International Journal of Science and Engineering Applications
Volume 7–Issue 10,375-380, 2018, ISSN:-2319–7560

Design Comparison for Rectangular and Round Winding Distribution Transformer (1000kVA)

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Abstract: The transformer is the most efficient of transmission and distribution system, with efficiencies typically in the high 90s, it is possible to reduce transformer costs and losses by using round and rectangular conductor winding. This journal presents the result of the difference between round conductor winding and rectangular conductor winding of distribution transformer. The most substation transformers are utilized either circular or rectangular in core and coil assembly. The transformers manufacturing industry improve transformer efficiency and reliability. This paper intended to prove the product would have improved outcomes, a higher standard and sustainability by adapting the product development to the road condition of the country of manufacture. In design consideration, selection of magnetic frame, choice of conductor size, choices of current density are considered.

Keywords: Distribution Transformer, Step Core, Core Type, Round and Rectangular winding, Tank and Losses

1. INTRODUCTION

A transformer is a static piece of apparatus used for transferring power from one circuit to another without change in frequency. Transformer can raise or lower the voltage with a corresponding decrease or increase in current. The voltage levels at the primary and secondary windings are usually different and any increase or decrease of the secondary voltage is accompanied by corresponding decrease or increase in current. A transformer consists of two conducting coils having a mutual inductance. When one of the windings is connected to an AC supply, an emf is induced on the other winding which is proportional to the number of turns. Transformers are commonly employed in the chain of electric power supply from generating stations to consumers of electric energy. Distribution transformers are used in the distribution networks in order to transmit energy from the medium voltage network to low voltage network of the consumers. Distribution transformers are energized for 24 hours with wide variation in load; therefore they are designed for low no-load losses.

2. BASIC PRINCIPLE OF DISTRIBUTION TRANSFORMER

A transformer is basically electromagnetic static equipment based on the principle of Faraday's Law of electromagnetic induction. The transformer is an electromagnetic conversion device in which electrical energy received by primary winding is first converted into magnetic energy which is reconverted back into a useful electrical energy in other circuits (secondary winding, tertiary winding, etc.). A transformer consists of laminated magnetic core forming the magnetic frame. The primary and secondary coils are wound up the three cores for three-phase of the magnetic frame, linked by the common magnetic flux. When an alternating voltage is applied across the primary coil, a current flow in it and the magnetic flux is produced in the transformer core. And then the secondary coil produces the output voltage. Thus, the primary and secondary windings are not connected electrically, but coupled magnetically. A transformer is termed as either a step-up or step-down transformer depending upon whether the secondary voltage is higher or lower than the primary voltage respectively.

