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A Review on Design Parameters and Testing of Transformer

Chinmayi Satish Thakare[1], Vishal Sanjay Raut[2], Prof. Akash A. Gophane[3]
Students, Final Year B.E. Electrical Engineering[1,2]
Assistant Professor, Electrical Engineering Department[3]
Jawaharlal Darda Institute Engineering and Technology, Yavatmal, India
cthakare002019@gmail.com, rautvishal163@gmail.com, akash_gophane@jdiet.ac.in

Abstract: *Transformers are used to change AC voltage levels as well as to provide galvanic isolation between circuits. Single-phase and three-phase transformers are extensively employed in the world's power distribution system. considers the design of single-phase power transformers. It reviews the classic transformer T-equivalent circuit and considers its use in steady-state phasor analysis. The chapter focuses on single-phase transformers. Single-phase transformers are often classified as being either core-type or shell-type. The chapter discusses transformer performance considerations such as the calculation of transformer parameters, regulation, magnetizing current, operating point analysis, and inrush current, all-in general terms. It also focuses on one specific class of transformer, develops a magnetic equivalent circuit, and ultimately develops a design approach. Core loss is a significant contributor to overall transformer loss and dominates no-load losses.*

Keywords: power transformers, transformer cores.

I. INTRODUCTION

Transformers are used extensively in electronics products to modify voltage before electrical energy can be transmitted. An alternate current in one coil produces a varying magnetic field that induces electromotive force, allowing power to be transferred from one coil to another through a magnetic field without a metallic connection. A transformer transfers electric power from one circuit to another without a change in frequency. It contains primary and secondary windings. The primary winding is connected to the main supply and the secondary to the required circuit. In our project circuit, we have taken the design of a low power (10 KVA) single phase 50 hertz power transformer as per our requirement in theproject.A transformer is an electrical device that transfers electrical energy between two or more circuits through electromagnetic induction. Electromagnetic induction produces an electromotive force within a conductor which is exposed to time varying magnetic fields. Transformers are used to increase or decrease the alternating voltages in electric power applications.

In this paper the various tests are performed on the transformer during theconstruction and after the construction. Some tests are performing routine which is called routine test. For confirming the specifications and performances of an electrical power transformer it has to go through numbers of testing procedures. Some tests are done at manufacturer premises before delivering the transformer .The performance of a transformer largely depends upon perfection of specific turns or voltage ratio of transformer. So, transformer ratio test is an essential type test of transformer. There are several internal connection of three phase transformer are available in market. These several connections give various magnitudes and phase of the secondary voltage; the magnitude can be adjusted for parallel operation by suitable choice of turn ratio, but the phase divergence cannot be compensated. So,thisperformvector group test. Dielectric tests of transformer are one kind of insulation test. This test is performed to ensure the expected overall insulation strength of transformer. Lighting is a common phenomenon in transmission lines because of their tall height. This lightning stroke on the line conductor causes impulse voltage. The connection diagram foropen circuit test on transformer is shown in the figure.

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II. DESIGN OF TANK WITH TUBES

Because of the losses in the transformer core and coil, the temperature of the core and coil increases. In small-capacity transformers, the surrounding air will cool the transformer effectively and keep the temperature rise well within the permissible limits. As the capacity of the transformer increases, the losses and the temperature rise. To keep the temperature rising within limits, air may have to be blown over the transformer. This is not advisable as the atmospheric air containing moisture, oil particles, etc., may affect the insulation. To overcome the problem of atmospheric hazards, the transformer is placed in a steel tank filled with oil. The oil conducts the heat from the core and coil to the tank walls. From the tank walls, the heat dissipated into the surrounding atmosphere due to radiation and convection.

Further, as the capacity of the transformer increases, the increased losses demand a higher dissipating area of the tank or a larger tank. This calls for more space and more volume of oil and increases the cost and transportation problems. To overcome these difficulties, the dissipating area is to be increased by artificial means without increasing the size of the tank. The dissipating area can be increased by

1. fitting fins to the tank walls
2. fitting tubes to the tank
3. using a corrugated tank
4. using auxiliary radiator tanks

