6

Transformers

6.1 OPERATING PRINCIPLES

A single-phase power system transformer consists basically of two windings wound onto an iron core. The iron core concentrates the flux and restricts it to a defined path. It also creates the maximum possible amount of flux for a given excitation. In order to maximise the mutual coupling the two windings are wound concentrically on to the same part of the iron core. Figure 6.1 shows the typical winding arrangement of a single-phase transformer. This is called shell-type construction.

Not all the flux created by one winding couples with the other winding. Furthermore the flux which does not couple both windings does not flow completely round the iron core, some of it flows in the air close to the windings. The common flux in the iron circuit is called the mutual or magnetising flux. The flux that escapes into the air and does not couple the windings is called the leakage flux. One winding is referred to as the primary winding and is connected to the source of supply voltage. The second winding is the secondary winding and is connected to the load. The primary may be either the low or the high voltage winding.

The magnetising flux is determined by the applied voltage to the primary winding. In power transformers the current drawn from the supply to magnetise the core is only a fraction of one percent of the rated primary winding current. The core design and type of iron is specially chosen to minimise the magnetising current.

When current is drawn from the secondary winding the effect on the magnetising flux is to reduce it. However, the magnetising flux density must be maintained and this is achieved by the primary winding drawing more current from the supply. More detailed explanations of the working principles of transformers can be found in References 1 to 4 in Chapter 5 herein.

Currents now exist in both windings. Therefore a volt-drop must exist in each winding due to its leakage reactance (due to leakage flux) and its conductor resistance. The equivalent circuit of a single-phase transformer can be represented as in Figure 6.2.

Where R_p Primary winding resistance.
X_p Primary winding leakage reactance.
R_s Secondary winding resistance.
X_s Secondary winding leakage reactance.
X_m Magnetising reactance.

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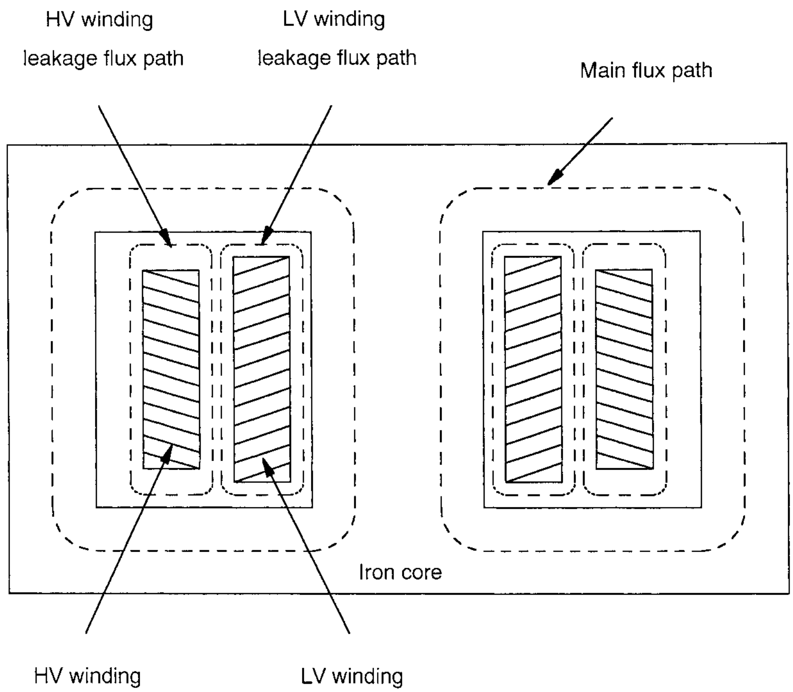

Figure 6.1 Flux paths in the core and windings of an iron cored transformer.

