regulated with the changer, without any supply interruptions. During the operation of an on-load tap changer ;

(i) the main circuit should not be opened otherwise dangerous sparking will occur and

(ii) no part of the tapped winding should get short-circuited.

One form of elementary on load tap-changer is illustrated in Fig. 1·46 (a). The centre tapped reactor C prevents the tapped

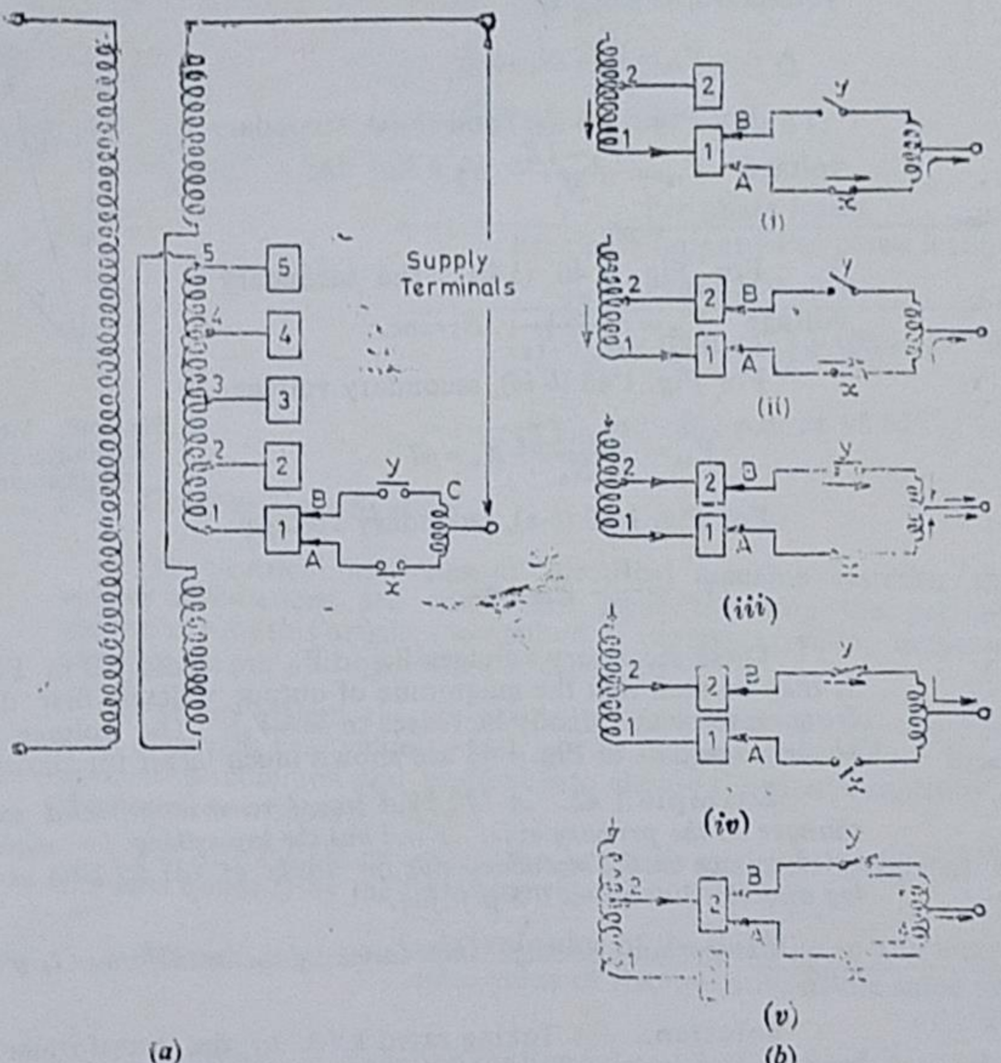


Fig. 1·46 (a) On-load tap-changer. (b) Sequence of operations from tapping 1 to tapping 2.

winding from getting short-circuited. The transformer tappings are connected to the correspondingly marked segments 1 to 5. Two movable fingers A and B, connected to centre-tapped reactor *via* switches *x* and *y*, make contact with any one of the segments under normal operation.

