-\sin(\omega t - \pi/2)] \\
&= N\,\phi_m\,\omega \sin(\omega t - 90^\circ)
\end{aligned}
$$

This equation is of the form

$$e = E_m \sin(\omega t - 90^\circ)$$

where $E_m = N\,\phi_m\,\omega$

or, $E_m = N\,\phi_m\,2\pi f$

We know for a sinusoidal voltage, the RMS value is $\frac{1}{\sqrt{2}}$ times its maximum value. If, E is the RMS value of the induced EMF, then

$$E = \frac{E_m}{\sqrt{2}} = \frac{N\phi_m 2\pi f}{\sqrt{2}} = \frac{N\phi_m 2 \times 3.14 f}{1.414}$$

or, $$E = 4.44\,\phi_m\,f N\,V \tag{6.2}$$

Primary winding has N_1 turns. The induced EMF in the primary winding E_1 is

$$E_1 = 4.44\,\phi_m\,f N_1\,V \tag{6.3}$$

Since the same flux producing E_1 also links the secondary winding having N_2 number of turns, the induced EMF in the secondary winding, E_2 is

$$E_2 = 4.44\,\phi_m\,f N_2\,V \tag{6.4}$$

Dividing eq. (6.3) by eq. (6.4),

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

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

K is called the ratio of voltage transformation. For a step-up

Transformer on no-load means that the secondary winding is open and no electrical load (like a motor, a heater, a fan, an air-conditioner, etc.) is connected across its terminals for supply of electrical power. Since the transformer on no-load is not doing any useful work except that it remains energized and is ready to supply electricity when required, its output on no-load is considered to be zero, On the input side, the transformer will draw some small amount of current, I_0. Simplified representation of a transformer on no-load has been shown in Fig. 6.7 (a). Since there is no load connected across the secondary winding, the circuit is open, and hence no current will flow through the secondary winding as has been shown. The primary supply voltage is V_1 and the current flowing through this winding is I_0. What will be the phasor relationship between V_1 and I_0? If the winding is a purely inductive one, I_0 will lag the voltage V_1 by 90°. However, there will be hysteresis loss and eddy current loss in the core. Thus, I_0 should have a component I_C in phase with V_1. The core loss is equal to $V_1 I_C$ Watts. Therefore, I_0 will lag V_1 by an angle somewhat less than 90°. If V_1 is shown vertical, I_0 will lag V_1 by an angle ϕ_0 of say 85° as has been shown in Fig. 6.7 (b).

The induced EMFs E_1 and E_2 which are due to a time-varying flux ϕ will lag ϕ by 90°. This can be observed from the EMF equation where it was shown that when $\phi = \phi_m \sin \omega t$, the induced EMF $E = E_m \sin(\omega t - \pi/2)$. Again, according to Lenz's law, the induced EMF E_1 must oppose the cause from which it is due, i.e., V_1. The magnitude of E_1 will be somewhat less than V_1. This can be observed from Fig. 6.7 (a) where it is seen that current I_0 flows from a higher potential V_1 to a comparatively lower potential E_1. Thus E_1 opposes V_1, E_1 is created by ϕ and lags ϕ by 90°. The phasor relationship of V_1, I_0, ϕ, E_1, E_2 has been shown in Fig. 6.7 (b). It has also been shown that I_0 can be resolved into two components I_m and I_c, where I_m is in phase with ϕ and is responsible for producing ϕ. This I_m is also called the magnetizing current because this current magnetizes the core, i.e., produces the required flux in the core. I_m is equal to $I_0 \sin \phi_0$. I_c is equal to $I_0 \cos \phi_0$. Therefore, $\sqrt{I_m^2 + I_c^2}$. The no-load power input W_0 is equal to $V_1 I_0 \cos \phi_0$ which equals $V_1 I_c$. The induced EMF in the secondary winding, i.e., E_2 has been shown lagging flux ϕ by 90°. It has been assumed that $N_2 > N_1$, and hence $E_2 > E_1$.

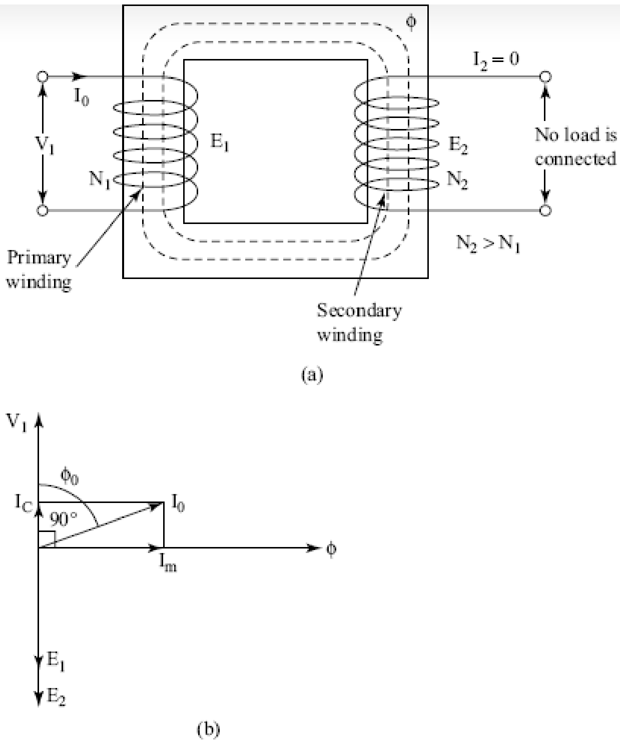


Figure 6.7 Transformer on no-load: (a) core and the windings; (b) no-load phasor diagram

Here, cos ϕ_0 is the no-load power factor which is very low (may be 0.1 or so).

The no-load power input is wasted as a loss as there is no output.

Input = output + losses

If output is zero, input equals losses. Let us see what are the no-load losses. Since current I_0 is flowing through the primary winding which has a resistance of, say R_1, there will be some amount of copper loss in the winding as $I_0^2 R_1$ Watts. However, since I_0 is small, $I_0^2 R_1$ will also be small. Since the core is made up of a magnetic material there will be loss in the core. The core loss is due to two reasons. One is called hysteresis loss. Hysteresis loss is caused due to the magnetization of the magnetic material in alternate directions in every half cycle of the supply voltage. The magnetic dipoles of the magnetic core material align themselves in alternate directions producing alternating flux. The work done due to this is equivalent to the input energy spent and is called hysteresis loss.

The other loss component is due to eddy current. Large number of small eddy currents flow in the magnetic core material due to the EMF induced in the core, which is subjected to alternating magnetic field similar to the two windings. EMFs get induced in the core material for the same reason as for the coils. This EMF induced in the core creates current which continues to circulate in the core and

$$W_0 = V_1 I_0 \cos\phi_0 = I_0^2 R_1 + W_h + W_e$$

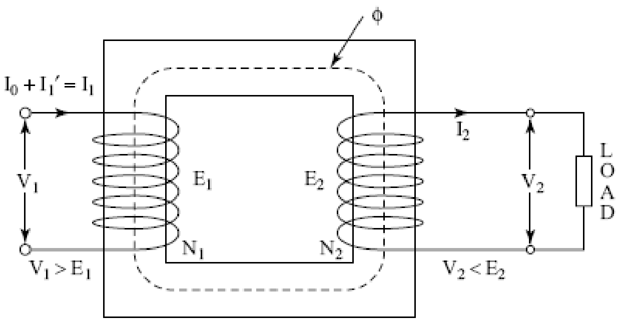
If we neglect the small amount of $I_0^2 R_1$ then, no-load input power

$$W_0 = W_h + W_e = W_c, \text{ i.e., equal to core loss}$$

6.7 TRANSFORMER ON LOAD

When some electrical load is connected across the secondary terminals, power will be supplied to the load from the primary supply via the magnetic circuit. A current of I_2 will flow in the secondary circuit. The voltage available across the load, V_2 will be somewhat less than E_2.

When the transformer is loaded, the secondary current I_2 will create flux in the core in the opposite direction to that of the original core flux ϕ which was produced on no-load. Thus, the resultant flux will get reduced momentarily. This will reduce the induced EMF E_1 and E_2. As E_1 is reduced, the difference between V_1 and E_1 will increase and due to this more current of amount I_1' will flow from the supply mains through the primary winding. This current will produce an opposing flux to that produced by I_2 such that $I_2 N_2 = I_1' N_1$. Then, the two fluxes will balance each other, and hence the original flux ϕ will remain unchanged in the core. Irrespective of the magnitude of the load current, the net core flux remains practically constant at all load conditions.



(a)

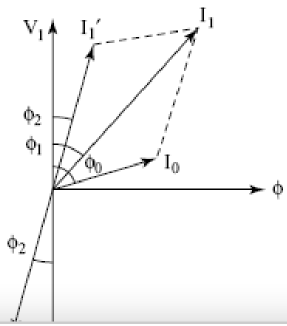


Figure 6.8 (a) Transformer on load; (b) simplified phasor diagram of a transformer on resistive–inductive load

Using ampere-turns balance equation

$$I_2 N_2 = I_1' N_1$$

or,
$$I_1' = \left(\frac{N_2}{N_1}\right) I_2 = K\, I_2$$

It may be noted that under load condition the primary current I_1 is equal to the sum of no-load current I_0 and I_1', which is K times I_2. I_1' is the additional current drawn by the primary winding due to the loading of the transformer.

Thus,
$$I_1 = I_0 + I_1' = I_0 + KI_2$$

The phasor diagram relating all the parameters under loading condition neglecting the voltage drop due to winding resistances and leakage reactances has been shown in Fig. 6.8 (b). The phasor diagram is for some resistive–inductive load when the load power factor angle is ϕ. That is why I_2 has been shown lagging the load voltage V_2 by an angle ϕ_2. I'_1 is the additional primary current drawn from the supply source to counter balance the magnetizing effect of $I_2(I_2 N_2 = I'_1 N_1)$.

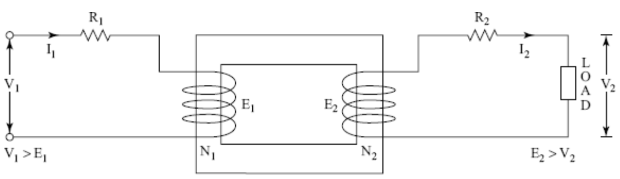


Figure 6.9 Transformer on load

6.8 TRANSFORMER CIRCUIT PARAMETERS AND EQUIVALENT CIRCUIT

Earlier, while explaining transformer on load, we had neglected the winding resistances and leakage reactances of the transformer. Since the windings are made of copper wire of certain cross-sectional area, they will have some resistance. Thinner the wire, higher will be the resistance, for a particular length of the wire. The resistances of the primary and secondary windings are called R_1 and R_2 respectively. When current flows through the windings there will be voltage drop $I_1 R_1$ and $I_2 R_2$ in the primary and secondary windings, respectively. The resistances R_1 and R_2 can be shown carrying current I_1 and I_2 as in Fig. 6.9. When the resistances have been shown may be noted that input voltage V_1 is higher than the induced EMF E_1 (current flows from higher potential V_1 to lower potential E_1). The induced EMF E_2 is greater than load terminal voltage V_2. Neglecting reactances of the windings, the voltage equation are

$$V_1 - I_1 R_1 = E_1$$

and $$E_2 - I_2 R_2 = V_2$$

The power loss in the primary and secondary windings are respectively, $I_1^2 R_1$ and $I_2^2 R_2$ These are also called copper losses. Note that the above two voltage equations have been written considering only the resistances of the windings. Voltage drop due to reactances of the windings has been neglected.

