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doi:10.15199/48.2021.04.03

Optimization Design Evaluation and IEC 60076 Standard Test for Large Oil Type Transformer

***Abstract**. The optimization of large distribution transformer is designed by using area elimination technique to change dimensional variables such as the number of turns in both sides of winding, induction flux density, electrical length, low current density and high voltage current density. To determine the lowest objective function such as minimum cost, minimum height, minimum weight, or total cost design that matches the consumer's specification, the combination of design technique and production technique was used in the real manufacturing process. This method was used for the design of 8000 kVA 22000 – 3300/1905 V. oil type large distribution transformer. After the design and production in the manufacturing process, the test results were found to be within guaranteed limitation. Furthermore, either the design parameters or the limit of the specification of distribution transformers were varied to find the optimal cost. In this regard, the design procedure of distribution transformers at desire characteristics and minimized total cost were achieved. The transformer was tested according to the IEC standard. It satisfactorily passed both routine and type tests.*

***Streszczenie.** W artykule opisano optymalizację projektu dużego transformatora prze odpowiedni dobór uzwojeń, indukcji w rdzeniu, gęstości prądu, wymiarów, wagi a także kosztów. Metodę zastosowano do projektu transformatora 8000 kVA 3300/1905 V. Transformator zbadano zgodnie z normą IEC. (**Optymalizacja projektu dużego transformatora olejowego i badania jego zgodnie z normą IEC 60076**)*

Keywords: Optimization evaluation, Oil type transformer, Area elimination method, IEC 60076 standard
Słowa kluczowe: duży transformator rozdzielczy, transformator olejowy, projekt, optymalizacja.

Introduction

In a new and challenging environment, there is an urgent need for the transformer manufacturing industry to improve the efficiency of transformers, and to reduce costs, as high quality, cheap products are the key to survival. To achieve precise designs with less time and economical methods, mathematic models have been used by digital computers[1,2]. Integrated methods have been developed for the design of electrical machinery, including transformers. The joint design is based on knowledge of the translation flow distribution in both angles, and in the limbs transformer designs with cost analysis [3]. The author has developed a step-by-step procedure for designing transformers that are related to material and labor costs[3,4].

Cost analysis involves detailed material costs and labor analysis provides detailed lists of labor required in creating transformers. Material cost analysis is listed in the form of parts list. Labor costs are summarized by listing all necessary operations in the unit of time. Many optimization techniques have been reported in the literature; annealing simulation (SA) techniques are used [5] to solve transformer design problems. Reducing material costs for evolutionary algorithm purposes based on the most suitable design of induction motors is discussed[5,6].

A method of integrating genetic algorithm networks with distribution transformers is proposed to reduce iron loss [7]. The design of the most suitable transformer as required by the specification using economically available materials for lower costs, reduced dimensions, and improved performance are discussed. Radial orientation with the most suitable design of a single-phase induction motors is presented[9].

The efficiency of the two optical design methods, Hooke Jeeves and the genetic algorithm, respectively, are compared in terms of efficiency and calculating time in the exercise design of the induction machine [8].

The main device that is considered to be the heart of the electricity distribution system is the distribution transformer that transmits electrical energy by converting voltage to various levels. In order to be suitable for the delivery system for consumers in houses or industrial plants, nowadays, the transformer manufacturing industry has a higher competition rate. To increase competition in the industry, manufacturers must have measures to reduce production costs appropriately to increase profits and be more competitive with other manufacturers. Therefore, to design transformers, distributors must design prices, low production costs and features that meet the needs of users. Nevertheless, there are many variables used to define such a structure. Designing specifications that are appropriate for production costs is sometimes a difficult decision. With the design method used as a trial and error method, many modifications are madefor individual's suitability which depends on the experience of the designer. Sometimes there are more user requirements, such as maximum power, loss maximum, weight, width, length, and maximum height, etc., that can cause difficulty in the design. If the designer lacks experience, it will not be able to find the right feature.

Both in terms of primary material prices such as laminated sheet of iron core and conductor wire imported from foreign countries with uncertain prices, to design for the right production cost, a new design must be made every time the material price changes. In causing difficulties in the design therefore, this research uses numerical optimization method together with the distribution transformer design to find the structure that has the characteristics that meet the needs of users and find the production cost to be lower.

The low cost and the design results are used to create a real prototype to verify the accuracy of the program. When the programs that have been designed for distribution transformers is accurate, they can be analyzed to design transformers for distribution at a reasonable price in various ways. Transformer design for industrial distribution will use the original design results to develop and find new design results for the trial and error methods to be modified in various parameters based on the experience of the designer. To obtain a more suitable new design result, therefore, the design results of distribution transformers are produced and used frequently, having quite a reasonable design result[9,10].

In the case of infrequent designs or new designs, it is difficult to find a suitable transformer structure. Therefore, this study proposes a design approach using numerical methods to find the suitable value by area elimination method together with the traditional design of distribution transformers in order to find the suitable structure with the characteristics that meet the requirements and have low production costs.