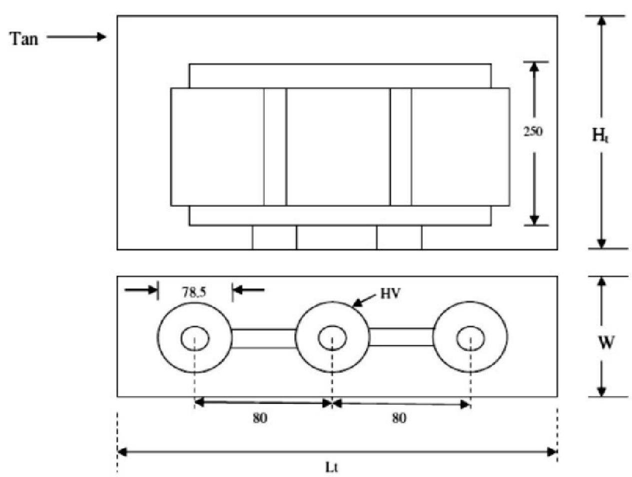
Since the fins are not effective in dissipating heat and corrugated tanks involve constructional difficulties, they are not much used nowadays. The tank with tubes is much used in practice.

Heat is dissipated to the atmosphere from the tank by radiation and convection. It has been found by experiment that 6.0W goes radiated per m. sq. of plain surface per degree centigrade and 6.5W goes dissipated by convection per meter sq. of plain surface per degree centigrade. Thus, a total of 12.5 W/meter sq. / degree centigrade goes dissipated to the surrounding area. If θ is the temperature rise, then at the final steady temperature condition, losses responsible for temperature rise are losses dissipated or transformer losses = 12.5 St θ.

Temp rise $\theta = \frac{\text{Total Loss}}{\text{specific heat dissipation} * \text{Surface}}$

Temp rise $\theta = \frac{P_i + P_c}{12.5 S_t}$

St = Heat the dissipating surface of the tank



All dimensions are in cms.

III. DESIGN PARAMETERS

For designing a transformer, we need:

- Power rating

- Voltage levels (primary and secondary)
- Currents on both sides
- Primary and secondary coils wire diameter/size
- Iron core area
- Numbers of turns (primary and secondary)

We are going to design a 50V step-down transformer of 230V to 12V. Necessary calculations along with formulae are given below in detail: -

As we are going to design a small transformer (of a small power rating) we are neglecting core and copper losses as they don't matter in small transformers and are seriously considered in designing power transformers (high power rating transformers).

IV. LOSSES

In any electrical machine, 'loss' can be defined as the difference between input power and output power. An electrical transformer is a static device, hence mechanical losses (like wind age or friction losses) are absent in it. A transformer only consists of electrical losses (iron losses and copper losses). Transformer losses are similar to losses in a DC machine, except that transformers do not have mechanical los Losses in transformer are explained below:

(I) Core Losses or Iron Losses

Eddy current loss and hysteresis loss depend upon the magnetic properties of the material used for the construction of core. Hence these losses are also known as **core losses** or **iron losses**.

Hysteresis loss in transformer: Hysteresis loss is due to reversal of magnetization in the transformer core. This loss depends upon the volume and grade of the iron, frequency of magnetic reversals and value of flux density. It can be given by, Steinmetz.

$$W_h=\eta B_{max}^{1.6} fV \text{ (watts)}$$

where, η=Steinmetz hysteresis constant

V = volume of the core in m^3

Eddy current loss in transformer: In transformer, AC current is supplied to the primary winding which sets up alternating magnetizing flux. When this flux links with secondary winding, it produces induced emf in it. But some part of this flux also gets linked with other conducting parts like steel core or iron body or the transformer, which will result in induced emf in those parts, causing small circulating current in them. This current is called as eddy current. Due to these eddy currents, some energy will be dissipated in the form of heat.

(II) Copper Loss In Transformer

Copper loss is due to ohmic resistance of the transformer windings. Copper loss for the primary winding is $I_1^2R_1$ and for secondary winding is $I_2^2R_2$. Where, I_1 and I_2 are current in primary and secondary winding respectively, R_1 and R_2 are the resistances of primary and secondary winding respectively. It is clear that Cu loss is proportional to square of the current, and current depends on the load. Hence copper loss in transformer varies with the load.

V. WINDINGS

Transformer windings form another important part of a transformer construction, because they are the main current-carrying conductors wound around the laminated sections of the core. In a single-phase two winding transformer, two windings would be present as shown. The one which is connected to the voltage source and creates the magnetic flux called the primary winding, and the second winding called the secondary in which a voltage is induced as a result of mutual induction.

Primary Winding: Primary winding is the winding at which the voltage source is connected. It is generally carrying the N1 numbers of turns.

Secondary winding: Secondary winding is the winding at which the load is connected. It is generally carrying the N2 no of turns.

