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Transformer

03
Chapter

Objective

In this chapter we will cover the following concepts:

- *Construction of a Transformer*
- *Ideal Transformer*
- *Practical Transformer*
- *Equivalent circuit of Transformer*
- *Testing of a Transformer*
- *Losses & Efficiency of Transformer*
- *Voltage regulation of Transformer*
- *Rating of a Transformer*
- *Transformer as magnetically coupled circuit*
- *Auto Transformer*
- *Three phase Transformer*
- *Parallel operation of Transformers*
- *Harmonics in a Transformer*

Introduction

The Transformer is a device that transfers electrical energy from one electrical circuit through the medium of magnetic filed without a change in frequency. The electrical circuit which receives energy from the supply mains is called as primary winding & the circuit which delivers electrical energy to the load is called as secondary winding. Primary & secondary windings of a Transformer are not electrically coupled, but are coupled magnetically. The coupling filed allows transfer in either direction from LV circuit to HV circuit and from HV circuit to LV circuit.

When secondary voltage is higher than primary voltage it is called as step-up Transformer. When secondary voltage is lower than primary voltage it is called as step-down transformer. In a Transformer, electrical energy is transferred without use of moving parts so it has highest efficiency out of all Electrical Machines. By means of Transformer we step-up the generated voltage from 11KV & 22KV to 400KV for transmission.

3.1 Applications of Transformers

1. For stepping up the voltage before transmission which is called as power transformer.
2. In communication, input transformers connect microphone output to first stage of an electronic amplifier.
3. In electronic & control circuits, transformers are used for impedance matching for maximum power transfer from source to load.
4. In power electronics transformers are used for pulse gate triggering.

3.2 Construction of Transformer

In a transformer, primary & secondary windings are would around the core of transformer. Core links the primary & secondary windings by magnetic flux. Core should possess the following properties.

1. High permeability & low reluctance
2. Generally made of Si steel due to following properties
   - *Ferromagnetic material*
   - *Low hysteresis coefficient 'x' to reduce hysteresis loss* $\left(P_h = K_h B_m^x f\right)$
   - *Generally, CRGO steel is used.*

3.2.1 Magnetic Core

1. The magnetic core is a stack of thin Si-steel laminations about 0.35 mm thick for 50 Hz Transformers.
2. To reduce eddy current loss, these layers are insulated form each other.
3. The materials used for insulation are:
   - *China clay*
   - *Japan varnish*
   - *Impregnated paper*
   - *Oxide paints*
4. Eddy current losses are proportional to path travailed by eddy currents & so to reduce eddy current losses we reduce path length by dividing the core into thin laminations.
5. Stacking Factor = iron Factor $= \dfrac{\text{Net CS Area}}{\text{Gross CS Area}} = \dfrac{A_n}{A_g} < 1$

   A_n: net cross-sectional area which is CS area of magnetic material excluding lamination
   A_g: gross cross-sectional area which is CS area of magnetic material including lamination
6. Laminations must be lightly riveted else air gap is introduced which increases reluctance & increases magnetizing current for same flux.
7. In high frequency transformers, eddy current losses are high & so to minimize such losses ferrimagnetic materials are used which have high resistivity.

> ***Points to Remember***
>
> - *Due to air gap, reluctance increases & hence mmf increases for same amount if flux. Due to increase in mmf required the magnetizing current required to establish flux increases & power factor reduces.*
> - *Eddy current loss is inversely proportional to resistivity so by use of Ferrimagnetic Materials, we can increase resistivity & reduce eddy current loss.*

3.2.2 Type of Core Structure

1. There are two types of core constructions
   - *Core Type*
   - *Shell type*
2. In core type transformer, some flux flows through the entire region whereas in shell type the flux divides into two parts in two side limbs

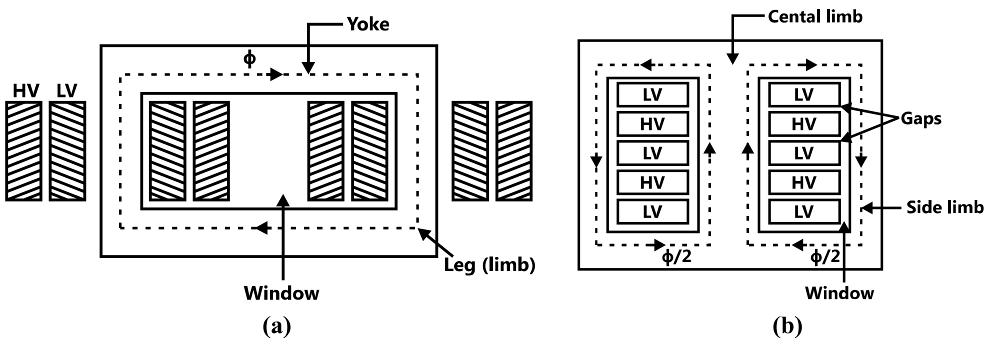


Figure 3.1 : Cross-sectional view of Transformer core and winding in (a) Core type (b) Shell type Transformer