The purpose of this research is to study the guidelines for the design of distribution transformers together with the method of determining the suitable value by the area elimination method. The objective is to design the structure of distribution transformers with low production cost, and have the needed features by studying the method of determining the optimum values by area emission method together with the design of distribution transformers in various fields, such as the design of the iron core, coil set, insulation, cooling in the set coil, margin for practical work including the calculation of power loss and short circuit impedance percentage. The results were then used to create a program to design transformers for distribution at reasonable prices by area elimination method [11].

Area Elimination Optimization Techniques

Structural design or systems in general engineering work are designed using direct problem solving, that is to design with the concepts of the designer. By assigning various information to the system, it helps to find the desired result from the trial and error process until the appropriate value is achieved as desired. Therefore wasting time in designing and the opportunity to achieve the right value as the set target is less likely. For this reason, the design principles are presented by automatic input methods from a defined range. To find the most suitable answer and in accordance with the conditions specified, we popularly call it the most suitable optimization (optimization)[12].

The area elimination technique used for dealing with multiple variable systems such as the grid search, in this method, the reduction of uncertainty is square or volume, which can be predicted and sized according to need. To illustrate, for example, two variables, grid search reduces uncertainty to a three-variable grid. Grid search reduces uncertainty to volume, therefore, we can define the unit dimension on the axis of the variable and create a plane at that point as shown in Fig.1. The plane's intersection between each axis is called a node (n) as in equation (1) , each node and the center point is considered. Therefore, in a three-variable system, m = 3 is obtained.

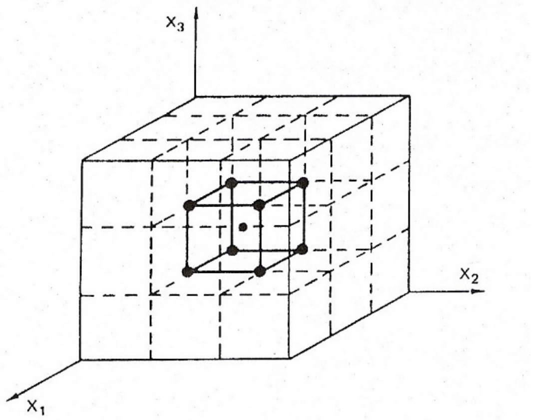

Fig.1 . The Grid search technique

One type of area elimination [13] that provides a manageable result is Mischke's grid search. In this technique, the area of uncertainty reduced is a hypercube. (Such as multiple dimensions of a square or cube) with predictable dimensions. For this reason, this is one of the two-dimensional techniques that show effective measurements in terms of the design space, along with two design variables that will help in understanding this search technique.

The area of original uncertainty is mapped to a square or hypercube unit (depending on the size of the area) so that the search is normalized with the area of the adjacent unit dimension through this hypercube in order to draw a table of symmetric matching. In the orthogonal plane parallel to the design variable axis, the intersection of the plane creates a line to intersect so that the points are known to the node. Merit values at each intersection and at the intersection of variables, the node, are made with the largest merit found and this position becomes the center of a small hypercube for further investigation[14,15,16].

For the star pattern as shown in Fig.2, functional evaluations are made at a central ordinate value and adjacent values corresponding to a single step in each ordinate direction. For this procedure, the total number of functional evaluations will be

(1) $$n = b(2^{m-1}) + m + 1$$

One of the major advantages of the space removal method is that users can know in advance how many functions they need to evaluate. (and the amount of calculation effort). This is to reduce the period of uncertainty to the desired amount (see the results in Table 1. (r=0.8,m=5):

Table 1.Total number of functional evaluations(n).

F=r^b	b	n=b(2*m)+1	total
0.8^1=0.8 (1.0)	1	1(2*5)+1	11
0.8^2=0.64 (0.75)	2	2(2*5)+1	21
0.8^4=0.409 (0.5)	4	4(2*5)+1	41
0.8^7=0.209 (0.25)	7	7(2*5)+1	71
0.8^{11}=0.085 (0.1)	11	11(2*5)+1	111
0.8^{21}=0.0092 (0.01)	21	21(2*5)+1	211
0.8^{31}=0.00099 (0.001)	31	31(2*5)+1	311
0.8^{42}=0.000085 (0.0001)	42	42(2*5)+1	421
0.8^{52}=0.0000091 (0.00001)	52	52(2*5)+1	521
0.8^{62}=0.00000098 (0.000001)	62	62(2*5)+1	621