In addition to the resistance of the windings, the windings will have leakage reactances due to the leakage flux in the core. The concept of leakage reactance due to leakage flux is explained below. Fig. 6.10 shows a transformer on load.

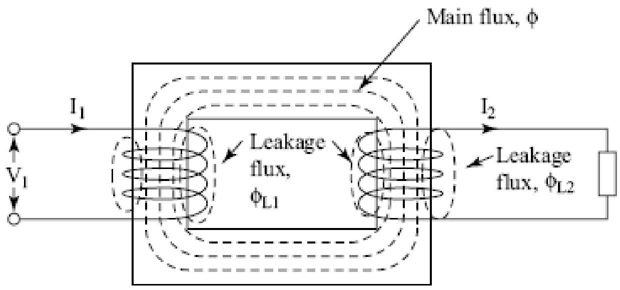


Figure 6.10 Leakage flux and leakage reactance of a transformer

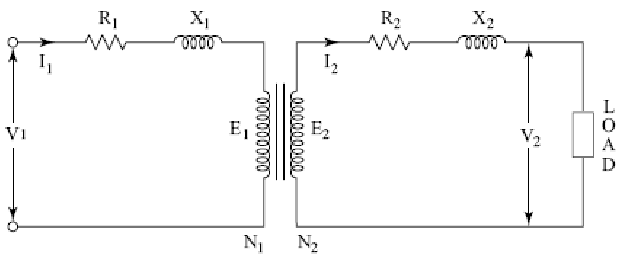


Figure 6.11 Transformer approximate equivalent circuit

The main flux ϕ is common to both the windings. This flux links both the primary and secondary windings. In addition, some more flux, called leakage flux, ϕ_L is created due to current I_1 and I_2 flow-be in phase with I_2. Φ_{L1} will induce an EMF E_{L1}, and Φ_{L2} will induce an EMF E_{L2} in the windings, respectively.

E_{L1} will lag I_1 by 90° and E_{L2} will lag I_2 by 90°. These induced voltages are balanced by the reactance voltage drop in the two windings, respectively. The primary and secondary winding leakage reactances are called, respectively, X_1 and X_2 so that $I_1 X_1$ is considered voltage drop in the primary winding due to leakage reactance X_1 and $I_2 X_2$ is considered voltage drop in secondary winding due to leakage reactance X_2. It is to be noted that EMFs E_1 and E_2 are induced in primary and secondary windings due to main flux Φ whereas E_{L1} and E_{L2} are induced in these windings due to their leakage fluxes Φ_{L1} and Φ_{L2}. The effect of leakage flux and the resulting induced EMF in the two windings are represented by two reactances X_1 and X_2 creating voltage drops. The reactances X_1 and X_2 are in fact two fictitious (imaginary) reactances considered to represent the effect of leakage flux. The complete transformer circuit with its parameters has been shown as in Fig. 6.11. In this circuit diagram we have not considered the no-load current, I_0 drawn by the transformer. So, the circuit shown in Fig. 6.11 is an approximate equivalent circuit of the transformer.

The primary circuit impedance is Z_1 and the secondary winding impedance is Z_2.

$$Z_1 = \sqrt{R_1^2 + X_1^2} \text{ and } Z_2 = \sqrt{R_2^2 + X_2^2}$$

Note that the transformer is a coupled circuit. For the sake of simplicity in calculation, we might like to convert it into a single circuit by transferring the circuit parameters of the primary circuit to the secondary circuit and vice versa.

Let us see how the secondary circuit parameters can be transferred to the primary side. Let R_2' be the value of R_2 when transferred to the primary side. By considering the same amount of losses in the resistance when transferred from one current level to the other, we can equate the copper losses as

$$I_2^2 R_2 = I_1^2 R_2'$$

or,

$$R_2' = R_2 \left(\frac{I_2}{I_1}\right)^2 = R_2 \left(\frac{N_1}{N_2}\right)^2$$

∴

$$R_2' = \frac{R_2}{K^2}, \quad \text{where} \quad K = \frac{N_2}{N_1}$$

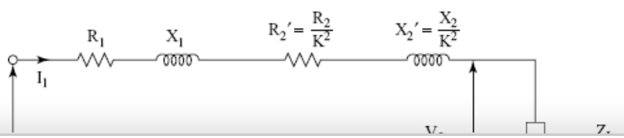


Figure 6.12 Transformer approximate equivalent circuit having transferred the secondary parameters to the primary side

Reactance X = ωL and $L = \frac{\mu N^2 A}{l}$

Therefore, X α N^2

Let X_2, when transferred from the secondary circuit to the primary circuit, be X_2'

$$X_2' = X_2 \left(\frac{N_1}{N_2}\right)^2 = \frac{X_2}{K^2} \qquad \because \frac{N_2}{N_1} = K$$

By transferring the circuit parameter on the primary side, the approximate equivalent circuit of the transformer can be represented as shown in Fig. 6.12.

This circuit can further be simplified by adding the resistances and the reactances for the sake of calculations.

Now we will consider the no-load current of the transformer along with the load currents I_2 and I_1 to draw the complete equivalent circuit.

It may be noted that I_1 is the sum of I_1' and I_0. I_0 has two components, I_m and I_c. I_m lags V_1 by 90° whereas I_c is in phase with V_1. I_m can be shown as a current flowing through an inductive reactance called the magnetizing reactance X_m whereas I_c can be shown as a current flowing through a resistance R_c as shown. The sum of I_m and I_c is I_0. Sum of I_0 and I_1' is I_1. The complete equivalent circuit representing all the parameters has been shown in Fig. 6.13.

The above circuit can be simplified by neglecting I_0 which is about three to five per cent of the rated current of the transformer. So by removing the parallel branch and adding the resistances and reactances we draw the approximate equivalent circuit as shown in Fig. 6.14. Thus, the circuit becomes the same as was drawn in Fig. 6.12 earlier.

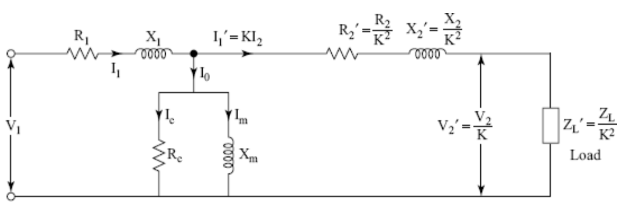


Figure 6.13 Exact equivalent circuit of a transformer

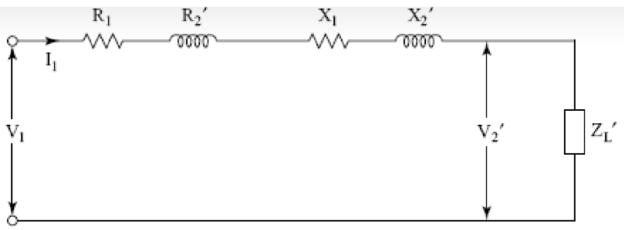


Figure 6.14 Approximate equivalent circuit of a transformer

Combining the resistances and reactances, the equivalent resistances R_e' and equivalent reactance X_e' are represented as Z_e' as has been shown in Fig. 6.15.

This simplified equivalent circuit of the transformer can be used to calculate the performance in terms of voltage regulation of the transformer under various loading conditions.

6.9 PHASOR DIAGRAM OF A TRANSFORMER

The complete phasor diagram of a transformer at a lagging Pf load has been shown in Fig. 6.16 (a).

Procedure for drawing the phasor diagram is given below.

Draw the flux vector as the reference vector along the x-axis. The voltage induced in the two windings, E_1 ans E_2 will lag flux by 90°. If it is a step-up transformer, E_2 will be bigger in length than E_1. Otherwise, they can also be shown as equal. Show two phasors E_1 and E_2 lagging flux ϕ by 90 °. Draw $-E_1$ in opposite direction to E_1, as has been shown in Fig. 6.16. Draw I_2 lagging E_2 by a certain angle. Draw I_1' opposite to I_1. Draw I_o lagging $(-E_1)$ by a large angle. Add I_1' and I_o vectorially to get I_1. Now we have to locate V_1 and V_2. We apply Kirchhoff's law in the primary winding circuit and write $V_1 - I_1 R_1 - jI_1 X_1 - E_1 = 0$

or, $$V_1 = E_1 + I_1 R_1 + jI_1 X_1 \qquad \text{(i)}$$

Similarly, for the secondary circuit we write $E_2 - I_2 R_2 - jI_2 X_2 - V_2 = 0$

or, $$V_2 = E_2 - I_2 I_2 - jI_2 X_2 \qquad \text{(ii)}$$

Using equation (i) develop the phasor diagram step by step.

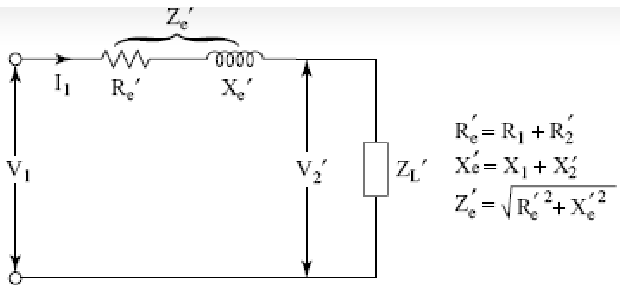


Figure 6.15 Approximate equivalent circuit of a transformer with secondary parameters referred to the primary side

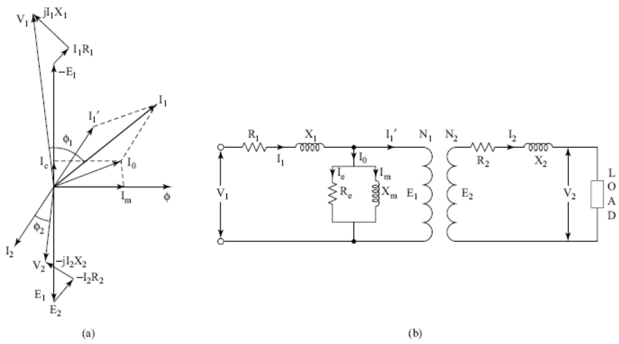


Figure 6.16 (a) Phasor diagram of a transformer on load; (b) equivalent circuit

Add I_1 R_1 with E_1 (E_1 drawn as $-E_1$) vectorially. The direction of I_1R_1 is in the direction of I_1. Then add j I_1X_1. This vector will make 90° with the direction of I_1 in the anticlockwise direction. The resultant vector will be V_1. To get V_2 we have to subtract vectorially I_2R_2 and jI_2X_2 from E_2. The no-load current, I_o is shown as the vector sum of I_m and I_c. I_m is the magnetizing component of the no-load current which produces the flux and is phase with the flux ϕ.

