Increasing cost efficiency through minimizing transformer losses: Design and performance analysis of a 250 kVA off-load tap changing step down transformer

Sairatun Nesa Soheli[1], Md Saidul Hasan[2], Md Refat Uddin[3]

[1,3] *Dept of EEE, IUBAT–International University of Business Agriculture and Technology*
[2] *Dept of EEE, Northern Science and Technology*

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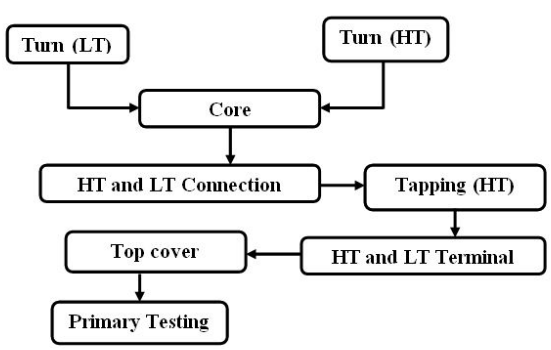
Abstract- A step down transformer can decrease the voltage level and increase the current level by keeping constant power and frequency which gives needful output to a substation. To get this require output transformer design should be splendid. This paper based on transformer design and analysis which can reduce copper and core losses with proficient cost. Step lop core lamination reduce no load voltage up to 8% no load current up to 50% with low noise level. Payback analysis will give the comparison between proposed designed transformer and normal designed transformer. For example: The electrical bill per year due to losses is around 1, 25, 356 bdt for proposed designed transformer rather than the normal transformer where the electrical bill per year due to losses is around 2, 34, 943 bdt and thus yearly saving due to energy efficient transformer is (2, 34, 943 - 1, 25, 356) = 1, 09, 587 bdt. By this way the huge amount of money will be saved by the consumer.

Index Terms- Design, inner connection, analysis, core design, payback analysis

I. INTRODUCTION

Before to start with a working design, a brief requirement of a 250 kVA, 11/0.415 kV copper-wound transformer has been conceived. The first step of the design is to select the number of turns of coils and continue further in the direction of estimating the coil construction, up to arriving at the window height of the core frame. Based on the calculated window height, the design of the secondary coil is done. After that, core diameter, limb center, step width, core stack, core area, flux density are calculated with the obtainable design output. The next step of design is the configuration of coils and limb center of the core frame. Based on the window height and limb center of the core frame, detailed design of core up to the weight of the absolute set of cores is estimated [1]. Manufacturing details of low and high voltage windings, placement of coils, internal clearances tapping and weight of conductor are done. Next step is that, calculation of performance figures. The procedure of calculation of resistance, ratio error, efficiency, losses, no-load current, percentage impedance, regulation have been dealt with. After the design of interior active part, the chapter has enclosed the process of tank design with different types of radiators. A small number of paragraphs have been added to established the procedure of designing the core frame part, core stud, tie rod, conservator etc. After that calculation of oil volume, overall weight and dimensions has also been discussed. The chapter ends with the procedure of filling up the guaranteed technical particulars with applicable calculation of performance parameters and generation of various drawings for submission. The thermal ability to withstand an external short-circuit has also been shown [2].

II. METHODOLOGY



- Determined number of turns of low and high tension side with core calculation
- Low and high tension side are connected by star and delta connection respectively

- Tap changer connected with high tension copper winding and determine the terminals of low and high tension side [3]
- Setting of two terminal by tap cover with initial testing

III. Specifications of the Proposed Transformer

- Rating 250 kVA; oil cooled
- No-load voltage ratio 11000/415
- No. of phase 3 Phase
- Frequency 50 Hz
- Winding material Electrolytic copper
- Tapping's on HV ± 2% to ± 8% (off circuit)
- No. load/load loss 450/2610 watt
- Impedance 5.5%
- Flux density 1.6 Tesla (max)
- Current density 2.6 A/sq. mm (max)
- Connection Delta/star, vector group Dyn 11
- Temperature rise 45/75°C
- Other specifications as per IS-2026
- High Tension (HT) = 11000 V
- Low Tension (LT) = 415 V
- Let, Current at low tension side, I_{LT} = 347.80 Amp
- Let, Current at high tension side, I_{HT} = 13.12 or 7.58 Amp

