Latest Transformer Technologies

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Abstract

For transformer designs, we are working on a new program by extensively using the latest 3D analysis and coupled analysis. For magnetic field analysis, we conduct precise analysis by using 3D analysis approach and it is utilized for loss reduction. Coupled analysis is carried out through the processes from magnetic field analysis, vibration analysis, and acoustic analysis for the reduction of audible sound levels. For product development, we are working on a light-weight and compact design of 20MVA distribution transformers. When these capacity distribution transformers are shipped from the factory, they are usually disassembled due to restrictions on trailer loading mass as well as the overall dimensional limitations for transport, according to laws and regulations in Japan. As a result, we can currently ship distribution transformers fully assembled without the need of removing the insulation oil. In order to clear product mass limitation for transport, it is necessary to reduce the total mass by approximately 10%. For this purpose, we worked on the rational design on insulation and cooling systems and worked on the compact tank design or adoption of thinner metal sheet for tank. In doing so, we reduced the total mass to the minimal possible level.

1 Preface

Power transformers for power transmission have a long history. Although the basic principle is unchanged, the applied technologies are always updating and progressing. By making full use of computer-based rapidly advancing analyzing technologies, we worked on better product characteristics and economics. In doing so, we contribute in building stable social power infrastructures.

For power transformers, the market recently calls for the reduction of initial investment costs, better economics considering the Life Cycle Cost (LCC), and better environmental performance by lower power losses and lower audible sound levels. In order to meet such current requirements, we conducted precise 3D magnetic field analysis and computation for loss reduction and mechanical forces in windings. Such forces are potential causes of operational noise. By conducting coupled analysis for the reduction of audible sound levels, we evaluated the noise released from the tank by mechanical vibration. We utilize the coupled analysis for the noise reduction for this.

Meanwhile, large numbers of distribution transformers are installed in order to build wide-area power network systems. The market demands a cost reduction of the main body, simpler on-site erection work, and a shorter installation work period.

This paper introduces our use of recent analysis technologies. We also introduce our newly developed and commercialized 20MVA distribution transformer which meets relevant transportation restrictions in Japan which allows for fully assembled transporting mode without disassembling after completion of shop testing.

2 Latest Analysis Technologies

Transformers are needed to satisfy required characteristics such as insulation, cooling, and mechanical strength. The market also calls for the reduction of its losses and lowering of audible sound levels in consideration of the ambient environment. In order to cope with the increasing competition in the global market, we need to reduce the development period more than ever before. To meet these requirements, it became very effective measures to grasp the physical phenomena of the product through analysis, predict performance results, and promote optimization of design. As a result, analysis technologies became indispensable for power transformer development and design.

Recently, analysis software became commercially and widely available and its usability was greatly improved. Application of such technologies to transformer design is in progress. In this paper, two cases of 3D analysis application are introduced below.

(1) Transformer stray loss

For large-sized structure steel material like a large transformer tank, it is necessary to make element decomposition perpendicular to the plate thickness as finely as possible so that the skin effect can be precisely calculated. Accordingly, the analysis model tends to become large-scale.

(2) Transformer vibration and operating noise caused by load currents

It is difficult to attain final acoustic analysis unless all factors like magnetic flux density generated by load currents, Lorentz force, winding vibration, oil-filled tank vibration, and acoustic radiation are considered in tandem. The coupled analysis of multiple phenomena is the feature of this analysis.

The degree of difficulty is naturally high for these analyses, and the analytical results must coincide with measured results from a variety of transformers under varying conditions. Based on this, we accumulated various analytical expertise through the reviews of our products. We are very close to a practical level.

2.1 Implementation of Stray Loss Analysis for Power Transformers

For the purpose of transformer stray loss reduction, there is a common approach in which a magnetic shield is installed inside the tank wall to prevent the intrusion of leakage flux into the tank. In the conventional method, there are several drawbacks. To determine magnetic shield size and arrangement, 2D loss analysis was carried out. In such 2D analysis, however, it is impossible to take 3D flux distribution into account. Further, it is impossible to accurately cope with a great change in structure and an adequate magnetic shield arrangement cannot be determined. As such, 3D loss analysis is indispensable for the effective reduction of stray loss with the limited quantity of magnetic shield.