VI. CALCULATIONS OF DESIGN PARAMETERS

5..1 Core Calculations:

Calculate the area of the core (central limb) by using the following formula:

$$\boldsymbol{Ai = \frac{1}{4.44 f B_m T_e}}$$

Ai= area of core

F= operating frequency

B_m = magnetic flux

T_e = turns per volts

Assumptions:

So, we know the frequency of the power system. We need magnetic flux and turns per volt.

For designing a small transformer magnetic flux is averagely taken as 1 to 1.2.

By putting values, we get the area of core.

The current density of copper wire is taken as 2.2A/mm^2 to 2.4 A/mm^2 (approximately).

So, putting values

F = 50 Hz

B_m = 1.2 wb/m^2

T_e = 4 (turns per volts)

$$\boldsymbol{Ai = \frac{1}{4.44 f B_m T_e}}$$

$$Ai = \frac{1}{4.44 * 50 * 1.2 * 4}$$

$$Ai \;=\; 9.384\;x\;10 - 4\;m2 \;\cong\; 1.45\;inch2$$

As we are going to design a practical transformer, we must consider the core available in the market. The standard bobbins available in the market are practically 1” x1”, 1.25”x1.5”, 1.5”x1.5”, and so on. We took the nearest core available for our calculation.

We took a bobbin of 2.25 inch^2 (1.5”x1.5”) or 0.00145161-meter square. We have the core area, so we can calculate turns per volt using this area by doing the following:

Putting

F = 50Hz; B_m = 1.2 wb/m^2; Ai= 0.001451m^2,

We get,

$$\boldsymbol{T_e = \frac{1}{4.44 f B_{mA_i}}}$$

$$T_e = \frac{1}{4.44 * 50 * 1.2 * 0.001451}$$

$$T_e = 2.58 \;\cong 2.6(turns\;per\;volt)$$

Hence, turns per volt are 2.6 turns per volts.

5.1.1 Primary Winding Calculations:

Primary voltage = Vp = 230V

Primary current = I1 = VA / Vp = 50 / 230 = 0.217

The transformer we are going to design will be 95% efficient so,

I1 = VA / (efficiency x Vp) = 50 / (95 x 230) x 100 = 0.22A

Primary Current = 0.22 amp (approx.)

Number of Turns:

Total number of turns = turns per volt x primary side voltage = 2.6 x 230

N1 = 598 ≈ 600 turns (approximately)

Size of Conductors:

As we know that

$$Current\ Density = \delta = \frac{1}{A}$$

For copper, the current density is taken as 2.3 A per mm^2 so, for the area of copper conductor.

$$area\ of\ primary\ conductor = a1 = \frac{0.22A}{2.3A\ mm} = 0.09 \sim 0.1\ mm2$$

So,

Primary conductor size = $0.1mm^2$ = 26 AWG (American wire gauge)

From the standard American wire gauge table, we can choose wire of the same thickness. It can be seen that it comes out that the required primary side wire is 27 gauge which can conduct the required current.

Selection of wire can also be done by calculating primary current and by cross-matching the standard table of copper wire according to their current handling capabilities.

5.1.2 Secondary Winding Calculations

Secondary voltage = Vs = 12V

Secondary current = Is = VA / Vs = 50 / 12 = 4.1 Amp (approx.)

$$area\ of\ secondary\ conductor = a2 = \frac{4.1\ A}{2.3\ A\ mm2}$$
$$= 1.78\ \approx 1.8\ mm2$$

From the standard copper wire, table it can be seen that wire of this thickness is of 15 gauge.

So for secondary winding, we need a 15 gauge wire.

So,

Secondary Wire = 15AWG

Number of Turns:

Number of secondary turns = turns per volt x secondary volts

N2 = 2.6 x 12 = 31.2 ≈ 32 turns (approx.)

Weight Estimation of Windings:

For weight calculations, the following steps will be followed:

Approximate length of copper wire = perimeter of bobbin x number of turns

Cross-sectional area of copper conductor

Volume = Approximate length x cross-sectional area

Mass = density of copper x volume

Density of copper = 8960 kg/m^3

Primary side:

Perimeter of bobbin = (1.75 x 4) = 7 inch = 0.1778 m

So,

Length of one turn = 0.1778 m

The total length of all turns of primary = L1

L1 = (length of one turn) x (total number of turns of primary)

L1 = 0.1778 x 600

L1 = 106 m (approx.)