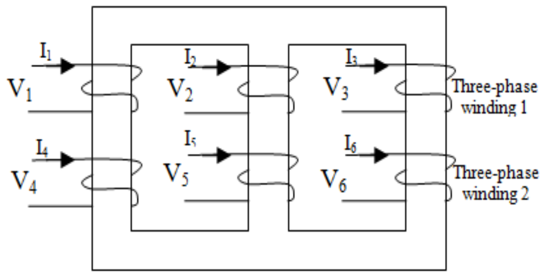


Figure 1. Three-phase two winding transformer

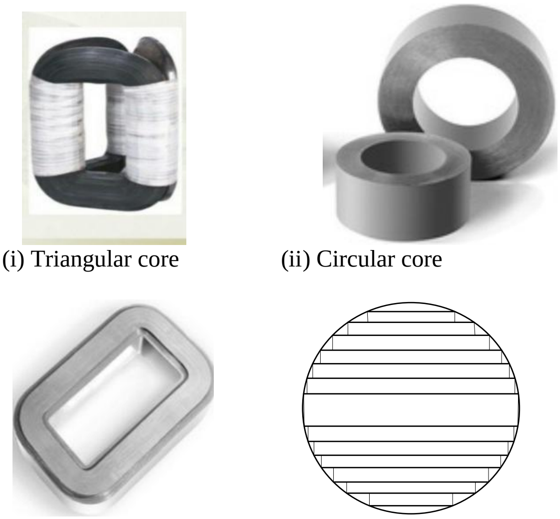
3. CONSTRUCTION OF TRANSFORMER

(i) Core
(ii) Windings
(iii) Tank
(iv) Off-load Tap Changer

3.1 Type of core

The core, which provides the magnetic path to channel the flux, consists of thin strips of high-grade steel, called laminations, which are electrically separated by a thin coating of insulating. Grain-Oriented Silicon Steel is used as the core material for transformer. The usual thickness of laminations are 0.23 mm, 0.27 mm and 0.3 mm. The core cross section can be classified in circular core, rectangular core, stepped core and triangular core. Rectangular cores are used for smaller ratings and as auxiliary transformers used within a power transformer. Rectangular cores use a single width of strip steel, while circular cores use a combination of different strip widths to approximate a circular cross-section. Stepped core can be reduced the two losses due to varying flux occur the eddy current and the hysteresis losses in the core.

There are two type of core construction used in transformer; core form and shell form. In a single phase core form, the windings are on the outside, a single path for the magnetic circuit. In the three-phase core form, the windings of a particular phase are typically on the same core leg. In a single-phase shell form, the windings are on the inside, multiple paths for the magnetic circuit. In the three-phase shell-form construction include five and seven-legged cores, depending on size and application. The Figure (2) shows the type of cores.



(i) Triangular core (ii) Circular core

(iii) Rectangular core (iv) Stepped core

Figure 2.Type of cores

3.2 Winding

Winding form, the electrical circuit of a transformer. The windings must be electrically and mechanically strong to withstand both over-voltages under transient surges, and mechanical stress during short circuit. The winding that is connected to the source is called the primary winding. The winding that is connected to the load is called the secondary winding. For core–type transformers, the windings are cylindrical, and are arranged concentrically. According to the voltage ratings and current ratings, we adopt one of the following types of windings.

- High Series Capacity Winding
- Continuous Disc Winding
- Helical Winding
- Cylindrical Winding

High Series Capacity Winding for transformer above highest system voltage 72.5kV, the series static capacitance of the windings is increased to such an extent that the initial potential distribution of incoming impulse voltage is made nearly linear. Continuous disc winding is most commonly used for coils above 24kV and these windings consist of number of disc wound from a single wire or number strip in parallel. In Helical Winding, the coil consists of a number of rectangular strips wound in parallel racially.

3.3 Coil Insulation and Insulation Paper

For oil immersed transformers, the insulation system comprises a mixed dielectric, oil and cellulosic material. The insulation structure must be arranged into major insulation and minor insulation. Major insulation comprises insulation of windings to earth and transformer core, other winding of the same phase (e.g. HV winding to LV winding) and between one phase and another. The insulation between different windings and inner winding to core consists of pressboard cylinders separated by oil ducts. Minor insulation refers to insulations between different parts of one winding, like insulation between turns, layers, etc. The insulation of the conductors is generally of paper, which is wrapped around the conductor. Pressed, oil ducts, spacers and insulating cylinders of high dielectric strength are used between low voltage winding and core, low and high voltage windings and layers of windings.

3.4 Tank

Transformer tank is to provide a protective cover to the core, windings and other internal parts including transformer oil. The transformer tank also provides external surface for dissipating heat. The tank surface cools by both radiation and convection. The oil provides a medium for insulation and heat dissipation. The heat from core and windings is dissipated by means of the circulating oil. The tank and cooling system contribute to the heat dissipation. Normally transformers up-to 50kVA could be manufactured without external cooling tubes. For transformers of higher rating, tanks are constructed with external cooling tubes to provide additional surface for heat dissipation.

3.5 Off-load Tap Changer

Off-load tap changer is the simplest arrangement. The changes are made when the transformer is isolated from the supply on both sides, in order to avoid arcing at the point of break. Thus, for changing the taps, energy supply has to be interrupted quite frequently, which is highly undesirable. As such, this method of tap changing is generally used in small and medium size transformers. Lager rating transformers are provided with on-load tap changer, because frequently discontinuity of power cannot be tolerated by the power system network. On-load tap changer is used to control large high-voltage distribution networks and to maintain correct system voltages.