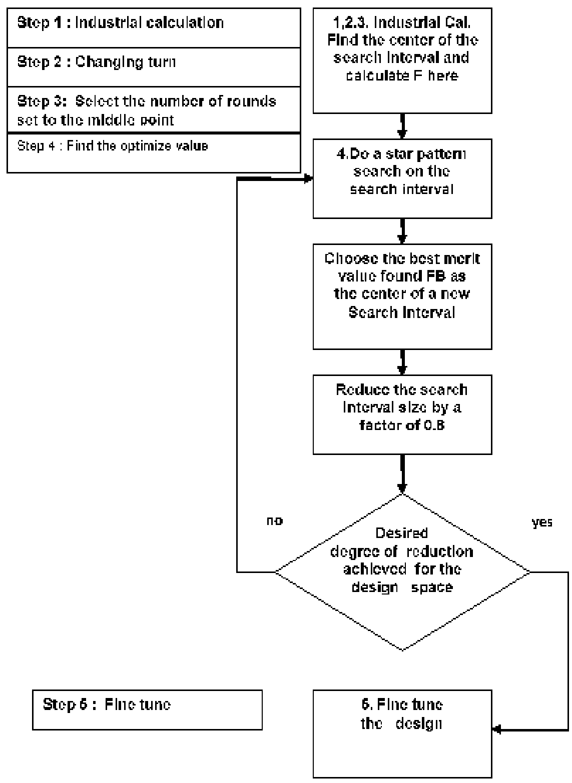

Fig. 2 The star-pattern search area elimination with fine tune

The design input data for design a transformer

The design input data for designing a transformer have to specify clearly, for example, rated primary voltage, secondary voltage, the number of phases, frequency, vector group, no-load loss, load l, % impedance, and the standard to reference for the testing condition. Because the design process have to take into account the issue of the best operation point for a transformer designed the core cross-section area, the core diameter, the number of step for core steel, after which no-load loss can be calculated, load loss and % impedance. Starting with the approximate for core cross-section area [17,18], it can be calculated as:

1.Core cross-section area (A_{FE})

(2) $$A_{Fe} = k_c\sqrt{\frac{S}{fP}}$$

where, A_{Fe} is core cross section area (mm^2); S is Rated power (VA); f is Frequency (Hz); P is the number of phase; k_c is core factor between 4-6 x 10^2 $mm^2.J^{-1/2}$

2. The number of step (Y(i)

The number of steps has to be defined according to the diameter and each width of silicon steel can be calculated as:

(3) $$Y(i) = \sqrt{(\frac{D}{2})^2 - (\frac{l(i)}{2})^2} - \sum_{j=0}^{i-i} Y(j)$$

where , i is the step ; D is the core mean diameter (mm); $l(i)$ is the width in each step (mm) ; $Y(i)$ is the thickness in each step

The core cross-section area can be calculate as follow:

(4) $$A_{Fe} = 2k_e\sum_{i=1}^{n} Y(i)(j)$$

where k_e is core stacking factor; n is the number of step
The induction B has select between 1.50- 1.75 Tesla.

3. The voltage per turn

The volt per turn can be calculated as follows:

(5) $$\frac{V_P}{N_P} = \frac{V_S}{N_S} = 4.44\ fB\,(A_{Fe}\,x10^{-6})$$

Where V_p and V_s are the voltage in primary and voltage in secondary side, respectively; N_p and N_s are as the number of turns in primary and secondary; $\mathbf{B}$ is the induction

The conductor current density has to be considered from the load loss, the temperature rise, and the cooling duct , but in industry given value of 3.5 A/mm^2 .The insulation depends on the testing voltage, but in an industry providing 3 kV/mm in oil, and 5 kV/mm in oil and insulated paper.

4. The core weight

The core weight combines three transformer legs and two transformer yokes which can be calculated as :

(6) $$W_i = A_{Fe}\gamma_i(3l_c + 2(2l_{cc} + l_{max}))$$

where W_i is the total core weight (kg) ; γ_I is the core steel density 7.65x10^{-6} (kg/mm^3); l_{max} is the maximum width of core steel (mm); l_c is the core window height (mm); l_{cc} is the core center to center (mm)

5. The conductor weight

The conductor weight can be calculate as follows:

(7) $$W_c = \gamma_c A_c L_m N$$

Where W_c is the conductor weight (kg); γ_c is the copper density 8.9x10^{-6} (kg/mm^3) ; A_c is the conductor cross section area (mm^2); L_m is the mean turn length of the winding (mm) ; N is the number of turns

6. The core loss

The core loss can be calculated as follows:

(8) $$P_{NL} = k_{wn}P_m W_i$$

where P_{NL} is No load loss (watts); k_{wn} is the core structural factor; P_m is the core loss coefficient in watts per kg from; core steel supplier (w/kg)

7. The load loss (P_{CL})

The load loss includes a resistance loss , stray loss , eddy current loss in conductor.