3. Since flux is some in core transformer it has a series magnetic circuit.

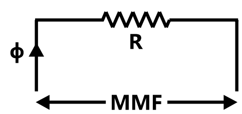


Figure 3.2 : Magnetic circuit of Core type Transformer

4. Since flux gets divide in shell type transformer, it has parallel magnetic circuit

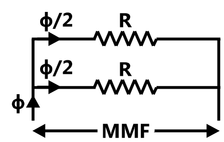


Figure 3.3 : Magnetic circuit of Shell type Transformer

5. The vertical legs of transformer core are called as limbs & horizontal legs are called as yoke.

3.2.3 Comparison of core type & shell type transformer

1. Construction

Core type transformer are much simpler in design & permit easier assembly & insulation of windings. Also, core type of transformer are easier to dismantle for repair work.

2. Force

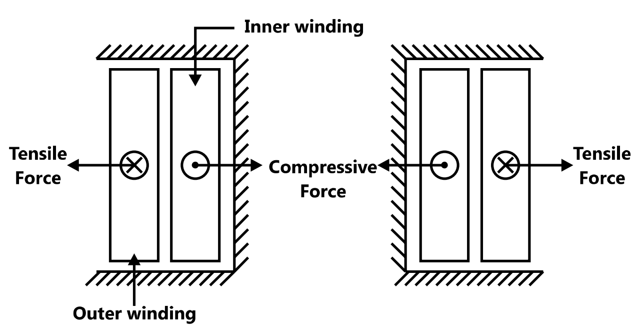


Figure 3.4 : Force on the windings in a Core type Transformer

- *The current carried both windings is in opposite directions so the force between them is repulsive.*
- *These currents tend to be very large in case of short circuit & force becomes very large so inner winding gets crushed into insulation & outer winding feels tensile force & is pushed outwards.*

- *The reliability of transformer operation is very important & therefore design should be such that windings suffer no damage when shorted.*
- *In Shell type Transformer, winding is surrounded by core so that windings are bettor supported mechanically.*
- *In Core type Transformer, winding are more susceptible to damage.*

3. Leakage Reactance

Due to large space between high & low voltage windings, it is not easily possible to subdivide the windings to a great extent in case of core type transformer. In Shell type transformers, leakage reactance can be reduced by use of sandwich coils.

4. Repairs

Windings are easily accessible in core type transformer so coils can be easily inspected. Also, core type transformer is easily to dismantle for repair.

5. Cooling

In core type transformer windings are exposed to atmosphere & therefore cooling is better in windings than in core. In shell type transformer, core is exposed to atmosphere & therefore cooling is better in core than windings. The most vulnerable part in transformer is winding insulation & due to better heat dissipation core construction is preferable.

Comparison Summary

S.No.	Core type	Shell Type
1	Easier to construct	Complex construction
2.	Less mechanical support	More mechanical support
3.	More leakage flux	Less leakage flux
4.	Eary to repair	Difficult to repair
5.	Better cooling	Less cooling
6.	High voltage, high power applications	Low voltage, low power applications
7.	Less insulation required	More insulation required
8.	More copper required	Less copper required
9.	Winding surrounds core	Core surrounds windings

3.2.4 Magnetostriction

1. Based on grain orientation, CRGO steel can be classified as conventional type or H1B type
2. H1B type has lower hysteresis losses
3. Magnetostriction is a phenomenon in which the dimension of a magnetic material changes when a magnetic field is applied.
4. If alternating field is applied the dimension of material increases and decreases in every half cycle.
5. Due to magnetostriction, there are periodic changes in the length of a body in an alternating field. The frequency of magnetostrictoin is twice as large as that of existing alternating field.
6. Magnetostriction gives rise to noise in core of transformer. Magnetostrictoin is minimum in rolling direction & maximum in 90° direction.
7. Transformer must be mounted on elastic surface or rubber to reduec the effect of magneto striction.