As,

Area of primary conductor = 0.1 mm^2

= ($0.1 \times 10^{-6}\ m^2$)

The volume of copper wire = area x length

Volume = ((0.1×10^{-6}) x 106) m^3

V1 = 1.06×10^{-5} m^3

Density of copper = 8960 Kg/m^3

So,

Weight = density x volume

W1 = 8960 x 1.06×10^{-5}

= 0.094 Kg

Weight of primary conductor = 0.095 x 1000 grams

≈ 100 grams

So we need approx. 100grams of 27 gauge wire

Secondary Winding Weight:

Perimeter of bobbin = (1.75 x 4) = 7 inch = 0.1778 m

So,

Length of one turn = 0.1778 m

The total length of all turns of primary = L1

L2 = (length of one turn) x (total number of turns of secondary)

L2 = 0.1778 x 32

L2 = 5.6 m ≈ 6 m (approx.)

As,

Area of primary conductor = 1.8 mm^2

= (1.8×10^{-6} m^2)

The volume of copper wire = area x length

Volume = ((1.8×10^{-6}) x 6) m^3

V2 = 1.08×10^{-5} m^3

Density of copper = 8960 Kg/m^3

So, Weight = density x volume

W2 = 8960 x 1.08×10^{-5}

= 0.0967 Kg

Weight of primary conductor = 0.096 x 1000 grams

≈ 100 grams

So we need approx. 100 grams of 15 gauge wire.

So, from the above calculations, we can summarize In the following table:

	Parameter	**Formula**	**Value**
Primary Side	Power Rating	(known)	50 VA
	Voltage	(known)	230V
	Current	VA/ Vp	50/230 = 0.21A
	Conductor size	$a1 = \frac{current}{current\ density}$	$a1 = \frac{0.22A}{2.3A\ mm}$ $0.09 \sim 0.1\ mm2$
	Wire gauge	(standard table)	28 AWG
	Numbers of turns	turns per volts x primary side voltage	N2 = 2.6 x 12 = 31.2 ≈ 32 turns
	Total wire length	(length of one turn) x (total number of turns of primary)	L1 = 0.1778 x 600 L1 = 106 m (approx.)
	Volume of conductor	area x length	Volume = ((0.1×10^{-6}) x 106) m^3 V1 = 1.06×10^{-5} m^3
	Weight	density x volume	W1 = 8960 x 1.06×10^{-5} = 0.094 Kg

Table 1: Primary Side

	Parameter	Formula	Value
Secondary Side	Power Rating	(known)	50 VA
	Voltage	(known)	12V
	Current	VA/ Vp	50/12 = 4.1A
	Conductor size	$a1 = \frac{current}{current\ density}$	$a2 = \frac{4.1\ A}{2.3\ A\ mm2}$ $= 1.78\ \approx 1.8\ mm2$
	Wire gauge	(standard table)	15 AWG
	Numbers of turns	turns per volts x primary side voltage	N2 = 2.6 x 12 = 31.2 ≈ 32 turns (approx.)
	Total wire length	(length of one turn) x (total number of turns of primary)	L2 = 0.1778 x 32 L2 = 5.6 m ≈ 6 m (approx.)
	Volume of conductor	area x length	Volume = $((1.8 \times 10^{-6}) \times 6)\ m^3$ V2 = $1.08 \times 10^{-5}\ m^3$
	Weight	density x volume	W2 = $8960 \times 1.08 \times 10^{-5}$ = 0.0967 Kg

Transformer Ratio Test:

The performance of a transformer largely depends upon perfection of specific turns or voltage ratio of transformer. So, transformer ratio test is an essential **type test of transformer.** This test also performed as **routine test of transformer.** So for ensuring proper performance of electrical power transformer, voltage and turn ratio test of transformer one of the vital tests.

The procedure of transformer ratio test is simple. We just apply three phase 415 V supply to HV winding, with keeping LV winding open. The we measure the induced voltages at HV and LV terminals of transformer to find out actual voltage ratio of transformer. We repeat the test for all tap position separately.

Procedure of Transformer Ratio Test

First, the tap changer of transformer is kept in the lowest position and LV terminals are kept open.

Then apply 3-phase 415 V supply on HV terminals. Measure the voltages applied on each phase (Phase-phase) on HV and induced voltages at LV terminals simultaneously.

After measuring the voltages at HV and LV terminals, the tap changer of transformer should be raised by one position and repeat test.

