DESIGN OF AN ENERGY EFFICIENT AUTOTRANSFORMER FOR STARTING AN INDUCTION MOTOR

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ABSTRACT

Induction motors are widely used in most of the Industries. Induction motors draw very high current in the order of 5 to 8 times the rated current during starting. Starting of a higher rating Induction motor using Autotransformer has been found great importance in limiting the starting current and improving the starting torque compared to star-delta starter. This paper discusses the design and analysis of an energy efficient Autotransformer starter of rating 6.6 kV, 110 kVA to start an induction motor of rating 6.6 kV, 250 KW. The Autotransformer was designed with on-load tap changing facility of eight tapping's ranging from 50 % to 85% with each step tapping of 5%. Laser Scribed 23ZDMH85 material and conductor of current density 3.07A/mm^2 are proposed in the present work to reduce the total losses. The feasibility of achieving a reduction of about 22% in total losses compared to conventional transformer is discussed in detail. At 50% tapping, unity power factor the estimated efficiency of the autotransformer is 99.21%.

Keywords: *induction motor, autotransformer, starting current, on-load tap-changer, Laser Scribed 23ZDMH85, losses*

1. INTRODUCTION

The increasing demand for electricity in India, all electric utility companies are going for energy efficient electrical equipment. Ninety percent of the motors used in industries are induction motors. When a 3- phase induction motor of higher rating is switched on directly from the mains, it draws a starting current of about 5 -8 times the full load (depending upon on the design) current. Also, this will cause a drop in the voltage affecting the performance of other loads connected to the mains. Therefore, starters are used to limit the starting current drawn by the 3-phase induction motors [1].

Common methods employed for starting an induction motor are Direct- on-line starter (DOL), Star-Delta starter, Autotransformer Starter and Soft starters. DOL starters are used to start induction motors of rating less than 5 HP and for starting medium rating induction motors, Star-Delta starters are used. For starting higher rating induction motors, Autotransformer starters are used and for very high rating induction motors, Soft starters are used.

The work carried out by the earlier researchers in the area of autotransformer starter design and development is briefly presented in this section.

Daniel J Rogers investigated characteristics of contact operated under new hybrid diverter design for on-load tap changer [2].

Wenzhou et al. investigated the effects of laser scribing on surface coating and magnetic properties of silicon steel [3].

Ajay et al. presented an overview of the transformer design, optimization and evaluation of energy efficient transformers from the literature related to this field for the past forty years [4].

Harsha et al. discussed and analysed different motor starters (conventional electromechanical and electronic starters), disadvantages and energy saving features of each type of starter [5].

Larry B Farr has discussed high voltage stress failures of auto transformer starter ratings ranging from 2400V to 11kV and the cause for failure [6].

Sewan et al. proposed several auto transformer arrangements to enhance the power quality of high current DC power supply [7].

In the present work, design and analysis of Autotransformer starter of rating 6.6 kV, 110 kVA to start an induction motor of rating 6.6 kV, 250 KW is discussed in detail.

1.1. Significance of Autotransformer

In Star-Delta starter the starting current is limited by a factor of (1/3). This limitation is overcome in Autotransformer starter. The starting current is given by $K^2 * I_{sc}$, where K is the transformation ratio and I_{sc} is the short circuit current.

An auto transformer starter is suitable for both star and delta connected motors. The starting current and torque can be adjusted to any desired value by selecting the suitable tapping position in an auto transformer. The schematic diagram of auto transformer is shown in Fig. 1 [1].

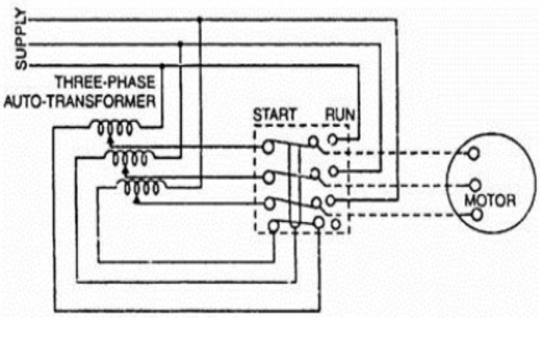

Fig. 1 Schematic diagram of auto transformer starter for starting an induction motor

Initially the starter is connected to start position where reduced voltage gets applied to the stator of the induction motor, once the motor reaches 80% of its rated speed the starter switch is positioned to RUN and full voltage gets applied to the stator.