In Fig. 1·46 (*a*), both the fingers are in contact with segment 1 and full winding is in circuit. Switches x, y are closed. One half of the total current flows through x, lower half of the reactor and then to the external circuit. The other half of the total current flows through y, upper half of the reactor and then to the external circuit. It is seen that currents in the upper and lower halves of the reactor flow in opposite directions. Since the whole reactor is wound in the same direction, the m.m.f. produced by one-half is opposite to the m.m.f. produced by the second half. These m.m.fs. are equal and the net m.m.f. is practically zero ; therefore, the reactor is almost non-inductive and the impedance offered by it is very small. Consequently the voltage drop in the centre-tapped reactor is negligible.

When a change in voltage is required, the fingers A and B can be brought to segment 2, by adopting the following sequence of operations :

(*i*) *Open switch y, Fig. 1·46 (b-i).* The entire current must now flow through the lower half of the reactor. It, therefore, becomes highly inductive and there is a large voltage drop. It should be noted that the reactor must be designed to handle full load current, momentarily.

(*ii*) The finger B carries no current and can, therefore, be moved to segment 2, without any sparking [Fig. 1·46 (*b-ii*)].

(*iii*) *Close switch y, Fig. 1·46 (b-iii).* The transformer winding between taps 1 and 2 gets connected across the reactor. Since the impedance offered by the reactor is high for a current flowing in only one direction, the local circulating current flowing through the reactor and tapped winding is quite small. In this manner, the reactor prevents the tapped winding from getting short-circuited. The terminal voltage will be mid-way between the potentials of tappings 1 and 2.

(*iv*) *Open switch x.* The entire current starts flowing through the upper half of the reactor, manifested by a large voltage drop, Fig. 1·46 (*b-iv*).

(*v*) Move the finger A from segment 1 to segment 2 and then close switch x. The winding between taps 1 and 2 is, therefore, completely out of circuit, Fig. 1·46 (*b-v*). If further change in voltage is required, the above sequence of operations is repeated.

For large power transformers, the switches x and y may be circuit-breakers.

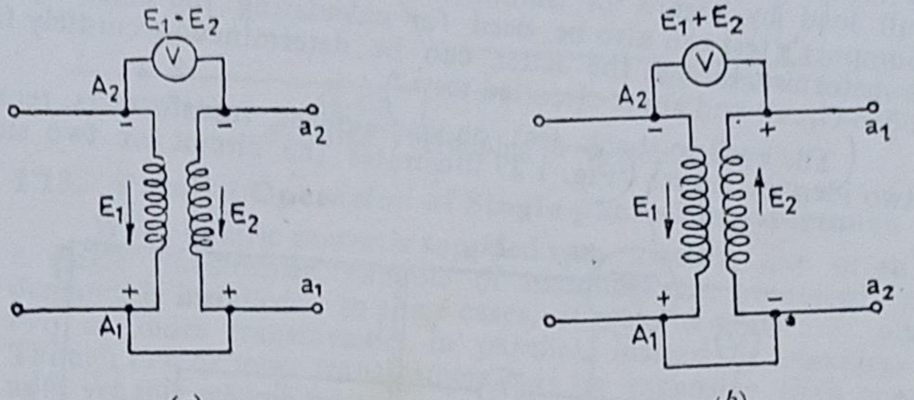
Another form of on-load tap-changer, also provided with a centre-tapped reactor, is illustrated in Fig. 1·47. The function of the reactor is again to prevent the short-circuit of the tapped winding. The switches 1, 2, ..., 5 are connected to the correspondingly marked taps.

1·11. Testing of Transformers

A wide variety of tests can be performed on a transformer and in this article, only a few of them are dealt with. The tests to be described here, are simple, can be performed easily in the laboratory and are helpful in gaining a better physical insight into the transformer behaviour.

(a) *Polarity test.* On the primary side of a two-winding transformer, one terminal is positive with respect to the other terminal at any one instant. At the same instant, one terminal of the secondary winding is positive with respect to the other terminal. These relative polarities of the primary and secondary terminals at any instant must be known if the transformers are to be operated in parallel or are to be used in a polyphase circuit.

When viewed from the h.v. side, the terminals are marked A_1 and A_2, the former, *i.e.* A_1 being on the extreme right, as per IS—2026. Terminals A_1 and A_2 are marked plus and minus arbitrarily in Fig. 1·26. Now terminal A_1 is connected to one end of the secondary winding and a voltmeter is connected between A_2 and other end of the secondary winding. A voltage of suitable value is now applied to the h.v. winding. Let E_1 and E_2 be the e m.fs.