IV. Blueprint of the Proposed Transformer

Copper is connected with high and low tension coil as well as the connection of high tension tapping diagrammatic concept given below:

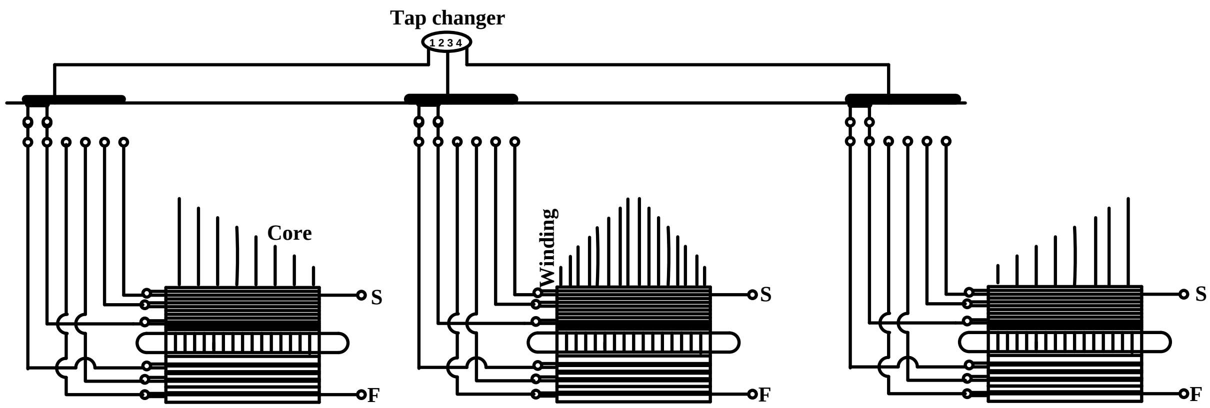


Figure 1: Blueprint of proposed design transformer

Here, 250 kVA of load tap changing transformer which have 5 tapping and here tapping 2 is the standard tapping position of the transformer. In this taping 2 position we get the standard output result of transformer. High tension copper has to be connected with two parts in per phase because of proper oil circulation [4]. We can see that core is surrounded by the low tension coil and then this low tension coil is surrounded by the high tension coil. High tension coil connected with delta ways and low tension coil connected with star ways. For tapping purpose here the high tension coil starting part indicate by `S` and finishing part of the coil indicate by `F`. The first tapping start and finish are shorted that's why all winding are become connected and the result is that we get minimum voltage as an output in low tension side. Again the 5th tapping position the minimum winds are connected in a low tension side and thus we get maximum voltage as an output result on low tension side of a transformer [5].

V. Performance Analysis of the Proposed Transformer

A. Low tension (HT) coil calculation

Connection: Star

Per turn voltage, $(V/T) = (1 \div C) * \sqrt{(kVA * 1000) \div 3}$ ……………..(1)

Here coefficient, C = 40 and kVA = 250

Now from equation (1);

$(V/T) = (1 \div 40) * \sqrt{(250 * 1000) \div 3} = 7.21688$ V

Voltage per phase, V_p = (low tension voltage $\div \sqrt{3}$) = (415 $\div \sqrt{3}$) = 239.60 V

Number of turn per phase, T = (voltage per phase ÷ per turn voltage)
= (239.6004 ÷ 7.21688) = 33.2

Number of turn of low tension side = 33.2 * $\sqrt{3}$ = 58

B. High Tension (HT) Coil Calculation

Connection: Delta
Copper type: Bare
Number of parts = 4
Per turn voltage, (V/T) = (1 ÷ C) * $\sqrt{(\text{kVA} * 1000) \div 3}$ ……………….. (2)
Here, coefficient, C= 40 and kVA = 250
Now from equation (1);
(V/T) = (1 ÷ 40) * $\sqrt{(250 * 1000) \div 3}$ = 7.21688 V
Voltage per phase, V_p = (high tension voltage ÷ $\sqrt{3}$) = (11000 ÷ $\sqrt{3}$) = 6350.85 V
Number of turn per phase, T = (voltage per phase ÷ per turn voltage)
= (6350.85 ÷ 7.21688) = 879.99

