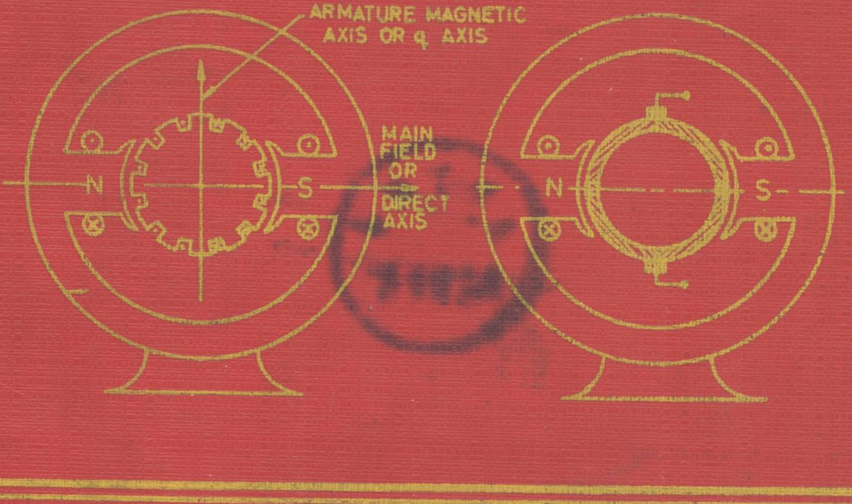
P. S. BIMBHRA

Electrical Machinery



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ELECTRICAL MACHINERY

[Theory, Performance and Applications]

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PREFACE

The primary aim of writing this book is to emphasise the physical concepts of electrical machines. In order to achieve this goal, the magnetic-flux view-point is used for studying the entire subject of electrical machinery. In each chapter, the theory is developed from elementary ideas in such a manner that their physical understanding is highlighted. The physical concepts regarding the internal behaviour of electrical machines are important, because these concepts only lead to creative engineering and motivation.

Chapter 1 deals with the treatment of transformers, for an understanding of transformer behaviour is essential to the study of electromechanical-energy-conversion devices. Chapter 2 is concerned with the basic principles of electro-mechanical-energy-conversion devices. In this chapter, it is emphasised that reaction of the coupling field is essential for the interconversion of energy from one to another form. This chapter shows how the energy stored in coupling magnetic field can be expressed in terms of circuit parameter L, which forms the basis of generalized theory of electrical machines. In chapter 3, basic principles of voltage generation and torque production are developed which are applicable both to a.c. and d.c. machines. The applicability of general voltage and torque equations to both a.c. and d.c. machines leads to their unified treatment and shows that electrical machines operate on the same basic principles. Chapters 4 to 6 pertain to the treatment of d.c. machines, synchronous machines and induction machines. Since machine windings form an integral part of all the electrical machines, the last chapter is devoted to these windings where there simplified treatments is presented.

The entire material given in this book has been class-room tested. Many illustrative examples are added in the text to explain many of the theoretical postulates. This book would be found suitable for undergraduate students of all the engineering colleges and institutes of India and foreign countries.

Now a days, the candidates for various competitive examinations are tested by means of objective type questions. In order to fulfil this need, multiple choice questions have been given in the appendix.

The author would welcome the advice and suggestions leading to the improvement of the book.

Patiala,
15th August, 1979

P.S. BIMBHRA

Dedicated to my wife

SURINDER

and sons

AMITPAL and PANCHAMPAL

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1

Transformers

The transformer is a device or a machine that transfers electrical energy from one electrical circuit to another electrical circuit through the medium of magnetic field and without a change in the frequency. The electric circuit which receives energy from the supply mains is called *primary* winding and the other circuit which delivers electric energy to the load is called the *secondary* winding. Actually the transformer is an electromagnetic energy conversion device, since the energy received by the primary is first converted to magnetic energy and it is then reconverted to useful electrical energy in the other circuits (secondary winding circuit, third winding circuit etc.). Thus primary and secondary windings of a transformer are not connected electrically, but are coupled magnetically. If the transfer of energy occurs at the same voltage, the purpose of the transformer is merely to isolate the two electric circuits and this use is very rare in power applications. If the secondary voltage is higher than the primary voltage, it is called a step-up transformer and if the secondary voltage is lower, then it is called a step-down transformer. Note that a step-up transformer can be used as a step-down transformer, in which case the secondary of step-up transformer becomes the primary of step-down transformer. Actually a transformer can be termed a step-up or step-down transformer only after it has been put into service. Therefore, when referring to the windings of a particular transformer, the terms high-voltage winding and low-voltage winding should be used instead of primary and secondary windings.