1.2. On-Load tap changer for an Autotransformer

Interruption of huge starting current results in arcing and damages the contacts. By using on-load tap changing mechanism, arcing at the contacts is avoided and the life of the contacts is increased. Fig. 2 to Fig. 4 shows the tap changing mechanism from 50% tapping to 55% taping position. S_1 & S_2 represent selector switches, T_1 & T_2 represents toggle switches and I_L represents the load current. During starting, tap changer is set to 50% tapping to provide required starting torque. As shown in Fig. 2, S_1 & S_2, T_1 & T_2 are in closed position, current flowing through the selector switch is half the total load current ($I_L/2$).

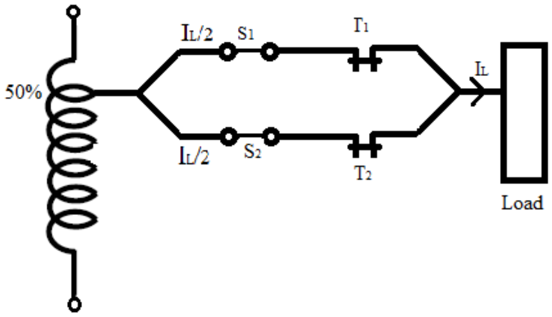

Fig. 2 On-Load tap changer at 50% tapping

The tapping has to be changed from 50% to 55%. First toggle switch T_2 is opened, the total load current gets diverted and flows through S_1 to the load. Now S_2 is moved to 55% as shown in Fig. 3(a). Now T_2 is closed as shown in Fig. 3(b) and there will be circulating current. In practice this current is limited by connecting reactors in the circuit and losses due to this current are minimized. In the next step T_1 is opened and the total load current flows through S_2. Selector switch S_1 is moved to 55% tapping as shown in Fig. 4 and T_1 is closed. The total load current gets divided equally and flows through the switches S_1 and S_2.

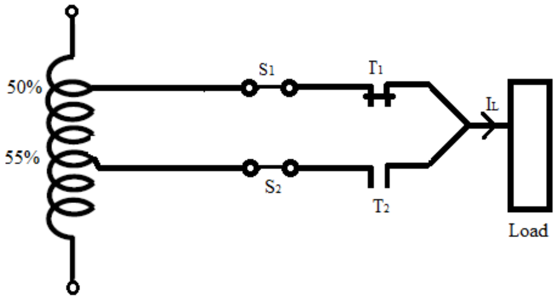

Fig. 3(a) On-Load tap changer with S_1 at 50% and S_2 at 55% tapping and T_2 open

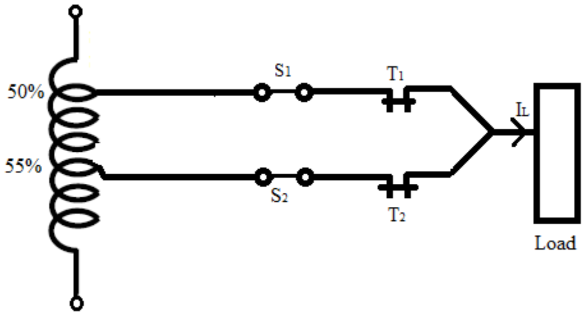

Fig. 3(b) On-Load tap changer with S_1 at 50% and S_2 at 55% tapping and T_2 closed