(9) $$P_{CL} = I_p^2 R_p + I_s^2 R_s$$

(10) $$R = \frac{\rho L_m N}{A_c}$$

where R is the resistance (ohm); ρ is the specific resistance at 75 °C (ohm – mm);
R_p and R_s is resistance in primary and secondary

8. The leakake flux

There are some leakage flux. It is more accurately to have some percent from the statiscal industrial, the reactance, resistance and the impedance, which can be calculate as:

(11) $$\%X = \frac{1.24\,I_s N_s^2 D_m k_R}{E_s L_{wm}\,x10^4}(a + \frac{b1 + b2}{3})$$

(12) $$\%R = \frac{P_{CL}}{S}x100$$

(13) $$\%Z = \sqrt{\%R^2 + \%X^2}$$

where I_S is the secondary current; N_S is the secondary number of turn ; D_m is main duct mean diameter (mm) ; k_R is Rogoski factor; E_S is the secondary voltage (volt) ; L_{wm} is the mean height of winding (mm) ; a is main duct (mm) ; $b1$ and $b2$ is the radial build for primary and secondary winding

Transformer design using area elimination technique

Transformer design in this paper is to search the minimum material cost as the objective function, calculate as :

(14)
$$FB = C_{Fe}W_{Fe} + C_S W_S + C_P W_P + C_{OIL}W_{OIL} + C_{\tan k}W_{\tan k}$$

where C_{Fe} is core steel cost in baht per kg; W_{Fe} is the core steel weight (kg) ; C_S is the secondary voltage conductor cost in baht per kg; W_S is the secondary voltage conductor weight (kg) ; C_p is primary voltage conductor cost in baht per kg ; W_p is the primary voltage conductor weight (kg); C_{OIL} is the transformer oil cost in baht per kg ; W_{OIL} is the transformer oil weight (kg) ; C_{tank} is transformer tank cost in baht per kg ; W_{tank} is the transformer tank weight (kg)

The constraint

The constraint is the output function.

1. No-load loss
2. Load loss
3. % impedance
4. The multidimensional variable used are:

- (1) is the secondary number of turns
- X(2) is the magnetic flux induction
- X(3) is the electrical length of winding
- X(4) is the secondary current density
- X(5) is the primary current density

Table 1. Constraint design

1.5 ≤ B≤ 1.75	T
1.0≤ Jp , Js ≤ 3.5	A/mm2
$4x10^2 \le k_c \le 6x10^2$	$mm^2J^{-1/2}$
%Z = 7.5	%
Load loss = 42000	watts
No load loss = 10000	watts
Gradient ≤ 18	°C
HV to Yoke	mm
LV to Yoke	mm
Phase to Phase	mm

Table 2. Output Design

Core cross section area	1274.4	cm2
Induction	17760	Gauss
Primary winding Current density	2.851 A/mm2	
Secondary winding Current density	2.856 A/mm2	
Core weight	5798	kg
Primary conductor weight	1130.6	kg
Secondary conductor weight	811.82	kg
Oil weight	2530	kg
Tank and radiator weight	2084	kg
No load loss	9037	W
Copper loss in primary at 75 oC	20980	W
Copper loss in secondary at 75 oC	17649	W
Other loss	8050	W
Total load loss at 75 oC		
%Impedance	7.353	%

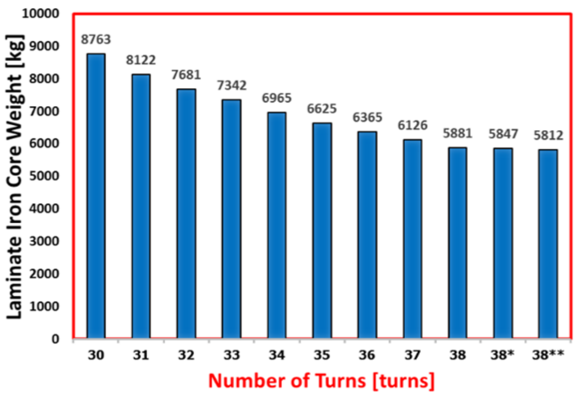

Fig. 3. Laminate Iron core weight

The iron core weight is continuously reduced from 30 to 38 cycles, but the density of the magnetic force line is adjusted upward to fully utilize the iron core. The least weight is 5812 kg with 38** fine tune.

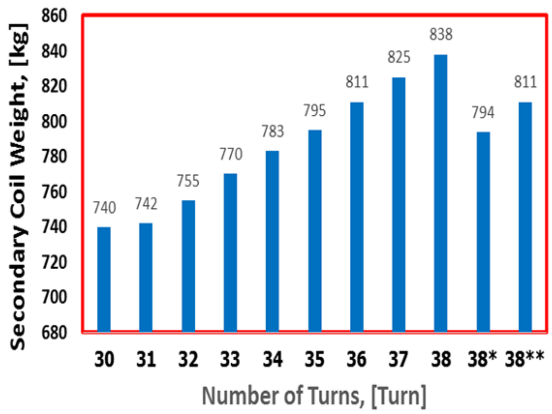

Fig.4. Secondary coil weight

The secondary coil weight continuously increases from 30 to 38 cycles, and when the 38 cycles are selected again to find the appropriate value of 38 * the secondary coil weight is noticeably reduced, then, the final adjustment to 38 **.