In a transformer, the electrical energy transfer from one circuit to another circuit takes place without the use of moving parts—it has, therefore, the highest possible efficiency out of all the electrical machines and requires almost neglegible amount of maintenance and supervision.

Insulation considerations limit the generation of alternator (ac) generator or synchronous generator) voltages from about 11 to 22 kV. By means of transformers, this voltage is stepped up to higher economical transmission voltages, 400 kV or even higher, in order to reduce the transmission losses. Wherever the electrical energy is required, transformers are installed to step down the voltage suitable for its utilisation for motors, illumination purposes etc. Thus the transformer is the main reason for the widespread popularity of a.c. systems over d.c. systems.

In addition to its use in power systems, transformers are widely employed in electronic and control circuits. Filament transformers are used to supply heating power to filaments of vacuum tubes. Input transformers connect the microphone output to the first stage of an electronic amplifier. Pulse transformers are used in radar, television and digital computers. Further use of transformers is

(*i*) for matching the impedances of a source and its load for maximum power transfer, and

(*ii*) for isolating d.c. while permitting the flow of a.c. between two circuits. Transformer is, therefore, an essential piece of apparatus both for high and low current circuits.

An electromechanical energy conversion device is one which converts energy from electrical to mechanical or from mechanical to electrical. The coupling between the electrical and mechanical systems is through the magnetic field. In a transformer also, the coupling between the primary and secondary windings is by means of the magnetic field. Both in electromechanical energy conversion devices and transformers, the coupling magnetic field behaves in a like manner Therefore, the fundamental principles involved in the analysis of a transformer are much more common in the analysis of electromechanical energy conversion devices.

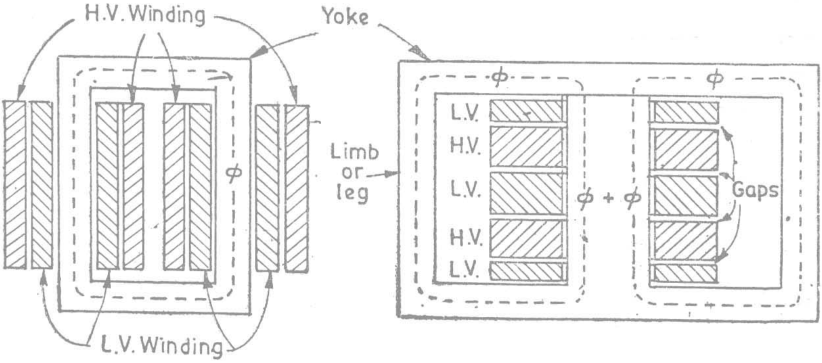
The transformer is a static piece of electric machinery and concepts about its behaviour can be understood in a comparatively simpler manner. In view of the above, the analysis of transformer must serve as a prelude to the study of electromechanical energy conversion devices. At the same time, a transformer is an important energy conversion device and detailed study of its behaviour is justified.

1·1. Transformer Construction

There are two general types of transformers, the core type and the shell type. These two types differ from each other by the manner in which the windings are wound around the magnetic core.

The magnetic core is a stack of thin steel laminations about 0·35 mm thick for 50 Hz transformers. In order to reduce the eddy current losses, these laminations are insulated from one another by thin layers of varnish. In the core type the windings surround a considerable part of steel core, Fig. 1·1 (*a*), whereas in the shell type, the steel core surrounds a major part of the windings Fig. 1·1 (*b*). The vertical portions of the core are usually called limbs or legs and the top and bottom portions are called the yoke.

In the core type transformer, half of the primary winding is wound over one leg and the other half, over the second leg or limb. Secondary winding is also wound half over one leg and the other half over the second leg, Fig. 1·1 (*a*). This sub-division of the windings is done to reduce the leakage fluxes and improve the performance of the transformer. Low voltage winding is placed adjacent to the steel core, in order to minimise the amount of insulation required.