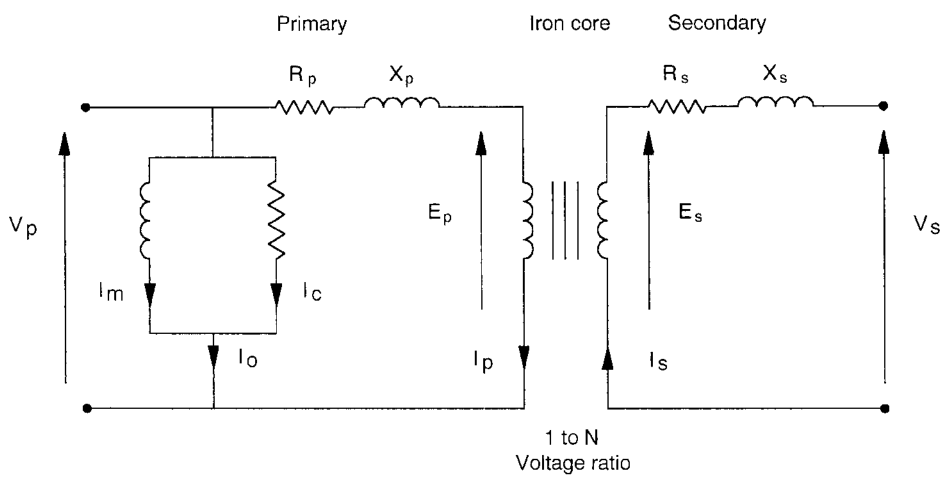

Figure 6.2 Equivalent circuit of an iron cored transformer.

R_c Resistance to account for eddy current losses in the iron core.
N Turns or transformation ratio.

It is possible to represent the equivalent circuit with all the winding components on either the primary side or the secondary side. The components that are moved across to the other side become what is called the 'referred' components. For example if the secondary winding impedance $R_s + jX_s$ is referred to as the primary side then the referred or equivalent impedance $R'_s + j\,X'_s$ in the primary circuit is,

$$R'_s + j\,X'_s = \frac{R_s + j\,X_s}{N^2}$$

Hence the total series impedance in the primary circuit becomes,

$$Z_p = (R_p + R'_s) + j(X_p + X'_s) \text{ ohms.}$$

At this stage all the components are ohmic values and are obtainable from tests.

The per-unit impedance Z_{pu} can be simply derived from the ohmic impedance values and knowing either the primary rated current or the kVA rating of the transformer. It will, however, be seen that the per-unit impedance Z_{pu} is the same whether it is calculated from the primary or the secondary data.

The standard kVA ratings of transformers follow the numbering sequence of ISO3 or BS2045 for units designed on the basis of European practice, e.g. 100, 125, 160, 200, 250, 315, 400, 500, 630, 800 kVA and decades above and below.

Figures 6.3 and 6.4 show typical values of the components of Z_{pu} for different ratings and voltage ratios of transformers (data given at a system frequency of 50 Hz and derived from different sources, for example References 1 and 2).

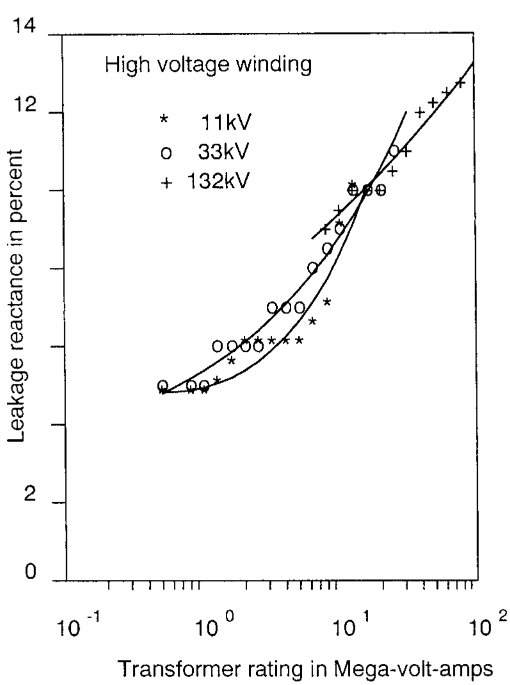

Figure 6.3 Leakage reactance in percent versus the MVA rating 50 Hz transformers.