It must be clarified here that E_1 has been taken as $-E_1$ and then the total phasor diagram drawn only for the sake of clarity.

6.10 CONCEPT OF VOLTAGE REGULATION

Voltage regulation of a transformer is defined as the percentage change in terminal voltage from full-load to no-load condition and is expressed as the percentage of the full-load voltage.

Percent voltage regulation $= \dfrac{E_2 - V_2}{V_2} \times 100$

The expression for voltage regulation in terms of load current, load power factor, and transformer circuit parameters can be found from the simplified equivalent circuit of the transformer. For convenience, we will consider the approximate equivalent circuit of the transformer with primary circuit parameters referred to the secondary side as shown in Fig. 6.17. The phasor diagram relating the various quantities has also been shown. R_e'' and X_e'' are the equivalent resistance and reactance, respectively, of the transformer referred to the secondary side.

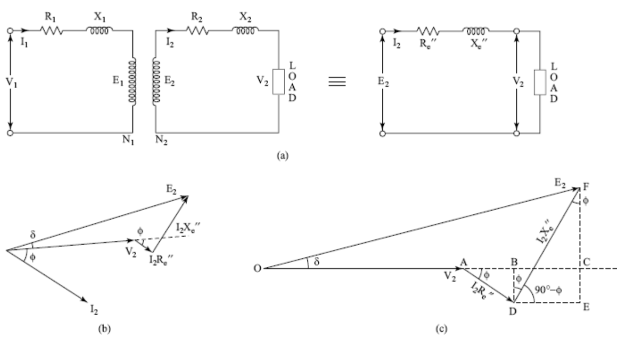


Figure 6.17 (a) Simplified equivalent circuit of a transformer; (b) phasor diagram; (c) use of the phasor diagram for calculation of the voltage drop

The equation relating E_2 and V_2 is

$$E_2 = V_2 + I_2 R_e'' + jI_2 X_e''$$

The phasor diagram shown in Fig. 6.17 (b) has been drawn using the above equation. I_2 has been shown lagging the voltage V_2 by the power factor angle ϕ. We add I_2R_e'' with V_2, I_2R_e'' being taken in the same direction as I_2. Then jI_2X_e'' is added which is at 90° anticlockwise with I_2. The phasor sum of V_2, I_2R_e'', jI_2X_e'' gives E_2. The approximate value of the voltage drop, i.e., the difference between E_2 and V_2 can be calculated. The phasor diagram shown in Fig. 6.17 (c) will be used to develop an expression for voltage regulation as has been done in section 6.16.

6.11 CONCEPT OF AN IDEAL TRANSFORMER

The no-load current I_o is about three to five per cent of the rated current, i.e., I_1 or I_2. The voltage drop due to I_o on $(R_1 + jX_1)$ will therefore be small. If we neglect this small effect of I_o, then the parallel branch of R_c and X_m can be shifted towards the left as shown in Fig. 6.18.

From the equivalent circuit, it can be observed that the circuit parameters of an actual transformer has been shown separately from its will have no loss in it and hence efficiency will be 100 per cent, which is not possible to achieve. Since there will be no voltage drop in the windings due to loading, the regulation will be zero which is again an ideal concept only.

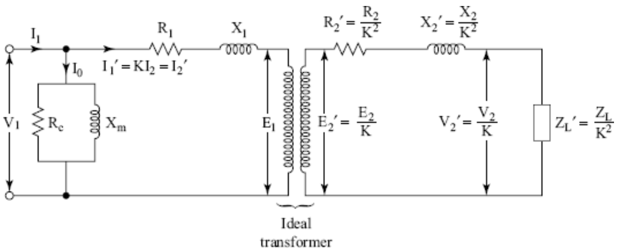


Figure 6.18 An ideal transformer

An ideal transformer is one which has no core loss, no winding losses, no resistance of its windings, no winding leakage reactances, and no voltage drop in the windings. The efficiency will be 100 per cent and voltage regulation will be zero. Such ideal conditions are not possible to achieve.

6.12 TRANSFORMER TESTS

The performance of a transformer in terms of its voltage regulation (i.e., percentage change in voltage from full-load to no-load) and efficiency under various loading conditions can be calculated using the approximate equivalent circuit explained earlier. However, the circuit parameters like R_e and X_e, R_c and X_m have to be known. These parameters and the losses in the transformer can be determined by performing two tests, viz the open-circuit test or the no-load test, and the short-circuit test. These tests are explained as follows.

6.12.1 Open-circuit Test or No-load Test

In this test the transformer primary winding is supplied with its rated voltage keeping the secondary winding unconnected to the load, i.e., with no-load on the secondary. Normally, the supply is given to the low-voltage winding. The high-voltage winding is kept open. Three measuring instruments, viz a wattmeter, a voltmeter, and an ammeter are connected to the low voltage side as shown in Fig. 6.19 (a).

The equivalent circuit of the transformer has also been shown under no-load condition in Fig. 6.19 (b). The wattmeter connected on the L.V. side will record the input power, W_o to the transformer. The supply voltage is measured by the voltmeter and the no-load line current is measured by the ammeter reading, I_o. The input power, W_o is

$$W_o = V_1 I_0 \cos\phi_0 \ W$$

$$\cos\phi_0 = \frac{W_o}{V_1 I_0}$$

$$I_c = I_0 \cos\phi_0$$

$$I_m = I_0 \sin\phi_0$$

From the equivalent circuit on no-load [see Fig. 6.19 (b)]

$$R_c = \frac{V_1}{I_c}\ \Omega \quad \text{and} \quad X_m = \frac{V_1}{I_m}\ \Omega$$

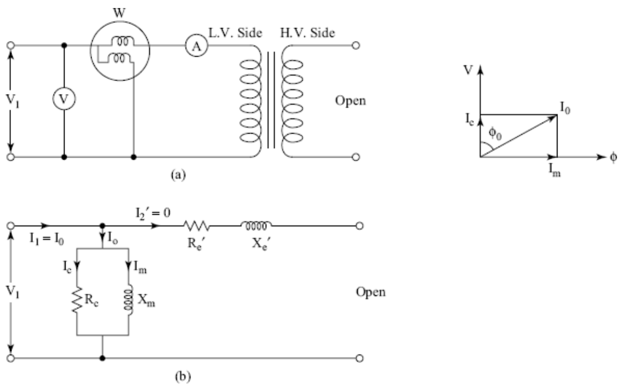


Figure 6.19 (a) Transformer on no load; (b) equivalent circuit on no load

Since on no-load the output is zero, the input power is utilized in supplying the no-load losses. At no-load there will be no current in the secondary winding, and hence no copper loss will take place in that winding. The primary winding current on no-load is small. There will be losses in the iron core which will have two components, viz hysteresis loss and eddy current loss. Thus, the wattmeter reading on no-load can be approximately equated to core loss only. From the no-load test data we, will be able to know the core loss of the transformer, no-load current, the no-load power factor, the magnetizing reactance, and the resistance R_c corresponding to core loss. Note that core loss calculated on no-load will be the same as on full-load or at any other load. That is why core loss of a transformer is considered to be a constant loss as it does not depend on the load currents. Core loss depends on the supply voltage and its frequency.

6.12.2 Short-circuit Test

the short-circuit condition, V_{sc}, the power consumed, W_{sc} and the current, I_{sc}, respectively. It may be noted that for convenience, the low-voltage winding is usually short circuited which forms the secondary winding. The instruments are connected in the high-voltage winding circuit where the rated current is comparatively lower than the low-voltage side, as has been shown in Fig. 6.20 (a). This is done by using an auto transformer. Under the short-circuit condition only a very small percentage of rated voltage, say about five per cent, has to be applied to the primary winding to circulate the full-load current through the windings. Current in the primary winding (H.V. winding) will also be lower than that of the low-voltage winding. Thus, by conducting the short-circuit test from the high voltage winding side with the low-voltage winding short-circuited, we can have an accurate measurement.

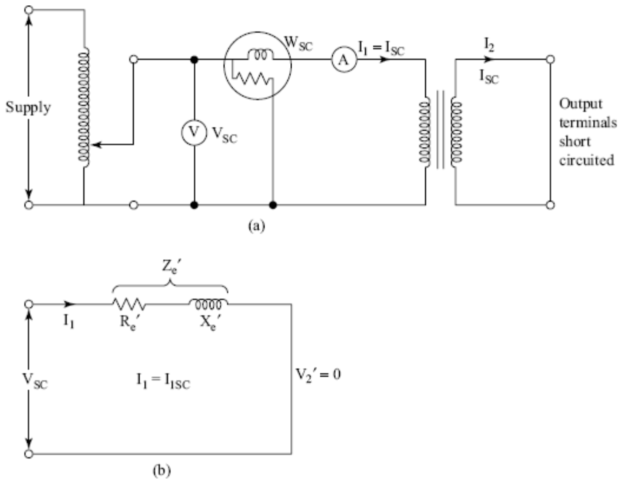


Figure 6.20 Short-circuit test on a transformer: (a) circuit diagram; (b) equivalent circuit under the short-circuit condition

It may also be noted that in the short-circuit test we create a condition when a full-load rated current will flow through both the primary and secondary windings. Therefore, the copper losses in the two windings will be equal to the amount of copper loss that would otherwise occur when the transformer is actually supplying full-load at the rated voltage. Creating this type of a loading condition of a transformer is called phantom loading or fictitious loading. The actual circuit diagram for the short-circuit test and the equivalent circuit of the transformer under the short-circuit condition have been shown in Fig. 6.20.

From the equivalent circuit shown, it may be observed that the core loss component of the equivalent circuit as was shown on the no-load test has been neglected here. This is because the voltage applied in the short-circuit test is not the full-load rated voltage but a small fraction of it. Since core loss is proportional to the applied voltage, for a small voltage applied under short circuit, the core loss component has been neglected. Thus, we can equate the wattmeter reading

From the readings of the three instruments, the following calculations are made.

W_{sc} = Copper losses in the two windings having the rated current flowing through them.

$$W_{sc} = I_{1(sc)}^2 R_e'$$

or,
$$R_e' = \frac{W_{sc}}{I_{1\,sc}^2}$$

$$Z_e' = \frac{V_{sc}}{I_{1(sc)}}\,\Omega$$

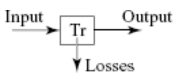
$$Z_e'^2 = R_e'^2 + X_e'^2$$

or,
$$X_e' = \sqrt{Z_e'^2 - R_e'^2}$$

From the data obtained from the no-load test and the short-circuit test, the efficiency and regulation of a transformer can be calculated without actually loading the transformer.