Number of turn of high tension side = 879.99 * $\sqrt{3} \approx 1524$

C. Iron Core Calculation

Core area $A_i = \frac{\text{Per turn voltage}}{4.44 * f * Bm * 0.92}$
Here, Frequency, f = 50 Hz
Flux density, B_m = 1.57
So, A_i = 0.022507 m^2 = 22506.7 mm^2
Again, Core $A_i = \pi D^2 / 4$
So, $\pi D^2 / 4$ = 22506.7
Diameter, D = 169.324 mm

Table 1: Usable core diameter rating

Core Diameter	163 mm
Number of turn in low tension side	32 T
Number of turn in high tension side	800 T

D. Determine of Low Tension Copper Size:

Current at low tension side, I_{LT} = 347.80 Amp
Copper current density = 2.89 Amp/mm^2 (std)
Required cross section area = $\frac{\text{Current at low tension side}}{\text{Copper current density}} = \frac{347.80}{2.89}$ = 120 mm^2

Copper Size (mm)		No of wire along depth	No of wire along depth	Area (mm^2) A = 126 mm^2
Width	Thickness			
9	3.5	2	2	

Now, 9 * 3.5 mm copper may be used for low tension coil with damp proof course (DPC) is 9.5 * 4.0
Determination of inner diameter (IO), outer diameter (OD), axial length (A/L) of low tension coil;
Core diameter (D) = 163 mm
Inner diameter (ID) = (D + press. thickness * 2) = 170 mm
Outer diameter (OD) = (ID + 2 * low tension radial depth) = 206 mm
Axial length (A/L) = [(T' * NT) * ($\frac{\text{Total number of turn}}{L}$)] + [(T') + Pressboard width min]
Axial length of low tension A / L_{LT} = 360 mm

E. Determine of High Tension Copper Size

Current at high tension side, I_{HT} = 7.58 Amp

Copper current density δ = 2.89 Amp/mm^2 (std)

Required cross section area = $\frac{\text{Current at high tension side}}{\text{Copper current density}} = \frac{7.58}{2.89}$ = 2.621 mm^2

Table 2: Copper size and area

Copper size		Area
Diameter(SWG)	Diameter (mm)	ATH (mm^2)
14	2.03	3.2349065

SWG is Standard Wire Gauge = 14 used for high tension coil
Damp proof course (DPC) copper size = 2.1 mm
Damp proof course (DPC) thickness = 0.07 mm
Here, (11000 * $\sqrt{3}$) / 415 = 45.910
Number of turn of high tension side = 1524
Determination of inner diameter (IO), Outer diameter (OD), Axial length (A/L) of high tension coil;
Total axial length, $(A/L)_{HT,T}$ = [$(A/L)_{LT}$ – gap for part coil] = 322 mm
Single axial length, $(A/L)_{HT,S} = \frac{(A/L)\ HT,T}{\text{no of parts}}$ = 80.5 mm
So, per layer turn, $T_p = \frac{(A/L)\ HT,T}{\text{total copper size}}$ = 38
Total calculated layer = $\frac{\text{turn per coil}}{T\ p}$ = 9.8217391
In practical no of layer = 10
Inner diameter (ID) = low tension outer diameter + gap between low tension and high tension coil = 245 mm
High tension outer diameter (OD) = inner diameter + (total copper wire diameter * 2 * no of layer) + oil duct (0) + leatheroid paper (5) = 292 mm
Axial length $(A/L)_{HT,S}$ = 80.5 mm

F. Overall Core Design of 250 kVA Step Down Transformer

Axial length, $(A/L)_{LT}$ = 360 mm
Window wide and height (W/H) = $(A/L)_{LT\,+}$ clearance = 360 + 25 = 385 mm
Core diameter, D = 163 mm
1st stack = 30 mm
Core width = 160 mm
P to P distance = high tension outer diameter + clearance = 292 + 10 = 302
A Core length, L_A = (window wide and height + 2 * core width) = (385 + 2 * 160) = 705 mm
B Core length, L_B = (window wide and height + core width) = (385 + 160) = 545 mm
C Core length, L_C = (2 * P to P distance core + core width) = 746 mm
X = [C core length, L_C – (3 * core width)] / 2 = [746 - (3 * 160)] = 142 mm