(a) (b)

Fig. 1·26. Polarity test on a two winding transformer.

induced on h.v. and l.v. sides respectively. If the voltmeter reading is equal to E_1-E_2, then secondary terminal connected to A_1 is positive and is marked a_1, the l.v. terminal connected to A_2 through the voltmeter is negative and is marked a_2 as shown in Fig. 1·26 (*a*). If voltmeter reading is equal to E_1+E_2, then the terminals connected to A_1 and A_2 are negative and positive and are marked a_2 and a_1 respectively as shown in Fig. 1·26 (*b*). The subscript numbers 1, 2 on the h.v. and l.v. windings are so arranged that when A_2 is negative with respect to A_1, a_2 is also negative with respect to a_1 at the same instant. In other words, if the instantaneous emf is directed from A_2 to A_1 in h.v. winding, it is at the same time directed from a_2 to a_1 in the l.v. winding.

When the voltmeter reads the difference E_1-E_2, the transformer is said to possess a subtractive polarity and when voltmeter reads E_1+E_2, the transformer has additive polarity. In subtractive polarity, the voltage between A_2 and a_2 (or A_1 and a_1) is reduced. The leads connected to these terminals and the two windings are therefore, not subjected to high voltage stress. In additive polarity the two windings and the leads connected to A_1, A_2, a_1 and a_2 are subjected to high voltage stresses. On account of these reasons, subtractive polarity is preferable to additive polarity.

(*b*) *Open circuit and* (*c*) *Short circuit tests.* These two tests have already been described in detail in Art. 1·7.

(*d*) *Load test* (*Back to back or Sumpner's test*). A load test on a transformer is necessary if its maximum temperature rise is to be determined. A small transformer can be put on full load by means of a suitable load impedance. But for large transformers, full load test is difficult, since it involves considerable waste of energy and a suitable load, capable of absorbing full load power, is not easily available. However, large transformers can be put on full load by means of Sumpuer's or back to back test. The Sumpner's test can also be used for calculating the efficiency of a transformer, though the latter can be determined accurately from open-circuit and short-circuited tests.

The back to back test on single-phase transformers, requires two identical units. Fig. 1·27 illustrates the circuit for two single-

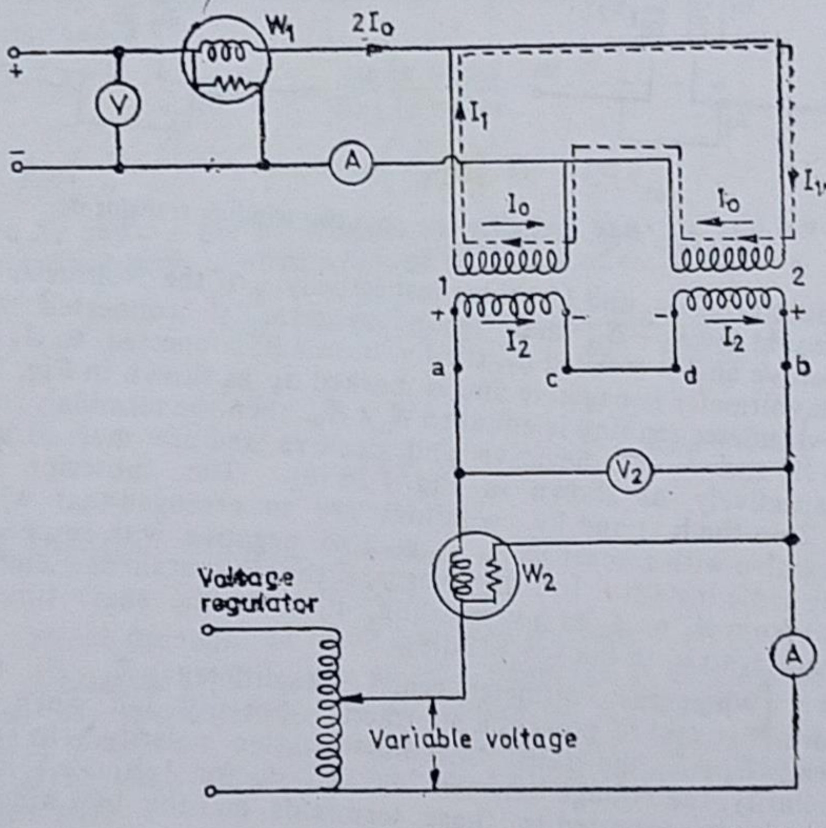


Fig. 1·27. Sumpner's (or back to back) test on two identical single-phase transformers.

