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Design and Optimization of 30/40MVA, 132/33kV Power Transformer Using Responses Surface Methodology

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Abstract

Transformer is the main apparatus of the power system for both transmission and distribution of electrical energy. It is the important component of electrical engineering because of its high efficiency and helps in step up and step down the voltage, impedance matching and circuit isolation. Team of designers, engineers and building owners struggled for high performance in order to maximize the transformer efficiencies and minimized losses, weight, volume and costs. Design and selection of material to construct a transformer core is a significant process. When designing transformers, especially power transformers, incorrect sizing of active components such as core geometry, low voltage winding and high voltage winding dimensions and tank dimensions can cause additional losses in the transformer. Determining these parameters at the design stage using optimization techniques has a very significant impact on the efficiency and cost effectiveness of the transformer. The purpose of this work is to design and optimized a practical 30/40MVA, 132/33kV, three phase power transformer using Octave and Responses Surface Methodology (RSM). From the work, it was concluded that the optimization of power transformer gives more accurate results as compared to the assume values. The percentage

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variations of core loss and copper loss in the optimized power transformer with respect to classical value were 4.35% and 13.48%, while that of efficiency was 0.14%.The percentage variations of reactance as well as the core area with classical values were 29.22% and 14.73%. Thus, for the accurate analysis of the result, it is important to optimize the power transformer.

Keywords: Transformer; Three-phase; Response Surface; MVA; kVA

INTRODUCTION

Power transformers are important elements in electrical networks because they enable the transmission and distribution of electrical energy. Even though transformers are passive devices with no rotating parts, they can be subject to malfunctioning, and if they fail, they can lead to power outages, directly impacting consumers and causing economic losses for electric companies. The electrical and magnetic performance of a transformer is determined by Maxwell's equations. It can also be explained more simply using Faraday's equation of induction and the equivalent electromagnetic circuit theory. Transformer manufacturers developed their own computer programs using simpler equations than electromagnetic theory, which were improved over the years based on many transformer manufacturing experiences. Alternatively, you can solve Maxwell's equations numerically in 2D or 3D, providing more accurate results than the manufacturer's design methods.

However, this approach has the disadvantage of increased computing time when used directly in the optimization process. Using symmetry can significantly reduce computation time. The manufacturer's design approach has the disadvantage of less accuracy, but the advantage is that its simplicity allows for faster solutions and faster designs. During the design process of a transformer, it is desirable to have the best design that can satisfy the constraints, and this can be achieved using optimization algorithms. First, a deterministic optimization algorithm was developed and used for transformer design. Over the past two decades, applying global optimization algorithms to improve power transformer design has been a topic of interest for academic and industrial researchers. Recently, global optimization algorithms that can handle multiple objectives are also used in engineering. RSM creates an approximate functional expression between the objective function and the variables. Visualize the original implicit objective function.

RSM is a mathematical and statistical optimization method that has been applied in many aspects. The literature has shown that RSM combined with genetic algorithms reduces the number of experiments and solves the fitness function selection problem. Additionally, RSM has been successfully applied to brake squeal mechanism, biochemistry, medicine, ships, mechanical design and other fields. The research presented above shows that the transformer industry can benefit from using powerful multi-objective evolutionary algorithms to design transformers that can meet complex goals and constraints. The emergence of optimization algorithms that can solve real-world optimization problems with multiple objectives can benefit electrical designers. A multi-objective problem with at least four objectives is called a many-objective problem, although some authors consider a problem with at least three objectives to be a many-objective problem. Numerical methods such as FEM have become sophisticated tools for transformer design. Additionally, multiphysics problems can be solved numerically to obtain optimal solutions to complex problems. Additionally, the role of statistics is important in process optimization using experimental design and surrogate models. Nevertheless, there are only a few publications on multi-objective optimization of power transformers, and none have applied the RSM algorithm proposed in this study.

This study presents an optimal design for determining the geometry of the core and high and low voltage windings of a power transformer. Multi target electromagnetic design minimizes copper and core losses and transformer leakage reactance to maximize both efficiency and yoke area. This problem is solved using an analytical mathematical model, Response Surface Methodology (RSM) polynomial model, and Octave. Analysis of the optimal solution and comparison before and after optimization using RSM are reported.

When designing transformers, especially power transformers, incorrect sizing of active components such as core geometry, low voltage winding and high voltage winding dimensions and tank dimensions can cause additional losses in the transformer. Determining these parameters at the design stage using optimization techniques has a very significant impact on the efficiency and cost effectiveness of the transformer. The objective of this project is to determine and compare design aspects of the active part of a power transformer before and after optimization. The proposed optimization framework could lead to a more robust solution that can be easily scaled to other quantities in the future.

METHODS

Experimental Data

After determining the experimental variables, a range of values suitable for the response surface experiment was selected, so α=2. The design and combination of the experimental sample points were carried out by the CCD method. Table 6 is the experimental data results of the sample points which were obtained by calling each other between RSM and OCTAVE.

The last five columns of Table 6 are the response of elements of the response surface methodology model. According to statistics, it only took 61.8 seconds to complete the above 46 CCD experiments. In the absence of a CCD method, 3125 RSM experiments are required. Therefore, the optimization efficiency was greatly improved by using the CCD method.

Table 1: Face centered CCD experimental design matrix and transformer responses for each run.

Run	B_m (T)	b_{cs} (mm)	b_{cp} (mm)	H_w (mm)	d_{duct} (mm)	$Core_{losses}$ (W)	Cu_{losses} (W)	X (H)	eff (%)	A_y (mm^2)
1	1.4	50	50	4	20	50056.72	858784.2	5.9542	96.6568	401247.3
2	1.7	50	50	2	20	39177.41	788592.6	5.1734	96.9429	330438.9
3	1.4	50	15	4	45	50057.3	840753.7	4.0136	96.7214	401247.3
4	1.7	15	15	4	45	39177.89	721235.6	1.8805	97.1861	330438.9
5	1.7	15	50	2	20	39177.41	737205.5	3.2442	97.1284	330438.9
6	1.7	15	15	4	20	39177.41	721235.6	1.8805	97.1861	330438.9
7	1.7	15	15	2	20	39177.41	719175	1.6076	97.1936	330438.9
8	1.4	50	15	2	20	50056.72	838693.1	3.6924	96.7288	401247.3
9	1.4	15	50	2	45	50057.3	805336.6	3.5451	96.8486	401247.3
10	1.4	50	15	2	45	50057.3	838693.1	3.6924	96.7288	401247.3
11	1.4	50	15	4	20	50056.72	840753.7	4.0136	96.7214	401247.3
12	1.7	50	15	4	20	39177.41	772622.7	3.6873	97.0004	330438.9
13	1.7	50	15	2	20	39177.41	770562	3.3915	97.0079	330438.9
14	1.7	50	50	4	45	39177.89	790653.2	0.4795	6.9355	30438.95
15	1.7	50	15	4	45	39177.89	772622.7	3.6873	97.0004	330438.9
16	1.4	15	15	2	20	50056.72	787306	1.7602	96.9134	401247.3
17	1.7	15	50	2	45	39177.89	737205.5	3.2442	97.1284	330438.9
18	1.4	15	50	2	20	50056.72	805336.6	3.5451	96.8486	401247.3
19	1.4	15	15	2	45	50057.3	787306	1.7602	96.9134	401247.3
20	1.4	15	50	4	20	50056.72	807397.2	3.8538	96.8412	401247.3
21	1.4	50	50	2	45	50057.3	856723.6	5.6226	96.6642	401247.3
22	1.4	50	50	4	45	50057.3	858784.2	5.9542	96.6568	401247.3
23	1.4	15	50	4	45	50057.3	807397.2	3.8538	96.8412	401247.3
24	1.55	32.5	32.5	3	32.5	44009.35	786504.7	3.6079	96.9353	362416.9
25	1.7	15	50	4	20	39177.41	739266.2	3.5275	97.1209	330438.9
26	1.4	15	15	4	45	50057.3	789366.7	2.0585	96.906	401247.3
27	1.4	15	15	4	20	50056.72	789366.7	2.0585	96.906	401247.3
28	1.4	50	50	2	20	50056.72	856723.6	5.6226	96.6642	401247.3
29	1.7	15	15	2	45	39177.89	719175	1.6076	97.1936	330438.9
30	1.7	15	50	4	45	39177.89	739266.2	3.5275	97.1209	330438.9
31	1.7	50	15	2	45	39177.89	770562	3.3915	97.0079	330438.9
32	1.7	50	50	4	20	39177.41	790653.2	0.4795	6.9355	30438.95
33	1.7	50	50	2	45	39177.89	788592.6	5.1734	96.9429	330438.9

Table 1 Cont.

34	1.4	32.5	32.5	3	32.5	50057.01	823045.1	3.7761	96.7849	401247.3
35	1.55	32.5	15	3	32.5	44009.35	777489.4	2.7254	96.9677	362416.9
36	1.55	32.5	32.5	3	45	44009.61	786504.7	3.6079	96.9353	362416.9
37	1.7	32.5	32.5	3	32.5	39177.65	754914.1	3.4625	97.0644	330438.9
38	1.55	32.5	32.5	3	32.5	44009.35	786504.7	3.6079	96.9353	362416.9
39	1.55	32.5	32.5	3	32.5	44009.35	786504.7	3.6079	96.9353	362416.9
40	1.55	32.5	32.5	3	32.5	44009.35	786504.7	3.6079	96.9353	362416.9
41	1.55	15	32.5	3	32.5	44009.35	760811.2	2.6667	97.0279	362416.9
42	1.55	50	32.5	3	32.5	44009.35	812198.2	4.6035	96.8428	362416.9
43	1.55	32.5	50	3	32.5	44009.35	795520	4.5086	96.9028	362416.9
44	1.55	32.5	32.5	4	32.5	44009.35	787535	3.7587	96.9316	362416.9
45	1.55	32.5	32.5	3	20	44009.08	786504.7	3.6079	96.9353	362416.9
46	1.55	32.5	32.5	2	32.5	44009.35	785474.4	3.4574	96.939	362416.9

RESULTS

D Response Surface Analysis

For a better demonstration of the influence of the interaction between two variables, the 3-D plots were adopted. If the interaction has a significant impact on the response surface, the variation of 3-D plot will be accordingly large.

Figure 3a show that when b_{cs} and b_{cp} interact, if we fix one of the variables and increase the other variable, the core and will decrease and increase, arriving at a global minimum at the centre point. For Figure 3b, as the variables are decreasing the copper loss also decreases. It can be seen from the trend of the surface graph, b_{cs} decreased faster than with b_{cp}, indicating that b_{cs} has a greater influence on the response value.

Comparing Figure 1a with Figure 1b, the response surface of Figure 1a increases with decrease in B_m, while for 1b it decreases with decrease in d_{duct}. b_{cs} has no significant effect on the core loss in both figure 1a and 1b.

As can be seen from Figure 2a, and 2b, compared with d_{duct} and B_m, increase in them cause s decrease in efficiency. The efficiency in Figure 3a and 3b has no effect on B_m but increase with decreases in b_{cs} and slightly change with H_w. d_{duct} increases with decrease in E_x for figure 4a as B_m decreases with increase in E_x.

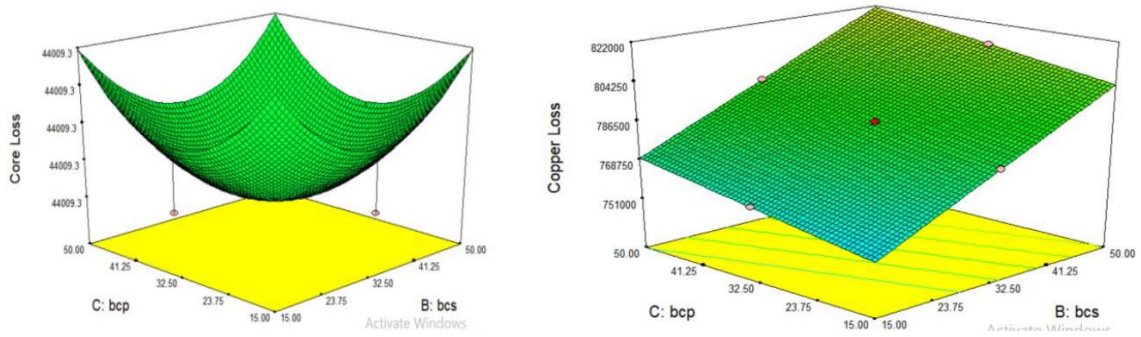


Figure 1: 3D plot of the interaction between two variables: (a) Core b_{cp} b_{cs}, (b) Copper b_{cp} b_{cs}

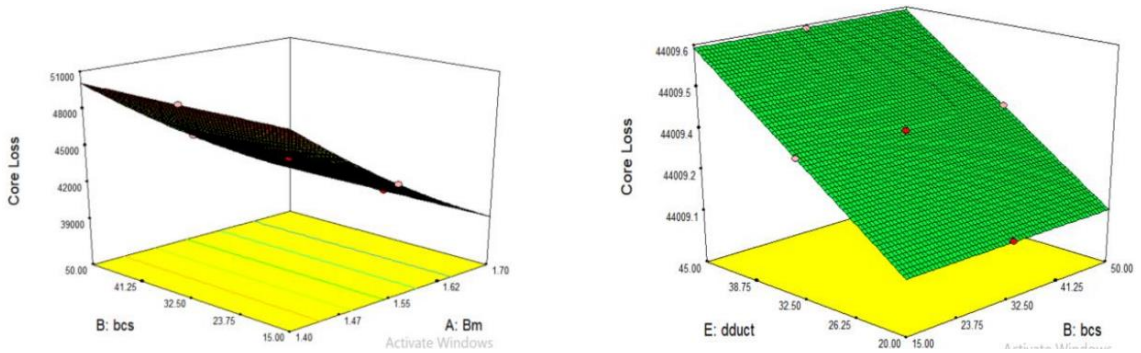


Figure 2: 3D plot of the interaction between two variables: (a) Core b_{cp} b_m, (b) Copper d_{duct} b_{cs}

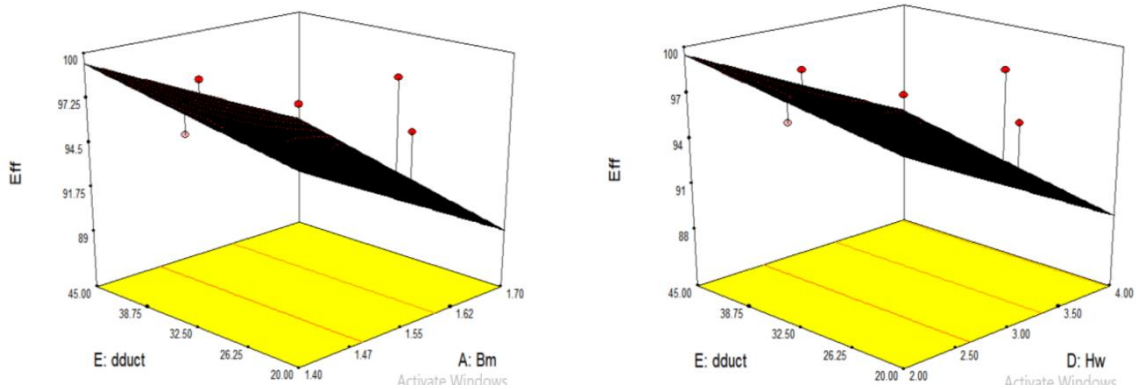


Figure 3: 3D plot of the interaction between two variables: (a) d_{duct} B_m, (b) d_{duct} H_w

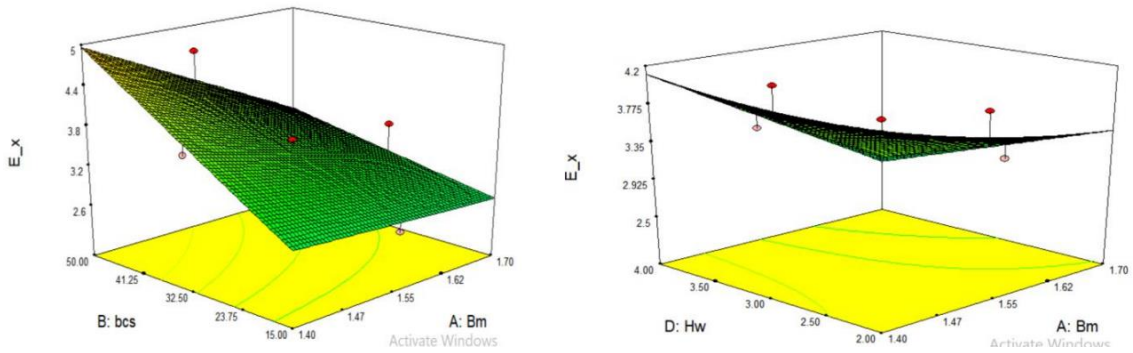


Figure 4: 3D plot of the interaction between two variables: (a) E_x: b_{cs} b_m, (b) E_x: H_w B_m

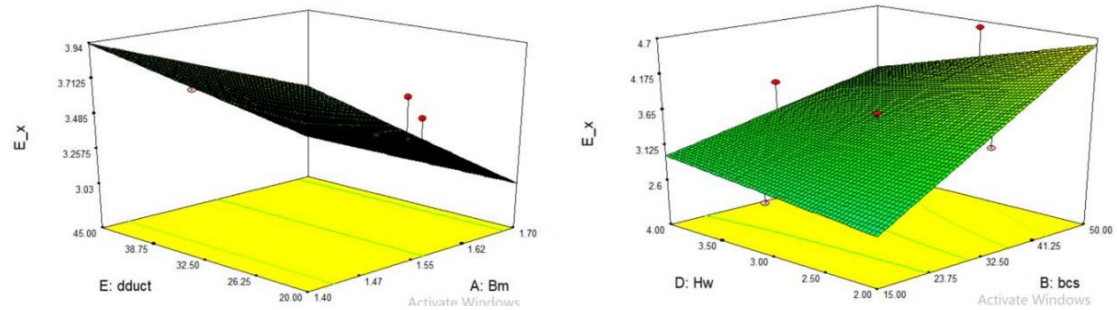


Figure 5: 3D plot of the interaction between two variables: (a) E_x: d_{duct} B_m, (b) E_x: H_w b_{cs}

The tabulated design parameter values of 3 phase power transformer are derived and calculated using appropriate formulae.

In order to verify the validity of the optimization, we compared the result of optimization before with that of optimization after. As can be seen from Table 1, the results obtained after optimization were consistent, which demonstrates the effectiveness of RSM optimization and also shows the high optimization efficiency and good prediction ability of this method.

Table 2: Input variable optimization results.

Before and after optimization	B_m T	b_{cs} mm	b_{cp} mm	H_w mm	d_{duct} mm
Before optimization	1.45	15	13.5	2.5	20
After optimization	1.7	15	50	2	20

Table 3: Responses variables optimization results.

Before and after optimization	Cu_{losses} kW	$Core_{losses}$ kW	A_y mm^2	X %	eff %
Before optimization	792.27	33.52	3.87×10^5	3.98	96.95
After optimization	757.81	29.00	3.30×10^5	5.62	97.09

A three-phase core transformer has three legs and two yokes. The core is equipped with high-voltage and low-voltage coils, and the yoke completes the feedback of the counter

current magnetic circuit. The limbs are typically stepped to approximate the cross-sectional perimeter of the limb to limit the distributed reactance to the lowest possible value.

The number of steps is determined by the power of the transformer, which is proportional to the total cross-sectional area A_{gi} of the core according to equation 25. To better understand the optimal parameterization of the core geometry, we use low- and high-voltage windings with their tank. Figure 6, 7, and 8 provides the optimal proposed diagram of the power transformer.

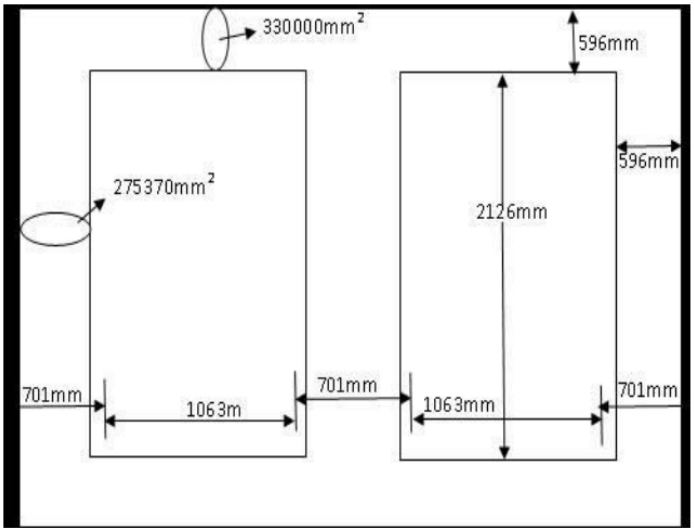


Figure 6: 2D Side view of transformer

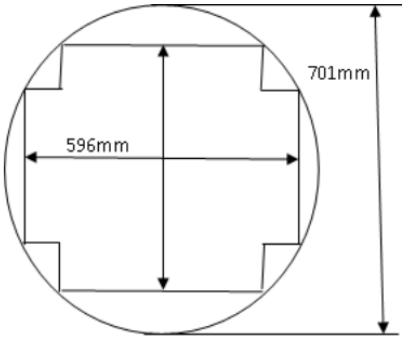
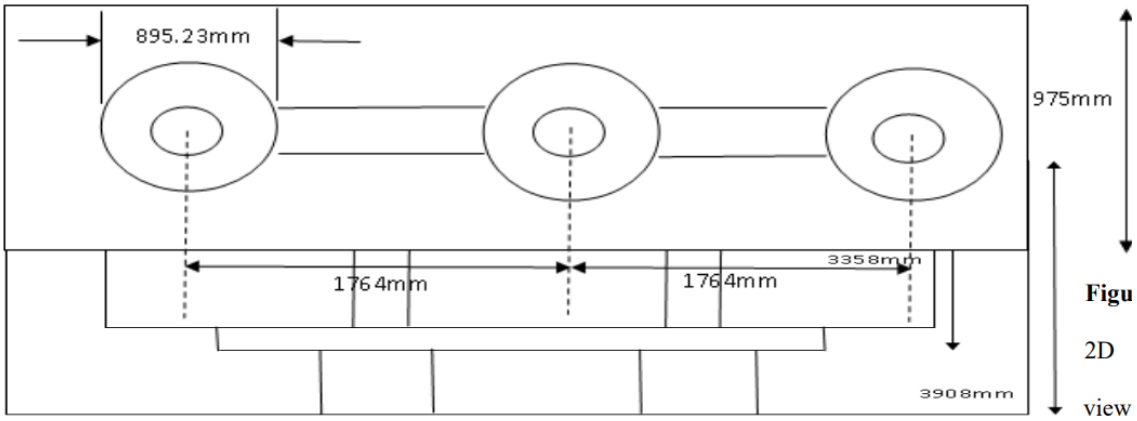


Figure 7: Cruciform Type



Figu
2D
view

Figure 8: 2D Top view of transformer

Summary

In this work, some analysis for the optimization of the core and copper losses with reactance, efficiency and core area are presented. Table 7 and 8 shows the performance of

the RSM for parameterization of the active part in the design of the three phase power transformer. Though from it, emphasis was given to the fact that optimizing the dimension gives better result compared to the classical values. The optimized active structural design prioritized the reduction in losses. As such a reduction of 4.35% and 13.48% was noted and 0.14% reduction in the efficiency when compared to the assume values. The leakage reactance reduced by 29.22%, and the core area was reduced by approximately 14.73%. The performance verified by RSMs shown to be more efficient.

CONCLUSION

In this study, response surface methodology, analytical formulation, and octave were combined to optimize a 30/40 MVA, 132/33 kV power transformer. Analysis formulas were solved automatically, and calls between Octave and RSM solved the repetitive manual coding problems of existing methods. To avoid increasing computational effort in experimental development due to the number of input elements, we used the CCD method to reduce the number of experiments and effectively simplify the optimization process.

Experimental points were constructed using the CCD experimental design method, and a response surface model was obtained. To ensure the accuracy and predictability of the model, the response surface model was analyzed through ANOVA, diagnostic analysis, and regression significance test, and the final response surface equation was determined. By comparing optimization results before and after optimization on the premise of ensuring accuracy, the efficiency is higher after optimization than before optimization.

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