Repeat the same for each of the tap position separately

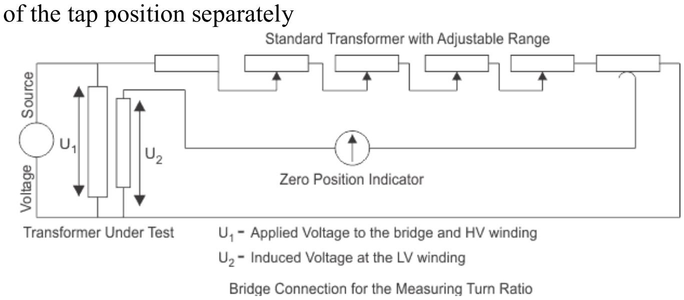


Fig 2: for turns ratio

The above transformer ratio test can also be performed by portable transformer turns ratio (TTR) meter. They have an in-built power supply, with the voltages commonly used being very low, such as 8-10 V and 50 Hz. The HV and LV windings of one phase of a transformer are connected to the instrument, and the internal bridge elements are varied to produce a null indication on the detector.

A phase voltage is applied to the one of the windings by means of a bridge circuit and the ratio of induced voltage is measured at the bridge. The accuracy of the measuring instrument is < 0.1 %

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$Theoretical\ turn\ ratio = \frac{HV\ winding\ volage}{LV\ winding\ voltage} * 100\%$

This theoretical turn ratio is adjusted on the transformer turn ratio tested or TTR by the adjustable transformer as shown in the figure above and it should be changed until a balance occurs in the percentage error indicator. The reading on this indicator implies the deviation of measured turn ratio from expected turn ratio in percentage

$$Deviation\ in\ percentage = \frac{measured\ turn\ ratio - expected\ turn\ ratio}{expected\ turn\ ratio} * 100\ \%$$

Out-of-tolerance, **ratio test of transformer** can be due to shorted turns, especially if there is an associated high excitation current. Open turns in HV winding will indicate very low exciting current and no output voltage since open turns in HV winding causes no excitation.

VII. TESTING OF TRANSFORMER

Measurement of insulation resistance test:

Insulation resistance test of transformer is essential type test. This test is carried out to ensure the healthiness of overall insulation system of an electrical power transformer.

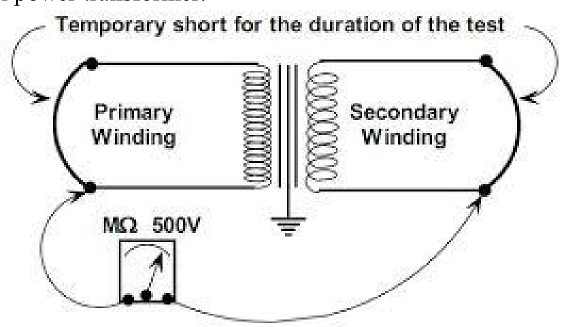

Fig 3

current in the winding means no flux hence no induced voltage. But open turn in LV winding causes, low fluctuating LV voltage but normal excitation current in HV winding. Hence open turns in LV winding will be indicated by normal levels of exciting current, but very low levels of unstable output voltage. The**turn ratio test of transformer** also detects high resistance connections in the lead circuitry or high contact resistance in tap changers by higher excitation current and a difficulty in balancing the bridge

Procedure of Insulation Resistance Test of Transformer

First disconnect all the line and neutral terminals of the transformer.

Megger leads to be connected to LV and HV bushing studs to measure insulation resistance IR value in between the LV and HV windings.

Megger leads to be connected to HV bushing studs and transformer tank earth point to measure insulation resistance IR value in between the HV windings and earth.

Megger leads to be connected to LV bushing studs and transformer tank earth point to measure insulation resistance IR value in between the LV windings and earth

Temperature correction Factor		
^oC	^oF	Correction Factor
0	32	0.25
5	41	0.36
10	50	0.50
15	59	0.720

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30	86	1.98
40	104	3.95
50	122	7.85

Table 3: Temperature correction Factor (Base 20°C)

7.1 Open Circuit Test on Transformer

The connection diagram for **open circuit test on transformer** is shown in the figure. A voltmeter, wattmeter, and an ammeter are connected in LV side of the transformer as shown. The voltage at rated frequency is applied to that LV side with the help of a variance of variable ratio auto transformer.

The HV side of the transformer is kept open. Now with the help of variance, applied voltage gets slowly increased until the voltmeter gives reading equal to the rated voltage of the LV side. After reaching at rated LV side voltage, all three instruments reading (Voltmeter, Ammeter and Wattmeter readings) are recorded.