6.13 EFFICIENCY OF A TRANSFORMER

The whole input power to a transformer is not available at the output, some is lost in the iron core as core loss and some is lost in the windings as copper loss. Since the transformer is a static device, there is no friction and windage loss (rotational loss) in the transformer.



$$\text{Input} = \text{Output} + \text{Losses}$$

Efficiency,
$$\eta = \frac{\text{Output}}{\text{Input}} = \frac{\text{Output}}{\text{Output} + \text{Losses}}$$

$$= \frac{\text{Output power}}{\text{Output power} + W_i + W_{cu}}$$

or,
$$\eta = \frac{V_2 I_2 \cos\phi_2}{V_2 I_2 \cos\phi_2 + W_i + W_{cu}}$$

where W_i = iron loss or core loss

and W_{cu} = copper loss in primary and secondary windings

V_2 = output voltage

I_2 = load current

$\cos\phi_2$ = load power factor.

The load at which efficiency will be maximum, that is the condition

The expression for η after dividing the numerator and denominator of the right-hand side of the expression for η by I_2 can is written as

$$\eta = \frac{V_2 \cos\phi_2}{V_2 \cos\phi_2 + (W_i / I_2) + (I_2^2 R_e'' / I_2)}$$

where R_e'' is the equivalent resistance of the transformer windings referred to the secondary side. Efficiency η will be maximum if the denominator is minimum. We can, therefore, minimize the denominator by differentiating it with respect to the load current, I_2 and equating to zero as

$$\frac{d}{dI_2}\left[V_2 \cos\phi_2 + \frac{W_i}{I_2} + I_2 R_e'' \right] = 0$$

or,

$$-\frac{W_i}{I_2^2} + R_e'' = 0$$

or,

$$I_2^2 R_e'' = W_i$$

When copper loss at a particular load equals the core loss, efficiency will be maximum at that load. The condition for maximum efficiency of a transformer is

Core loss = Copper loss

The value of the load current at maximum efficiency is determined as

$$I_2^2 = \frac{W_i}{R_e''}$$

or,

$$I_2 = \sqrt{\frac{W_i}{R_e''}}$$

If we want to know at what percentage of full-load, the efficiency will be maximum, (ie if we would like to know if efficiency is maximum at 75% of the full load or at 80% of the full load or at 100% of the full load) we can determine as follows.

Determination of load at which efficiency will be maximum

Let us assume that x is the fraction of the full load at which the efficiency is maximum. The core loss or the iron loss W_i will remain constant at all loads. The copper loss will vary as the square of the load.

This means if at full load copper loss is $= W_{cu}$

at one-third of full load copper loss $= \frac{1}{9} W_{cu}$

Thus, at x load, copper loss $= x^2 W_{cu}$

satisfying the condition for maximum efficiency

$$W_i = x^2 W_{cu}$$

or, $$x = \sqrt{\frac{W_i}{W_{cu}}}$$

where W_{cu} is the full-load copper loss and x is the fraction of the full-load at which efficiency will be maximum.

If we want to know the kVA of the transformer at maximum efficiency, we would determine it as follows:

kVA at η_{max} = x × Full-load kVA

Therefore, kVA at maximum efficiency

$$= \sqrt{\frac{W_i}{W_{cu}}} \times \text{Full-load kVA}$$

Efficiency of a transformer is often expressed in terms of energy output in 24 hours in a day to the energy input. Such a calculated efficiency is known as all-day efficiency which is explained as follows.

6.15 ALL-DAY EFFICIENCY

A transformer when connected to the load has to remain energized all the time ready to supply the load connected to it. Even when all the loads are switched off, i.e., no one is utilizing any electricity, the transformer has to remain on. Thus, irrespective of the load on the transformer, the core loss will occur for all the 24 hours of the day. However, the copper loss will depend on the magnitude of the load current, and will eventually vary from time to time. All-day efficiency is calculated by considering the energy output (power multiplied by time, i.e., energy) in 24 hours to the energy input in 24 hours as

All-day Efficiency

$$= \frac{\text{Output energy in 24 hours.}}{\text{Output energy in 24 hours + Iron loss in 24 hours + copper loss in 24 hours}}$$

Both commercial efficiency which is the ratio of the output power to the input power and the all-day efficiency as stated above are calculated for distribution transformers. Distribution transformers are connected to the load all the time.

All-day efficiency of such transformers which are always connected to the load at the output side is somewhat less than their commer-

When a transformer is not supplying any load, the voltage across the output terminals is the same as that induced in the secondary winding, i.e., E_2. Now, when the transformer is connected to the load, the voltage available across the output terminals, V_2 becomes somewhat less than E_2.

The reduction in the output voltage from no-load to load is due to the voltage drop in the winding resistance and leakage reactance. The students are to refer to the phasor diagram as shown in Fig. 6.17 (c) for determination of voltage regulation which has been redrawn here.

In the phasor diagram shown in Fig. 6.21, we will consider E_2, i.e., length OF as equal to length OC as the angle δ is actually very small. This approximation is made to simplify the determination of an expression for voltage regulation.

Thus,

$$
\begin{aligned}
E_2 &= OF = OC = OA + AB + BC = OA + AB + DE \\
&= V_2 + I_2 R_e'' \cos\phi + DF \cos(90 - \phi) \\
&= V_2 + I_2 R_e'' \cos\phi + I_2 X_e'' \sin\phi
\end{aligned}
$$

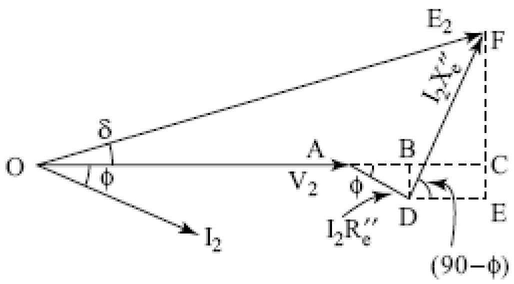


Figure 6.21 Phasor diagram of a transformer as in Fig. 6.17 (c)

Percentage regulation $= \dfrac{E_2 - V_2}{V_2} \times 100$

$$= \frac{I_2 R_e'' \cos\phi + I_2 X_e'' \sin\phi}{V_2} \times 100$$

If the power factor is leading, then we will have

Percentage regulation

$I_2 R_e'' \cos\phi - I_2 X_e'' \sin\phi \times 100$

Since a transformer is a static device, there is no rotational part in it, and hence there is no rotational or frictional losses. Due to current flow through the windings, there will be $I^2 R$ loss in both the primary and secondary windings. Thus,

Copper loss = $I_1^2 R_1 + I_2^2 R_2$

Copper loss is proportional to the square of the current. With the secondary circuit resistance referred to the primary side, the total effective resistance, $R'_e = R_1 + \frac{R_2}{K^2}$

Similarly, the primary circuit resistance when referred to the secondary side, the total effective resistance of the transformer windings

$$R''_e = R_2 + K^2 R_1 \quad \text{where } K = \frac{N_2}{N_1}$$

The copper loss $= I_2^2 R''_e = I_1^2 R'_e$

When the load current is changed, say from full load, I_2 to half load $\frac{I_2}{2}$, the copper loss becomes one-fourth of its value at full load.

The losses that take place in the iron core is called iron loss or core loss. Iron loss consists of two parts, viz Hysteresis loss and eddy-current loss. These are explained in detail as follows.

(a) Hysteresis loss

When alternating voltage is applied to the primary winding of the transformer, the core gets magnetized. The magnetization of the core takes place in alternate directions every half cycle of the supply voltage. Magnetization in alternate directions basically means that the magnetic dipoles of the magnetic material changes their orientation in opposite directions every half cycle. This gives rise to loss of energy which is expressed as

$$W_h = \eta B_m^{1.6} f V \ \text{W}$$

where W_h is the hysteresis loss in Watts

B_m is the maximum value of flux density in Wb/m^2

f is the supply frequency

V is the volume of the iron core in m^3

η is the steinmetz constant.

(b) Eddy current loss

When the core is subjected to an alternate magnetic field, EMF is induced in the core material also. This EMF causes circulating current in the core, and thereby producing loss-resulting generation of heat. If the core gets heated up, it produces an undesirable effect on the insulation material used in the windings. Eddy current loss is expressed as

$$W_e = K B_m^2 f^2 t^2 \ \ W$$

where W_e is the eddy current loss in Watts

B_m is the maximum value of flux density

f is the supply frequency

t is the thickness of the core material.

Eddy current loss is minimized by using a thin laminated sheet steel as the core material instead of a solid core. The laminated steel sheets are assembled together and are insulated from each other using insulating varnish. This creates an obstruction to the flow of eddy current, and hence reduces the eddy current loss.

6.18 SOLVED NUMERICAL PROBLEMS

Example 6.1 A transformer has 1000 turns on its primary and 500 turns on the secondary. When a voltage, V of frequency f is connected across the primary winding a maximum flux of 2×10^{-3} Wb is produced in the core which links both the windings. Calculate the value of the EMF induced in the two windings.

Solution:

Let E_1 and E_2 be the EMFs induced in primary and secondary windings, respectively. Here, N_1 = 1000 and N_2 = 500.

$$\begin{aligned} E_1 &= 4.44 \phi_m f N_1 \\ &= 4.44 \times 2 \times 10^{-3} \times 50 \times 1000. \\ &= 444 \ \ V \end{aligned}$$

and

$$\begin{aligned} E_2 &= 4.44 \phi_m f N_2 \\ &= 4.44 \times 2 \times 10^{-3} \times 50 \times 500 \\ &= 222 \ V \end{aligned}$$

We obsere that,

$$\frac{E_1}{E_2} = \frac{444}{222} = 2$$

and

$$\frac{N_1}{N_2} = \frac{1000}{500} = 2$$

Therefore

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

Example 6.2 A transformer has 900 turns on its primary winding ary winding. Also calculate the value of maximum flux density in the core.

Solution:

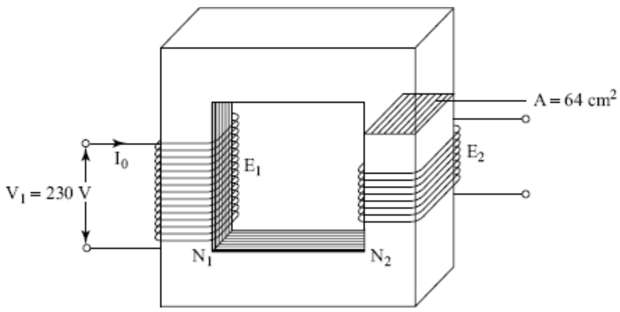


Figure 6.22

Given V_1 = 230 V.

The induced EMF in the primary windings is E_1. E_1 is slightly less than V_1 because there will be some voltage drop in the winding.

$V_1 > E_1$, $V_1 - E_1$ = Voltage drop in the primary winding due to current, I_0 flowing through it.