3.2.5 Core cross section

1. Small core type transformers have rectangular section limbs with rectangular coils.

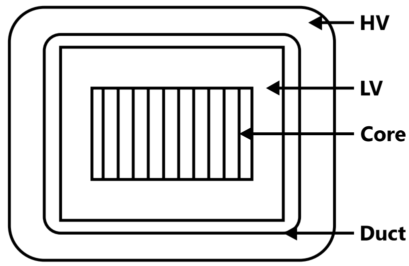


Figure 3.5 : Top view of Core type Transformer

2. In large capacity transformers, economic use of core material requires circular cross-section.
3. **Advantages of circular cross-section**
   - *Less core material required*
   - *Less Copper required because circle has smallest circumference.*
   - *Reduced I^2R losses.*
4. A circular cross section would require a large number of laminations of different sizes which is time consuming & uneconomical
5. So, we can approximate circular cross-section by a stepped core.
6. A 2 stepped core is also called as cruciform "core"

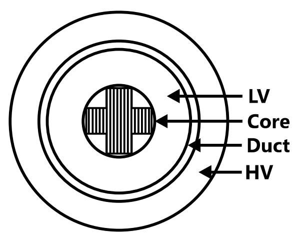


Figure 3.6: Top view of Stepped Core type Transformer

7. In small transformer, the entire core can be punched as a whole but this will lead to wastage of sheet if followed for large transformers.
8. The magnetic core is mode of different type of laminations to give it a proper shape.
9. Joints at different junction introduce are gap which lead to increase in reluctance & magnetizing current so joints must be tightly riveted to reduce are gap

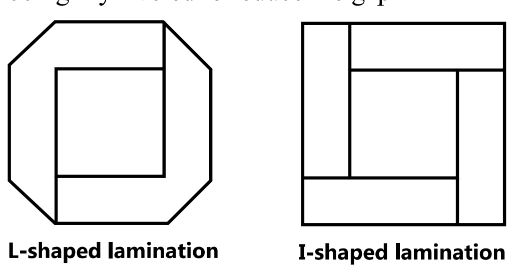


Figure 3.7 : Shape of lamination in Core type Transformer

10. The gaps between laminations must not be greater than 1-2 mm
11. The layers should be such that air gap is not continuous & reluctance is not increased.

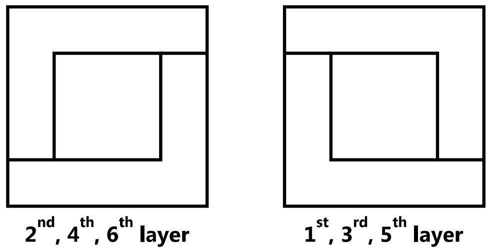


Figure 3.8 : Placement of laminations in Core type transformer

12. During transformer construction, first primary & secondary windings are wound & then core is pushed through coil opening.

3.2.6 Transformer windings

1. Concentric winding

Each limb is wound with a group of coils consisting to each other. The low voltage winding is placed next to core to minimize the insulation requirement between winding & core.

2. Sandwich winding

In shell type of transformers, coils shaped as pancakes are used. Both LV & HV coils are split into a number of windings & each HV coil is sandwiched between two LV coils. This results in better coupling & less leakage flux & less leakage reactance.

The direction of HV & LV flux should be opposite so if both are on same limb they carry current in opposite directions but if they are on diff limbs they carry current in same direction.

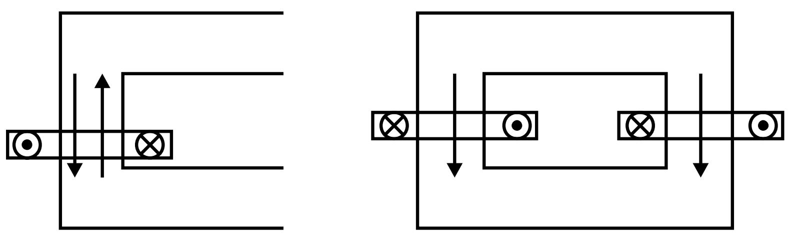


Figure 3.9 : The direction of currents in windings to satisfy Lenz's law

3.2.7 Transformer insulation

Oil is used in transformer to provide insulation. Oil has primarily two functions:

1. To create an acceptable level of insulation in conjunction with insulated conductor & coils
2. To provide a cooling medium capable of extracting quantities of heat without deterioration as on insulating medium.

3.2.8 Bushings

1. The bushing consists of a current carrying part in form of a conducting rod installed in a hole in transformer cover & used for isolating the current carrying part
2. The busing used for transformer having voltage above 36 KV are either oil filled or capacitor type.
3. Oil filled consists of a cylinder passing through its axis & oil separating the cylinder and the inside of porcelain.
4. It is used to separate transformer from high voltage lines to avoid flashover

Exercises

Level-01

Problem 1: How is power transformer different from distribution transformers?