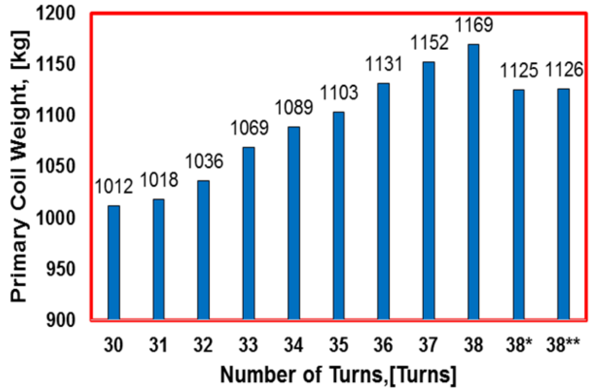

Fig.5. Primary coil weight

The primary coil weight continuously increases from 30 to 38 cycles, and when 38 cycles are selected again to find the appropriate value of 38 * the primary coil weight is noticeably reduced, then, the final adjustment to 38 **. This agrees with the secondary coil result.

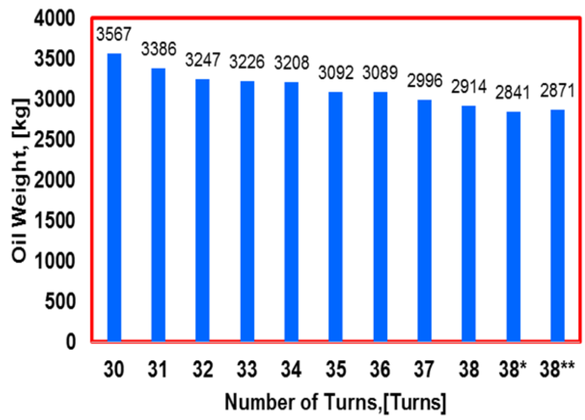

Fig.6. Oil weight

The oil weight is continuously reduced from the number of turn 30 to 38, and there are slight changes at turn 38 * and 38 **.

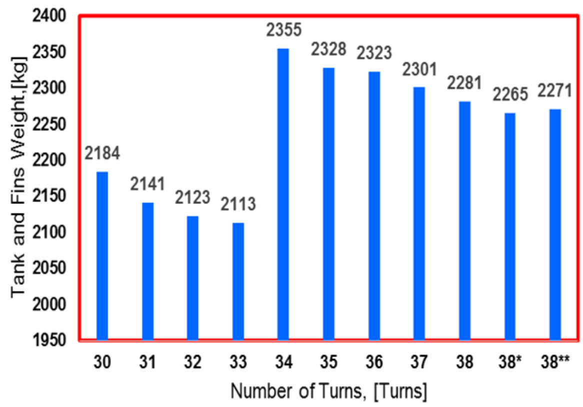

Fig. 7 Tank and fins weight

The weight of the heat sink fins is continuously reduced from the number of turns 30 to 33, but there is an increase at around 34 because the height of the fins has changed from 1200 mm to 1300 mm causing a lot of weight gain, and after that, it continually decreases.

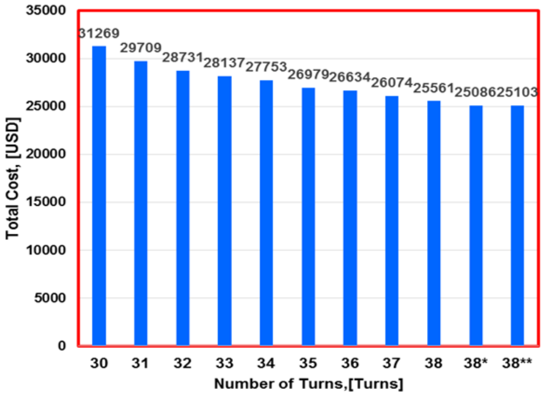

Fig.8 Total cost

Design results at 38 ** turns can be designed to meet the design requirements. There are 5 main raw material costs (equals to 1). Cost from iron core weight 2. Cost of secondary coil weight 3. Cost of primary coil weight 4. Cost of oil weight 5. The cost of body weight including total fin can be 25100 USD (778,194 THB) as shown in Fig.8, and with a 19.71% reduction in cost as shown in Fig.9.

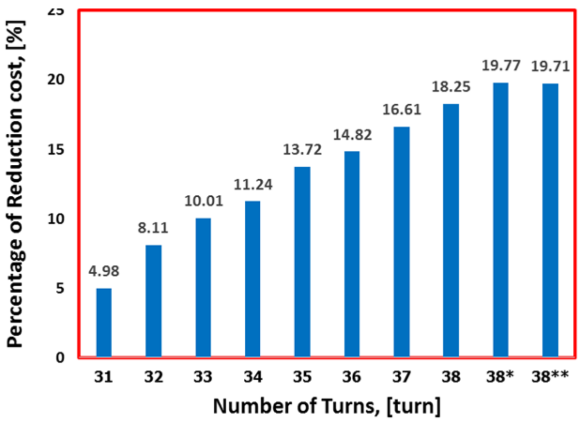

Fig.9. Total reduction in cost

Summary of design of distribution transformers by the method of finding the suitable value rated power 8000 kVA 3 phase, 50 Hz, primary voltage 22,000V, secondary voltage 3300/1905 V, the percentage of voltage junction at primary aspect +2 x 2.5%, and the impedance percentage at 7.5%. Dyn 11 transformer has design specifications which are no-load power loss no more than 9200 W, on-load power loss no more than 44,000 W, referenced to design following IEC 60076, 75^{o}C coil temperature increase, 60^{o}C oil temperature and 40^{o}C room temperature.