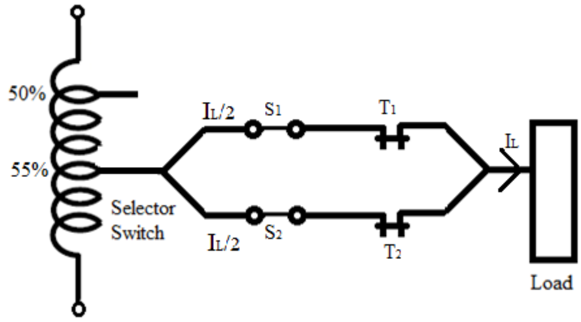

Fig. 4 On-Load tap changer at 55% tapping

2. DESIGN OF AUTOTRANSFORMER

The flow chart for designing autotransformer is shown in Fig. 5. The design of 6.6 kV, 110 kVA auto transformer is carried out in accordance with Indian Standards. The materials used for designing the autotransformer are ferromagnetic core, conductors, insulating materials, sealing materials etc. For energy efficient application, to minimize the core loss, laser scribed 0.23 mm thickness 23ZDMH85 CRGO silicon steel which has specific loss of 0.56 watts/kg and conductor of current density 3.07 A/mm2 is considered. The tapings are provided from 50% to 85% with a step voltage of 5%.

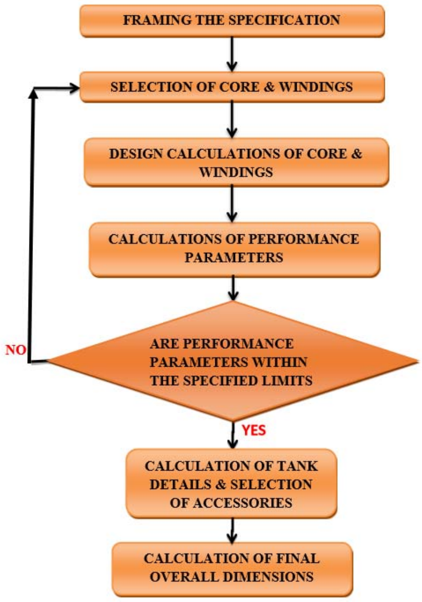

Fig. 5 Flowchart for design of Autotransformer

2.1. Design of stepped core

In a Non-step Lap joint the flux which crosses the air gap contributes to “leakage of flux” and therefore requires more no- load current to achieve the required flux density. Further the over-saturation of flux at the corner joints [8] also leads to higher magnetostriction of the core, which is the main cause of noise level in a transformer.

In stepped Lap core, there will be more layers of laminations available for distributing the flux resulting in lower losses at the corner joints. Therefore, in conventional transformers, non-step lap core is used and in energy efficient transformers step lap core is used. In the present work, to minimize the core losses, Laser scribed 0.3 mm thickness 23ZDMH85 CRGO silicon steel which has a specific loss of 0.56 watts/kg was used.

2.1.1. Parameters of a stepped core

Volts per turn is given by

$$\frac{\mathrm{V}}{\mathrm{T}} = \mathrm{k}\sqrt{\mathrm{kVA}} \tag{1}$$

For designing a 6.6 kV, 110 kVA energy efficient transformer, k value was chosen as 0.5. Therefore, from equation (1), volts per turn are 5.23.

Voltage per phase $= \frac{6.6kV}{\sqrt{3}} = 3810\ V$

Number of turns per phase $= \frac{3810V}{5.23\ V/turn} = 728$

Actual turns per phase are 720. Therefore, volts per turn is 5.29. The EMF equation of a transformer is given by equation (2)

$$E\ = 4.44 * \mathrm{f} * B_m * A_i * \mathrm{T} * 10^{-6} \tag{2}$$

E = V, equation (2) is simplified as

$$\frac{V}{T} = 4.44 * \mathrm{f} * B_m * A_i * 10^{-6} \tag{3}$$

Substituting the values of (V/T), frequency=50Hz and B=1.5T in equation (3), Net area, A_i is obtained and is equal to 15893 mm^2. Gross area is given by

$$\frac{\pi D^2}{4} = \frac{\text{Net area}}{\text{packing factor}}\ \frac{15893}{0.91} = 17465\ mm^2$$

Table 1 Stepped core parameters

Steps	Width mm	Stack height mm	Gross Area mm^2	Net area mm^2	ΣArea mm^2
1	145	38	5510	5344	5344
2	135	26	3510	3404	8748
3	125	18	2250	2182	10930
4	115	14	1610	1561	12491
5	105	10	1050	1018	13509
6	95	10	950	921	14430
7	65	18	1170	1134	15564
8	35	11	385	373	15937

From above, D = 150 mm and 8 steps are considered in the present case. Between any two consecutive steps from step 1 to step 6, difference of 10 mm is maintained and to balance in last two steps 30 mm difference is maintained.