Against, we conducted loss analysis on a prototype by the 3D finite element method. Fig. 1 shows a 3D model (conventional structure design). In order to study the effective design policy by grasping the source of loss generation, we made smart visualization on magnetic flux and loss distribution to articulate the measures. For each measure-taking point, we made various adjustments for magnetic shield size, quantity, and layout in order to find out a new structure. Fig. 2 shows the loss analysis result and actual measurement result of the conventional and new structures. The analysis results show values close to those from actual measurements for both conventional and new structures. This analysis method is deemed to be at the practical application

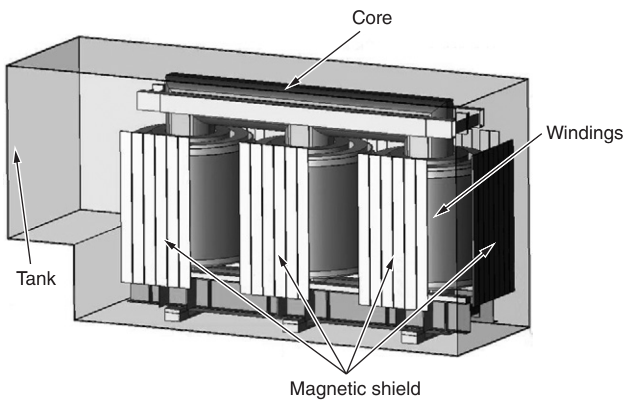


Fig. 1 3D Model (Conventional Structure Design)

A 3D model shows a product composed of the core, windings, tank, magnetic shields, and other components.

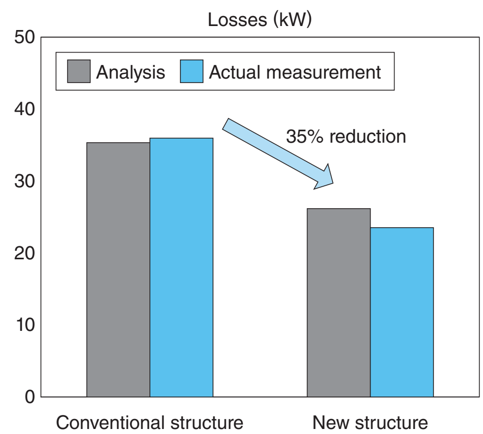
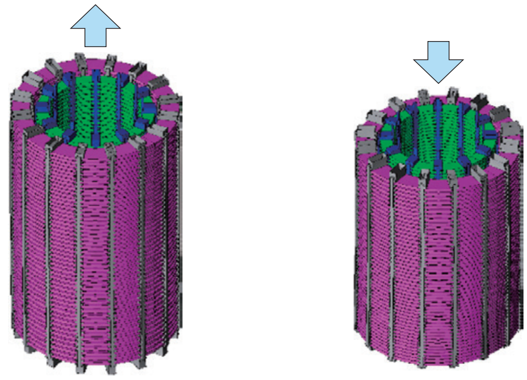


Fig. 2 Loss Analysis Result and Actual Measurement Result

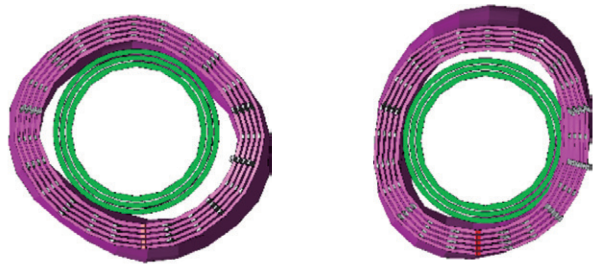
This shows the result of loss analysis and actual measurement result on the conventional structure and new structure design. The result of analysis is found to be close to that of the actual measurement result. In this example, the reduction level is about 35% according to the actual measurement.

level, even in terms of accuracy. In this example, values from actual measurements suggest that stray loss can be reduced by approximately 35%. We verified its effectiveness.