phase transformers, where two primaries connected in parallel, are energised at rated voltage and rated frequency. With secondaries open, the wattmeter W_1 records the core losses of both the transformers. The two secondaries are connected in series with their polarities in phase opposition, which can be checked by means of a voltmeter. The range of this voltmeter connected across terminals ab, Fig. 1·27, should be double the rated voltage of either transformer secondary. Zero voltmeter reading ($V_{ab}=0$) indicates the secondaries are connected in opposition. Now, if the terminals ab are short-circuited, the current in the secondary would be zero because $V_{ab}=0$ and the wattmeter reading W_1 remains unaltered. In case the voltmeter reads the sum of the two secondary voltages, the secondaries are in the same phase. In order to bring them in phase opposition, terminals ad should be joined together to result in zero voltage across terminals bc.

In Fig. 1·27, it is assumed that voltage across ab is zero and the two secondaries are in phase opposition. Now a voltage is injected in the secondary circuit by means of a voltage regulator, fed from the source connected to the primaries or from a separate source. The injected voltage is adjusted till rated current flows in the two series-connected secondaries. By transformer action, primary windings also carry rated current. Note that the full load current in the primaries, completes its path through the main bus bars (shown dotted) and, therefore, the reading of wattmeter W_1 remains unaffected. It may be seen that the reading of voltmeter V_2 is equal to the sum of leakage impedance drops in both the transformers. The low-injected voltage has given rise to full load currents in primary and secondary windings, therefore, the full load ohmic losses of both the transformers are measured by the wattmeter W_2 (Fig. 1·27). If P_c and P_{sc} are the core and ohmic losses in each transformer, then the reading of wattmeter $W_1=2P_c$ and that of wattmeter $W_2=2P_{sc}$. The efficiency can now be determined by using Eq. (1·52) or Eq. (1·55).

It is seen from above that in Sumpner's test, even though the transformers are not supplying any load current, yet full iron-loss occurs in their cores and full copper-loss occurs in their windings. Net power input to the two transformers is $(2P_c+2P_{sc})$. If temperature rise of the two transformers is to be measured, then the two transformers are kept under rated loss conditions for several hours till maximum stable temperature is reached.

If $2I_0$ is the no load current, then for the assumed directions of I_0 and I_2, the primary current of transformer 1 is less (difference of $\bar{I}_1$ and $\bar{I}_0$) than the primary current of transformer 2 (sum of $\bar{I}_1$ and $\bar{I}_0$). Therefore, the two transformers do not operate under identical conditions—one may have slightly less temperature than the other.

Cooling :- The various methods of cooling of transformer are given below-

(i) AN — Air Natural. The transformer core and coils are open all round to air and are cooled by natural circulation without any ~~dev~~ additional device.

(ii) AB — Air Blast. Cooling is improved by using air blast instead of natural circulation.

(iii) ON — Oil Natural. The heat developed in the transformer is passed to tank walls through oil where it is dissipated by natural circulation of air.

(iv) OB — Oil Blast. Improved cooling of ON-type transformer is achieved by blasting air over the outside of the tank.

(v) OFN — Oil Forced Natural. Forced circulation of oil is done by a pump while cooling is done by natural circulation of air.

(vi) OFB — Oil Forced (Air) Blast. The cooling of OFN-type transformers is improved by employing air-blast over the coolers.

(vii) OW — Oil Water cooled. Oil is cooled by circulation of water over the cooling tubes.

(viii) OFW — Oil Forced Water cooled. Similar to OFB with the difference that oil is cooled by water instead of ~~at~~ air-blast.

In addition, there are several mixed cooling methods viz., ON/OB, ON/OFN, ON/OFB, ON/OFW, ON/OB/OFB, ON/OW/OFN etc..

7.9 HARMONICS IN TRANSFORMERS

In addition to the operation of transformers on the sinusoidal supplies, the harmonic behaviour becomes important as the size and rating of the transformer increases. Harmonic signals are those having frequency other than the fundamental frequency. The effects of the harmonic currents are:

1. Additional copper losses due to harmonic currents
2. Additional core losses due to Increased Eddy current loss
3. Increased electro-magnetic interference with nearby communication circuits.

On the other hand, the harmonic voltages in a transformer cause

1. Increased dielectric stress on insulation
2. Electro-static interference with nearby communication circuits.
3. Resonance between winding reactance and transmission line capacitance.