Gross area = stack width * stack height

Net area = Gross area * packing factor

Here, packing factor is taken as 0.97. The stepped core parameters are shown in Table 1.

2.2. Design of common winding

An autotransformer has a single winding, the primary and secondary circuits therefore have a number of winding turns in common. The schematic of autotransformer is shown in Fig. 6.

The maximum current in the common winding is given by $\frac{110*\mathrm{KVA}}{\sqrt{3}*6.6*\mathrm{KV}} \cong 9.63\mathrm{A}$. The cross section of conductor is given by

$$\frac{\text{maximum current}}{\text{maximum current density}} = \frac{9.63}{3.26} = 2.95\mathrm{mm}^2 \tag{4}$$

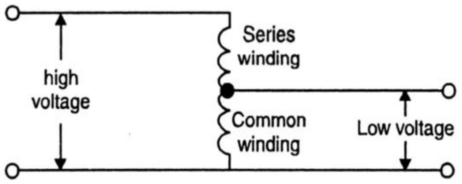

Fig. 6 Schematic diagram of an autotransformer

From equation (4), the diameter of the bare conductor, b is 2mm. The total insulation between two bare conductors is 0.25 mm. Therefore, insulated conductor diameter, b_i is 2.25 mm. For 6.6 kV application, as per IS standard 2026, yoke to common winding clearance is 30 mm.

Common winding length is given by

window height – (2*end clearance)

= 375 – (2*30) = 315 mm (5)

Axial forces are more than radial forces, hence we consider turns axially.

$$Turns\ per\ layer = \frac{winding\ length}{insulated\ conductor\ diameter} - 1$$

$$Turns\ per\ layer = \frac{315}{2.25} - 1 = 139 \tag{6}$$

Common winding turns = 360

$$Number\ of\ layers = \frac{winding\ turns}{Turns\ per\ layer} = \frac{360}{139} = 2.58$$

The window height for an autotransformer starter can be 2 to 4 times the diameter of the core. In the present work, the window height is considered as 2.5 times the diameter of the core and is equal to 375 mm. For 6600 V application, as per IS 2026, the clearance required between core and inner winding is 9 mm. Inner diameter, ID of common winding is given by

= D + (2*clearance) = 150 + (2*9) = 168 mm (7)

Radial height of common winding is given by

(b_i*oil duct between two layers) +

(no of ducts*oil duct between two layers)
= (2.25*3) + (2*3) = 13 mm (8)

Outer diameter, OD of common winding is given by
Inner diameter + radial height
= 168 + (2*13) = 194 mm (9)

$$Length\ of\ mean\ turn, lmt = \left(\frac{\text{ID+OD}}{2}\right) * \pi \quad (10)$$

Using equation (10), lmt = 568 mm = 0.568 m.

Length of conductor is given by
lmt * no of turns * no of limbs
= 0.568m*360*3 = 615 m (11)

Volume of conductor is given by
area of conductor * length of conductor (12)

Bare weight, w of common winding conductor is given by
Volume of conductor * density of copper

$$\frac{\pi}{4} * 200^2 * 10^{-4}\ cm^2 * 615 * 10^2\ cm * 8.89 * 10^{-3}\ \frac{kg}{cc}$$

= 17.2 kg (13)