Fig. 10 HV and LV winding coil

The core dimensions are core mean diameter 420.4 mm and core 9 step (width 410,390,360,330,300,250,210,150 and 90 mm) .The construction of the HV and LV winding as shown in Fig.10 are 16 conductors in parallel redial direction and 1 conductor in the axial direction. With a conductor dimension of 3.50 x 9.00 mm2, there is 42 disc per phase, the distance between disc is 4.5 mm.and the number of turns is 38. At HV winding disc coil, there are 3 conductors in parallel in the radial direction and 1 conductor in the axial direction, conductor dimension is 2.00 x 11.00 mm^2, there are 36 discs per phase, and the distance between disc is 4.84 mm.

Testing results of distribution transformers
Measurement of winding resistance

Winding resistance measurement measures with a high-precision bridge. To calculate the power loss in the copper coil that issued to determine the temperature of the windings in testing the temperature rise of the transformers. The resistance measurement must specify the temperature of the coil while measuring if the ambient temperature of the transformers is constant for a long time. It is estimated that the temperature of the windings is equal to the temperature of the atmosphere surrounding the transformer. The measured resistance transforms the resistance to a reference temperature of 75 ^{o} C [19]. For copper coils, it is calculated according to the following equation:

$$R_r = R_a \frac{235 + \theta_r}{235 + \theta_a} \tag{17}$$

where R_a is the resistance of the coil at θ_a a constant temperature, R_r Is the resistance of the coil at the reference temperature θ_r (75^{o}C)

When measuring the resistance, the polarity A, B, and C of the high-voltage windings connected inside are in the Delta type (Δ). Therefore, if the resistance of the A and B polarities is measured, the phase resistance is equal to 3 / 2 of the measured values. For low-voltage coils that are internal to Star (Y), when measuring between poles a and b, the phase resistance value is equal to "1/2" of the measured value.

Table 3. Resistance RH (Ohm) , Test tap 3 , at 30.2 ^{o}C

Tap	1	2	3	4	5
H1-H2	0.2698	0.2625	0.2567	0.2495	0.2418
H2-H3	0.2655	0.2607	0.2544	0.2479	0.2414
H3-H1	0.2675	0.2623	0.2558	0.2493	0.2428

Table 4. Resistance RL (mOhm) , at 30.2 ^{o}C

x1-x2	4.501
x2-x3	4.491
x3-x1	4.439

Voltage ratio measurement and checking the arrangement of the phase.

Measurement of voltage ratios using the bridge meter can measure the voltage ratio between high voltage coils. Low voltage coils must be in phase and have the same vector direction. Looking at Fig. 10. , the Dyn11 vector group shows that the high-voltage (A - B) and the low-voltage (a - b) have different angles of 30 degrees.
For this reason, it is impossible to adjust the ratio bridge. The meter can be balanced, but it can be balanced if compared between the high voltage (A - B) and the phase voltage of the low voltage (a - n). For this reason, the voltage ratio can be checked. Get vector groups at the same time, show the measurement results in Table 5.

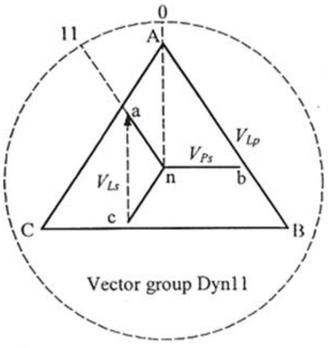

Fig.10. Measuring the voltage ratio of vector groups Dyn11.

Table 6. Voltage Ratio and Vector (%DEV) , Using Ratio Bridge

Tap	1	2	3	4	5
Voltage	23100	22550	22000	21450	20900
Ratio	12.12	11.84	11.55	11.26	10.97
H1-H2	-0.10	-0.18	-0.18	-0.18	-0.18
H2-H3	-0.10	-0.18	-.0.18	-.0.18	-.0.18
H3-H1	-0.10	-0.18	-0.19	-0.19	-0.19

Loss measurement without load and no-load current

The power loss and current without load are measured at the rated voltage and frequency by feeding the alternating current into the low-voltage coil. The reading from the wattmeter is the power loss of the transformer while there is no load. And the current value with current when there is no load of the transformer shows the test circuit as shown in Fig.11 and the test results are shown in Table 7.