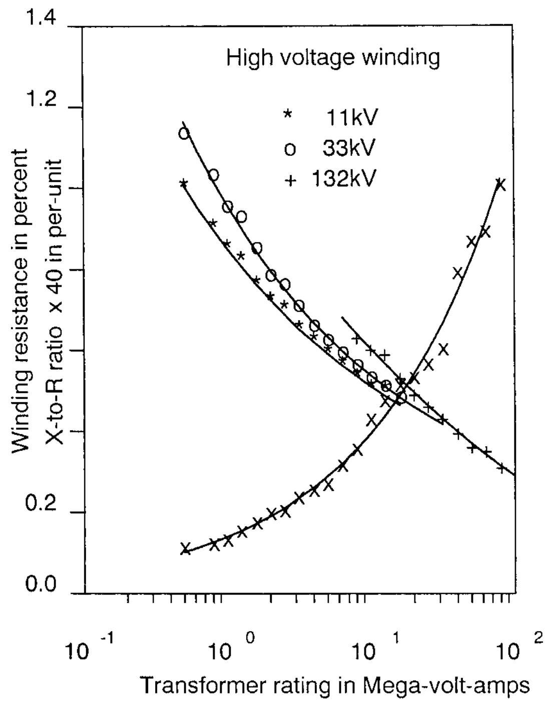

Figure 6.4 Winding resistance in percent and X-to-R ratio in per-unit versus the MVA rating of 50 Hz transformers.

6.2 EFFICIENCY OF A TRANSFORMER

Since the equivalent circuit contains two winding resistances and a core-loss resistance then power is lost as heating energy inside the transformer. Hence the conversion of power through the transformer cannot be 100%, a small loss of efficiency occurs. This is usually less then about 2% for power transformers. Assume all resistances and reactances are referred to the secondary winding. The efficiency can be expressed as,

$$\text{Efficiency} = \frac{\text{Output power}}{\text{Input power}} = \frac{\text{Output power}}{\text{Output power} + \text{power losses}}$$

$$= \frac{V_s \cos\emptyset}{V_s \cos\emptyset + I_s(R_s + R'_p) + \dfrac{P_c}{I_s}}$$

Where $\cos\emptyset$ is the power factor of the load
P_c is the core-loss
I_s is the secondary current
V_s is the secondary voltage
E_s is the secondary emf.

This formula applies to single-phase transformers, or to one phase of a three-phase transformer.

6.3 REGULATION OF A TRANSFORMER

Regulation is a subject that regularly occurs in power systems. Regulation is a measure of the voltage drop in a device or circuit. It compares the volt-drop at full-load with the terminal voltage at no-load, both of which can be obtained for a transformer from simple factory tests.

The voltage regulation of a transformer is the change in the terminal voltage V_s between no-load and full-load at a given power factor. It is usually expressed as a percentage of the rated voltage. The phasor diagram for the single-phase transformer or one phase of three-phase transformer is Figure 6.5.

$$\text{Percentage regulation} = \frac{E_s - V_s}{V_s} \times 100\%$$

$$E_s = \sqrt{\text{OC}^2 + \text{AC}^2}$$

Let R_{se} = Equivalent resistance in the secondary circuit

X_{se} = Equivalent leakage resistance in the secondary circuit

For % regulations less than 20% it can be seen that the quadature components have little effect on the magnitude of E_s. Hence AC can be ignored and so.

$$E_s = \sqrt{(\text{OC}^2)} = \text{OC} = V_s + I_s\ R_{se} \cos \text{Ø} + I_s\ X_{se} \sin \text{Ø}$$

$$\%\ \text{Regulation} = \frac{(I_s R_{se} \cos \text{Ø} + I_s\ X_{se} \sin \text{Ø})\ 100\%}{V_s}$$

(Note: See Chapter 9 for a similar expression used with cable volt-drop).

In most power transformers R_{se} is much smaller than X_{se} and so R_{se} can be ignored in regulation and fault level calculations.