Insulated weight, w_i is given by

$$\left\{\left(\frac{\text{b}_\text{i}{}^2 - \text{b}^2}{\text{b}} * \frac{\text{Density of insulation}}{\text{Density of conductor}}\right) + 1\right\} * \text{ bare weight}$$

$$=\left\{\left(\frac{2.25^2 - 2^2}{2^2} * \frac{1*10^{-3}}{8.89*10^{-3}}\right) + 1\right\} * 17.2 \quad \approx 17.8 \text{ kgs} \quad (14)$$

Stray loss, W_s is given by

$$\left(\sqrt{\frac{\text{b}*(^{\text{T}}/_{\text{l}})}{\text{bi}*(^{T}/_{l})-\text{insulation}}} * \text{ Stray loss factor } * \frac{\text{h}}{10}\right)^4 *$$

$$\left(\frac{(\text{no.of radial parallel}*\text{no.of layers})^2 - 0.2}{9}\right) * 100$$

$$\left(\sqrt{\frac{2*139}{(2.25*139)-0.25}} * 0.8 * \frac{2}{10}\right)^4 * \frac{(3*1)^2 - 0.2}{9} * 100$$

$$= 0.051 \quad (15)$$

Current density, J is 3.07 A/mm^2 and load loss is always defined at 75°C (20 + 55), since average ambient temperature is 20°C and as per IS2026 winding temperature in India is considered as 55 °C. Load loss, W_L is given by

Load loss factor * bare weight * (current density)^2 * stray losses (16)

As per Indian standards, Load loss factor is 2.4 and load loss at 75°C is

$$2.4 * 17.2 * (3.07)^2 \left(\frac{0.051}{100} + 1\right) \cong 390\text{W}$$

The temperature gradient is given by

$$\frac{\text{LoadLoss}}{(\text{No of limbs } * \text{ no of surfaces } * \text{ heat dissipation factor } * \text{ winding length } * \text{ length of mean turn})}$$

$$= \frac{390}{(3*4.5*60*0.315*0.568)} \cong 2.7\ ^\circ\text{C} \quad (17)$$

As per IS2026, hot spot temperature is 98°C and yearly weighted average ambient temperature in India is 32°C. Therefore, the maximum winding temperature is 66°C (98-32). Maximum permissible temperature gradient is $\frac{66-50}{1.1} \cong 14.5\ ^\circ$C.

2.3. Design of series winding

When an autotransformer operates at 50% of the rated voltage, the maximum current that flows in the series winding of 360 turns is 9.63 A. In the present work, conductor of diameter 2 mm with current density 3.07 A/mm^2 was considered. The series winding parameters were estimated using the equations given in section 2.2.

Inner diameter of series winding = 206 mm
Outer diameter of series winding = 232 mm
Length of mean turn = 0.688 m
Length of conductor = 744 m
Bare weight of conductor = 20.8 kg
Insulated weight of conductor = 21.5 kg
Stray loss = 0.051%
Load loss = 475W
Temperature gradient = 2.6 ℃

As per IS2026, tank loss is given as 1W/kVA. For 110 kVA transformer, total tank losses are 110W.

Total load loss is given by
Load losses in common winding + Load losses in series winding + Tank losses
= 475 + 390 + 110 = 975W (18)

2.4. Estimation of core dimensions

2.4.1. Estimation of Length and center distance of core [11]

The schematic of core is shown in Fig. 7.

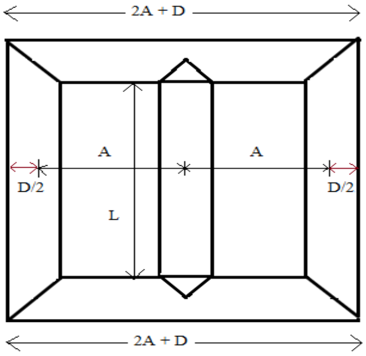

Fig. 7 Schematic of core

Diameter of core = 150 mm
Window height, L = 375 mm

Centre to center distance, A is given by
Outer diameter of series winding + clearance
= 232 + 13 = 245 mm (19)

Length of the core = 4A+2D+3L
= (2*150+3*375+4*245) = 2405 mm (20)