(*a*) Core-type of transformers. (*b*) Shell-type of transformers.

Fig. 1·1.

In the shell type transformer, the primary and secondary windings are wound over the central limb and are interleaved or sandwiched as shown in Fig. 1·1 (*b*). Note that the bottom and top L.V. coils are of half the size of other L.V. coils.

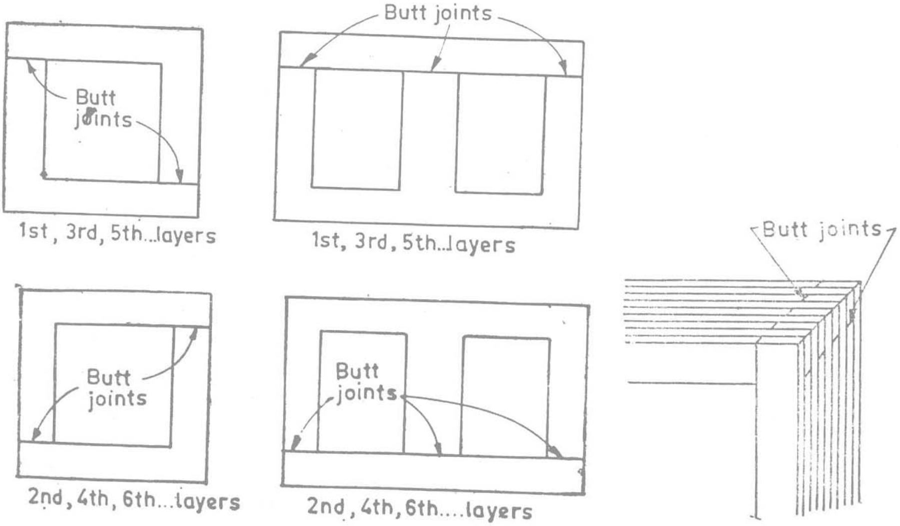
One type of laminations for the core and shell-type of transformers are illustrated in Fig. 1·2 (*a*) and (*b*) respectively. The steel core is assembled in such a manner that the butt joints in adjacent layers are staggered as illustrated in Fig. 1·2 (*c*). The staggering of the butt joints avoids continuous air gap and, therefore, the reluctance of the magnetic circuit is not increased. At the same time, a continuous air gap would reduce the mechanical strength of the core and, therefore, the staggering of the butt joints is essential.

During the transformer construction, first the primary and secondary windings are wound, then the laminations are pushed through the coil openings, layer by layer and the steel core is prepared.

Low power transformers are air-cooled whereas large power transformers are immersed in oil for better cooling.

For power frequency range of 25 to 400 Hz, transformers are constructed with 0·35 mm thick steel laminations. For audio-frequency range of 20 to 20,000 Hz, iron core with suitable refinements is used. For high frequencies employed in communication circuits, core is made up of powdered ferromagnetic alloy.

Air-cored transformers are also used for these high frequency ranges.



(*a*) Core (*b*) Shell type of transformers. (*c*) Arrangement of butt joints in a magnetic core.

Fig. 1·2. Two adjacent layers.

1·2. Principle of Transformer Action

A transformer works on the principle of electromagnetic induction. According to this principle, an e.m.f. is induced in a coil if it links a changing flux.

The schematic diagram of a two winding transformer (core- or shell-type) is as shown in Fig. 1·3, even though half of the primary (and secondary) winding is on one limb and the other half is on the second limb. The primary winding P is connected

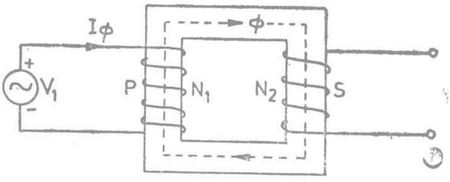


Fig. 1·3. Schematic diagram of a two-winding transformer.

to an alternating voltage source, therefore, an alternating current I_ϕ starts flowing through N_1 turns. The alternating mmf $N_1 I_\phi$ sets up alternating flux ϕ which is confined to the high permeability iron path as indicated in Fig. 1·3. The alternating flux induces voltage E_1 in the primary P and E_2 in the secondary S. If the load is connected across the secondary, a load current starts flowing.