The no-load current, I_0 is very small as compared to the current that would flow when some electrical load is connected across the secondary winding. Here, the transformer is on no-load, i.e., no load has been connected to its secondary winding.

If we neglect the no-load voltage drop in the winding, we can write $V_1 = E_1$.

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

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

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

or, $$E_2 = E_1\left(\frac{N_2}{N_1}\right) = 230\left(\frac{300}{900}\right) = 76.7\text{ V}$$

Again, $$E_1 = 4.44\,\phi_m\,f\,N_1$$
$$= 4.44\,B_m\,A\,f\,N_1$$

when B_m is the maximum flux density and A is the cross-sectional area of the core.

Substituting values

$$230 = 4.44\,B_m \times \frac{64}{10^4} \times 50 \times 900$$

Example 6.3 A 110 V/220 V transformer is supplied with 110 V, 50 Hz supply to its low-voltage side. It is desired to have maximum value of core flux as 4.2 mWbs. Calculate the required number of turns in its primary winding.

Solution:

V_1 = 110 V. Neglecting the winding voltage drop under no-load condition, $V_1 = E_1$ = 110 V.

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

Substituting values, $110 = 4.44 \times 4.2 \times 10^{-3} \times 50 \times N_1$

or, $$N_1 = \frac{110 \times 10^3}{4.44 \times 4.2 \times 50} = 119 \text{ turns}$$

Example 6.4 A 100 kVA, 1100/220 V, 50 Hz transformer has 100 turns on its secondary winding. Calculate the number of turns of the primary winding; the currents that would flow in both the windings when fully loaded, and the maximum value of flux in the core.

Solution:

Given, $N_2 = 100$

$$V_1 \approx E_1 \text{ and } V_2 \approx E_2$$

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

$$N_1 = N_2\left(\frac{E_1}{E_2}\right) = 100\left(\frac{1100}{220}\right) = 500 \text{ turns}$$

Rating of the transformer is = 100 kVA = 100×10^3 VA.

Primary current,

$$I_1 = \frac{VA}{V_1} = \frac{100 \times 10^3}{1100} = 90.1 \text{ A}$$

Since volt-ampere rating is the same for the transformer on both the sides,

scondary current,

$$I_2 = \frac{VA}{V_2} = \frac{100 \times 10^3}{220} = 450.5 \text{ A}$$

For calculating ϕ_m, we will use the EMF equation.

Example 6.5 The maximum flux density in the core of a 1100/220 V, 50 Hz, 100 kVA transformer is 3.5 Wb/m^2. Calculate the area of cross section of the core and the number of turns of the primary and secondary windings if the EMF per turn is 5.5 V.

Solution:

$V_1 = E_1 = 1100$ V
EMF per turn × No. of turns = total induced EMF
or, $5.5 \times N_1 = E_1$

or, $$N_1 = \frac{1100}{5.5} = 200 \text{ turns}$$

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

$$N_2 = N_1\left(\frac{E_2}{E_1}\right) = 200\left(\frac{220}{1100}\right) = 50 \text{ turns}$$

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

or, $$E_1 = 4.44\, B_m\, A\, f N_1$$

$$A = \frac{E_1}{4.44\, B_m f N_1} = \frac{1100}{4.44 \times 3.5 \times 50 \times 200}$$
$$= 70 \times 10^{-4}\ m^2$$
$$= 70\ cm^2$$

Example 6.6 The no-load input power to a transformer is 100 W. The no-load current is 3 A when the primary applied voltage is 230 V at 50 Hz. The resistance of the primary winding in 0.5 Ω. Calculate the value of iron loss and no-load power factor.

Solution:

At no-load, the input power is lost as a small amount of I^2R loss in the winding and as core loss.

In an ac circuit, power = VI cos ϕ

Let No-load input power be W_0

$$W_0 = V_1 I_0 \cos\phi_0$$
$$\cos\phi_0 = \frac{W_0}{V_1 I_0}$$
$$\cos\phi_0 = \frac{100}{230 \times 3} = 0.15 \text{ lagging}$$

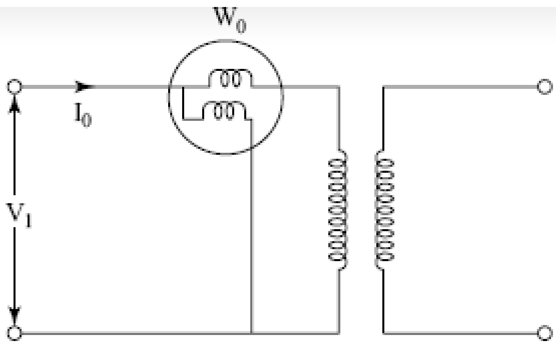


Figure 6.23

$\cos \Phi_0$ is the no-load power factor of the transformer. At no-load, primary winding copper loss is equal to

$$I_0^2 R_1 = 3^2 \times 0.5 = 4.5 \text{ W}$$

The wattmeter reading W_0 indicates the power loss in the core as also in the winding.

Core loss, or iron loss, $W_0 = W_0 - I_0^2 R_1$

= 100 − 4.5

= 95.5 W

Example 6.7 A 100 kVA, 2400/240 V, 50 Hz transformer has a no-load current of 0.64 A and a core loss of 700 W, when its high-voltage side is energized at rated voltage and frequency. Calculate the components of the no-load current and no-load branch parameters of the equivalent circuit.

Solution:

Neglecting the small amount of copper loss at no-load,

$$V_1 I_0 \cos\phi_0 = \text{Iron loss}$$

$$I_0 \cos\phi_0 = \frac{\text{Iron loss}}{V_1} = \frac{700}{2400} = 0.29\text{ A}$$

$$I_c = I_0 \cos\phi_0 = 0.29\text{ A}$$

$$\cos\phi_0 = \frac{0.29}{I_0} = \frac{0.29}{0.64} = 0.45$$

$$\sin\phi_0 = 0.89$$

$$I_m = I_0 \sin\phi_0 = 0.64 \times 0.89 = 0.57\text{ A}$$

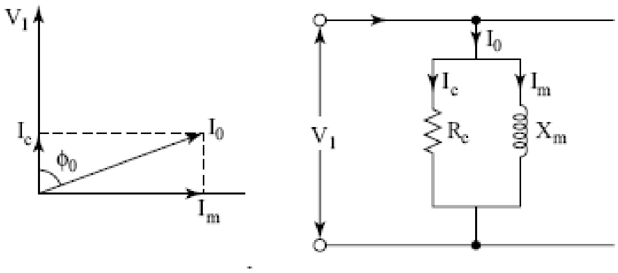


Figure 6.24

$$X_m = \frac{V_1}{I_m} = \frac{2400}{0.57}$$
$$= 4.2 \times 10^3\ \Omega$$

$$R_c = \frac{V_1}{I_c} = \frac{2400}{0.29} = 8.27 \times 10^3\ \Omega$$

Example 6.8 A 400/200 V, 50 Hz transformer draws a no-load current of 6 A at 0.2 power factor lagging. The transformer supplies a current of 100 A at 200 V to the load. The load power factor is 0.8 lagging. What is the magnitude of current drawn by the transformer from the supply mains?

Solution:

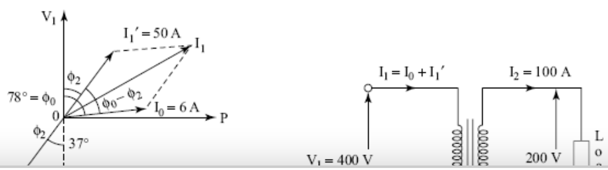


Figure 6.25

The circuit diagram and the phasor diagram showing the currents with reference to supply voltage, V_1 have been shown in Fig. 6.25. I_0 is the no-load current making an angle of lag ϕ_0 with V_1 where cos ϕ_0 = 0.2 or ϕ_o = 78° (lagging). The load power factor, cos ϕ_2 = 0.8 or, ϕ_2 = 37°. I_2 is the load current. I'_1 is the additional current drawn by the primary to balance the load current I_2 such that

$$I_1' N_1 = I_2 N_2$$

substituting values

$$I_1' = 100\left(\frac{N_2}{N_1}\right) = 100\left(\frac{V_2}{V_1}\right) = 100\left(\frac{200}{400}\right)$$
$$= 50 \text{ A.}$$

As shown in Fig. 6.25, it is observed that the phasor sum of I_0 and I'_1 is the primary current when the transformer is loaded. The angle between I_0 and I'_1 is $\phi_0 - \phi_2$, i.e., (78° − 37°) = 41°.

Using law of parallelogram,

$$I_1^2 = (I_1')^2 + (I_o)^2 + 2 I_1' I_o \cos(\phi_o - \phi_2)$$

substituting values

$$I_1^2 = (50)^2 + (6)^2 + 2 \times 50 \times 6 \cos 41^\circ$$

or, $$I_1^2 = 2986$$

or, $$I_1 = 54.6 \text{ A}$$

Example 6.9 A 400/200 V, 50 Hz, 10 kVA transformer has primary and secondary winding resistances of 2.5 Ω and 0.5 Ω and winding leakage reactances of 5 Ω and 1 Ω, respectively. Calculate the equivalent resistance and reactance of the transformer referred to the secondary side. What amount of power will be lost in the windings?

Solution:

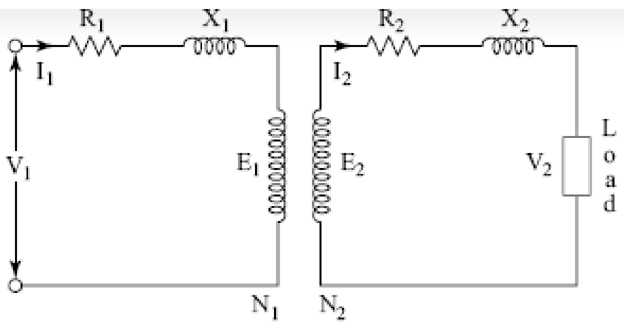


Figure 6.26 (a)

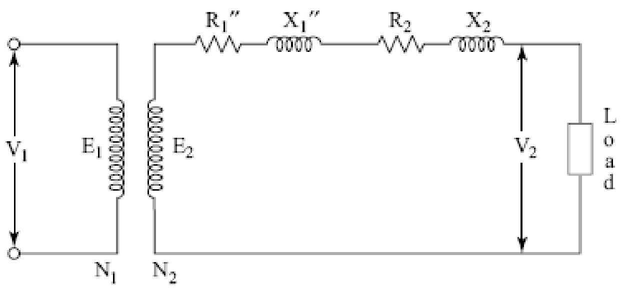


Figure 6.26 (b)

Given, $R_1 = 2.5\ \Omega, X_1 = 5\ \Omega, R_2 = 0.5\ \Omega, X_2 = 1.0\ \Omega$

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = \frac{V_2}{V_1} = \frac{200}{400} = \frac{1}{2} = K \qquad \text{(assuming } V_1 = E_1 \text{ and } V_2 = E_2\text{)}$$

$$I_1^2 R_1 = I_2^2 R_1'' \text{or}, R_1'' = R_1\left(\frac{I_1}{I_2}\right)^2 = R_1\left(\frac{N_2}{N_1}\right)^2 = K^2 R_1$$

thus, $$R_1'' = \left(\frac{1}{2}\right)^2 R_1 = \frac{2.5}{4} = 0.625\ \Omega$$

Similarly,

$$X_1'' = X_1 K^2 = \frac{5}{4} = 1.25\ \Omega.$$

$$R_e'' = R_1'' + R_2 = 0.625 + 0.5$$
$$= 1.125\ \Omega.$$
$$X_e'' = X_1'' + X_2 = 1.25 + 1.0$$
$$= 2.25\ \Omega.$$

Given, $$\text{kVA} = 10$$
$$\text{VA} = 10 \times 1000$$
$$V_2 I_2 = 10 \times 1000$$

$$I_2 = \frac{10 \times 1000}{V_2} = \frac{10 \times 1000}{200} = 50\text{ A}$$

This current I_2 is passing through the equivalent resistance, R_e'' =

Example 6.10 A 25 kVA, 2000/200 V transformer has constant loss, i.e., iron loss of 350 W and full-load copper loss called the variable loss of 400 W. Calculate the efficiency of the transformer at full load and at half load 0.8 power factor lagging.