In the case of the application of 3D loss analysis to large-capacity transformer design, the analytical model becomes a large scale and the time for analysis is increased with a rise in the number of elements. Accordingly, in practical application, it became critical to shorten the time required for such analysis time. Prior to starting a large-scale analysis, we were able to shorten the analysis time to a practical analysis time by simplifying element shapes and by adopting parallel computation. Further, heavy currents tend to be carried on the low-voltage side, particularly in the case of a large-capacity transformer. We are working on improving the analytical accuracy by factoring losses generated around heavy-current lead wires in bushing pockets.



(a) Axial expansion/contraction mode for disc windings



(b) Slantwise oval mode in radial direction for layer windings

Fig. 3 Result of Frequency Response Analysis on Windings

For two types (disc and layer) of windings, vibration caused by the Lorentz force was analyzed. As a result, the axial expansion/contraction mode (for disc windings) and the slantwise oval mode in radial direction (for layer windings), that observed by actual measurement were respectively reproduced by response analysis.

2.2 Analysis of Transformer Vibration and Operating Noise Caused by Load Currents

2.2.1 Evaluation of Winding Vibration through Coupled Analysis of Magnetic Field and Structure

Fig. 3 shows a result of frequency response analysis on windings. For two types of windings (disc and layer), winding vibration were analyzed. The vibration is caused by the Lorentz force of currents carried in air. By this analysis, we reproduced the result of the model experiment. The object of analysis is the transformer's core-and-coil assembly except for a tank. An analysis method to determine the electromagnetic force in windings is applied not only to short-circuit currents but also to the load currents. We utilize this method to examine the transformer noise generated while currents are carried. For winding vibration analysis in normal operation, inherent vibration characteristics of windings and the distribution of Lorentz force as an acceleration force are important factors. We conducted 3D modal analysis and frequency response analysis. Compared with short-circuit events, the generated force is minor, as is also the resultant structural deformation. Accordingly, we modeled oil-immersed pressboards as a linear material (the elasticity was kept constant).

Depending on winding design, the predominant mode falls into 100Hz (twice the source frequency of 50Hz as shown in Fig. 3). This is based on the result of this analysis in this example. For disc windings, expansion and contraction in axial direction are important while the slantwise oval mode in radial direction shows expansion and contraction for layer windings. In this case, the result of experiments under the same conditions is shown. We recognized that the result of acceleration for response analysis is close to that of the experiments when a proper damping coefficient is set up at the time of vibration analysis.

As described above, it is possible to control winding vibration if vibration analysis is carried out in consideration of electromagnetic phenomena caused in windings. By reducing winding vibration, reduction of transformer noise can be expected.

2.2.2 Evaluation of Transformer Noise on Prototypes through Coupled Analysis of Structural and Acoustic Facts

When load current noise of a transformer is evaluated by an analysis method, it is necessary to take several physical phenomena into consideration and more advanced techniques are required. In particular, the analysis of noise generated in oil-immersed transformers is subject to a problem of vibration analysis in consideration of the effect of insulation oil in the transformer tank. In such a case, we find a solution by utilizing an element where oil viscosity can be neglected, and mass and wave propagation is considered. In this manner, computation coherency and calculation cost can be improved more effectively than ordinary handling of fluid elements. Even at the time of fundamental experiments, vibration characteristics show a satisfactory coincidence between analysis and actual measurements.

An example of acoustic evaluation on an actual model is introduced below. Prior to frequency response analysis with an actual model, modeling is carried out with a shell element for the tank and an element for the insulation oil. The tank interior is omitted. Heavy articles (radiators, bushings, conservator, etc.) are installed outside the tank. These articles are modeled into a concentrated mass and beams so that the analytical model cannot become too large. For the vibration source, a domain is established where the winding portion (for three phases) in cylindrical shape is removed from the fluid portion inside the tank. Forced vibration is then applied to the resultant boundary surface in conformity to the vibration mode of windings (ref. aforementioned winding vibration analysis) by shifting the phase by 120° in consideration of 3-phse alternative current. **Fig. 4** shows the result of frequency response analysis on actual model.

In the case of acoustic analysis, part of components (radiators, bushings, conservator, etc.) and internal fluid element are removed from the model used for vibration analysis. An acoustic evaluation flatplate is newly created in the position that is stipulated by JEC-2200-2014. The ground surface is assumed to be a total reflection. Since the boundary element method is used for an analytical approach, it is unnecessary to distribute the elements throughout the space. This is effective in reducing the computation cost.