In addition to the secondary winding, there may be a third (or tertiary) winding on the same iron core. The emf induced in the secondary or tertiary winding is usually referred to as the emf due to transformer action. Thus the transformer action requires the existence of alternating flux linking the various winding on the common magnetic core.

1·3. Ideal Two-winding Transformer

In the beginning, a transformer is assumed to be an ideal one, merely for obtaining an easier explanation of what happens in a transformer. For a transformer to be an ideal one, the various assumptions are as follows :

1. Winding resistances are neglegible.
2. All the flux set up by the primary links the secondary winding, *i.e.* all the flux is confined to the magnetic core.
3. The core losses (hysteresis and eddy current losses) are neglegible, and
4. The core has constant permeability, *i.e.* the magnetisation curve for the core is linear.

At a later stage, the effect of these assumptions will be taken up one by one.

Let the voltage V_1 applied to the primary be sinusoidal. Then the current I_ϕ will also be a sine wave. The mmf $N_1 I_\phi$ and, therefore the flux ϕ will follow the variations of I_ϕ very closely. That is, the flux ϕ is in time phase with the current I_ϕ and varies sinusoidally. If I_ϕ is zero, ϕ is zero and if I_ϕ is maximum positive, ϕ is also maximum positive and so on. Therefore, if the applied voltage V_1 has sine waveform, the flux ϕ must also have a sine waveform. Let the sinusoidal variation of flux ϕ be expressed as

$$\phi = \phi_m \sin \omega t \qquad \ldots(1{\cdot}1)$$

where ϕ_m is the maximum value of the magnetic flux and $\omega = 2\pi f$, is the angular frequency in rad/sec.

The emf induced in the primary N_1 turns by the alternating flux is given by

$$\begin{aligned} e_1 &= -N_1 \frac{d\phi}{dt} \qquad \ldots(1{\cdot}2) \\ &= -N_1 \omega \phi_m \cos \omega t \\ &= N_1\, \omega \phi_m \sin\left(\omega t - \frac{\pi}{2}\right) \end{aligned}$$

Its maximum value, E_{1max} occurs when $\sin\left(\omega t-\frac{\pi}{2}\right)$ is equal to 1.

$$\therefore \quad E_{1max}=N_1\omega\phi_m$$

and
$$e_1=E_{1max}\sin\left(\omega t-\frac{\pi}{2}\right) \qquad \text{...(1·3)}$$

$$\therefore \quad E_1=\frac{E_{1max}}{\sqrt{2}}=\frac{2\pi}{\sqrt{2}}fN_1\phi_m$$

$$=\sqrt{2}\,\pi fN_1\phi_m \qquad \text{...(1·4)}$$

The current I_ϕ in the primary is assumed to flow along the path *abcda*, Fig. 1·4. The e.m.f. e_1 induced in N_1 turns must be in such a direction as to oppose the cause, *i.e.* I_ϕ ; as a per Lenz's law. Therefore, the direction of e_1 is as shown by the arrows in the primary N_1 turns and it is seen to oppose v_1. Since primary winding resistance is negligible, e_1 at every instant, must be equal and opposite to v_1

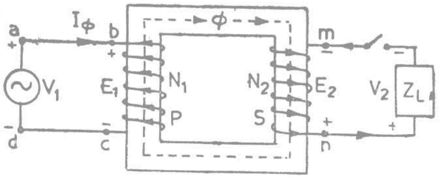


Fig. 1·4. Ideal transformer on load.

i.e.
$$\left.\begin{aligned} v_1&=-e_1=N_1\frac{d\phi}{dt} \\ \text{or} \quad V_1&=-E_1 \end{aligned}\right\} \qquad \text{...(1·5)}$$

The emf. induced in the secondary is

$$e_2=-N_2\frac{d\phi}{dt}=-N_2\,\omega\phi_m\cos\omega t$$

$$=N_2\,\omega\phi_m\sin\left(\omega t-\frac{\pi}{2}\right)$$

$$=E_{2max}\sin\left(\omega t-\frac{\pi}{2}\right) \qquad \text{...(1·6)}$$

$$\therefore \quad E_2=\frac{E_{2max}}{\sqrt{2}}=\sqrt{2}\,\pi f N_2\,\phi_m \qquad \text{...(1·7)}$$