In present times, a greater awareness is generated by the problems of harmonic voltages and currents produced by non-linear loads like the power electronic converters. In addition to these external effects, non-linear nature of transformer core produces distortions in voltage and currents and increase the power loss. Study of harmonics is thus of great practical significance for operation of transformers.

7.9.1 Excitation Phenomena in Transformers

Excitation refers to the magnetization phenomenon that takes place in the transformer core and deals with the current, voltage, flux, and EMF related to the magnetization process. In an ideal transformer, the iron core is considered to be operating below the saturation level so that the permeability and reluctance are constants, i.e., the B-H characteristic is a straight line. This property of linearity of the magnetic core is utilized in developing the transformer equivalent circuit and corresponding phasor diagram. The effect of saturation and resulting magnetic non-linearity cannot be incorporated in the electrical equivalent circuit of a transformer. For such a linearized magnetization curve, the flux is proportional to the magnetization current and their waveforms are identical. Flux and exciting current is simply related by the equation:

$$\phi = \frac{\text{MMF}}{\text{Reluctance}} = \frac{T_p I_\phi}{S}$$

where T_p is the primary winding number of turns, I_ϕ the magnetizing current, and S the reluctance of core. If the supply voltage V_1 is purely sinusoidal, then the induced EMF E_1 must be sinusoidal so that it can correctly oppose the supply voltage (neglecting winding voltage drops).

Mathematically, the relation between induced EMF and flux is:

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

Thus, the flux should also be sinusoidal (rather co-sinusoidal) when the EMF is sinusoidal.

When the flux is of sinusoidal nature, the magnetizing current is also sinusoidal for a linear magnetic material.

Thus, in an ideal situation, when the primary supply voltage is sinusoidal, the exciting current (magnetizing current), flux in the core, and induced EMF are all pure sinusoids. This situation can be graphically described as below:

Considering linear magnetization characteristics, the B-H curve of the core magnetic material is shown in Figure 7.77.

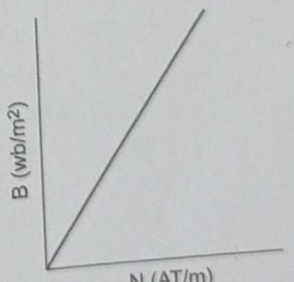


Fig. 7.77 Linear magnetization characteristics (B-H curve) of transformer core

Note that the Y-axis variable flux density (B) is proportional to the flux ϕ ($\phi = B \times$ Area) and the X-axis variable magnetizing force (H) is proportional to the magnetizing current I_ϕ ($I_\phi = H \times L/T_p$). Thus, axes variables of Figure 7.77 can be replaced by ϕ and I_ϕ in place of B and H, respectively, so that the magnetizing current I_ϕ values can be directly read from the graph.

For that purpose let us redraw the B-H curve of Figure 7.77 in the form of a ϕ-I_ϕ graph as shown in Figure 7.78. In Figure 7.78, only one-half cycle of the input voltage (sine wave) has been considered. This will make the flux wave also to look sinusoidal as shown in Figure 7.78.

Consider the point a on the flux wave. Draw a horizontal line from a that meets the *magnetization* curve at 1. The flux value at this instant is A-1. Corresponding value of the magnetizing current as read from the magnetization curve is o′-A. This condition occurs at a time t_1 which is at a distance o-t_1 from the origin of the flux wave. At the same instant of time o′-t_1', the value of magnetizing current is t_1'-a' (= o′-A) which is required to set up the flux A-1. The point a' is obtained as the point of intersection of a horizontal line drawn from t_1' and extending the vertical line from 1-A downwards.

Consider another point b on the flux wave. Draw a horizontal line from b that meets the *magnetization* curve at 2. The flux value at this condition is B-2. Corresponding value of the magnetizing current as read from the magnetization curve is o′-B. This condition occurs at a time t_2 which is at a distance o-t_2 from the origin of the flux wave. At the same instant of time o′-t_2', the value of magnetizing current is t_2'-b′ (= o′-B) which is required to set up the flux B-2. The point b′ is obtained as the point of intersection of a horizontal line drawn from t_2' and extending the vertical line from 2-B downwards.