Weight of core is given by
Length * area*density of CRGO steel [9]
=2405*15937*7.65*10^{-6}kg ≈ 294 kg (21)

Core loss is given by
Weight of core * specific loss * build factor
= 294*0.56*1.15 = 190W (22)

2.4.2. Design of core blades

2.4.2.1. Side limb

Length of side limb = L+D = 520 mm
Width = 145 mm, stacking factor = 0.97, density of CRGO steel = 7.65g/cc and Core stack = 38 mm

Weight of side limb is given by
Length*width*stacking factor*core stack* density of CRGO steel
$= 520*145*0.97*38*7.65*10^{-6} = 21.26$ kg (23)

2.4.2.2. Centre limb

The schematic of centre limb is shown in Fig. 8.

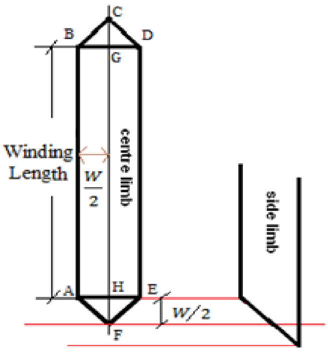

Fig. 8 Schematic of Centre limb

From Fig. 8, total area of the center limb is given by Rectangle ABDE + Area of four triangles (BCG, DCG, AFH & EFH)
$= (375*145) + (4*145*145/4) = 75400$ mm^2 (24)

Stacking factor = 0.97, density of CRGO steel = 7.65g/cc and core stack = 38mm
From equation (23), weight of center limb
$= 75400*0.97*38*7.65*10^{-6} = 21.26$ kg

2.4.2.3. Top yoke

The schematic of top yoke is shown in Fig. 9.

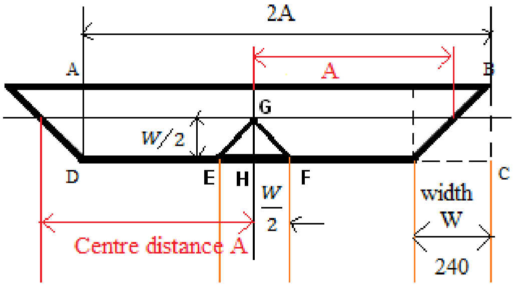

Fig. 9 Schematic of Top yoke

Total area of top yoke is given by
Area of rectangle ABCD – area of triangles (EGH &FGH)
i.e. $2AW - (W^2/4) = 65794$mm^2 (25)

For stack = 38 mm, stacking factor = 0.97 and density = 7.65g/cc, the weight of top yoke is calculated using equation (22) and is equal to 18.55 kg. The weight of bottom yoke = weight of top yoke = 18.55 kg.

2.5. Design of tank

The top view of transformer tank with three phase windings is shown in Fig. 10.

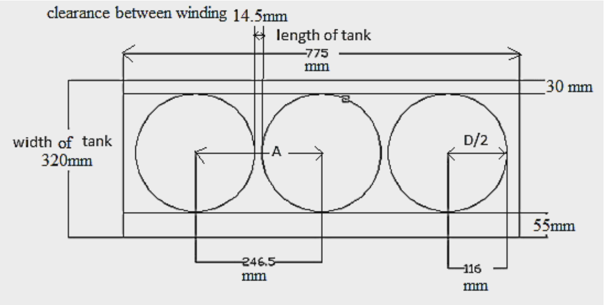

Fig. 10 Top view of transformer tank

From Fig. 10, the center distance is given by
Outer diameter of series winding + phase to phase clearance = 232 + 14.5 = 246.5 mm (26)
Length of the tank, L is given by
(2* tank to winding clearance) + OD of series winding + (2* centre distance)
$=(2*25) + 232 + (2*246.5) = 775$ mm = 0.775 m (27)
Width of the tank, B is given by
winding to tank clearance at the top and bottom + OD of series winding
= 30 (top clearance) +55 (bottom clearance) +232 =320 mm = 0.32 m (28)
Height of tank, H shown in Fig. 11 is given by winding length + diameter of top and bottom yoke +clearance at bottom of the tank + clearance at top of the tank (tap changer clearance)
$= 380 + (2*145) + 10 + 100 = 780$ mm = 0.78 m (29)