From Eqs. (1·4) and (1·7),

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

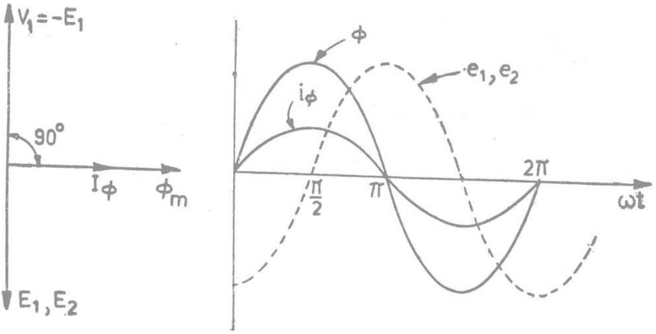
or

$$\frac{E_1}{N_2}=\frac{E_2}{N_2}=\sqrt{2}\,\pi f\,\phi_m \qquad \ldots(1{\cdot}8)$$

i.e. emf per turn in primary=Emf per turn in the secondary.

The relation expressed by Eq. (1·8) is very significant and must always be kept in mind.

For drawing the phasor diagram of an ideal transformer at no load, the waveforms of ϕ_1, e_1 and e_2 are drawn in Fig. 1·5 (*b*), with the help of Eqs. (1·1), (1·3) and (1·6). At time $t=0$, the flux is zero, therefore, it is drawn horizontally, Fig. 1·5 (*a*). Note that the vertical projection of a phasor in the phasor diagram must be equal to its value in the time diagram. The values of e_1 and e_2 are maximum negative at $t=0$, these are, therefore, drawn downward along the vertical axis. Here N_1 and N_2 are assumed equal for convenience and, therefore, $E_1=E_2$. The applied voltage V_1 is equal and opposite to E_1 and it is accordingly drawn opposing E_1. It is seen from Fig. 1·5, that e.m.fs. E_1 and E_2 lag by 90° the flux ϕ_m that induces them. The applied voltage leads the flux ϕ_m by 90°.



(*a*) Phasor diagram. (*b*) Time digram.

Fig. 1·5. Ideal transformer.

In Fig. 1·4, if the switch S is closed, a load impedance Z_L gets connected across the secondary terminals. Since the secondary winding resistance is zero, $V_2=E_2$. According to Lenz's law, the direction of secondary current I_2 should be such that the secondary mmf. F_2 $(=I_2N_2)$ is opposite to main flux ϕ_m in the core. For F_2 to be directed against ϕ_m, the current I_2 must leave the terminal n and enter the terminal m, Fig, 1·4. The secondary winding behaves like a voltage source, therefore, terminal n must be treated as positive and terminal m as negative. The mmf. F_2, being opposite to ϕ_m, tends to reduce the alternating flux ϕ_m. Any reduction in ϕ_m would reduce E_1 For an ideal transformer, $V_1=-E_1$. If the applied voltage V_1 is constant, E_1 and therefore flux ϕ_m must remain constant, as per Eq. 1·4. This can happen only if the primary draws more current I_1' from the source, in order to neutralise the demagnetising effect of F_2 In manner I_2 causes the primary to take more current I_1', in addition to I_ϕ such that

$$I_1' N_1=I_2N_2 \qquad \text{...(1·9)}$$

Assuming I_2 to lag behind V_2 by an angle θ_2, the phasor diagram under load for an ideal transformer can be drawn as shown in Fig. 1·6. Since mmfs. F_1 and F_2 tend to magnetise the core in opposite directions, they are shown in phase opposition in Fig. 1·6.

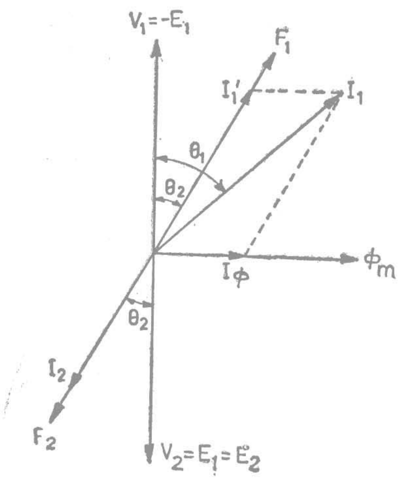


Fig. 1·6. Phasor diagram of an ideal transformer for inductive load.