Figure 6.4 shows the per-unit values of R_{se} for typical transformers.

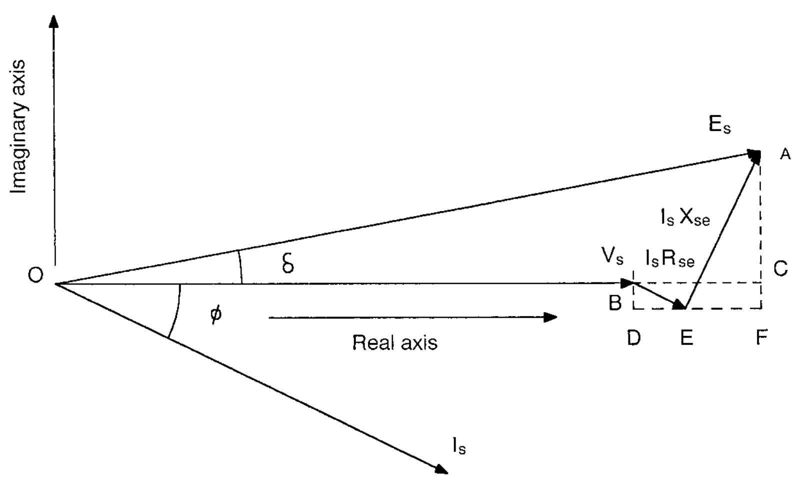

Figure 6.5 Phasor diagram of a loaded transformer at a lagging power factor.

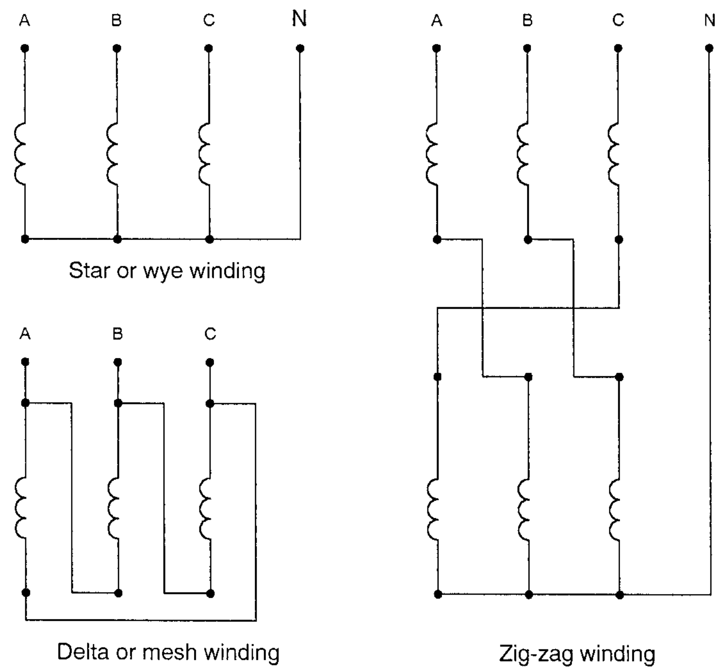

Figure 6.6 Commonly used primary and secondary winding connections for three-phase transformers.

6.4 THREE-PHASE TRANSFORMER WINDING ARRANGEMENTS

Three methods of arranging the windings of three-phase transformers are commonly encountered: star, delta and zig-zag. Each method can be applied to either or both of the primary and secondary windings, Figure 6.6 shows the three forms.

Star windings are used when a neutral connection is required for earthing or for un-balanced loads (these are usually groups of single-phase loads placed between separate phases of the supply and its neutral. Each group may not be identical and hence the system will be unbalanced).

Delta windings are most frequently used on the high voltage winding, which is usually the winding connected to the supply. The delta connection also allows third harmonic currents to circulate which improves the waveforms of the line currents and voltages on both side of the transformer. Delta windings may be slightly more expensive because the insulation has to withstand the full line-to-line voltage.