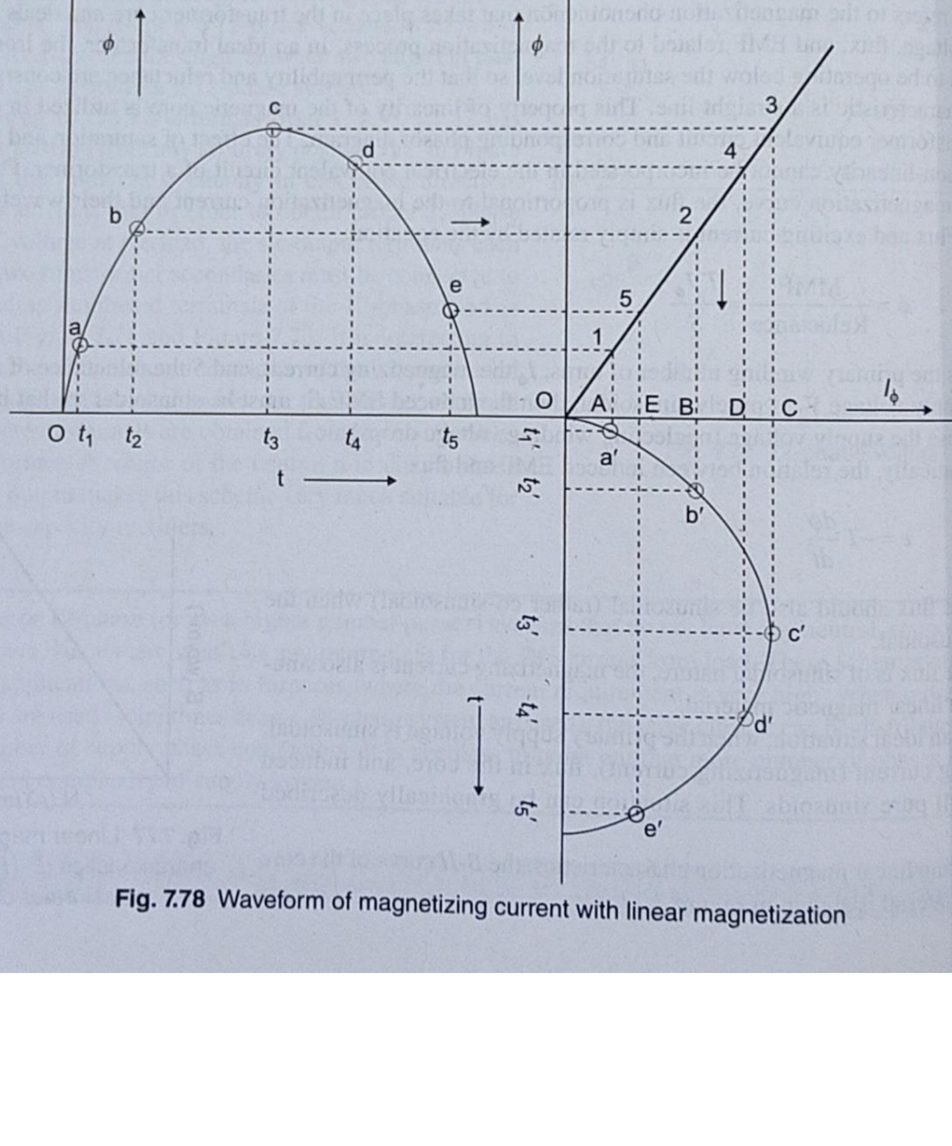


Fig. 7.78 Waveform of magnetizing current with linear magnetization

Similarly, travelling along the sinusoidal flux wave, the points c, d, and e can be located and the corresponding magnetizing current values are obtained at c′, d′, and e′, respectively. Joining the points a′, b′, c′, d′, e′ sequentially. A curve joining all these points represents the waveform of magnetizing current. As seen in Figure 7.78 that the magnetizing current waveform is also sinusoidal.

Next, consider the magnetization characteristic is non-linear, but without any Hysteresis. Sometimes for meeting the requirement of material saving, transformers are operated with high value of flux such that the core material can go into saturation. Figure 7.79 shows such a situation when the flux wave peak has reached at the point 3 on the magnetization curve which is well up to saturation. When a sinusoidal voltage is applied to the primary, the flux wave is also sinusoidal (rather co-sinusoidal), and nature of the magnetization current can be found out in the same manner as was in Figure 7.78 as described by Figure 7.79 below.