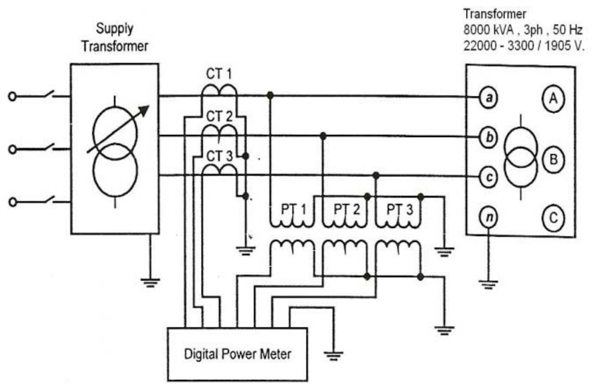

Fig.11. The test circuit for finding the power loss and current while there is no load.

Table. 7 No-Load Loss (NLL)

(Vrms)	(Vmean)	(A)	(W)
3248	3300	2.018	6970

Short circuit impedance measurement and the loss has loads while dispensing loads at the rated load. The power loss value at the moment of the load is the power that is lost to the transformer when the current is supplied at the rating. This can be measured by short-circuiting the low-voltage coil and entering the current at the high-voltage coil-side. The power loss, while the load is read, consists of the power loss from the resistance in the windings and losing power while having other loads. In the short-circuit impedance measurement and loss, there is a load while the load is at the rated load.

The test circuit for finding the power loss while having the load and short-circuit impedance percentage is shown in Fig. 12. The test results and the calculation results are compensated to the reference temperature 75 as specified by the standards shown in Table 8 and Fig. 12, respectively.

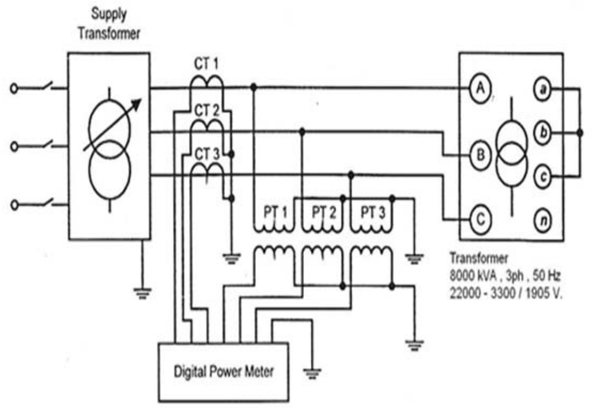

Fig.12. The test circuit for finding the power loss and current while there is on load.

Table 8. Load Loss(LL) , at 30°C

(V)	(A)	(W)
1580.1	207.5	37300

Table 9. Calculation of power loss while loading at the main junction Tap 3.

Temperature (°C)	30 °C	75 °C
Loss of power from primary coil windings (W)	16889	19762
Loss of power from secondary coil windings (W)	13146	15382
Loss of power from total resistance (W)	30034	35144
Loss of power while having another load (W)	8150	6965
Loss of power while loading at the main junction (W)	38184	42109

Table 10. Efficiency and Voltage Regulation at pf =1.

Temperature (°C)	30 °C	75 °C
Loss power, no load (W)	7079.8	7079.8
Loss power, on load (W)	38184	42109
Total loss (W)	45264	49189
Efficiency (%)	-	99.39
% Z (%)	-	7.27

Table 11. Oil breakdown , IEC60156 , Passed

Gap 2.5 mm	59.1 kV

Table 12. Test result

	Declared	Min	Max	Tested	
NLL	11000	-	12750	7079.8	Passed
LL	50000	-	57500	42109	Passed
TL	61000	-	67300	49189	Passed
%Imp	8.00	7.2	8.7	7.27	Passed

Table 13. Comparison of characteristics, design results and test results

Distribution transformer Parameters	Condition	Design	Test	Error
Loss power while no load (W)	9200	9124	7079.8	22%
Loss while being loaded at 75°C (W)	44000	42980	42109	2%
Total loss (W)	53200	52104	49188.8	5.5%
Impedance percentage (+/- 10%)	7.5	7.329	7.27	0.8%
Temperature increasing of primary coil °C	65	64.4	64.05	1%
Temperature increasing of secondary winding °C	65	64.4	62.12	3.5%
Temperature increasing of oil °C	60	57	52.33	8%

From the comparison of designs and testings in Table 13, it is found that the power loss tests with no load yield lower power loss than the design results. The coefficient times multiplied by the factors of the operation of the iron core is better than general because it is a step-cutting steel and the multiplied coefficient. Due to the operation factors in the coil, there is tolerance for errors that may occur from the production system or the materials used, resulting in a test result that is slightly lower than the design result, but it can be assured that the design output will not exceed the value specified by the design results; the design power is losing while there is no load. There is as much as 22% error, but compared to the total loss of power is only 5.5%, which is acceptable.