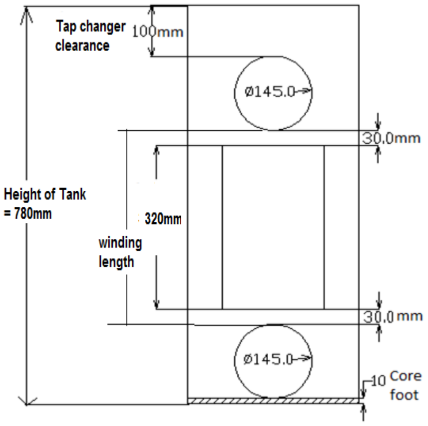

Fig. 11 Schematic of side view of tank

Volume of tank
$= L*B*H = 0.775*0.32*0.78 = 0.193$m^3 = 193 litres.
Oil displacement due to core is given by

$$\frac{\text{Weight of core}}{\text{Density}} = \frac{294}{7.65} = 38\ litres \quad (30)$$

Oil displacement due to winding is given by

$$\frac{\text{Weight of winding(series \& common)} + connections}{\text{Density}}$$

$$= \frac{17.2 + 20.8 + 3}{8.89} \cong 5 \text{ litres} \quad (31)$$

Oil displacement due to insulation is 5 litres.
Oil displacement due to mild steel parts is 4 litres.
Total oil displacement due to active parts is given by
38 + 5 + 5 + 4 = 52 litres.

Volume of oil in tank is given by tank capacity- total oil displacement due to active parts = 193-52 = 141 litres.
No load loss = 190W, total load loss = 975W.
Heat dissipated is given by

$$\left(\frac{55}{50}\right)^{1/0.7} * (No\ load\ loss + 1.1 * Load\ loss)$$
$$= 1.146 *(190+ (1.1*975)) = 1450W \qquad (32)$$

The bottom plate does not contribute to any heat dissipation and on top surface the LV and HV bushings are present, do not allow any heat dissipation by tank wall surface. Therefore, only four sides of the tank were considered. As per standards [10] 500 W/m^2 is dissipated.
Surface Area is given by 2(l + b) * h

$$= 2(0.775+ 0.32) *0.78 =1.708\ m^2 \qquad (33)$$

Heat dissipated by tank = 1.708 * 500 = 850W

Heat dissipated in Radiators is given by
Heat to be dissipated – Heat dissipated by Tank
= 1450 – 850 = 600 W.

Considering the temperature of oil as 45^{o}C, as per standards [10], the heat dissipated by the radiator is 400W/m^2. Therefore, the estimated surface area is given by (600/400) = 1.5m^2.

2.6. Design of Radiator

It is a standard practice [12] to mount the radiator top pipe at a distance of 90mm from the lid and 10mm clearance at bottom of tank. From Fig.11, height of the radiator is given by
height of the tank – clearances – pipe diameter

$$= 780 -100 - 145- 10 = 520\ mm \qquad (34)$$

Surface area/fin=0.226m^2, no of fins is given by surface area / surface area per fin and is approximately equal to 12 fins.

3. EFFICIENCY OF AUTOTRANSFORMER

The efficiency of an autotransformer is given by

$$\%\eta = \frac{\text{kVA}*\text{x}}{(\text{kVA}*\text{x})+[(\text{x}^2*\text{load loss})+\text{no load loss}]} \qquad (35)$$