Solution:

Output in kVA = 25, output in kW = kVA cosϕ = 25 × 0.8 = 20 kW

Efficiency, $\eta = \frac{\text{Output}}{\text{Input}} \times 100 = \frac{\text{Output} \times 100}{\text{Output} + \text{Losses}}$

Output in Watts $= 20 \times 1000$ W

Core loss or iron loss $= 350$ W

Full-load copper loss $= 400$ W

$$\eta = \frac{\text{Output} \times 100}{\text{Output} + \text{Core loss} + \text{Copper loss}}$$

$$= \frac{200 \times 1000 \times 100}{20 \times 1000 + 350 + 400} = 96.4 \text{ per cent}$$

At half load

Output $= 10 \times 10^3$

Core loss $= 350$ W (remains constant at all loads)

Copper loss $= \frac{400}{4} = 100$ W (variable loss, varies as square of the load)

$$\eta = \frac{10 \times 1000 \times 100}{10 \times 1000 + 350 + 100} = 95.7 \text{ per cent}$$

Example 6.11 A 5 kVA, 1000/200 V, 50 Hz single-phase transformer has the following no-load test, i.e., the open-circuit test and the short-circuit test data.

No-load test conducted at the low-voltage side:

$$W_0 = 90 \text{ W}, \qquad I_0 = 1.2 \text{ A}, \qquad V = 200 \text{ V}$$

The short-circuit test conducted at the high-voltage side:

$$W_{sc} = 110 \text{ W}, \qquad I_{sc} = 5 \text{ A}, \qquad V_{sc} = 50 \text{ V}$$

Calculate the efficiency of the transformer at full-load 0.8 p.f. lagging. What will be the equivalent resistance of the transformer windings referred to high voltage side?

Solution:

Power consumed on no-load test can be taken approximately equal to the core loss, and power loss on the short-circuit test when the rated current flows through the windings can be taken as equal to full-load copper loss.

$I_{sc} = 5$ A; and full-load current at the high-voltage side $= \frac{\text{VA rating}}{\text{voltage}}$

Thus, we see that the short-circuit test was conducted under the full-load condition.

Therefore, copper loss $= W_{SC} = 110\ \text{W} = \frac{110}{1000}\ \text{kW}$

and iron loss $= W_0 = 90\ \text{W} = \frac{90}{1000}\ \text{kW}$

Efficiency $$\eta = \frac{\text{kVA}\cos\phi \times 100}{\text{kVA}\cos\phi + W_{sc} + W_0}$$

$$= \frac{5 \times 0.8 \times 100}{5 \times 0.8 + (110/1000) + (90/1000)} = 95.24 \text{ per cent}$$

Full load copper loss $= I_1^2 R_e' = 110\ \text{W}$ or $R_e' = \frac{110}{5^2} = 4.4\ \Omega.$

Example 6.12 A 20 kVA, 1000/200 V, 50 Hz has core loss and copper loss as 400 W and 600 W, respectively, under the full-load condition. Calculate the efficiency at full load 0.8 lagging power factor. At what percentage of full load will the efficiency be maximum and what is the value of maximum efficiency?

Solution:

Full-load efficiency at 0.8 lagging p.f., $$\eta = \frac{\text{kW output} \times 100}{\text{kW output} + \text{losses}}$$

$$= \frac{\text{kVA}\cos\phi \times 100}{\text{kVA}\cos\phi + W_c + W_{cu}}$$

Substituting values, $$\eta = \frac{20 \times 0.8 \times 100}{20 \times 0.8 + 0.4 + 0.6}$$

$$= \frac{16 \times 100}{17} = 94 \text{ per cent}$$

Now we have to determine at what load the efficiency will be maximum.

Let x be the fraction of full load at which the efficiency will be maximum. Since copper loss is proportional to the square of the load, and at maximum efficiency core loss equals copper loss

$$x^2 \times W_{cu} = W_c$$

$$x = \sqrt{\frac{W_c}{W_{cu}}}$$

Substituting values $$x = \sqrt{\frac{400}{600}} = 0.82$$

Therefore, efficiency will be maximum when the load is 0.82 of 20 kVA, i.e., 0.82 × 20 = 16.4 kVA. At this load, core loss equals copper loss; and maximum efficiency is

Example 6.13 Efficiency of 400/200 V, 200 kVA transformer is 98.5 per cent at full load at 0.8 lagging power factor. At half load, 0.8 power factor lagging the efficiency is 97.5 per cent. Calculate the values of core loss and full-load copper loss.

Solution:

Let W_c be the core loss and W_{cu} be the full-load copper loss.

$$\eta_{F.L} = 0.985 = \frac{200 \times 0.8}{200 \times 0.8 + W_c + W_{cu}}$$

or, $$0.985 = \frac{160}{160 + W_c + W_{cu}}$$

or, $$\frac{160}{0.985} = 160 + W_c + W_{cu}$$

or, $$W_c + W_{cu} = 2.43 \text{ kW} = 2430 \text{ W} \qquad \text{(i)}$$

At half load, W_c will remain the same but W_{cu} will be one-fourth its full-load value. Efficiency at half load is

$$\eta_{H.L} = \frac{100 \times 0.8}{100 \times 0.8 + W_c + (W_{cu}/4)} = \frac{80}{80 + W_c + (W_{cu}/4)}$$

or, $$0.975 = \frac{320}{320 + 4W_c + W_{cu}}$$

or, $$\frac{320}{0.975} = 320 + 4W_c + W_{cu}$$

or, $$4\,W_c + W_{cu} = 8.2 \text{ kW} = 8200 \text{ W} \qquad \text{(ii)}$$

From (i) and (ii), $$W_c = 1923 \text{ W}$$

and $$W_{cu} = 507 \text{ W}$$

Example 6.14 The equivalent circuit parameters of a 300 kVA, 2200/200 V, 50 Hz single-phase transformer are: primary winding resistance, $R_1 = 0.1\ \Omega$; secondary winding resistance, $R_2 = 0.01\ \Omega$; primary leakage reactance, $X_1 = 0.4\ \Omega$; secondary leakage reactance, $X_2 = 0.03\ \Omega$; resistance representing core loss, $R_c = 6 \times 10^3\ \Omega$, magnetizing reactance $X_m = 2 \times 10^3\ \Omega$. Calculate the voltage regulation and efficiency of the transformer at full load at 0.8 power factor lagging.

Solution:

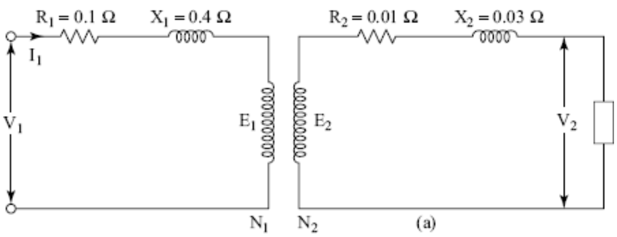


Figure 6.27

Transformation ratio, $K = \dfrac{N_2}{N_1} = \dfrac{E_2}{E_1} = \dfrac{220}{2200} = \dfrac{1}{10} = 0.1$

By transferring the secondary quantities to the primary side we will calculate the equivalent resistance and equivalent reactance of the transformer as

$$R_e' = R_1 + \frac{R_2}{K^2} = 0.1 + \frac{0.01}{(0.1)^2} = 1.1\ \Omega$$

$$X_e' = X_1 + \frac{X_2}{K^2} = 0.4 + \frac{0.04}{(0.1)^2} = 1.4\ \Omega$$

$$\text{kVA rating} = 300$$

$$\text{VA rating} = 300 \times 1000$$

$$I_1 = \frac{VA}{E_1} = \frac{300 \times 1000}{2200} = 136\text{ A}$$

$$\text{p.f} = \cos\phi = 0.8;\ \sin\phi = 0.6$$

The equivalent circuit with the secondary quantities referred to the primary side and the phasor diagram have been shown in Fig. 6.28.

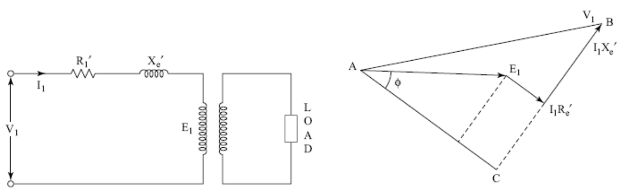


Figure 6.28

$$V_1^2 = AC^2 + CB^2$$

$$= (E_1\cos\phi + I_1R_e')^2 + (E_1\sin\phi + I_1X_e')^2$$

$$= (2200 \times 0.8 + 136 \times 1.1)^2 + (2200 \times 0.6 + 136 \times 1.4)^2$$

$$= (1909)^2 + (1510.4)^2$$

$$V_1 = 2400\text{ V}$$

Voltage regulation $= \dfrac{V_1 - E_1}{V_1} \times 100 = \dfrac{(2400 - 2200)}{2400} \times 100$

$= 8.3$ per cent.

To calculate efficiency, we need to calculate the copper loss and core loss.

Full- oad copper loss, $W_{cu} = I_1^2 R_e' = (136)^2 \times 1.1 = 20.345$ kW

Core loss $= V_1 I_c = V_1 \dfrac{V_1}{R_c} = \dfrac{V_1^2}{R_c} = \dfrac{(2400)^2}{6 \times 10^3} = 960$ W

$= 0.96$ kW

Efficiency,

$$\eta = \frac{\text{Output} \times 100}{\text{Output} + W_{cu} + W_c}$$

$$= \frac{300 \times 0.8 \times 100}{300 \times 0.8 + 20.345 + 0.96}$$

$$= \frac{240 \times 100}{261.3} = 91.84 \text{ per cent}$$

Example 6.15 A 10 kVA 440/220 V, 50 Hz single-phase transformer gave the following test results when both the following tests were conducted on the high-voltage side:

Open circuit test : 440 V, 1.0 A, 100 W

Short circuit test : 20 V, 22.7 A, 130 W.