Problem 2: Why is transformer core loss independent of load current?

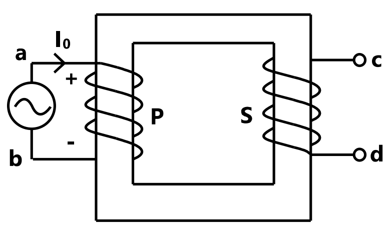
Problem 3: Why an OC test is generally performed at rated voltage on LV side of transformer. Why is the copper loss almost negligible in this test?

Problem 4: Why is the SC test performed at reduced voltage on the HV side? Why is the core loss almost negligible is this test?

Problem 5: Why is the core loss represented on shunt resistance in a transformer circuit model? What are its limitation?

Problem 6: A 6300/210 V. 50 Hz, single-phase transformer has per turn emf of about 9 volts maximum flux density of 1.2 T. Find the number of high-voltage and low-voltage turns and the net cross-sectional area of the core.

Problem 7: The instantaneous polarity of primary winding of an ideal transformer is shown in figure below. The direction of flux and polarity of the instantaneous voltage induced in secondary is.



Problem 8: The voltage applied to the primary winding of an unloaded single phase transformer is given by $V = (400\cos\omega t + 100\cos 3\omega t)$. The primary has 500 turns and frequency of the fundamental component of the applied voltage is 50Hz. If no load current is found to be.

$i_0 = 0.43\cos(\omega t + 60^0) + 0.08\cos(3\omega t - 60^0)\,A$

Find total core loss

Problem 9: A 1-phase transformer has the following data:
Peak flux density in core = 1.40 T
Net core area = $0.012\,m^2$
Current density in conductors = $2.5\,MA/m^2$
Conductor dia. = 2.0 mm; Primary voltage = 230 V, 50 Hz
Calculate the kVA rating of the transformer and the number of turns on the primary winding.

Problem 10: A 3300/300V, $1-\phi$ transformer has an equivalent resistance of 0.01pu and equivalent reactance of 0.04pu. find the secondary terminal voltage at full load & 0.08 pf lag for primary voltage of 3300V.

Problem 11: A $1-\phi$ transformer has regulation of 8% when delivering full load at unity pf & 14% when delivering same load at 0.8 pf lagging. What would be regulation if transformer is delivering half at 0.8 pf leading

Problem 12: The leakage impedance of 10kVA, 3300/330V transformer is 10%. Determine
(a) Voltage that must be applied on H.V side to circulate rated current with L.V side shorted
(b) Maximum possible voltage regulation

Problem 13: A 200V, 50Hz, $1-\phi$ transformer has Hysteresis & eddy current losses of 250W & 90W respectively of transformers is now energized from 230V, 50Hz. Calculate its core loss. Assume steinmetz constant equal to 2

Problem 14: A 10kVA, 500/250V, $1-\phi$ transformer given following test results

Exercises

Level-01

1. Ans: -----
Solution:
Distribution transformers are used at lower end of the distribution system where load diversity is low. To supply this type of load, the transformer is on 24 hours, feeding to core loss while copper loss being proportional to square of current varies widely but average copper loss is low. For high all day efficiency,
P_i [iron loss]/ P_c [copper loss]<1

In subtransmission and HV transformission levels transformers supply bulk power & their load is the sum of large load centres, whose diversity causes the transformer load to remain close to full load most of the time. So, these transformer are designed for peak power efficiency near full load, i.e.
$$\frac{P_i}{P_c} \simeq 1$$

2. Ans: -----
Solution:
Winding resistances and leakage reactance in transformers are very small. So the voltage drop is of orders 2-5% which is almost negligible
So, even on load, $V_1 \simeq E_1 = 4.44\,fN\phi$

So, core flux is almost constant i.e., independent of load current

3. Ans: -----
Solution:
Voltage source at LV side rating of transformer is of order 11kV which is easily available in the lab
So, OC test is performed at rated voltage on LV side
Under OC test, transformer source only magnetizing current which is small compared to full load current
So, copper loss is negligibly small and proportional to square of current

4. Ans: -----
Solution:
Under SC condition transformers input impedance is the equivalent impedance as seen on the HV side on which test is performed. To pass full load current under these conditions, voltage needed is 6-8% of rated voltage which is easily provided for the test
So SC test is performed at reduced voltage
As applied voltage is 6-8% of rated value so case maximum flux is reduced, core loss being proportional to flux is reduced to negligible value
So, core loss is ignored on SC test

5. Ans: -----
Solution:
Core loss, $P_i \propto \phi_m^{1.6}$
$$\phi_m = \frac{V_1(\approx E_i)}{4.44\,fN}$$
So, $P_i = k_i (V_1)^{1.6}$ .... (i)