Fig. 5 shows the result of acoustic analysis. Based on the analytical result, sound pressure distribution on the acoustic evaluation plane can be outputted. There is a favorable coincidence with actual measurements when a mean power value of the result of sound pressure analysis is determined in the same position of the actual measurement. We confirmed that the difference between high and low sound levels can be reproduced when the result of acoustic analysis is compared with that of the actual measurements for the transformers that have the same capacity but different tank structures.

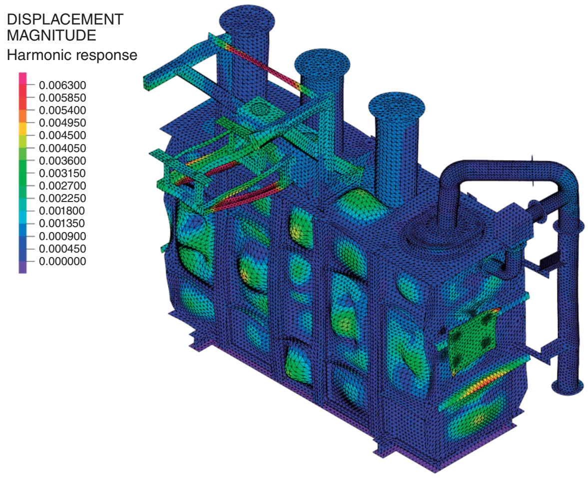


Fig. 4 Result of Frequency Response Analysis on Actual Model

It shows the vibration analysis result on the tank on which forced winding vibration was applied. This result reflects the due consideration of inner insulation oil.

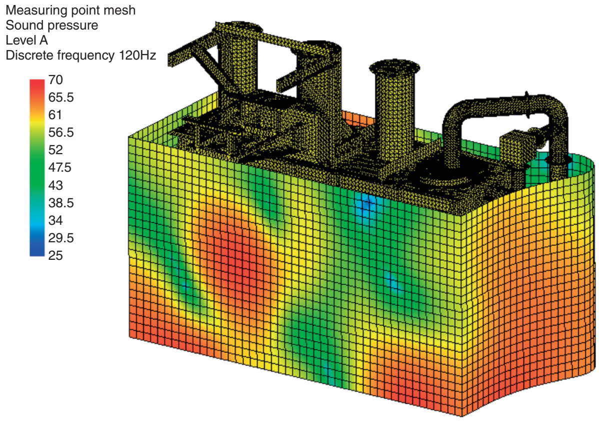
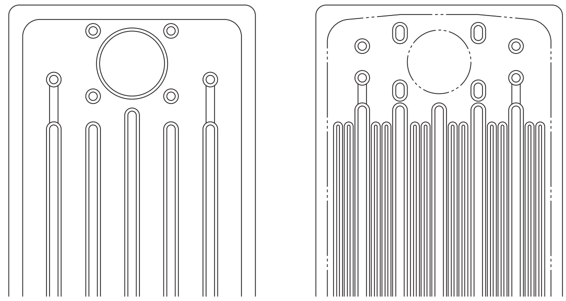


Fig. 5 Result of Acoustic Analysis

This shows the result of acoustic analysis. This was performed in accordance with the JEC Standard for noise level evaluation. This result shows the mean power level from the results of sound pressure analysis indicates the same values of the actual measurements. The measuring points of actual measurement and the precondition points for computation for acoustic analysis are same points.

3 Development of New Radiators

For transformer cooling, panel type radiators are generally arranged around the tank to increase the heat dissipation area because only the tank surface area only is insufficient to secure ample heat



(a) Conventional SRSF type (b) New HRSF type

Fig. 6 Comparison of Panel Shapes

A shape difference between conventional panel and a new one is shown. In order to increase the heat dissipation area and mechanical strength, the new radiator has a design addition: more bent sections and welded parts.

dissipation area to cover heat losses generated. Temperature rise in insulation oil is suppressed by virtue of enough capable heat dissipation. Our overseas Meiden Group firm, Meiden Metal Engineering Sdn. Bhd.in Malaysia, manufactures and sells the panel type radiators in two types: narrow-panel SRSF type and broad-panel RSD type.