Using the test data, calculate the efficiency and voltage regulation at 0.8 power factor lagging.

Solution:

Full-load current on the high-voltage side

$$= \frac{10 \times 1000}{440} = 22.7 \text{ A}$$

This shows that the short-circuit test has been conducted on full load. The wattmeter reading, therefore, represents the full-load copper loss.

$W_{cu} = 130$ W and from oc test data,

$W_c = 100$ W

Full-load efficiency is calculated as

$$\eta = \frac{\text{Output}}{\text{Output} + W_{cu} + W_c} \times 100$$

$$= \frac{10 \times 0.8}{10 \times 0.8 + 0.13 + 0.1} \times 100$$

$$= 97.2 \text{ per cent}$$

Calculation of voltage regulation

From the short-circuit test data, wattmeter reading can be taken as equal to copper losses in the windings.

$$W_{SC} = 130 = I_1^2 R_e' = (22.7)^2 R_e'$$

Therefore,

$$R_e' = \frac{130}{(22.7)^2} = 0.25\ \Omega$$

$$Z_e' = \frac{V_{sc}}{I_{sc}} = \frac{20}{22.7} = 0.88\ \Omega$$

$$Z_e^2 = R_e^{2\prime} + X_e^{2\prime}$$

$$X_e' = \sqrt{(0.88)^2 - (0.25)^2} = 0.84\ \Omega$$

$$\cos\phi = 0.8,\ \sin\phi = 0.6$$

Regulation

$$= \frac{(I_1 R_e' \cos\phi + I_1 X_e' \sin\phi)}{V_1} \times 100$$

$$= \frac{(22.7 \times 0.25 \times 0.8 + 22.7 \times 0.84 \times 0.6)}{440} \times 100$$

$$= \frac{(4.54 + 11.44)}{440} \times 100$$

$$= 3.63 \text{ per cent}$$

Example 6.16 A 440/220 V single-phase transformer has percentage resistance drop and reactance drop of 1.2 per cent and 6 per cent, respectively. Calculate the voltage regulation of the transformer at 0.8 power factor lagging.

Solution:

Percentage voltage regulation

$$= \frac{(I_2 R_e'' \cos\phi + I_2 X_e'' \sin\phi)}{E_2} \times 100$$

$$= \frac{I_2 R_e''}{E_2} \cos\phi \times 100 + \frac{I_2 X_e''}{E_2} \sin\phi \times 100$$

Given,

$$\frac{I_2 R_e''}{E_2} \times 100 = 1.2,\ \frac{I_2 X_e''}{E_2} \times 100 = 6.0,\ \cos\phi = 0.8$$

$$\sin\phi = 0.6.$$

Substituting values regulation

$$= \frac{I_2 R_e''}{E_2} \cos\phi + \frac{I_2 X_e''}{E_2} \sin\phi$$

$$= 1.2 \times .0.8 + 6.0 \times 0.6$$

$$= 4.56 \text{ per cent}$$

Example 6.17 A 230/115 V, 5 kVA transformer has circuit parameters as R_1= 0.2 Ω, X_1 = 0.8 Ω, R_2 = 0.1 Ω, X_2 = 0.2 Ω. Calculate the regulation of the transformer at 0.8 power factor lagging. At what value of power factor will the regulation be zero? Can the value of regulation be negative for any power factor load ?

Solution

The transformation ratio,

$$K = \frac{N_2}{N_1} = \frac{E_2}{E_1} = \frac{115}{230} = 0.5$$

$$
\begin{aligned}
R_e'' &= R_2 + R_1'' \\
&= R_2 + K^2 R_1 \\
&= 0.1 + (.5)^2 \times 0.2 \\
&= 0.15\ \Omega
\end{aligned}
$$

$$X_e'' = X_2 + X_1'' = X_2 + K^2 X_1 = 0.2 + (0.25)^2 \times 0.8 = 0.4\ \Omega$$

$$\cos\phi = 0.8, \sin\phi = 0.6, I_2 = \frac{5 \times 1000}{115} = 43.8\ \text{A}$$

Regulation
$$
\begin{aligned}
&= \frac{(I_2 R_e'' \cos\phi + I_2 X_e'' \sin\phi)}{E_2} \times 100 \\
&= \frac{(43.8 \times 0.15 \times 0.8 + 43.8 \times 0.4 \times 0.6) \times 100}{115} \\
&= 13.7 \text{ per cent}
\end{aligned}
$$

We know regulation can be negative only when the power factor is leading and when the expression for regulation is

Regulation
$$= \frac{(I_2 R_e'' \cos\phi - I_2 X_e'' \sin\phi) \times 100}{E_2}$$

Regulation will be zero when the numerator of the above expression will be zero. That is

$$I_2 R_e'' \cos\phi = I_2 X_e'' \sin\phi$$

or,
$$\tan\phi = \frac{R_e''}{X_e''} = \frac{0.15}{0.4} = 0.375, \quad \text{or} \quad \phi = 20.6^\circ$$

The power factor at which regulation will be zero is cos 20.6° = 0.94 leading

Regulation will be negative if the power factor angle is more than 20.6° leading. To verify, let the angle of lead of load current be higher than 20.6°. If we assume this angle as 37°, the power factor is 0.8 leading. The regulation at 0.8 leading is calculated as

Regulation
$$
\begin{aligned}
&= \frac{(I_2 R_e'' \cos\phi - I_2 X_e'' \sin\phi)}{E_2} \times 100 \\
&= \frac{(43.8 \times 0.15 \times 0.8 - 43.8 \times 0.4 \times 0.6) \times 100}{115} \\
&= \frac{(5.256 - 10.512)}{115} \times 100 \\
&= -4.57 \text{ per cent}
\end{aligned}
$$

Example 6.18 Calculate the all-day efficiency of a 25 kVA distribution transformer whose loading pattern is as follows:

15 kW at 0.8 power factor for 6 hours

12 kW at 0.7 power factor for 6 hours

The core loss is 500 W and full-load copper loss is 800 W.

Solution:

Output of the transformer in 24 hours is calculated as

$$15\text{ kW} \times 6 + 12\text{ kW} \times 6 + 10\text{ kW} \times 8 + 0 \times 4$$
$$= 242\text{ kWh} = \text{output energy}$$

We have to calculate the core loss and copper loss for 24 hours at different loading conditions as Core loss remains constant at all loads. Therefore,

$$\text{Core loss for 24 hours} = 0.5 \times 24 = 12\text{ kWh}$$
$$= \text{Energy lost in the core}$$

Copper loss varies as the square of the load. The loads on transformer have to be calculated in terms of kVA.

$$15\text{ kW at 0.8 p.f.} = \frac{15\text{ kW}}{0.8} = 18.75\text{ kVA}$$

$$12\text{ kW at 0.7 p.f.} = \frac{12\text{ kW}}{0.7} = 17.14\text{ kVA}$$

$$10\text{ kW at 0.9 p.f.} = \frac{10\text{ kw}}{0.9} = 11.11\text{ kVA}$$

at 25 kVA load copper loss $= 0.8$ kW.

at 18.75 kVA load copper loss $= 0.8 \times \left(\frac{18.75}{25}\right)^2 = 450\text{ W} = 0.45\text{ kW}$

at 17.14 kVA load copper loss $= 0.8 \times \left(\frac{17.14}{25}\right)^2 = 376\text{ W} = 0.376\text{ kW}$

at 11.11 kVA load copper loss $= 0.8 \times \left(\frac{11.11}{25}\right)^2 = 157\text{ W}$

$= 0.157$ kW

All day efficiency

$$= \frac{\text{Energy output in 24 hours}}{\text{Energy output in 24 hours} + \text{Energy loss in core in 24 hours} + \text{Energy loss in copper for 24 hours}}$$

$$= \frac{242}{242 + 12 + (0.45 \times 6 + 0.376 \times 6 + 0.157 \times 10 + 0 \times 4)}$$

$$= \frac{242}{242 + 12 + 6.47} = \frac{242}{260.47} = 0.929$$

Thus $\eta_{\text{all-day}} = 0.929 = 92.9$ per cent

6.19 REVIEW QUESTIONS

A. Short Answer Type Questions

1. Explain with examples why transformers are required in transmission and distribution of electrical power.

4. Derive the EMF equation of a transformer.
5. What are the losses in a transformer and how can these be kept low?
6. What is eddy current loss and how can this loss be reduced?
7. Why do we use laminated sheets to build the core of a transformer instead of using a solid core?
8. Distinguish between core-type and shell-type construction of the transformer core.
9. Explain why the frequency of output voltage is the same as input voltage in a transformer.
10. Distinguish between magnetizing reactance and leakage reactance of a transformer.
11. Draw the equivalent circuit of a transformer under the no-load condition.
12. Explain the concept of an ideal transformer.
13. What is meant by voltage regulation of a transformer? Is it desirable to have a high-voltage regulation of a transformer? Justify your answer.
14. How can we calculate the efficiency of a transformer by knowing its losses?
15. Draw the no-load phasor diagram of a transformer. What are the two components of a no-load current ?
16. Draw the full-load phasor diagram of a transformer neglecting the voltage drop in the windings.
17. Derive the condition for maximum efficiency of a transformer.
18. What is all-day efficiency of a transformer? What is its significance?
19. How can you determine the efficiency of a transformer indirectly, i.e., without actually loading the transformer?
20. What is the expression for voltage regulation of a transformer in terms of its equivalent resistance, equivalent reactance, power factor, and the output voltage?
21. How can you determine the efficiency of a transformer of a given rating at any load if the values of full-load losses are known?
22. Explain how the short-circuit test on a transformer is to be conducted. What information do you get from the short-circuit test data?
23. Draw and explain the exact equivalent circuit of a transformer.
24. Explain how in a transformer, the primary current increases as the secondary current, i.e., load current increases.
25. Why is the core of a transformer made of magnetic material?
26. What is the difference between a practical transformer and an ideal transformer?
27. Why do we consider core loss as a constant loss and copper loss as a variable loss?
28. Distinguish between a power transformer and a distribution transformer.
29. Is efficiency of a transformer same at a particular load but at different power factors?
30. Is efficiency of a transformer at a particular load same at 0.8 power factor lagging and 0.8 power factor lagging?
31. What may be the main reason for a constant humming noise in a transformer when it is supplying some load?

34. Write short notes on the following: (i) magnetizing reactance; (ii) leakage reactance; (iii) eddy current loss; (iv) hysteresis loss; (v) all-day efficiency.