The magnetization current waveform is traced out by joining the points a′, b′, c′, d′, e′ sequentially corresponding to the points a, b, c, d, and e on the flux wave. As seen in Figure 7.79, even with sinusoidal input supply voltage and sinusoidal flux, the magnetization current wave does not remain sinusoidal; rather it becomes peaky in nature. The peaky waveform, however, is symmetrical about its peak value. It is also to be noted that the peak values of the voltage, flux, and the magnetizing current takes place at the same time instant. *Remember that when the input supply voltage is sinusoidal, the induced EMF and hence the flux is always sinusoidal, even with a non-sinusoidal magnetizing current.*

Fourier analysis of the non-sinusoidal magnetizing current will show that it contains the fundamental signal along with higher order odd harmonics, predominantly the third harmonic as shown in Figure 7.80.

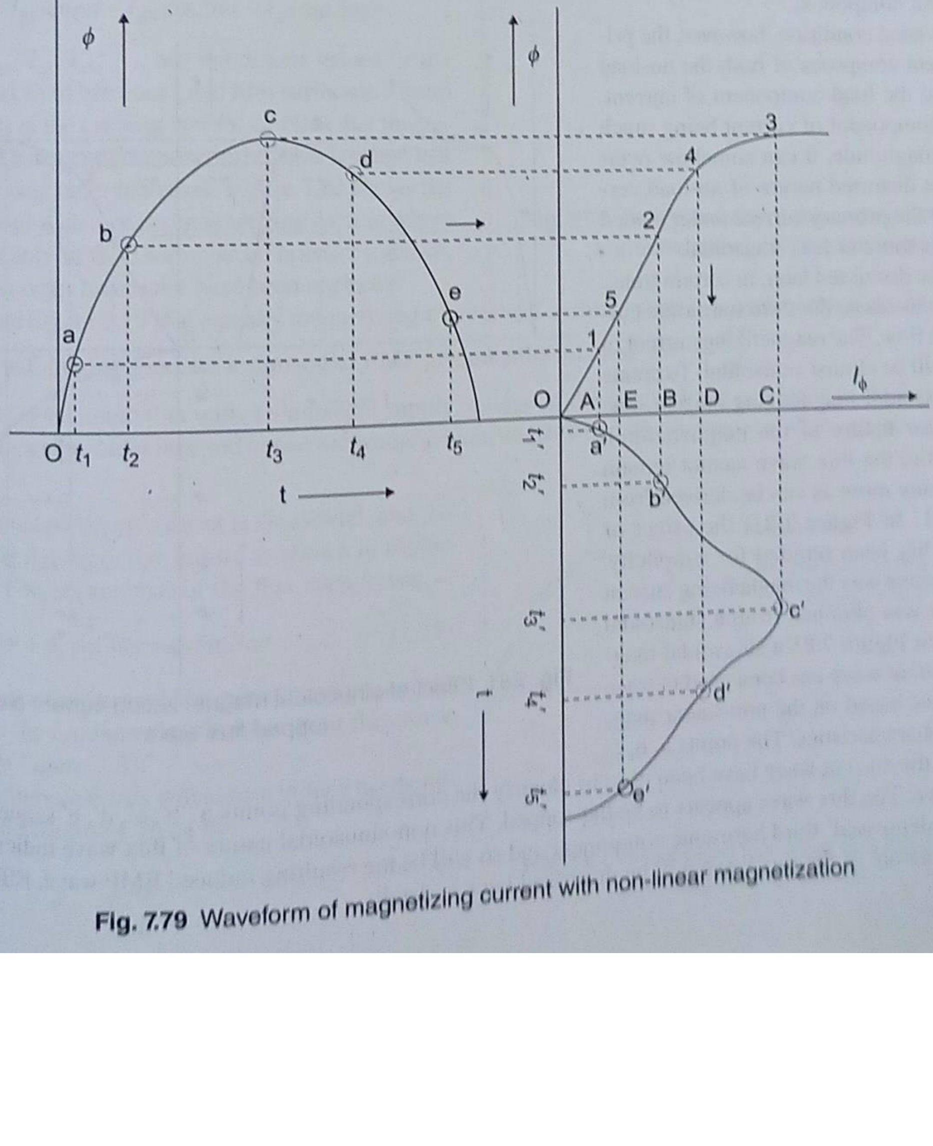


Fig. 7.79 Waveform of magnetizing current with non-linear magnetization

As seen from Figure 7.80, the fundamental component of magnetizing current I_ϕ is in the same phase with the flux ϕ. Since ϕ is 90° out of phase with the supply voltage V_1, the power loss due to this fundamental component of magnetizing current ($I_{\phi f}$) is zero ($V_1 \times I_{\phi f} \cos 90° = 0$). Similarly, all odd harmonic, including the third harmonic components of the magnetizing current has a time phase difference of n 90° with the supply voltage V_1, where n is the order of the harmonic. Thus, power associated with the voltage V_1 and fundamental as well as all odd harmonic components of the magnetizing current is zero. Thus, even if there is saturation in the core magnetic material, without Hysteresis, there is no associated power loss. The effect of saturation is only to distort the magnetizing current.