4. DESIGN THEORY OF TRANSFORMER

The design of the distribution transformer is to obtain main dimensions of the magnetic circuit (core), yoke and window, low voltage and high voltage windings, performance characteristics and the cooling tank.

The selection of number of turns with the equation is

The e.m.f. per turn, $E_t = k\sqrt{Q}$

The e.m.f per turn, $E_t = 4.44 \times f \times B_m \times A_g \times 10^{-4}$

Where,

B_m = maximum flux density in the core, Tesla

f = rated frequency, 50Hz

Ag = gross core area in sq.cm

Number of turn per phase in low voltage winding,

$$T_2 = \frac{V_2}{E_t}$$

Number of turn per phase in high voltage winding,

$$T_1 = T_2 \times \frac{V_1}{V_2}$$

The design is to select the number of turns of coils and proceed further towards estimating the coil configuration till arriving at the window height of the core frame. Based on the calculated window height, the design of the low voltage coil is done.

Output of transformer for three-phase,

$$Q = 3.33f\, B_m\, \delta\, K_w\, A_w\, A_i\, 10^{-6} \text{ Volt - A}$$

Where, δ = average value of current density, A/ mm^2

The window space facer depends upon the voltage rating of the windings, mainly the highest voltage and kVA rating of the transformer.

Window area, $A_w = L(D - d)$

Overall length of the yoke, $W = 2D + d_1$

Gross yoke area, $A_y = 1.15 \times A_i$

Width of the yoke, $b_y = 0.9d$

Height of the yoke, $h_y = \dfrac{A_y}{b_y}$

The core cross-section is rectangular in the case of a small capacity transformer or polygonal, inscribing a circle, in the case of a large capacity transformer in order to utilize fully the space available, which mean smaller diameter of the circle over the stepped core. The number of steps depends upon the kVA rating of the transformer and its gross core section. Figure (3) describes the inscribing polygonal of 7steps core form. In Figure (4), main dimension of window consists of the height and the width of the window. Main dimension of the yoke consists of overall length (W), width of the yoke and the height of the yoke.

Volume of the core $= N_c \times A_c \times L$

Weight of the core = Volume of the core x density of steel

Iron losses in the cores = Weight of the core x losses per kg

Volume of the yoke $= N_y \times A_y \times W$

Iron losses in the yokes = Weight of the yoke x losses per kg

Total iron losses = Iron losses in the core + Iron losses in the yoke

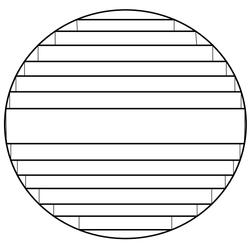


Figure 3. Main dimensions of magnetic frame

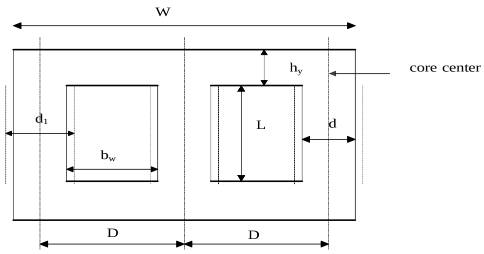


Figure 4. Main dimension of magnetic frame

The magnetizing component of no-load current,

$$I_m = \frac{VA/kg \times kg}{3 \times \text{phase voltage}}$$

Hysteresis and eddy current component from no-load loss and rated secondary phase voltage,