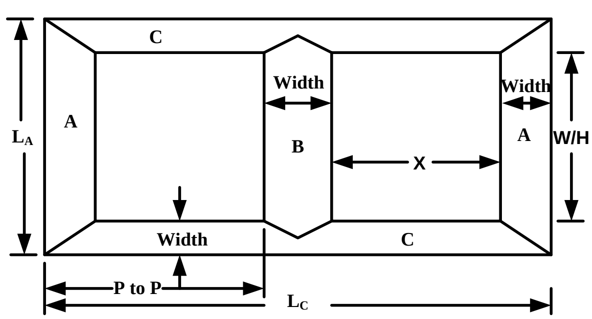


Figure 1: Limbed Core

Part A

Length of lamination (L) is calculated as (W/H + 2W) mm, where W/H and W are in mm
Similarly, weight is calculated as = 28 [(L – W) * W * core stack * density * 0.97 * 10^{-3}]
Where L, W and core stack are in cm

Table 3: Core A cutting

Core A					
SI. no	L_2	b	L_1	Stack	Weight(kg)
1	385	155	700	60	40.09
2	390	150	695	40	25.62
3	395	145	690	27	16.93
4	400	140	685	22	13.03
5	405	135	675	18	10.62
6	410	125	665	30	16.21
7	415	115	655	24	12.07
8	420	105	645	20	9.02
9	425	95	635	17	7.08
10	430	85	625	14	5.42
11	435	75	615	12	4.11
12	440	65	605	10	3.05
13	445	55	595	9	2.19
14	450	45	585	7	1.51
15	455	35	580	6	0.97
Total weight = 139.18 kg					

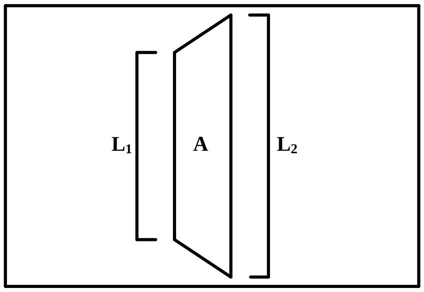


Figure 2: Core A cutting design

PART B

Length of lamination, L is calculated as (W/H + W) mm; where W/H and W are in mm
Similarly, weight is calculated as = $(L - 1/2\ W) * W *$ core stack * density * 0.97 $*10^{-3}$ kg
Where L, W and core stack are in cm

Table.4: Core B cutting

Core B					
SI. no	L_2	b	L_1	Stack	Weight(kg)
1	385	155	454	30	17.10
2	390	150	454	19.77	10.98
3	395	145	454	14	7.30
4	400	140	454	11	5.65
5	405	135	454	9	4.63
6	410	125	454	15	7.14
7	415	115	454	12	5.37
8	420	105	454	10	4.14
9	425	95	454	8	3.21
10	430	85	454	7	2.49
11	435	75	454	6	1.90
12	440	65	454	5	1.43
13	445	55	454	4	1.04

14	450	45	454	4	0.72
15	455	35	454	3	0.47
Core weight =60 and stack =154.04604					

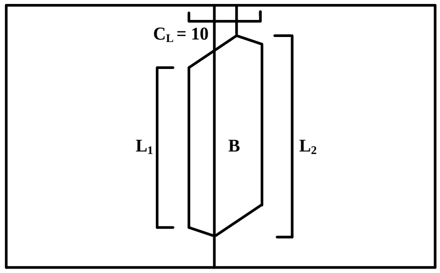


Figure 3: Design of B core

PART C

Length of lamination (L) is calculated as (2 C/L + W) mm
Where C/L, W are in mm similarly
Weight is calculated as = 2 * [(L – W) * W – 1/2 W2] * Core stack * density * 0.97 *10^{-3} kg
Where L, W and core stack are in cm
Length of 1st step = (2 * 460 + 240) = 1160
Weight of 1st step = 2 * [(116 – 24) * 24 – $(\frac{1}{2} * 24)^2$] * 6.248 * 7.65 * 0.97 * 10^{-3} = 191.38 kg