With our recent renovation of our press forming facilities, we newly developed the HRSF type. This is a successor model of the SRSF type. Fig. 6 shows a comparison of the panel shapes. We will work on the increase of heat dissipation area and the reduction of insulation oil volume as the development concept for the HRSF type. We will also work on the reduction of radiator panel thickness. In doing so, it will help in realizing a light-weight and compact size transformer.

For the development of the HRSF type, press forming analysis was carried out by using the finite element method (elastic-plastic). We worked on maximizing the heat dissipation area and minimizing insulation oil quantity under the restrictions of press forming workability and breaking limits. Fig. 7 shows result of radiator panel analysis. Likewise, for the purpose of maximization of fracture strength, the upper and lower header structures and spot-welding intervals were examined. In order to maintain compatibility with the SRSF type, the HRSF type was designed to have the same panel width, mounting pipe diameter, and panel pitch so that it can be used for existing power transformers. The features of the newly developed HRSF type are as follows:

(1) Increase in heat dissipation area
(2) Reduction of insulation oil quantity
(3) Realization of a light-weight design

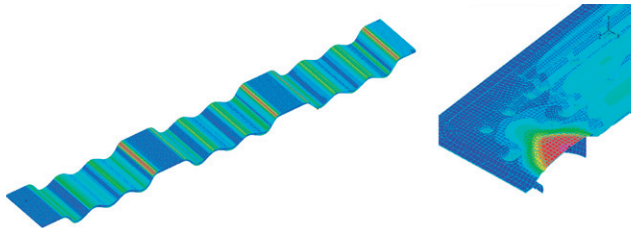


Fig. 7 Result of Radiator Panel Analysis

This is a result of analysis and shows a distribution of strain. Analysis was made to avoid generation of cracks when the panel is folded.

Table 1 Verification Result of Newly Developed Radiators

This shows the verification test results on the radiator prototype. The heat decapitation area is increased and oil quantity and mass are decreased. The test result indicates that there is no compromise in strength and temperature characteristics.

Verification items	Measured value	Verification method
Heat dissipation area※1	+6%	Confirmed by heat run
Quantity of oil※1	−30%	Mass measurement
Steel mass※1	−6%	Mass measurement
Fatigue test	Cleared	Pressure test: 22,000 times
Destruction test	0.7MPa or above	Destruction test

Note: ※1. Comparison with conventional SRSF type

(4) Reinforcement of structural strength (shape and welding)
(5) Securing the compatibility with the former model

A verification test was carried out by a prototype model and the test result is as shown in Table 1. We verified that the heat dissipation area increased, and both the oil quantity and mass of steel materials were reduced, while the fracture strength was found to be higher than that of the conventional products. The test result was very positive. We will apply this design concept into our various products.

4 Realizing Fully Assembled Transportation of Power Distribution Transformers

4.1 Development Concept

In Japan, the capacities of distribution transformers used in power network systems generally range from 10MVA to 30MVA. In terms of the power demand, the most manufactured transformers are those rated at 20MVA. When transporting a 20MVA transformer, it is generally disassembled into several portions and the internal insulation oil is drained out due to transporting restrictions of mass and size stipulated by the related transportation laws and regulations in Japan. In this case, reassembly on the project site is needed and the tank must be refilled with insulation oil again. Such on-site work can greatly affect the on-site construction schedule. If this transformer can be transported without disassembly like a small-capacity model, it will benefit both the transformer supplier and the end-user. For this reason, we embarked on the development of most popular capacity size 20MVA transformer that can be transported already fully assembled. According to the current industry definition of “fully assembled” transportation in Japan, it may include transportation with the insulation oil drained out. Yet, our target was to realize the fully assembled transformer that can be transported already filled with insulation oil. In this case, we could omit the in-house disassembly work and also avoid partial shipments to the site and on-site re-assembly work. As a result, we could expect the reduction of delivery schedule and on-site installation work schedule. Further, in the event of equipment failure due to a natural disaster, an exchange the defective unit for a new fully assembled unit transported there can contribute to the earlier restoration of power.