Conclusion

This study presented the development of an oil-immersed type large distribution transformer cost design using an area elimination technique. The construction of primary winding was disc coil using rectangular copper wire, a secondary winding, and also a disc coil using rectangular copper wire. This research sought to change the parameter from the range of variable to get the suitable parameter of each variable consisted of the guarantee no-load loss, load loss, and short circuit impedance, which had the limitation of the temperature gradient. The characteristics of optimal transformer design were also compared with industrial design. The prototype transformer (8000 kVA, 3 phase, 50 Hz, Primary voltage 22000 V., secondary voltage 3300/1905 V. primary tap +2,-2*2.5%, Dyn_11.) was manufactured according to the optimal cost design result of large distribution transformer and tested in laboratories. The test results were within guarantee limitation. Furthermore, either the design parameters or the limit of specification of distribution transformers were varied to find the optimal cost. In this regard, the design procedure of distribution transformers at desire characteristics and minimize total cost were achieved and corroborated with the results as reported in [14].

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REFERENCES

[1] Vadim MANUSOV, Pavel MATRENIN, Nasrullo KHASANZODA," Power Loss Minimization by Voltage Transformer Turns Ratio Selection based on Particle Swarm Optimization," PRZEGLĄD ELEKTROTECHNICZNY,R. 95 NR 8/2019, pp.127-131.

[2] Petro STAKHIV1, Oksana HOHOLYUK2, Liliana BYCZKOWSKA-LIPIŃSKA1 Vadim MANUSOV, Pavel MATRENIN, Nasrullo KHASANZODA," Power Loss Minimization by Voltage Transformer Turns Ratio Selection based on Particle Swarm Optimization," PRZEGLĄD ELEKTROTECHNICZNY,R. 95 NR 8/2019, pp.127-131.

[3] Andersen, O.W. Optimum design of electrical machines. IEEE Trans. actions on Power Apparatus and Systems. 1967, no. 6, pp 707-11..

[4] Anthony, J., Moses and Bleddyn Thomas. 1974. Problems in the design of power transformers. IEEE Transactions on Magnetics. vol. 10, no .2, pp. 148-150.

[5] Odessey, P.H. 1974. Transformer design by computer. IEEE Transactions on Magnetics. vol. 3, no.1, pp.1-17.

[6] Padma, S., Bhuvaneswari, R., and Subramanian, S. 2006. Optimal design of power transformer using simulated annealing technique. IEEE Conference, International Conference on Industrial Technology (ICIT), December 15-17, pp. 1015-1019, Mumbai, India.

[7] Bharat Heavy Electricals Limited, 1987, Transformers, Delhi : Tata McGraw – Hill Publishing Company Limited.

[8] Jan Pawel Wieczorek, ozdemir Gol and Zbigniew Michalewicz. 1998. An evolutionary algorithm for the optimal design of induction motors. IEEE Transactions on Magnetics. Vol. 34, no. 6, pp. 3882 – 3887.

[9] Sawhney, A.K. A Cause in Electrical Machine Design Delhi : Dhanpat Rai & Sons.

[10] Intrajit Dasgupta, Design of Transformers, New Delhi, Tata McGraw – Hill Publishing Company Limited. Sawhney, A.K. A Cause in Electrical Machine Design Delhi : Dhanpat Rai & Sons.

[11]Georgilakis, P.S., Doulamis, N.D., Doulamis, A.D., Hatziargyriou, N.D., and Kollais,S.D. 2001. A novel iron loss reduction technique for distribution transformer based on a combined genetic algorithm-neural network approach. IEEE Transaction on System, man, Cybernetics. vol. 31, no. 1, pp. 16-34.

[12] Terry E. Shoup, Farrokh Mistree, " Optimization Methods with Applications for Personal Computers" Englewood Cliffs, New Jersey 07632,1987.

[13] H. Banspach, "Transformer Design," Lecture Notes, Thai-German Technical Teacher College,1975,Thailand.

[14] Pavlos, S., Georgilakis, Marina Tsili, A. and Athanassios Souflaris. T. 2007. A heuristic solution to the transformer manufacturing cost optimization problem. Journal of Materials Processing Technology. vol. 181, no. 1-3, pp. 260–266.

[15] Bhuvaneswari,R., and Subramanian,S. 2005. Optimization of single-phase induction motor design using radial basis function network. IEEE Indicon Conference, Dec.11-13, pp. 35-40, Chennai, India.

[16] Lucian Tutelea and Ion Boldea. 2010. Induction motor electromagnetic design optimization: Hooke Jeeves method versus Genetic Algorithms. In proceedings of 12th International Conference on Optimization of Electrical and Electronic Equipment, OPTIM, May 20-22, pp. 485-492, Basova.

[17] Nippon steel Corporation, "Technical Data on Electrical Steel Sheet , Japan

[18] Agarwal, R.K. 1997. Principles of Electrical Machine Design. 3rd Ed., S.K. Kataria and Sons, New Delhi.

[19] IEC 60076 International Standard, "Power Transformer," 2000.