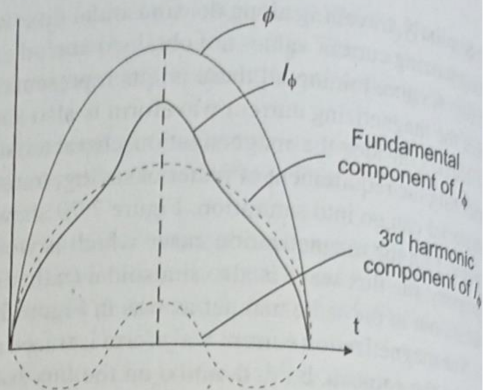


Fig. 7.80 Fundamental and third harmonic components of I_ϕ

For more detail, go to online resources.

The no-load current in the above case is found to contain third, fifth, and seventh and other higher odd-harmonic components, and their magnitudes increase rapidly as the transformer operation is pushed more into saturation. Magnitude of the third harmonic component is predominant; amounting may be up to as high as 10% of the fundamental component.

Under loaded condition, however, the primary current composes of both the no-load current and the load component of current. The load component of current being much higher in magnitude, it can somehow overshadow the distorted nature of no-load current so that the primary current under loaded condition is more or less sinusoidal.

As will be discussed later, in certain transformer connections, the third harmonic current cannot flow. The magnetizing current in that case will be almost sinusoidal. To create such a sinusoidal magnetizing current, due to non-linear nature of the magnetization characteristic, the flux wave cannot remain sinusoidal any more as can be derived from Figure 7.81. In Figure 7.81, the effect of Hysteresis has been omitted for simplicity. Like in the same way the magnetizing current wave shape was obtained from a sinusoidal flux wave, in Figure 7.81 a sinusoidal magnetizing current wave has been used to trace the flux wave based on the non-linear magnetization characteristics. The points a, b, c, d, and e on the current wave have been used to identify the corresponding points a′, b′, c′, d′, e′ sequentially on the flux wave. The flux wave appears to be flat-topped. This non-sinusoidal nature of flux wave indicates that it contains a 'depressed' third harmonic component and so will be the resulting induced EMF wave. Effect of this flat-topped nature of the flux wave will be discussed later in details.

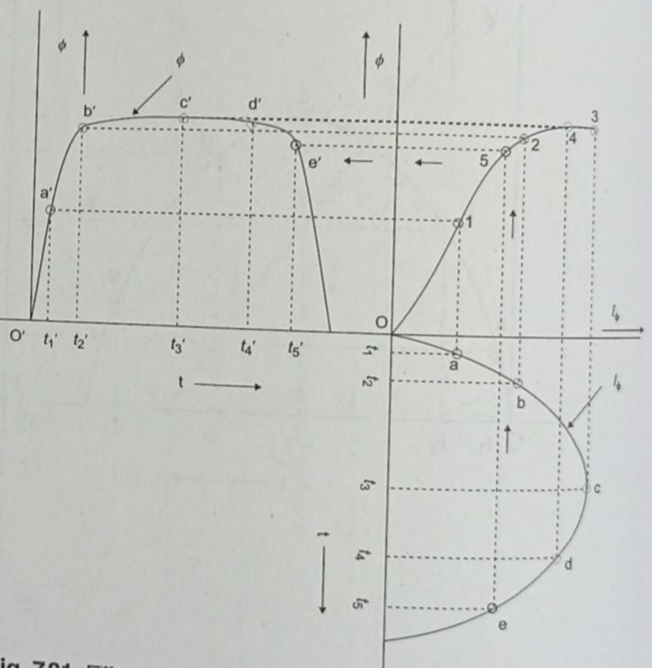


Fig. 7.81 Effect of sinusoidal magnetization current creating flat-topped flux wave