The zig-zag winding requires each three-phase winding to be split in half. Each half is interconnected with a half-winding on another core limb. Zig-zag windings are used to suppress third harmonics or to provide a neutral connection as an earthing transformer, and to obtain a phase angle shift. Zig-zag windings are sometimes used for power rectifier circuits when high order harmonic can be nuisance and have to be minimised.

A procedure has been adopted (IEC60076 part 4) for identifying the winding connections. Letters and numbers are used as follows. The high voltage (HV) terminals have upper-case letters e.g. A-B-C, R-Y-B, U-V-W, L1-L2-L3 and the low voltage (LV) terminals have lower-case letters

Table 6.1. Letters used to identify three-phase windings

Geographical area	Letters and numbers used		
USA	L1	L2	L3
	1	2	3
Europe	U	V	W
	R	S	T
United Kingdom	R	Y	B
	A	B	C

e.g. a-b-c, r-y-b, u-v-w, l_1-l_2-l_3. Each winding has a start numbered 1 and a finish numbered 2. Tappings are numbered 3, 4, 5 etc. from the start terminal.

The choice of letters and numbers tends to be a national preference, see Table 6.1 as a rule-of-thumb guide.

Corresponding windings on the same core limb are numbered such that if the emf in winding A_1 A_2 is in the direction of A_1 positive with respect to A_2 at a given instant, then the corresponding emf in the LV winding will have a_1 positive with respect to a_2. Figure 5a in IEC60076 Part 4, or Figure 46 in Reference 2, which gives more detail, shows the induced emf directions and phase angle displacements for the more common connection arrangements.

The type of winding e.g. star, delta is given a letter, again upper case for HV and lower case for LV windings. The letters are,

D for Delta HV,	d for delta LV
Y for Star HV,	y for star LV
Z for Zig-zag HV,	z for zig-zag LV

Since a phase angle displacement can occur across the transformer due to its method of connection it is necessary to identify this displacement. The numbering system for this is based on the hands of a clock. Each five-minute position on a clock gives 30° phase displacement hence,

12 o'clock gives zero displacement
1 o'clock gives −30° displacement
6 o'clock gives 180° displacement
11 o'clock gives +30° displacement

These are the commonly encountered displacements. (Note that the phasor rotation is anti-clockwise.)

For example a transformer has a delta HV winding a star LV winding and a +30° displacement. It is described by letters and numbers as a Dyll transformer.

6.5 CONSTRUCTION OF TRANSFORMERS

Most power system transformers fall into two types of construction, dry-type or liquid immersed type. Dry-type include air insulated and solid insulated construction. Solid insulation is usually epoxy resin.

Liquid immersed types use various forms of oil and special synthetic liquids. The chlorinated liquids, e.g. polychlorinated-biphenyl, have been banned in most countries because they are very strong pollutants and are almost impossible to destroy, except by intensive burning in a special furnace. Modern liquids are synthetic compounds typically silicone based, and are usually specified to be flame retardant. IEC60296, 60836, and 60944 describe suitable liquids. These transformers are the type normally used in oil and gas plants. Resin insulated transformers are very suitable for indoor locations and off-shore plants because they contain no flammable liquid, produce no spillage and require minimal maintenance. They are usually more expensive than conventional liquid immersed transformers.

Liquid immersed transformers usually have some form of external radiator to dissipate the heat generated internally by the windings and the core. The radiator is often the surfaces of the tank specially folded into corrugated fins, or is in the form of fins, which are attached to the tank sides.

As the transformer ratings become larger it is more difficult to dissipate the heat. The next method used requires external tubes to be attached in groups at the top and bottom of the tank. The liquid circulates between the tubes and the tank by natural convection. Further increase in ratings require external banks of fin-type radiators with increased surface area. There are many variation in the design of tubes and radiators. Eventually the problem requires a separately mounted radiator and forced circulation liquid pump between the radiator and the tank. All of these methods of cooling liquid immersed transformers can be supplemented with external forced air fans. The addition of a simple system of fans can increase the base rating of the transformer by typically 25% to 35%. These fans can be arranged to start by detecting the temperature rise of the windings or liquid, or by measuring the current in either winding of the transformer. It is usual practice in oil and gas plant engineering to purchase transformers complete with the fans or at least with the fittings to enable fans to be added later. However, the power cables and switchgear associated with the transformer should be rated for the fan-assisted operation, otherwise the benefit of the fans will not be achieved conveniently or even economically.