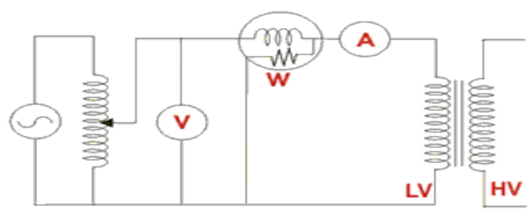

Fig 4: Open circuit test

7.2 Short Circuit Test on Transformer

The connection diagram for **short circuit test on transformer**is shown in the figure. A voltmeter, wattmeter, and an ammeter are connected in HV side of the transformer as shown. The voltage at rated frequency is applied to that HV side with the help of a variac of variable ratio auto transformer.

The LV side of the transformer is short circuited. Now with the help of variac applied voltage is slowly increased until the ammeter gives reading equal to the rated current of the HV side. After reaching at rated current of HV side, all three instruments reading (Voltmeter, Ammeter and Watt-meter readings) are recorded. The ammeter reading gives the primary equivalent of full load current I_L.

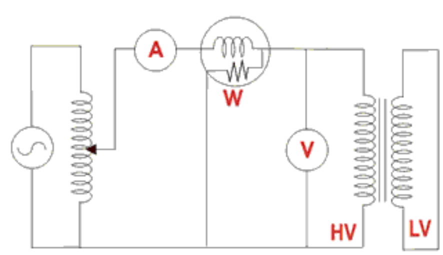

Fig 5: Short circuit test of transformer

Cooling of transformer

The coolant used in transformers is air and oil.

Transformers using air as coolant are called Dry-type transformers while transformers that use oil as coolant are called Oil immersed transformers.

Methods of Cooling of Transformers: The choice of cooling method depends upon the size, type of application, and the type of conditions of installation sites.

The symbols designated for these methods depend upon the medium of cooling used and the type of circulation employed.

Medium:- Air-A, Gas-G, Oil-O, Water-W, Solid insulation-S

Circulation:- Natural-N, Forced-F

Cooling of Dry-type transformer

Air Natural (AN), Air Blast (AB)

Cooling of oil-immersed transformer

Oil Natural (ON)

Oil Natural Air Forced (ONAF)

Oil Natural Water Forced (ONWF)

Forced Circulation of Oil (OF)

Oil Forced Air Natural (OFAN)

Oil Forced Air Forced (OFAF)

Oil Forced Water Forced (OFWF)

VIII. CONCLUSION

This report describes a calculation of the transformer. A procedure for the optimal transformer. A transformer is a passive electrical device that can change the voltage in an alternating current (AC) electric circuit. Transformers are used to increase or decrease the operating voltage levels between circuits. Transformers are essential components in various electrical systems, enabling the transfer of electrical energy from one circuit to another. Their design involves a careful selection of parameters to ensure optimal performance and reliability. Key design parameters of transformers include core material, core size, number of turns, wire size, insulation, and cooling system. Each parameter plays a critical role in determining the transformer's efficiency, operating frequency, voltage transformation ratio, current handling capability, electrical safety, and thermal management. The choice of core material significantly influences the transformer's efficiency and operating frequency. Different materials exhibit varying permeability, loss factor, and temperature stability, affecting the transformer's ability to transfer energy effectively and withstand high frequencies. Core size is determined by the transformer's power rating and operating voltage. A sufficiently large core is crucial to accommodate the magnetic flux without saturating the core material, ensuring efficient operation and preventing overheating. The number of turns on the primary and secondary windings determines the transformer's voltage transformation ratio. This ratio dictates how much the voltage is stepped up or down, enabling the transformer to match voltage levels between circuits.In the report we have seen that the various test is performed on the transformer during the construction and after the construction. Some test is performing routine which is called routine test. For confirming the specifications and performances of an electrical power transformer it has to go through numbers of testing procedures. Some tests are done at manufacturer premises before delivering the transformer .The performance of a transformer largely depends upon perfection of specific turns or voltage ratio of transformer. So transformer ratio test is an essential type test of transformer. There are several internal connection of three phase transformer are available in market. These several connections gives various magnitudes and phase of the secondary voltage; the magnitude can be adjusted for parallel operation by suitable choice of turn ratio, but the phase divergence cannot be compensated. So we perform vactor group test. Dielectric tests of transformer are one kind of insulation test. This test is performed to ensure the expected over all insulation strength of transformer. Lighting is a common phenomenon in transmission lines because of their tall height. This lightning stroke on the line conductor causes impulsevoltage. The connection diagram for open circuit test on transformer is shown in the figure.

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