Recently, there has been a trend that trailers that are lighter in mass and have a heavier loading mass. We have been working on exploring the possibility of fully assembled transportation without using a special type of lighter trailer. In such a case, we had to achieve a 10% reduction of mass from our conventional design model. We were working on a light-weight and compact design transformer; a challenge to achieve this 10% reduction. For a light-weight design, we first reviewed the panel design for radiators. We studied the effective design on insulation distance and cooling systems to realize the compact design of inner assembly. We tried to thin the sheet panel of the tank and narrow the tank design. In doing so, we realized the design targets.

Considering the requirement to get transportation permits, the development goal was set for 35 tons or lower for the mass and W3000 × H3620 × L6000mm (floor surface) or less in size. This considers the need for passing through a narrow road in a residential area.

4.2 Mass Reduction for Inner Assembly

To realize the compact design and mass reduction of the inner assembly of transformer, we worked on accuracy improvement of an insulation examination method and on a temperature evaluation method. We realized the targets by studying the effective design on insulation and cooling systems. For insulation analysis, we use our internally developed software which offers a relatively high accuracy level. The software, however, partially needs some correction and as such, we made the design with some margin. For the improvement of accuracy, we reviewed the program and improved the smart visualization function by showing contour diagrams in addition to the conventional indication of the equipotential line. As a result of improvement on the insulation review method, we studied the reduction of insulation distance in the sections with the design margin in the conventional structure design. In doing so, we realized a maximum of about 15% reduction in insulation distance.

In the design review of products, on top of the review of insulation matters, thermal evaluation is also an essential factor. There is a mutually exclusive relationship between cooling and insulation. When an insulation distance is shortened in the winding, this action will affect the flow of cooling medium like insulation oil. It is, therefore, necessary to make an effective design on the insulation and cooling. This requires highly accurate temperature evaluation technologies that can factor various conditions. In this case, it must perform overall analysis on the transformer. Even with current technology of the highly advanced computers, it is impossible to conduct temperature analysis on an overall transformer, due to its very complicated structures.

For the purpose of overall transformer evaluation, we established a new method to realize precise computation of an overall thermal evaluation. In this method, we utilized some parts of individual analysis results and we actively used the 1D (1 Dimension) analysis. The new method shows very similar values between measured ones and analysis values. We verified there is sufficient accuracy. We will explain this point later.

It is now possible to make accurate thermal evaluation for various equipment under different conditions. Thanks to this method, we could make a highly precise thermal evaluation even in case of dealing with various equipment or under different conditions. Through the advances of these technologies, we improved the accuracy level and performed the thermal evaluation review more easily.

As a result, a 4% mass reduction for the inner assembly of transformer was realized.

4.3 Mass Reduction for Transformer Tank Structures

For the mass reduction of the transformer tank structure, we targeted the transformer insulation oil and tank occupying a large part of total transformer mass. For a conventional 20MVA distribution transformer, insulation oil takes about 25% of total mass and steel products takes about 15%. Reduction of target item mass is greatly effective for transformer total mass reduction. For this reason, we reviewed the tank structure design. We worked on the insulation oil quantity reduction by reducing the internal volume of transformer tank. We also worked on mass reduction by making the tank with a thin steel sheet.

For the reduction of inner volume of transformer tank, we changed the tank design into a semi-oval body. It fits the compact inner assembly of the new model. As a result, the oil quantity was reduced. In addition, the tank body was narrowed while securing sufficient insulation distance and the required entry space for the inner assembly unit. In addition to the adoption of a new type radiators introduced in Section **3**, the total volume of insulation oil was reduced about 16%.

4.4 Mass Reduction for Transformer Tank by Using Thin Metal Sheet

The use of a thin metal sheet for the transformer tank is very effective for mass reduction. At the same time, however, it may affect the tank's structural robustness and may cause more noise generation. As such, we carefully thought about such a design. The strength of the tank can be computed by using theoretical calculation formula if the tank's shape is not complicated. As for the transformer tank described in this paper, however, it has complex structures – a narrowed tank body and an oval structure adoption which calls for more precise computation.

As a result, we utilized the tank strength verification method by using the CAE system. **Fig. 8** shows the result of vacuum durability analysis. We conducted the design review on the number of reinforcement steel members used and arrangement of pitches. We designed to reinforce the stress level to clear the allowable levels. We realized the oil volume reduction of about 19%.