A method of lettering is used to denote the form of cooling for a particular transformer.

Four upper case letters are used.

The first pair of letters are for the heat removal from the windings and core, i.e.

- AN AIR-NATURAL:- Natural cooling by the internal air circulating amongst the winding and core by natural convexion.
- ON OIL-NATURAL:- Natural cooling by oil that circulates amongst the windings and core by natural convexion.
- LN LIQUID-NATURAL:- As for ON but a synthetic liquid is used.
- OF OIL-FORCED:- The oil is circulated by the use of an oil pump, which is usually mounted externally in the lower interconnecting pipework between the external radiator bank and the side of the tank. This method is seldom used in the oil industry because it pertains to very large ratings of transformers.
- LF LIQUID-FORCED:- As for OF but a synthetic liquid is used.

The second pair of letters are for the external surface heat removal, i.e.

- AN AIR-NATURAL:- Natural cooling by atmospheric air circulation. The windings and core are directly exposed to the air, as in the case of a dry-type or resin insulated transformer.

- AF AIR-FORCED:- Air forced cooling is arranged by using fans and trunking on the outside of the transformer. These can be applied to dry-type or liquid insulated transformers.

Transformers rated up to approximately 2.5 MVA are usually fitted with cooling tubes or tank mounted radiators. These units would typically feed low voltage switchboards. Between 2.5 MVA and 15 MVA the use of tubes would be inadequate and tank mounted radiators would be necessary. Above about 10 MVA the radiators would be separately mounted from the tank and coupled by pipework.

The overall construction of oil and liquid filled transformers would be IP55 as defined in IEC60529.

Oil industry sites are often located in hostile environments which also have aggressive transport routes for the delivery of their equipment. It is therefore necessary to construct the windings and core components in such a manner that they can withstand impacts and rough handling during transportation to site. The windings should be robustly braced to ensure that they do not move during transportation.

Other variations including using water-cooling are possible but these are not commonly encountered.

The amount of heat typically dissipated from a liquid-immersed transformer is about 12.5 watts per square metre of surface area per degree C. If such a transformer is inside a room or module then this heat must be removed by changing the air regularly, or by the HVAC cooling system. The heat dissipation can also be calculated directly from the known efficiency of the transformer at full load.

Transformers are usually fitted with devices to indicate the temperature of liquid, windings and the core. These may be direct-reading thermometers, indirect resistance temperature detectors (RTDs) or thermocouples. Signals from these devices are used to trip the feeder switchgear in the event of excessive temperature.

Liquid-immersed transformers are fitted with special safety relays and devices to safeguard the unit from internal faults and explosions. Slowly generated faults tend to produce gas from the oil or liquid.

The gas accumulates in a special chamber which is fitted with two float switches, and these operate alarms and trips when the gas accumulates slowly or rushes in during internal explosions. This system is called a Buchholz relay, and is normally used only on transformers fitted with conservator tanks. Transformers below about 1600 kVA are often sealed type liquid-immersed units. Internal explosions are released by using a special blow-off valve. Often the space above the liquid level in this type of unit is filled with an inert gas such as nitrogen.

Reference 3 gives an excellent description of all the aspects of transformer design, testing and operation.

6.5.1 Conservator and Sealed Type Tanks

Conservator type transformers are fitted with an overhead tank which is approximately half full of the oil or liquid insulant. The overhead tank is allowed to breath to atmosphere as the liquid level varies with the average temperature inside the transformer. It breathes through a small vessel filled with silica gel which absorbs the water vapour that may pass into or out of the transformer.