Table 5: Core C cutting

Core B					
SI. no	L_2	b	L_1	Stack	Weight(kg)
1	225	155	715	60	38.53
2	130	150	710	40	24.72
3	135	145	705	27	16.42
4	140	140	700	22	12.70
5	145	135	695	18	10.40
6	155	125	685	30	16.03
7	165	115	675	24	12.04
8	175	105	665	20	9.27
9	185	95	655	17	7.19
10	195	85	645	14	5.56
11	205	75	635	12	4.25
12	205	65	635	10	3.18
13	205	55	635	9	2.31
14	205	45	635	7	1.60
15	205	35	635	6	1.04
Total core weight C= 145.70 kg					

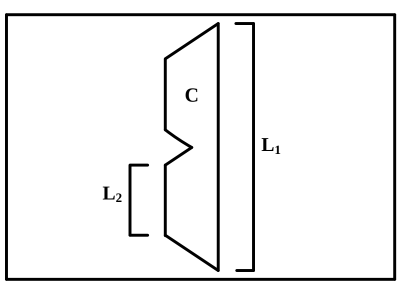


Figure 1: Design of core C

Total weight of core,
Weight of Part *A* = 139.18 kg
Weight of Part *B* = 60.04 kg
Weight of Part *C* = 145.70 kg
Total weight of core = 344.92 kg
So, designed of 250 kVA step down transformers is strongly considering all losses as core and copper losses

Table 6: All losses are considered for design of transformer

Design validation sheet				
kVA	250	Voltage 11/.415kV	+ 2.5% to - 7.5% in step of 2.5% Taping	
SI. no	Description	Units	Guaranteed	Designed
1	No load loss	W	275	273.74
2	No load current	A	1% OF FL	-
3	Load loss	W	2650	2648
4	I^2R loss	W	-	2443
5	Stray loss	W	-	205
6	Impedance	%	4	4.08
7	Reactance	%	-	3.86
8	HV resistance @ 75°C	Ω	-	12.95
9	LV resistance @ 75°C	Ω	-	0.004373
10	Temp rise oil	°C	60	-
11	Temp rise wedge	°C	65	-
12	LV per coil weight	Kg's	-	23.0
13	HV per coil weight	Kg's	-	7.36
14	Total job weight	Kg's	-	1034

VI. Tap Changing Process of the Proposed Transformer

Tap changing process is the process of selecting or cutting out a certain number of turns on the transformer winding thus obtaining a variable turns ratio. This is done in order to maintain the output voltage within desirable limits because the equipment works satisfactory in the power system [3]. According to the diagram, used 2.5 % tapping for the off load tap changing transformer for this reason output voltage might be five different values and thus from tapping one to tapping five voltage level increase respectively up to a certain position.

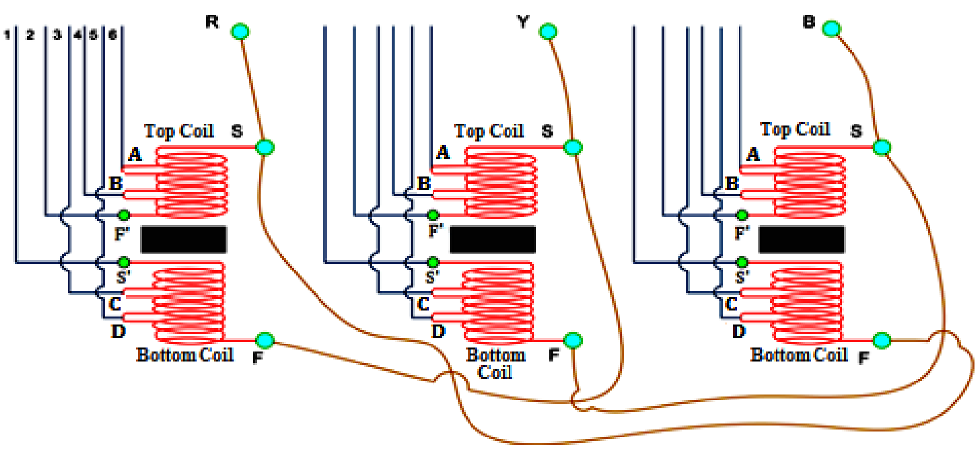


Figure 5: Off load tapping connection on 250 kVA transformer

Tapping calculation given below:
For 250 kVA transformer used 2.5% tapping
High tension coil number of turns = 1524
So the tapping turns will be for 2.5% =1524 * (2.5 / 100) = 38 turns
For better voltage control the total primary turns will be (1524 + 38) = 1562 $\approx$ 1600
High tension coil have two parts, one is top coil and another is bottom coil