B. Numerical Problems

35. A 40 kVA 3200/400 V, single phase, 50 Hz transformer has 112 turns on the secondary winding. Calculate the number of turns on the primary winding. What is the secondary current at full load? What should be the cross-sectional area of the core for a core flux density of 1.2 Wb/m^2?

[Ans 896, 100 A, 01362 m^2]

36. A 400 kVA transformer has a full-load core loss of 800 W and copper loss of 2500 W. What will be the values of these losses at $\frac{1}{2}$ load?

[Ans 800 W, 625 W]

37. A single-phase transformer is required to step down the voltage from 1100 V to 400 V at 50 Hz. The core has a cross-sectional area of 25 cm^2 and the maximum flux density is 5Wb/m^2. Determine the number of turns of the primary and secondary windings.

[Ans 396, 144]

38. A single phase 40 kVA transformer has primary and secondary voltages of 6600 V and 230 V, respectively. The number of turns of the secondary winding is 30. Calculate the number of turns of the primary winding. Also calculate the primary and secondary winding currents.

[Ans 860, 6.06 A, 173.9 A]

39. A transformer on no load takes 4.5 A at a power factor of 0.25 lagging when connected to a 230 V, 50 Hz supply. The number of turns of the primary winding is 250. Calculate (a) the magnetizing current, (b) the core loss, and (c) the maximum value of flux in the core.

[Ans I_m= 4.35, P_c = 259 W, ϕ_m = 4.14 × 10^{-3} Wb]

40. A 660 V/ 220 V single-phase transformer takes a no-load current of 2A at a power factor of 0.225 lagging. The transformer supplies a load of 30 A at a power factor of 0.9 lagging. Calculate the current drawn by the primary from the mains and primary power

[Ans I_1 = 11.38 A, cos ϕ_1 = 0.829 lag]

41. A 100 kVA transformer has 400 turns on the primary and 80 turns on the secondary. The primary and secondary resistances are 0.3 ϕ and 0.01 ϕ, respectively, and the corresponding leakage reactances are 1.1 ϕ and 0.035 ϕ, respectively. Calculate the equivalent impedance referred to the primary side.

[Ans Z'_e = 2.05 Ω]

42. A 660 V/220 V single-phase transformer takes a no-load current of 2 A at a power factor of 0.255 lagging. The transformer supplies a load of 30 A at a power factor of 0.9 lagging. Calculate the current drawn by the primary from the mains and primary power factor. Neglect winding resistances and reactances.

[Ans I_1 = 11.4 A, cos ϕ_1 = 0.83 lagging]

43. The primary and secondary windings of a 500 kVA transformer have R_1 = 0.4 Ω and R_2 = 0.001 Ω, respectively. The primary and secondary voltages are 6600 V and 400 V, respectively. The iron loss is 3 kW. Calculate the efficiency on full load at 0.8 power factor lagging.

[Ans 98.3 per cent]

44. A 5 kVA 200/400 V, 50 Hz single phase transformer gave the following test data:

1. L.V. side open-circuit test–220 V, 0.7 A, 60 W
2. H.V. side short-circuit test–22 V, 16 A, 120 W

Calculate the regulation of the transformer under the full-load condition.

[Ans 3 per cent]

45. The no-load current of a transformer is 15 A at a power factor of 0.2 lagging when connected to a 460 V, 50 Hz supply. If the primary winding has 550 turns, calculate (i) magnetizing component of the no-load current, (ii) the iron loss, and (iii) maximum value of flux in the core.

[Ans I_m = 14.67 A, 780 W, 2.129 mwb]

46. A single-phase, 100 kVA distribution transformer is loaded as mentioned during 24 hours:
4 hours : no load
8 hours : 50 per cent load at power factor = 1

[Ans 92.5 per cent]

47. A 12 kVA, 200/400 V, 50 Hz single-phase transformer gave the following readings on the open-circuit test and the short-circuit test: open-circuit test : 200 V, 1.3 A, 120 W
short-circuit test conducted on the H.V. side: 22 V, 30 A, 200 W
Calculate the equivalent circuit parameters as referred to the low voltage side. Also calculate the magnetizing component of the no-load circuit.

[Ans R_c = 333 Ω, X_m = 174 Ω, R_e' = 0.055 Ω, X'_e = 0.175 Ω, I_m = 1.15A]

C. Multiple Choice Questions

1. A transformer having number of turns in the primary and secondary winding of 1000 and 500, respectively, is supplied with 230 V at 50 Hz. The induced EMF in the secondary winding will be
   1. 460 V at 50 Hz
   2. 115 V at 25 Hz
   3. 115 V at 50 Hz
   4. 500 V at 50 Hz.
2. The core of the transformers is made of laminated steel sheets so as to
   1. Reduce hysteresis loss
   2. Reduce eddy current loss
   3. Increase output voltage
   4. Reduce both hysteresis loss and eddy current loss.
3. The EMF induced in the windings of a transformer
   1. Lags the core flux by 90°
   2. Leads the core flux by 90°
   3. Is in phase with the core flux
   4. Is in opposition to the core flux.
4. To reduce the core losses in a transformer
   1. The core is made of silicon steel laminations
   2. The core is fastened very tight so that the core flux do not fly away
   3. The core is made of solid steel
   4. The core is made of copper laminations.
5. The no-load current of a 10 kVA, 230 V/115 V transformer wire will be about
   1. 5 per cent of its rated current
   2. 20 per cent of its rated current
   3. 30 per cent of its rated current
   4. 0.1 per cent of its rated current.
6. The no-load current of a 15 kVA, 230/1100 V single-phase transformer will be about
   1. 15.33 A
   2. 3 A
   3. 12 A
   4. 73.3 A.
7. Efficiency of a transformer is higher tham that of a motor or a generator of similar rating because
   1. There is no hysteresis and eddy current loss in a

    4. Transformers are connected to high-voltage transmission lines whereas motors and generators are connected to low-voltage supply lines.
8. Which of the following losses in a transformer vary with load
    1. Hysteresis loss
    2. Eddy current loss
    3. Copper losses in the windings
    4. Iron loss.
9. Open-circuit test and short-circuit test on a transformer are performed to determine, respectively, the following losses
    1. Copper loss and core loss
    2. Core loss and copper loss
    3. Eddy current loss and hysteresis loss
    4. Hysteresis loss and eddy current loss.
10. Maximum efficiency of a transformer is obtained at a load at which its
    1. Core loss becomes the minimum
    2. Copper loss becomes the minimum
    3. Copper loss equals core loss
    4. Core loss becomes negligible.
11. A transformer has 350 primary turns and 1050 secondary turns. The primary winding is connected across a 230 V, 50 Hz supply. The induced EMF in the secondary will be
    1. 690 V, 50 Hz
    2. 690 V, 100 Hz
    3. 690 V, 150 Hz
    4. 115 V, 50 Hz.
12. The rating of a transformer is expressed in
    1. kW
    2. kVA
    3. kWh
    4. cos ϕ.
13. The ampere-turns balance equation for a transformer on load can be expressed as
    1. $I_1N_1 = I_2N_2$
    2. $I_1N_1 >> I_2N_2$
    3. $I_1N_1 = I_2N_2$
    4. $I_1N_1 < I_2N_2$.
14. Which of the following characteristic assumptions for an ideal transformer are true?
    1. Coupling coefficient between the windings is unity
    2. There are absolutely no core and copper losses
    3. The core is made up material having infinite permeability
    4. All the characteristics as in (a), (b), and (c).
15. The EMF equation for a transformer is
    1. $E = 4.44 \phi f N^2$
    2. $E = 4.44 \phi fN$
    3. $E = 4.44 \phi f^2 N$
    4. $E = 4.44 \phi_n f N$.
16. Which of the following statements is true for a transformer?
    1. A transformer is an energy conversion device
    2. A transformer changes the voltage and frequency

17. Which of the following effects will the secondary load current of a transformer will have on the main flux created by the magnetizing current?
    1. Magnetization
    2. Demagnetization
    3. Polarization
    4. No effect.
18. On which of the following does the voltage regulation of a transformer depend?
    1. Load power factor
    2. Magnitude of load
    3. Winding resistance and reactance
    4. all factor as in (a), (b), and (c).
19. The no-load current of a transformer is
    1. The algebraic sum of I_m and I_c
    2. Phasor sum of I_m and I_c
    3. Algebraic sum of I_o and I_1^1
    4. Phasor sum of I_o and I_1^1.
20. The no-load current of a transformer as compared to its full-load current can be expressed as
    1. 0 to 2 per cent
    2. 2 to 5 per cent
    3. 10 to 20 per cent
    4. 20 to 30 per cent.
21. Power factor of a transformer of no load is low due to
    1. Large component of magnitizing current, which lags the voltage by 90°
    2. Large component of loss component of current
    3. Secondary ampere-turns interfering with the primary ampere-turns
    4. The fact that the primary and secondary windings are not firmly coupled.
22. The core loss and copper loss of a transformer on full load are 400 W and 600 W, respectively. Their values at one-third full load will be
    1. 133.3 W and 200 W
    2. 400 W and 66.66 W
    3. 133.3 W and 600 W
    4. 400 W and 200 W.
23. The full-load core loss and copper loss of a transformer are 400 W and 600 W, respectively. At approximately what percentage of full-load will the efficiency be maximum?
    1. 81 per cent
    2. 91 per cent
    3. 95 per cent
    4. 99 per cent.
24. The full load output of a transformer at unity power factor is 800 W. Its output at half load 0.8 power factor will be
    1. 400 W
    2. 320 W
    3. 160 W
    4. 640 W.
25. Large capacity transformers are placed in tanks filled with transformer oil. Which of the following are not valid for the above?
    1. Oil provides insulation between the two windings.
    2. Oil cools the transformer.

26. The full-load copper loss of a transformer is 1200 W. At half load the copper loss will be
    1. 600 W
    2. 1200 W
    3. 300 W
    4. 900 W.
27. The full-load core loss of a transformer is 1200 W. At half load the core loss will be
    1. 600 W
    2. 1200 W
    3. 300 W
    4. 900 W.
28. The no-load current of a certain transformer is 2 A. Its magnetizing component may be
    1. 1.8 A
    2. 0.2 A
    3. 0.4 A
    4. 0.02 A.
29. When the primary and secondary windings of a transformer are perfectly magnetically coupled
    1. The leakage reactance will be high and voltage regulation will be high (i.e., poor)
    2. The leakage reactance will be low and voltage regulation will be low (i.e., good)
    3. The leakage reactance will be low and voltage regulation will be high (i.e., poor)
    4. The leakage reactance will be high and voltage regulation will be low (i.e., good).

Answers to Multiple Choice Questions

1. (c)
2. (b)
3. (a)
4. (a)
5. (a)
6. (b)
7. (c)
8. (c)
9. (b)
10. (c)
11. (a)
12. (b)
13. (c)
14. (d)
15. (d)
16. (d)
17. (b)
18. (d)
19. (b)
20. (b)
21. (a)
22. (b)
23. (a)
24. (b)
25. (c)
26. (c)