An alternative design which has the advantage of reduced periodic maintenance of the oil or liquid is the sealed type. The main tank is designed not to breath and is provided with a gas or vapour space between the top surface of the liquid and the underside of the tank lid. The lid is bolted onto the tank using a gas tight gasket, to form a hermetic seal.

The expansion of the liquid requires extra space in the tank and so the liquid level rises and falls in the space provided under the lid. The space is usually filled with nitrogen gas at a pressure slightly above atmospheric pressure.

6.6 TRANSFORMER INRUSH CURRENT

Power transformers have a core that consists of a large volume of laminated iron. Under normal operating conditions the flux density in the core is just above or near to the point where saturation begins. The core has no air-gaps and is capable of retaining a significant amount of residual flux when the transformer is de-energised. The amount of flux retained depends upon the point on the sine wave of the applied voltage when the primary current is switched off. The iron core has a hysteresis characteristic associated with the magnetising current, which introduces a small lagging phase angle in the waveform of the magnetising current. For the purpose of illustrating the build up of current in-rush this phase angle can be ignored. It can therefore be assumed that the magnetising current lags the applied voltage by almost 90 degrees. A small angle will exist across the impedance of the primary winding both at no-load and at any load on the secondary winding. The residual flux is determined by the instant of opening the primary circuit, and by the phase and magnitude of the voltage in the winding at the instant.

Assume the transformer is energised by its primary winding but not connected to a load. Also assume that it is required to switch off the transformer. The opening process of the AC circuit relies on the fact that the switching device requires a current zero to de-ionise and extinguish the arc. Since the circuit is highly inductive the applied voltage will not be zero when the current is zero. It will be close to its maximum positive or maximum negative value. The flux will be almost zero when the opening process is complete, hence the residual flux will be very small or zero.

When the transformer is loaded the situation is different. The power factor of the load is usually between 0.8 and 0.95 lagging, which means that the primary current will be nearly in phase with the applied voltage, and the voltage across the magnetising branch in the equivalent circuit. At the instant of opening the primary circuit the current will be zero and these voltages will not be at or near to their maximum extremes. Hence the flux will not be zero and consequently a high value of residual flux will be retained in the core. It can be seen that switching a loaded transformer out of service will create a situation where a high residual flux will exist in the transformer. This flux will remain for a long time, long enough to be present when the transformer is required to be switched back into service. The existence of residual flux can be minimised by unloading the secondary circuit before switching off the primary circuit. However, in three-phase transformers this desirable situation cannot be completely achieved due to the 120 degree phase angles between three applied voltages. At least one limb of the core will have some residual flux established in it after the switching is complete, and this flux will then be distributed in the other limbs.

If the transformer is to be switched into service and its core has high level of residual flux stored in it, then upon closing the switch the magneto-motive force created by the applied voltage will cause the magnetising flux to be superimposed on the residual flux in the core. During the cyclic magnetisation the total flux density will exceed the designed or nominal level, which will be in the saturated region of the magnetisation curve. The magnetising current required to establish the total flux will be very large in comparison with its normal value. This high level of current is called the 'inrush current' and it contains significant harmonic components while it persists.

Suppose that the residual flux density at the instant of switching the transformer into service is B_o Wb/m^2, and that the range of flux density for rated primary voltage is ± 1.0 Wb/m^2. If the primary impedance volt-drop is neglected during the initial switching process, then an excursion of 2.0 Wb/m^2 will be required above initial value of B_o Wb/m^2 in order that the required emf is induced to match the applied voltage. The following numerical example will illustrate what happens during the cyclic variations of the primary applied voltage. If B_o starts at say 0.7 Wb/m^2 as shown in Figure 6.7 then the theoretical maximum flux density will 2.7 Wb/m^2 corresponding to a magnetising current which is approximately 475 times the steady state maximum value of the magnetising current, or 10 time the rated primary current. Note that the design value of the magnetising inductive branch in the equivalent circuit can be further represented by a series circuit. This revised circuit consists of the primary winding resistance and constant inductance, together with a non-linear inductance that accounts for the saturation of the core iron. It can be seen that when the value of the magnetising current is high, during the saturated state of the core, the emf in the non-linear inductance is reduced because of the volt-drop in the primary winding components. This will have the effect of reducing the excursions of the flux density which may reach say 1.5 Wb/m^2, instead of 2.0 Wb/m^2 if the winding volt-drop were to be ignored. During the next two half cycles the emf must again be induced and so the range of flux density will need to be greater then 1.5 Wb/m^2, since at the lower instantaneous densities the current will be approaching its normal range of values. Let the range be 1.9 Wb/m^2 for the cycle, and so the minimum flux density will become say 0.3 Wb/m^2, which is significantly less than B_o. This process is repeated cyclically until B_o disappears and the variation in the flux density is symmetrical about the time axis and has extreme values of ± 1.0 Wb/m^2 equal to the design values, and the magnetising current settles at its designed rms value.