The total primary current I_1 is the phasor sum of I'_1 and I_ϕ, *i.e.*

$$\bar{I}_1=\bar{I}_1'+\bar{I}_\phi$$

The power factor on the primary side of the ideal transformer is cos θ_1.

If the magnetising current I_ϕ is neglected, then Eq. 1·9 becomes

$$I_1N_1=I_2N_2 \qquad \text{...(1·10)}$$

i.e. Primary ampere-turns = Secondary ampere-turns.

Thus for an ideal transformer, with $I_\phi=0$, we have

$$\frac{V}{V_2}=\frac{E_1}{E_2}=\frac{N_1}{N_2}=\frac{I_2}{I_1} \qquad \text{...(1·11}$$

and $$E_1\,I_1=E_2\,I_2$$

or $$V_1\,I_1=V_2\,I_2 \qquad \text{...(1·12)}$$

i.e. Primary volt-amperes = Secondary volt-amperes.

If Kirchhoff's voltage law is applied to the primary winding circuit *abcda* of Fig. 1·4, then terminal *b* must be positive with respect to terminal *c*, since current I_ϕ can flow from a high potential to a lower potential only.

∴ For the circuit *abcda*, the Kirchhoff's voltage law gives,

$$v_1-e_1=0$$
$$v_1=e_1$$

From Eq. (1·5),

$$v_1=N_1\frac{d\phi}{dt}, \quad \therefore \quad e_1=N_1\frac{d\phi}{dt} \qquad \text{...(1·13)}$$

Here the e.m.f. e_1 is treated as a voltage drop in the direction of current I_ϕ and its instantaneous value is given by Eq. 1·13.

Now current I_ϕ flows from b to c, through the primary winding. If I_ϕ and therefore, flux ϕ is increasing, then e.m.f. e_1 induced in the the primary should be in such a direction that if e_1 acted alone, it would establish a current opposite to I_ϕ as per Lenz's law. Accordingly the direction of e_1 is indicated by arrows in the primary winding, terminal b is again positive with respect to terminal c and e_1 is seen to be acting opposite to v_1. This fact is written in mathematical form as

$$v_1=-e_1=N_1\frac{d\phi}{dt}$$

where e_1 is treated as a reaction e.m.f., counter e.m.f. or generated e.m.f.

The approach which led to the relation $e_1=N_1\frac{d\phi}{dt}$ is usually referred to as the circuit view-point. The second approach which gave the relation $e_1=-N_1\frac{d\phi}{dt}$ is referred to as the field or flux view-point. Any of the two view-points may be followed. Since the field view-point gives better physical concepts of the internal behaviour of a trpnsformer, it is adopted in this book.

1·4. Transformer Phasor Diagrams

The purpose of first considering an ideal transformer, *i.e.* a transformer with no core losses, no winding resistances, no magnetic leakage and constant permeability, is merely to highlight the most important aspects of transformer action. Such a transformer never exists and now the phasor diagrams of a real transformer with various imperfections will be considered.

Magnetisation curve of the actual transformer core is non-linear and its effect is to introduce higher order harmonics in the magnetising current. Since all the quantities in a phasor diagram must be of the same frequency, these higher order harmonics (whose frequencies are odd multiples of fundamental frequency) can't be represented in the phasor diagram. So a linear magnetisation curve for the transformer core will continue to be assumed.

The phasor diagram of a transformer is now developed, first at no load and then under load.

1·4·1. Transformer phasor diagram at no load. The magnetic flux ϕ_m being common to both the primary and secondary, is drawn first. The induced emfs. E_1 and E_2 lag ϕ_m by 90° and are shown accordingly in Fig. 1·7 (*b*). The voltage $-E_1$ is being replaced by V_1' just for convenience. Alternatively V_1' may be treated as a voltage drop in the primary, in the direction of flow of primary