$$I_{h+e} = \frac{\text{No-load loss}}{3 \times \text{Phase voltage}}$$

No-load current, $I_o = \sqrt{I_m^2 + I_{h+e}^2}$

For rectangular conductor,

Cross sectional area, $a = \dfrac{I}{\delta}$

For round conductor,

Cross sectional area, $a = \dfrac{\pi D^2}{4}$

Outer diameter of insulating cylinder,

$$di_0 = d + 2t_i$$

Inner diameter of L.V winding,

$$Di_2 = di_0 + 2t_0$$

Outer diameter of L.V winding,

$$Do_2 = Di_2 + 2b_2$$

Mean diameter of L.V winding,

$$Dm_2 = \frac{D_{i2} + D_{o2}}{2}$$

Mean length of L.V turn, $l_{mt2} = \pi D_{m2}$

Resistance per phase of L.V winding,

$$r_2 = \frac{\rho L_{mt2} T_2}{a_2} \times 10^{-3}$$

Total copper losses $= 3I^2R$

Total losses = Total iron losses + Total copper losses

Efficiency of transformer = $\frac{Q}{Q+\text{Total losses}}$

Percentage reactance of high voltage winding,

$$Ex = \frac{7.91\times f\times I_s\times T_1\times\pi\times D}{V_s\times A_L}\times\left(a+\frac{b_1+b_2}{3}\right)\times10^{-6}\,\Omega$$

Percentage reactance of low voltage winding,

$$E_x = \frac{7.91\times f\times I_s\times T_1\times\pi\times D}{V_s\times A_L}\times\left(a+\frac{b_1+b_2}{3}\right)\times10^{-6}\,\Omega$$

Percentage resistance, $E_r = \frac{IR}{V}$

Percentage impedance $E_z = \sqrt{R^2+X^2}$

Percentage regulation,

$$(n.E_r\%\cos\theta+n.E_x\%\sin\theta)+\frac{(n.E_r\%\cos\theta+n.E_x\%\sin\theta)^2}{200}$$

The length of the tank for three-phase transformer,

$$l_t = 2D+D_{o1}+\Delta l$$

The width of the tank for three-phase transformer,

$$b_t = D_{o1}+\Delta b$$

The height of the tank for three-phase transformer,

$$h_t = L+2h_y+\Delta h + h_1$$

Where Δl, Δb, Δh are total clearance length-wise, width-wise and height-wise

5. ROUND AND RECTANGULAR WIRE OF DISTRIBUTION TRANSFORMER DESIGN

To calculate the transformer design, first step is based on the main data and the properly assumed values

Table 1. Specifications of Distribution Transformer Design

Specifications	Symbol	Unit	Rating
Output	Q	VA	1×10^6
Number of phase	-	-	3
H.V winding voltage	V1	V	11000
L.V winding voltage	V2	V	400
Frequency	F	Hz	50
Connection of H.V/L.V	-	-	Delta/Star
Limit of oil temperature	ϴ	˚C	60
Limit of winding temperature	ϴ	˚C	65

Table 2. Specifications of Distribution Transformer Magnetic Frame Design

Specifications	Symbol	Unit	Design Values
Diameter of circumcircle	D	mm	206
Length of core	L	mm	570
Length of yoke	W	mm	980
Height of yoke	h_y	mm	190
Width of window	b_w	mm	205
Distance between core center	D	mm	395
Weight of cores and yokes	-	kg	866.042

Table 3. Design Comparison of Distribution Transformer for L.V Winding Design

	Specifications	Symbol	Unit	Design Values
Rectangular	Turn per phase	T_2	-	20
	Phase current	I_2	A	1443.37
	Conductor section	a_2	mm^2	456.7
	Conductor size	d_2	mm	3.8 x 10
	Copper weight	-	kg	187.03
	Inner diameter of Windings	D_{i2}	mm	215.78
	Outer diameter of	D_{o2}	mm	273.2

	Windings			
	Radial width of Windings	b_2	mm	28.71
	Resistance per phase	r_2	Ω	0.000727
Rectangular	Turn per phase	T_2	-	20
	Phase current	I_2	A	1443.37
	Conductor section	a_2	mm^2	456.7
	Conductor size	d_2	mm^2	3.8 x 10
	Copper weight	-	kg	187.03
	Inner diameter of Windings	D_{i2}	mm	215.78
	Outer diameter of Windings	D_{o2}	mm	273.2
	Radial width of Windings	b_2	mm	28.71
	Resistance per phase	r_2	Ω	0.000727