Where,
x = fraction of load or percentage of load

3.1. Efficiency of conventional Autotransformer

As per IS standards 2026, the maximum permissible current density is 3.63 A/ mm^2 and this value is considered for computing load losses for a conventional autotransformer. All the parameters defined in section 2 are estimated and summarised below:
The cross section of conductor = 2.65 mm^2,
diameter of bare wire = 1.85 mm,
length of common winding = 315 mm,
turns per layer = 139 turns for first two layers &
82 turns for the last layer,
No of layers for common winding = 3,
length of mean turn = 0.5683 mm,
length of wire = 615 mm,
resistance per phase @ 75 °C = 1.63Ω,
weight of the conductor = 14.66 kg,
stray loss of the conductor = 0.051%,
specific loss = 1.02,
build factor = 1.3,
core losses = 390W,
load losses of common winding = 465W,
load losses of series winding losses = 512W,
tank losses = 110W,
total losses in conventional auto transformer is given by
core losses + series winding loss + common winding loss + tank loss

$$= 390 + 465 + 512 + 110 = 1477W \qquad (36)$$

Total load losses is given by

$$\text{Total losses-core losses} = 1477\text{-}390 = 1087W \qquad (37)$$

Efficiency of a conventional auto transformer η_c for 50% taping at unity power factor is given by

$$\%\eta_c = \frac{110*0.5}{(110*0.5)+[(0.5^2*1087)+390]} = 98.80\% \qquad (38)$$

3.2. Efficiency of Energy efficient Autotransformer

From section 2,
Core losses = 190W,
Total load losses = 975W
Total losses = 975 +190 = 1165W
Efficiency of a energy efficient auto transformer η_e for 50% taping at unity power factor is given by

$$\%\eta_e = \frac{110*0.5}{(110*0.5)+[(0.5^2*975)+190]} = 99.21\% \qquad (39)$$

From above total reduction in losses in energy efficient autotransformer compared to conventional autotransformer is given by

$$1477 - 1165 = 312W \qquad (40)$$

In a year total number of units saved is given by

$$0.312*24*365 = 2733\ kWh \qquad (41)$$

The life of the transformer is expected to be 30 years. Therefore, total number of units saved in 30 years
= 2733*30 = 81993 kWh.
At present, cost of one unit = Rs.5.25
Total savings in Rs = 81993*5.25 = Rs. 4,30,469

4. CONCLUSIONS

This paper provides a detailed analysis of a design of a 6.6 kV, 110 kVA energy efficient Autotransformer for starting a three phase induction motor of rating 6.6 kV, 250 kW. In the present work, core losses are reduced by selecting superior material in place of conventional material i.e. laser scribed 23ZDMH85. The core losses were brought down from 390 W to 190 W by using this superior material. To reduce the load losses, lower current density conductor 3.07 A/mm^2 was preferred in lieu of standard value 3.68 A/mm^2 (IS - 2026). The total estimated losses for an energy efficient autotransformer and conventional autotransformer are 1165W and 1477W respectively and there is a significant reduction in losses of about 22% when compared to a conventional transformer.

In the present work, the total losses of the energy efficient autotransformer are 1165 W which are well within the permissible limits [13] and thus validates the method of estimation of total losses with IS standards. The life of the autotransformer was assumed to be about 30 years and the total net savings will be about Rs 4,30,469. The estimated efficiency of the autotransformer operating at 50% tapping, unity power factor with energy efficient autotransformer and conventional autotransformer was 99.21% and 98.8% respectively. This detailed information helps an electrical engineer to design an energy efficient autotransformer of any rating.

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NOMENCLATURE

K = Transformation ratio
I_{sc} = Short circuit current, A
D = diameter of the core, mm
ID = Inner diameter of conductor, mm
OD = Outer diameter of conductor, mm
A_i = Net area, mm^2
f = Supply frequency, Hz
B = Flux density, tesla
HV = High voltage
LV = Low voltage
CRGO = Cold rolled grain oriented
L = Window height, mm
A = Centre to center distance, mm
H = height of transformer tank, mm
b = Width of conductor without insulation, mm
b_i = Width of conductor with insulation, mm
h = Radial height
W_s = Stray loss ,%
W_L = Load loss, W
lmt = Length of mean turn, m
(T/l) = Turns per layer
J = Current density, A/ mm^2
w = Weight of bare conductor, kg
w_i = Weight of conductor with insulation, kg
HP = Horse power = 735.5 watts
EMF = Electromotive force

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