Shunt resistance, R_i, loss $= \frac{V_1^2}{R_i}$ .... (ii)

To represent core loss as shunt resistance
$$P_i = k_i (V_1)^{1.6} = \frac{V_1^2}{R_i}$$
$$R_i \left(\frac{1}{k_i}\right) V_1^{0.4} \text{ .... (iii)}$$

So, we can represent core losses shunt resistance across applied voltage
From equation (iii) resistance is dependent on the value of applied voltage
So, it is an accurate represent only if V_1 varies in a narrow range

6. Ans: N_1 = 720, N_2 = 24, A_c = 328.33cm^2
Solution:
EMF per turn = 9
$$N_2 = \frac{\text{Secondary Voltage}}{9} = \frac{210}{9} = 23.31 \simeq 24$$

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

$$\frac{N_1}{24} = \frac{6300}{210} \Rightarrow N_1 = 720$$

$$E = 4.44 fN\phi_{max}$$

$$E = 4.44 fN \times B \times A$$

$$6300 = 4.44 \times 50 \times 720 \times 1.2 \times A$$

$$A = 0.032833m^2 = 328.33cm^2$$

7. Ans: -----
Solution:
'd' negative and 'c' positive
For given direction of current and polarity of induced voltage in primary according to principle of right hand rule, direction of flux will be anticlockwise and as the instantaneous direction of flux is ACW
So, according to Lenz rule, the polarity of instantaneous voltage inducted in secondary is 'd' negative and 'c' positive

8. Ans: 45W
Solution:
No load current
$= 0.43\cos(\omega t - 60^0) + 0.08\cos(3\omega t - 60^0)$

Voltage $= 400\cos\omega t + 100\cos 3\omega t$

Core loss is obtained calculating power consumed by transformer at no load

$$P_{core} = V_{rms} I_{rms} \cos\theta_0$$

$$P_{core} = \frac{V_{m1}}{\sqrt{2}}\frac{I_{m1}}{\sqrt{2}}\cos\theta_1 + \frac{V_{m2}}{\sqrt{2}}\frac{I_{m2}}{\sqrt{2}}\cos\theta_2$$

$$P_{core} = \frac{1}{2} \times 400 \times 0.43 \times \cos 60^0 + \frac{1}{2} \times 100 \times 0.08 \times \cos 60^0$$

$$P_{core} = 43 + 2 = 45W$$

9. Ans: 1.806kVA, 62
Solution:
Current through the conductor = Current density × Area

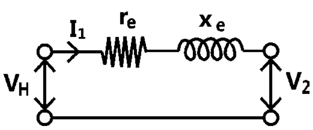
$$= 2.5 \times 10^6 \times \pi\left(\frac{d}{2}\right)^2 = 2.5 \times 10^6 \times \pi \times 10^{-6} = 2.5\pi A$$

kVA rating $= V_1 I_1 = 230 \times 2.5\pi = 1.806kVA$

$$V_1 = 4.44 fNBA$$

$$230 = 4.44 \times 50 \times N \times 1.4 \times 0.012 N = 61.63 \simeq 62$$

10. Ans: 290.4V
Solution:



$$R_1(pu) = 0.01 \ pu$$

$$X_1(pu) = 0.04 \ pu$$

$$V_{base} = 3300V$$

$$V_H = \frac{3300}{3300} = 1 \ pu$$

$$I_1 = 1 \ pu$$

$$V_H = V_2' + I_1'(r_e\cos\theta + x_e\sin\theta)$$

$$1 = V_2' + 1(0.01 \times 0.8 + 0.04 \times 0.6)$$

$$V_2' = 0.968 pu$$

Actual voltage $= 0.968 \times 3300 = 3194.4V$

Actual secondary voltage

$$= \left(\frac{300}{3300}\right) \times 3194.4 = 290.4V$$

11. Ans: -0.58%
Solution:
% Regulation $= IR_{pu}\cos\theta + IX_{pu}\sin\theta$

$$0.08 = R_{pu} \times 1 \Rightarrow R_{pu} = 0.08$$

$$0.14 = R_{pu} \times 0.8 + X_{pu} \times 0.6$$

$$0.14 = 0.08 \times 0.8 + X_{pu} \times 0.6$$

$$X_{pu} = 0.126$$

So % regulation at 0.8 leading pf at half load

$$= \frac{1}{2}[0.08 \times 0.8 - 0.126 \times 0.6] \times 100 = -0.58\%$$

12. Ans: (a) 330V, (b) 10%
Solution: