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Transformer Tank Optimization using Design of Experiments

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Abstract

Background / Objective: Present study deals with the optimization of 6.6 MVA 66/11.5 KV transformer tank using Design Of Experiments (DOE) concepts such as Screening Methodology, Central Composite Design (CCD) and Response Surface Methodology (RSM). Objective is to reduce the weight of the transformer tank. **Methods / Analysis:** To achieve objective mentioned above individual wall analysis and optimization approach was used to reduce complexity and time requirement. In fact DOE simplified the number of FEA simulations. Screening Methodology is used for filter out the parameters or design variables which are not necessary for optimization. CCD technique helps to create quadratic model for response or objective variable and hence preparation of DOE matrix. Response surface was generated from the resulted DOE matrix to obtain optimum design point. **Findings:** Individual wall analysis is found time saving and verified with whole analysis. Approximately 15% reduction in weight of the wall resulted from the study. Same approach can be used for other walls of the transformer to get optimization of whole tank. Also methodology can be used to study different stiffener arrangement of the tank wall to get optimum response such as weight, stresses and deformation.

Keywords: Central Composite Design, Design of Experiments, Finite Element Analysis, Optimization, Response Surface Methodology, Tank, Transformer

1. Introduction

The transformer is one of the most expensive electrical power equipment. In operating condition, failures such as oil leakage, tank deformation and explosion due to excessive pressure generated inside the tank would cause expensive loss. Hence, its fundamental requirement of transformer or power industry is to design and manufacture a tank with structural stability and security. Simultaneously tank should require minimum material as per current trend in industry that is material and cost optimization such that SIX SIGMA will be achieved. Indirectly requirement is of high quality design, high performance and high security but with optimum material/cost.

The transformer tank has complex structure with 10-15% of the total weight of the transformer. In operating condition the transformer has to be filled with oil which exerts pressure on the tank walls. A nearly full vacuum that is (1 atm vacuum) has to be created to ensure that there is no trace of moisture. As per Central Board of Irrigation and Power (CBIP) norms the tank is designed to withstand the pressure test and vacuum test. Stress analysis of such a complex structure is difficult by classical or conventional methods. In this study *Finite Element Method* (FEM) analysis is carried out on transformer tank under full vacuum test condition. Further, concepts of Design of Experiments such as screening methodology, central composite design and response surface methodology used in present study to optimize the tank. These concepts applied on tank at different steps. The effect of variation of stiffener position along the length of tank and tank behavior will be studied. Objective of this study is to optimize 6.6 MVA 66/11.5 KV transformer tank Figure 1 with the structural safety of tank unaltered. This optimization process is complex process. Hence ANSYS 15 is used to simulate the design, analysis and optimization. Further,

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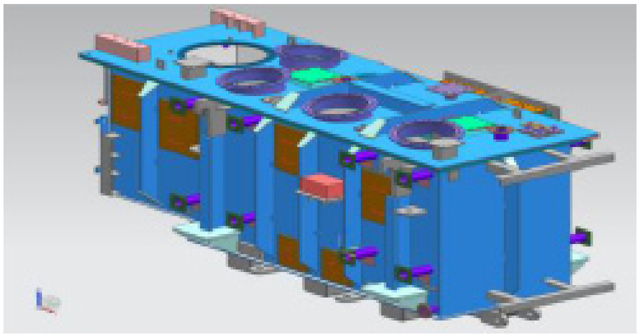

Figure 1. CAD model of Transformer Tank

ANSYS DesignXplorer® module performs optimization simulation tasks by applying Design-Of-Experiment (DOE) algorithms efficiently.

It was noted that the tank design or model under study is fabricated and passed all necessary quality tests. Hence, the vacuum test simulation results for this tank model are taken as benchmark for comparison. Following Fig shows the procedure used for analysis of transformer tank. Analysis is done in ANSYS Workbench. Material used is structural steel (Young's Modulus: 200GPa, Poisson' ratio: 0.3, Tensile Yield Strength: 250 MPa). For this study average stresses are considered since maximum stresses resulted in ANSYS are due to improper meshing at corners or complex geometry at some places.

The concept "optimization" has been used commonly and frequently in chemical industry for discovering chemical or surrounding condition so that best possible response can be obtained. In[1] used CCD, a DOE concept to find optimal conditions for factors to degrade Methyl Orange effectively by Fenton reaction. Most of the mathematical applications or system in science and engineering are complex. Further, finding factors which are significant for such complex system among all factors is very difficult task. Also how these factors affect the response is often difficult. In[2] mentioned that generally full factorial design of experiments concept was used to determine and to test combinations of all factors. The best option is full factorial design when anyone interested to study response under various operating conditions applied to all factors. Since response can be change in unforeseen ways. But the drawback of Full Factorial Design approach is that the number of requirement of experimental trials is large, because number of experimental trials increases with increase in number of factors affecting response. Hence the RSM in combination with CCD gives effective and efficient way to discover relation between significant factors and the response of system experimentally.Also[3], have taken advantage of RSM along with CCD concept to improve degradation of AR274 dye by optimization. RSM is used to optimize process variables to improve degradation of AR274 in this study. The effect of variation of these variables simultaneously on response is determined. In this study it is concluded that CCD is an effective design. Further, it provides sequential experimentation and also gives sufficient information for testing or experimental examination. Though there is no involvement of large number of design points or experimental trials. Box and Wilson were the first who published and suggested that DOE with CCD technique best suited for quadratic surface fitting which works for optimization process efficiently.In one of the literature[4]compared rotatable central design composite designs with orthogonal array that is Taguchi method. It is mentioned that rotatable CCD which is also called as classical CCD is complex and difficult to use for practical application since if number of process parameters are large in number then number of experiments to be carried out is large. But on the other side, advantageous thing regarding rotatable CCD is that there is possibility to get mathematical equation or mathematical model. This mathematical model is powerful enough to indicate change in response due to variation in input parameter in the experimental domain. It is also mentioned that the optimum design point or optimum condition will be any at any of parameters points. This facility is absent in Taguchi method hence it is a drawback of Taguchi orthogonal array method. Application under current study is transformer tank. While different approaches were used for optimization of transformer tank. One of them is Quantum behaved Particle Swarm Optimization (QPSO) algorithm. This algorithm was used[5] to address optimization problem of transformer tank design. Further, finite Element Methods also used by them for numerical simulation and analysis purpose. ANSYS software was used for this FEM. Also *International Electrotechnical Commission* (IEC) standards and industry standards were used for testing. This literature introduces new and effective method to obtain mechanical property of tank.It is known that the tank must be design for the high amount of loads which can be several tons. During its manufacturing process transformer tank has to pass through vacuum test which imposes loading on tank and cover. Attempt was made [6]to optimize the mechanical design of the tank. Reduction in weight was obtained by considering geometry of cover. Three different geometries were compared. Resulted optimum geometry has greatest stiffness and lowest weight in comparison with other two geometries. Advantage was taken of non-flatness of the cover. It has few longitudinal folds in between. This can be the way to reduce weight of the tank without disturbing structural stiffness of the tank.In the present study focus is on tank while focus of one the literatures were on the cover geometry.In commercial or industrial point of view cost optimization having highest importance as per current trend. Further, time is equally important such that complete utilization of resources can be obtained. FEA software and optimization software were used in another literature published [7]to reduce weight of the transformer tank. ANSYS were used as FEA software and OptiSlang used as optimization software. Reduced weight resulted in material cost reduction and usage software resulted in time saving. This was achieved without altering the structural stability of tank. Problem was formulated by parameterization, design variables and objective function. *ANSYS Parametric Design Language* (APDL) macros and integrated use of ANSYS and OptiSlang leaded to achieve target. Application of fractional factorial concept to determining optimum condition for leaching of high rutile having slag in sulphuric acid. In[8] Further for multi objective task. In developed a heuristic method which is a genetic algorithm for non-dominated sorting[9]. Also different applications and literatures studied including literature which deals with genetic algorithm which generates optimum assembly plan for fixture assembly[10].

2. Methodology

2.2 Simplification for Optimization Study

It can be observed that the optimization study for the whole tank is difficult due to different arrangement or structure of walls, since parameters increases with different arrangements on different walls. Hence it is feasible to optimize individual wall separately. Further, verification is required between stresses and deformation on wall when whole tank is analyzed and when individual wall (separated) is analyzed. Following procedure is followed for the verification mentioned Figure 2. Each tank wall is modeled separately in CAD software tool with the exact dimensions as of original tank model. Both tank model and wall model are exported in parasolid format from CAD software tool. Further parasolid model of tank is imported in Static Structural module of ANSYS Workbench. Meshing is done to convert geometric model into finite element model for further analysis. Vacuum load of 1 atmosphere is applied on all inner surfaces of the tank.

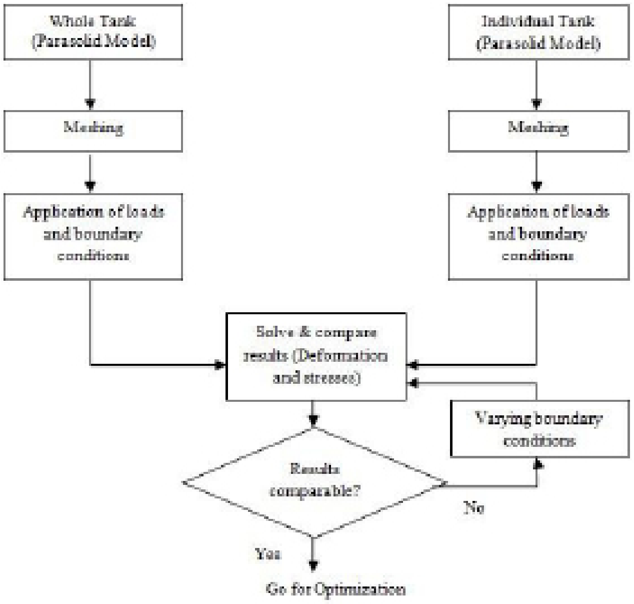

Figure 2. Work Flow-Initial Analysis

Fixed support is given to bottom most surface of the model. Since transformer is a static device resting on the foundation built on the ground surface. Then it is solved to get results such as equivalent stresses and deformations. Exact procedure is used to analyze individual wall model. Vacuum load and element size will be same while analyzing tank model. Here boundary conditions are different from tank analysis, as individual wall is to be analyzed fixed support is applied on all the edges of the tank. This can be compared with the same wall while analyzing whole tank. Further, this is verified by the results. It is observed that maximum stresses and maximum deformation values are approximately equal or with acceptable difference. It can also be observed from Figure 3 and 4 that pattern of equivalent stresses and deformation.

From the above analysis procedure and results it can be conclude that individual wall can be consider of optimization study instead of whole tank. It is advantageous that number of parameters will be reduced, further reduction in complexity of the problem.

2.3 Optimizations Methodology

Design of experiments is well known technique in various industrial field such as chemical, textile, and

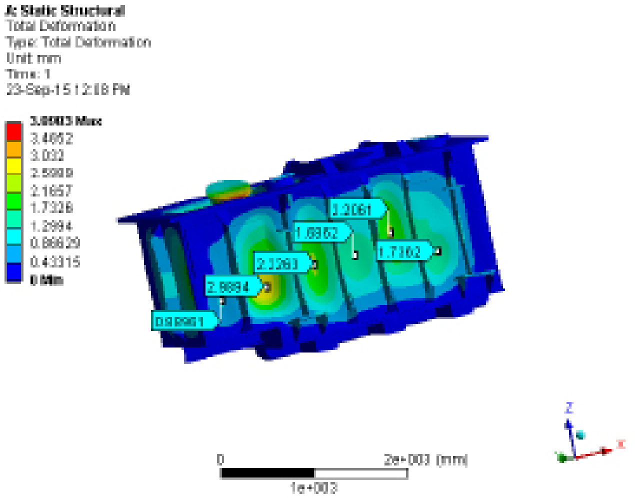

Figure 3. Result Plot (Tank)

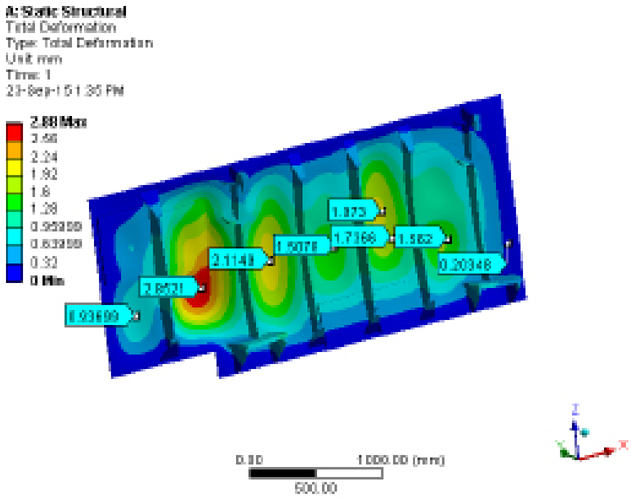

Figure 4. Result Plot (Individual wall)

aerospace[11,12]. Design of experiments can be used when more than one parameters or there combinations affecting objective parameter or response parameter. Here in this case objective parameter is weight or mass of the tank. Design exploration module is used for optimization study. Further, design exploration module applies Design of Experiments algorithms to optimize and factor the design efficiently. Following steps followed to optimization of tank wall using Design of Experiments technique.

Step 1: Screening Methodology is used for filter out the parameters or design variables which are not necessary for optimization. It allows generation of sample set of parameters and sorts it based on objective and constraints. In other words parameters which are affecting object or response parameter considerably are to be considered for further optimization study. Also variation in parameters or design variable which leads to infeasible design or errors in geometric modeling can be filtered out in this step.

Step 2: DOE is applied on the parameter design variable set resulted from step 1. DOE matrix generated containing design variables, objective and constraints. While making DOE matrix, CCD technique is used. CCD technique helps to create quadratic model for response or objective variable.

Step 3: Response surface is obtained from the DOE matrix resulted from step 2. Further, optimized design or parameter values are obtained from the Response Surface.

To apply steps mentioned above it is required to model a parametric model of tank wall in design modeler of ANSYS Workbench. Further it is meshed with element size equal to the element size used in previous analysis. Further, model solved for same vacuum load and boundary condition as before. Table 1 shows parameters or design variables, objective and constraints of the current study on tank wall before screening step.

Screening of the parameters is done for studying effect of parameters on response that is on objective and

Table 1. Parameters before screening

	Sr.	Parameter Name
Design Parameters	P1	Stiff_thickness
	P2	distance_1
	P3	Stiff_hight
	P4	b_stiff_thickness
	P5	distance_1b
	P6	distance_2
	P7	distance_4
	P8	distance_2b
	P9	distance_3
	P10	Wall_thickness
Objective & constraints	P11	Geometry Mass
	P13	Equivalent Stress Maximum
	P12	Total Deformation Maximum

constraints parameters. After screening, parameter P2 – distance_1 is eliminated from the study. Since P2 is not affecting response considerably. Table 2 shows sample DOE matrix obtained by using central composite design technique. Further, response surface obtained from the data obtained from DOE matrix and optimum candidate point is obtained. This is obtained from the response surface optimization module of Design Exploration of ANSYS 15. Further, response surfaces obtained for all parameters against objective and constraints. For generating response surface ANSYS uses data from DOE matrix shown in Table 2. Some of the response surfaces are shown in Figure 5.

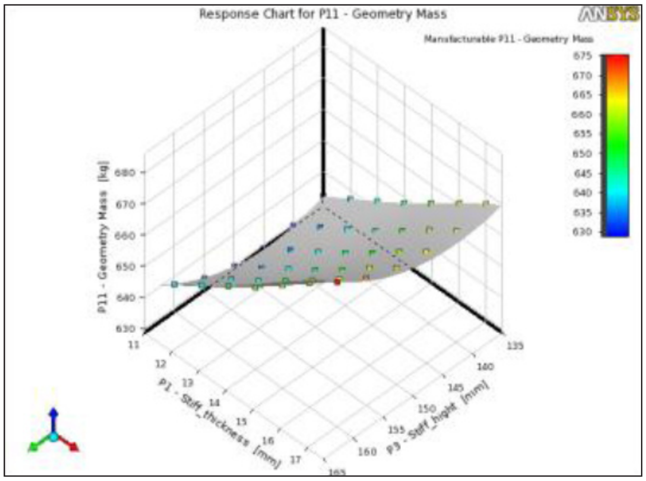

Figure 5. Response surfaces for various parameters

3. Results and Discussion

After generating response surfaces it becomes easy to find optimum point on the response surface. This point shows the parameter value at which response is optimum. In this case, optimum point represents lowest geometric mass on one axis. While, on other two axes either constraint parameter or any of the design parameter can be represented. After analyzing various response surfaces, optimization sub-module suggests three candidate design points out of which one can be the possible optimum design point which can be selected manually. Number of candidate design points can be selected manually as per study requirements. Table 3 shows, candidate design points suggested by optimization sub-module of response surface optimization module.

After comparing all three candidate design points, candidate design point 3 was selected as it gives low geometric mass with comparatively low stress and deformation. Further, selected candidate design point compared with current design parameters, objective and constraints as shown in Table 4.

It can be observed that deformation and stresses increase as compared with current values. But the deformation is under limit that is well below 10 mm (as per CBIP norms)[13]. Regarding stresses, for verification of obtained results design was remodeled as per design parameter after optimization. It was observed that Equivalent Stress

Table 2. Sample DOE matrix

Design Point	P1	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
1	14.3	150	19	695	498	451	497	451	9.5	715.1	3.35	299
2	14.3	150	19	695	448.2	451	497	451	9.5	715.1	3.383	307.1
3	12.77	143	17.6	662.7	521.2	430	520.1	430	10.2	731.1	2.654	254.3
4	15.83	143	17.6	662.7	521.2	430	520.1	472	10.2	749.7	2.559	258.1
5	12.77	157	17.6	662.7	521.2	430	520.1	472	10.2	737.3	2.543	263.7
6	15.83	157	17.6	662.7	521.2	430	520.1	430	10.2	756.7	2.446	253.1
7	12.77	143	20.4	662.7	521.2	430	520.1	472	10.2	737.3	2.585	255.4
8	15.83	143	20.4	662.7	521.2	430	520.1	430	10.2	755.9	2.485	255.2
9	12.77	157	20.4	662.7	521.2	430	520.1	430	10.2	743.8	2.448	244.7
10	15.83	157	20.4	662.7	521.2	430	520.1	472	10.2	763.2	2.408	249.4
11	12.77	143	17.6	727.3	521.2	430	520.1	472	8.802	674.2	4.535	349.5
12	15.83	143	17.6	727.3	521.2	430	520.1	430	8.802	692.8	4.465	347.7
13	14.3	150	19	695	547.8	451	497	451	9.5	715.1	3.311	305.1
14	12.77	157	17.6	727.3	521.2	430	520.1	430	8.802	680.4	4.42	346.1
15	15.83	157	17.6	727.3	521.2	430	520.1	472	8.802	699.9	4.367	341.9

Maximum was equal to value obtained by optimization as obvious. Average stress values were considered, 150-180 MPa which are well below the limit. Maximum stress values may result due to improper meshing at corners or edges. Since equivalent stress maximum values observed at edges or corners or at complex geometry.

Table 3. Candidate design points

	Sr. No.	Parameter Name	Candidate Points suggested		
			Candidate 1	Candidate 2	Candidate 3
Design Parameters	P1	Stiff_thickness	11	11	11
	P3	Stiff_hight	135	160	150
	P4	b_stiff_ thickness	16	16	18
	P5	distance_1b	626.2	625.5	654
	P6	distance_2	448.6	448.2	463
	P7	distance_4	406.3	496.1	414.5
	P8	distance_2b	447.8	447.3	455.4
	P9	distance_3	406.3	405.9	411.7
	P10	Wall_ thickness	8	10	8
Objective and constraints	P11	Geometry Mass	627.3	723.4	631.7
	P13	Equivalent Stress Maximum	386.3	69.2	359.6
	P12	Total Deformation Maximum	5.2	2.2	4

Table 4. Comparison between values before and after optimization

	Sr. No.	Parameter Name	Units	Current Value	Values after optimization
Design Parameters	P1	Stiff_thickness	mm	16	11
	P3	Stiff_hight	mm	150	150
	P4	b_stiff_ thickness	mm	20	18
	P5	distance_1b	mm	695	654
	P6	distance_2	mm	498	463
	P7	distance_4	mm	451	414.5
	P8	distance_2b	mm	497	455.4
	P9	distance_3	mm	451	411.7
	P10	Wall_thickness	mm	10	8
Objective and Constraints	P11	Geometry Mass	Kg	747.98	631.7
	P13	Equivalent Stress Maximum	MPa	282.67	359.6
	P12	Total Deformation Maximum	mm	2.99	4

4. Conclusion

It can be concluded from results shown in Table 4 that approximately 15% of the weight reduced by keeping deformation and stresses under limit. Hence structural stability was unaltered. Same procedure can be used for remaining walls of the tank and hence whole tank can be optimized. Also the effect of variation in the distance between two stiffeners can be studied such that optimum results can be obtained.

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