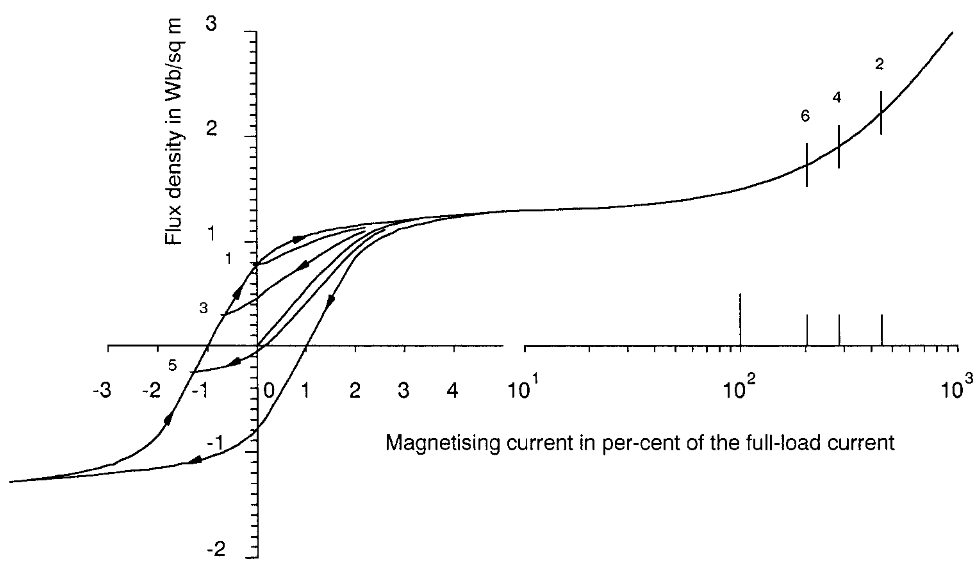

Figure 6.7 An illustration of the in-rush current in a transformer. The effect of residual flux and hysteresis is shown.

It can seen that the instantaneous, and short-term root-mean-square, values of the primary current can be much higher than their rated values, typically by as much as 10 times. Reference 4 Chapter 5 section XIV explains the phenomenon and offers a method of calculating the shape of the first half-cycle of in-rush current. The reference also points out that if a HV/LV transformer is energised from the LV secondary terminals, the in-rush current may in some designs be up to twice the value in per unit than if the energising is carried out at the primary terminals.

These high values of current cause two particular problems. Firstly the designer of the transformer must brace the winding to withstand the very high electromagnetic forces that will exist between the coils of the windings. These forces will be instantaneous and proportional to the square of the current magnitude. Secondly these asymmetrical large currents will be seen by the protective relays upstream of the transformer. They will appear as unbalanced currents in the three lines that are supplying the transformer. This imposes a stability problem for the designer of the overcurrent relays. A special circuit will be needed within the relay to stabilise its operation when these in-rush switching currents occur. Care also need to be taken in setting the relay current versus time curves. An amount of time delay is usually incorporated into the settings to override the transient time of the in-rush current, which usually lasts for about 5 cycles of fundamental current.

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