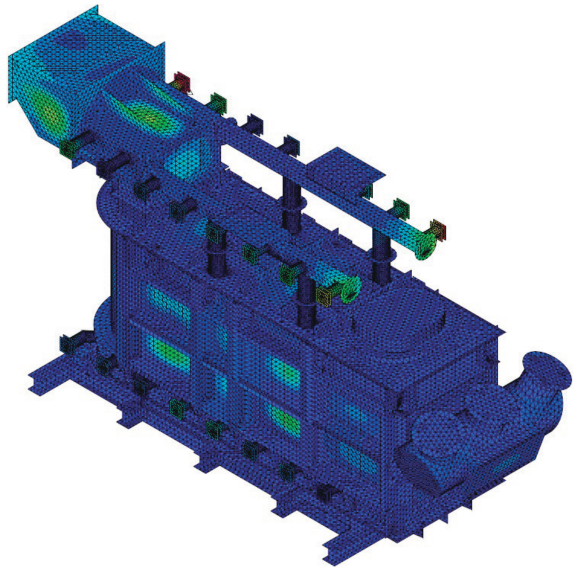


Fig. 8 **Result of Vacuum Durability Analysis**

A distribution of stress is shown. At the time of design review of reinforced structures, we conducted a strength analysis.

Table 2 **Results of Prototype Verification**

The verification items for the prototype and the result of verification are shown. The result was satisfactory for all verification items.

Items	Result of verification	Result of verification for test items	
Insulation	○	Examination	Computation accuracy improved, insulation distance reduced (15% Max.)
		Verification	Insulation test cleared
Temperature	○	Examination	Accuracy improved by total system analysis by using ID analysis
		Verification	Oil temperature error within 1K for actual measurement values
Noise	○	Examination	Sheet metal thickness reduction by 30~50% compared with conventional design system; examination of low-noise structure
		Verification	Noise level being almost the same compared with conventional design values
Other characteristics	○		

4.5 Verification and Commercialization

We reviewed the design to realize the compact and light-weight design of the transformer. We completed design work which exceeded the original target values and we made a prototype model. **Table 2** shows the results of the prototype verification. The results of verification test were positive and had a high prospect of commercialization of this product. We later commercialized it and recently supplied a fully assembled 20MVA distribution transformers to the site of a power utility company in Japan.

5 Postscript

This paper introduced our recent transformer technologies. We showed some cases of design review to reduce transformer losses and noise by using 3D analysis, our development of new radiators, and our program to realize the fully assembled transportation of our 20MVA distribution transformer without the need of removing the insulation oil.

Analysis technologies are constantly advancing and they have become necessary elements in our development and design work of transformers. Even in the processes of product design, we are actively using 3D analysis, coupled analysis, and are working on new programs. For magnetic field analysis, we conduct a precise 3D analysis and use it for the reduction of stray loss of structure materials. We conduct a design review to realize a low-noise transformer reduction. For this purpose, we conduct coupled analysis through magnetic field analysis, winding vibration analysis/vibration analysis for the oil-immersed tank, and acoustic noise analysis.

We will continue to pursue higher analysis accuracy by actively using the actual products to compare the measured data of actual products with the analysis virtual data. By effectively using actual products, we intend on making the best use of analysis technologies for reinforcing the competitive edge of our transformers.

For the development of new radiators, we worked on several programs to realize a light-weight and compact design transformer. We worked on increasing the heat dissipation area, reducting the oil quantity, and designing a thinner panel metal sheet.

For product development, we worked on realizing the light-weight and compact design of the 20MVA distribution transformer. Until recently, for this capacity size transformer, we were not able to ship by trailer line fully assembled due to the regulated weight limitations in Japan.

Under this program, we realized the transportation, fully assembled, without removing the insulation oil in the inner enclosure of the transformer.

To meet the transportation limitations, we reduced the total mass of about 10%. We made an effective design on insulation distance and cooling method. We also narrowed the tank design and used a thin sheet metal. In doing so, we realized a mass reduction as much as possible.

Going forward, we will make every effort to contribute to social infrastructure building by utilizing these technologies discussed in this paper.