So, within this 1600 turns the top coil have 800 turns and the bottom coil have 800 turns. The top coil tapping is given at the end of the turns and the three tapping connections for the top coil are given below:

Total Number of turns 800
Start of HT coil (S) = 0 turn
Finish of top coil (F') = 800 turns
Tapping point B = 800 – 38 = 762 turns
Tapping point A = 762 – 38 = 724 turns
The bottom coil tapping are given at the beginning of the turns and the three tapping connections for the bottom coil are given below:

Start of Bottom Coil (S') = 800 turns
Finish of LT coil (F) = 0 turn
Tapping point C = 800 – 38 = 762 turns
Tapping point D = 762 – 38 = 724 turns

VII. Payback Analysis of the Proposed Transformer

The payback period is the length of time required to recuperate the preliminary cash expenditure on the project. The proposed transformer has a proven and reliable design which ensures an economical life of the transformer for more than 20 years. The energy efficiency transformer reduces the electricity bill by reducing the total losses as shown in the following example:

Sl no	Payback analysis	250 kVA
1	Losses are considered for full load application (utilization factor)	1
2	Electricity charges considered per kWH (cost of Tk./unit)	4.5
3	Rating considered	250 kVA
4	No. of hours in a year (24 * 365)	8760

A	Proposed designed energy efficient transformer	
	No load loss + Full load loss	(0.360+2.82) kW
	Total load loss (kW)	3.18 kW

B	Normal designed ordinary transformer	
	No load loss + load loss	(0.56 + 5.4) kW
	Total load losses (kW)	5.96 kW

A_1	Electricity bill per year due to losses for proposed transformer	
	Utilization (1) * price per unit (4.5) * total no of hrs (8760) * loss (22.6)	1, 25, 356 bdt

B_1	Electrical bill per year due to losses (bdt)	
	Utilization (1) * price per unit (4.5) * total no of hrs (8760) * loss (35.6)	2, 34, 943.20 bdt

X	Yearly saving due to energy efficient transformer (B_1 - A_1)	1, 09, 587.00 bdt
P_1	Approximate price of 250 kVA transformer	4, 00, 000.00 bdt
P_2	Price of 250 kVA ordinary transformer	3, 30, 000.00 bdt
P_1-P_2	Price difference for energy efficient design	70, 000.00 bdt
P_B	Payback period in year, $P_B = \frac{P_1 - P_2}{X}$	0.64 year
P'_B	Payback period in month = P_B * 12	7.6 month

VIII. Result

Manufacture of the transformer by using this design, core and copper losses are very low. It is also eco-friendly cause of the noise is very low and output voltage is 99% which reduce electric bills and gives long-lasting life. Core and copper calculations such an accurate that the economical transformer design cost becomes low. Payback and Resulting analysis are discussed in this paper robustly.

XI. Conclusion

In this paper agitated in regard to design hermetically sealed shell type oil immersed distribution transformers with minimum evaluated cost according to the IEC standards. Here very calculatedly describe about the transformer design with proper equations as well as the consequently core and copper design then internal total connection of the transformer. Distribution transformer model and design constraints are implemented as a user-friendly an objective function for total evaluated cost is optimized subjected to ten constraints according to IEC 60076 in addition to geometrical constraints. A design example on a 250kVA transformer is presented for illustration.

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Authors

First Author – Sairatun Nesa Soheli, Senior Lecturer, IUBAT–International University of Business Agriculture and Technology, soheli@iubat.edu

Second Author – Md Saidul Hasan, Instructor, Northern Science and Technology, mdsaidulhasan2@gmail.com

Third Author – Md Refat Uddin, IUBAT–International University of Business Agriculture and Technology, rashedrefat@gmail.com

Correspondence Author – Sairatun Nesa Soheli, Senior Lecturer, IUBAT–International University of Business Agriculture and Technology, soheli@iubat.edu