Table 4. Design Comparison of Distribution Transformer for H.V Winding Design

	Specifications	Symbol	Unit	Design Values
	Turn per phase	T_1	-	976
	Phase current	I_1	A	30.3
	Conductor section	a_1	mm^2	9.6
	Conductor size	d_1	mm^2	1.6 x 6

Rectangular	Copper weight	-	kg	258.687
	Inner diameter of Windings	D_{i1}	mm	287.8
	Outer diameter of Windings	D_{o1}	mm	370.5
	Radial width of Windings	b_1	mm	41.35
	Resistance per phase	r_1	Ω	2.27
Round	Turn per phase	T_1	-	976
	Phase current	I_1	A	30.3
	Conductor section	a_1	mm^2	5.939
	Conductor size	d_1	mm	2.75 x 2
	Copper weight	-	kg	260.689
	Inner diameter of Windings	D_{i1}	mm	286.5
	Outer diameter of Windings	D_{o1}	mm	377.08
	Radial width of Windings	b_1	mm	45.29
	Resistance per phase	r_1	Ω	1.849

Table 5. Performance Summary of Distribution Transformer

Specifications	Symbol	Unit	Design Values(rect-rect)	Design Values(round-rect)
No load current	I_o	A	0.3	0.3
Iron losses	P_i	kW	1.2098	1.2098
Copper losses	P_c	kW	11.88	10.604
Total losses	P_t	kW	13.089	11.814
Full load efficiency	η	%	98.39	98.54

Table 6. Design Summary of Transformer for Regulation

Specifications	Symbol	Unit	Design Values (Rect-Rect)	Design Values(Round-Rect)
Per unit reactance	E_x	p.u	0.0585	0.06
Per unit resistance	E_r	p.u	0.0119	0.0106
Per unit impedance	E_z	p.u	0.0597	0.0609
Regulation at full load	-	p.u	0.0425	0.0417

Table 7. Design Comparison for Calculation Results and Experimental Test Results (Rectangular-Rectangular)

Specifications	Calculation Results	Experimental Test Results
Winding resistance for L.V	0.000727 Ω	0.0007716 Ω
Winding resistance for H.V	1.51 Ω	1.36 Ω
No-load losses	1209.85W	1303 W
No-load current (%)	0.31%	0.38%
Load losses	11880 W	13642 W
Voltage impedance (%)	5.969%	6.38 %

Table 8. Design Comparison for Calculation Results and Experimental Test Results (Round-Rectangular)

Specifications	Calculation Results	Experimental Test Results
Winding resistance for LV	0.000727 Ω	0.0007299 Ω
Winding resistance for H.V	1.23 Ω	1.35 Ω
No-load losses	1209.85W	1266 W
No-load current	0.31%	0.37%
Load losses	10604.54 W	13748 W
Voltage impedance	6.09 %	6.08

6. CONCLUSION

In this journal, 1000kVA, 50Hz, 11/0.4kV, three-phase two winding, and delta-star connected, core type distribution transformers are already designed by using round and rectangular conductor. But magnetic frame designed is used the same type for both transformer. The design is carried out to reduce losses of transformer and in turn improve efficiency of power system. This transformer design is utilized to step down the transmission voltage to the low voltage for the power distribution requirement with minimize losses and cost, and improve efficiency of power system components. Transformer efficiency is improved by reducing load and no-load losses and transformer reliability is improved mainly by the accurate evaluation of the short-circuit reactance and the resulting forces on transformer windings under short-circuit, since these enable the avoidance of mechanical damage and failures during short-circuit tests and power system faults.

7. ACKNOWLEDGEMENTS

The author is deeply grateful to Dr. Myo Thet Tun, my dissertation supervisor and Daw Hnin Wint Aung, my co-supervisor. The author also thanks to all teachers at Technological University (Thanlyin) and all who provided her with HISEM Electric& Machinery Co., LTD. The author wishes to express her guidance to all persons who helped directly or indirectly towards the successful completion of paper. Finally, the author wishes to express her special thanks to her parents for their support and encouragement to attain her destination without any trouble.

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