COMPUTATION AND SIMULATION OF DEFORMATION AND STRESS ON THE TANK OF POWER TRANSFORMERS BY A NUMERICAL METHOD

TÍNH TOÁN MÔ PHỎNG BIẾN DẠNG VÀ ỨNG SUẤT TRÊN BỀ MẶT VỎ MÁY BIẾN ÁP BẰNG KỸ THUẬT PHẦN TỬ HỮU HẠN

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DOI: https://doi.org/10.57001/huih5804.2025.322

ABSTRACT

Super high voltage power transformers play a critical role in the national power transmission system, particularly at voltage levels of 110kV, 220kV, and 500kV. During the research, design, and manufacturing process of 500kV power transformers, the analysis and evaluation of stress and deformation acting on the transformer tank structure are fundamental technical requirements to ensure mechanical strength, operational safety, and equipment longevity. This paper employs the finite element method (FEM) to calculate and simulate the deformation and stress on the transformer tank surface under two different loading scenarios: transportation without oil and transportation with oil. The simulation results indicate that all stress and deformation values remain within the allowable limits of the material, thereby confirming the structural safety of the design and demonstrating Vietnam's capability in mastering the technology for manufacturing high-capacity, high-voltage power transformers.

Keywords: *500kV power transformer, deformation simulation, stress analysis, finite element method (FEM).*

TÓM TẮT

Máy biến áp siêu cao áp đóng vai trò thiết yếu trong hệ thống truyền tải điện năng quốc gia, đặc biệt tại các cấp điện áp 110kV, 220kV và 500kV. Trong quá trình nghiên cứu, thiết kế và chế tạo máy biến áp 500kV, việc phân tích và đánh giá ứng suất - biến dạng tác động lên kết cấu vỏ máy là một yêu cầu kỹ thuật cốt lõi nhằm đảm bảo độ bền cơ học, an toàn vận hành và tuổi thọ thiết bị. Bài báo sử dụng phương pháp phần tử hữu hạn (FEM) để tính toán và mô phỏng biến dạng và ứng suất trên bề mặt vỏ máy biến áp với hai trường hợp tải trọng khác nhau: vận chuyển máy biến áp khi không dầu và vận chuyển máy biến áp khi có đầy dầu. Kết quả mô phỏng cho thấy tất cả giá trị ứng suất và độ biến dạng đều nằm trong giới hạn cho phép của vật liệu, qua đó khẳng định tính an toàn của thiết kế và năng lực làm chủ công nghệ chế tạo máy biến áp công suất lớn, điện áp cao của Việt Nam.

***Từ khóa**: Máy biến áp công suất lớn 500kV, phân tích ứng suất, biến dạng vỏ máy biến áp, phương pháp phần tử hữu hạn.*

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Received: 01/6/2025
Revised: 10/7/2025
Accepted: 28/9/2025

1. INTRODUCTION

Power transformers (PTs) are essential components of the national power system, performing the critical function of transforming and transmitting electrical energy across different voltage levels. In particular, within the supper-high-voltage (SHV) transmission grid, 500kV transformers play a pivotal role in linking major generation centers with load areas. Ensuring the reliability, safety, and longevity of 500kV PTs requires highly accurate electromechanical calculations, designs, and manufacturing processes [1, 2].

Recently, Dong Anh Electrical Equipment Manufacturing Joint Stock Company (EEMC) successfully localized the design and manufacturing of a 500kV - 3x300MVA transformer, marking a significant milestone for Vietnam's electrical equipment industry. However, the fabrication and testing of SHV transformers present considerable technical challenges, particularly concerning the mechanical integrity of the transformer tank the enclosure that must withstand both environmental impacts and internal pressures. Previous studies have employed finite element method (FEM) analyses combined with 3D modeling to investigate the mechanical behavior of high-voltage transformers (110 - 220kV) under fault conditions such as arcing or short circuits, helping to identify critical stress concentration areas on the windings or tank. Nonetheless, limited research has focused on the mechanical behavior of transformer tanks during specific manufacturing stages, such as vacuum drying or oil leak testing conditions that may induce substantial mechanical loads, potentially leading to deformation, cracking, or localized failure if not properly controlled.

Building on this gap, this paper applies the finite element method to simulate the deformation and stress distribution on the surface of a 500kV transformer tank under two practical conditions: (1) transportation without oil, and (2) transportation with oil fully filled. The simulation model is based on actual geometry and specific material properties. The obtained results show that the stress and strain values remain within permissible limits, confirming the structural safety and the effectiveness of the domestically developed design and manufacturing technologies for large-capacity, high-voltage transformers. Furthermore, the findings provide a technical foundation for proposing structural improvements aimed at optimizing the mechanical durability and operational performance of transformer tanks in the future.

Accordingly, this study employs the finite element method (FEM) to simulate the deformation and stress distribution on the surface of a 500kV PT tank under two practical scenarios: (1) transportation of the transformer without insulating oil; and (2) transportation with the transformer fully filled with oil. The simulation model is constructed based on the actual geometric configuration and specific material properties of the tank. The results indicate that both stress and strain values remain within the allowable limits, thereby validating the structural integrity and safety of the design, as well as demonstrating the effectiveness of the domestically developed technology for the design and manufacturing of large-capacity, high-voltage transformers. Furthermore, these findings provide a solid technical basis for proposing structural enhancements aimed at optimizing the mechanical strength and operational performance of transformer tanks in future applications.

2. BACKGROUND MODEL

During operation, the PTs may experience fault conditions that lead to a sudden increase in internal pressure, resulting in significant mechanical stresses acting on the tank and causing structural deformation. The deformation behavior of the transformer tank under such conditions is modeled using a system of three fundamental partial differential equations: *(i) the transient equilibrium equation*, *(ii) the constitutive material equation*, and *(iii) the geometric compatibility equation* [3]. Among these, the transient equilibrium equation establishes the relationship between the applied loads and the internal stress distribution within the structure, and is expressed in the following form [3, 4]:

$$\rho_t \frac{\partial^2 \mathbf{u}}{\partial t^2} - \nabla \cdot \sigma_t = F_\upsilon \qquad (1)$$

In this equation, ρ_t (kg/m^3) denotes the density of the material used for the transformer tank; $\mathbf{u}$ (m) is the displacement vector representing the deformation of the tank under fault conditions; σ_t (N/m^2) is the stress tensor; and F_υ (N/m^3) is the body force density acting on the tank structure. This force component is determined based on the ratio between the pressure distributed on the tank wall and the wall thickness of the transformer. Subsequently, the relationship between stress and strain is described by the constitutive equation, which follows the "Duhamel-Hooke law", expressed as follows [4, 10-13]:

$$\sigma_t - \sigma_0 = \mathbf{C} : \left(\mathcal{E}_t - \mathcal{E}_0 - \mathcal{E}_p - \mathcal{E}_{th}\right) \qquad (2)$$

where σ_0 and $\mathcal{E}_0$ denote the initial stress and strain states, respectively; **C** is the fourth-order elasticity tensor that defines the linear relationship between stress and strain within the elastic limit; $\mathcal{E}_p$ represents the plastic strain component; and $\mathcal{E}_{th}$ for the strain induced by temperature effects.

In this study, the term of $\mathcal{E}_{th}$ is assumed to be negligible and is therefore excluded from the analytical model. The relationship between strain and the displacement gradient of the transformer tank is described by the compatibility equation, given as follows [4, 10-13]:

$$\epsilon = \frac{1}{2}[\nabla\mathbf{u} + (\nabla u)^{T}] \tag{3}$$

In the equation (3), the tensor is symmetrically the displacement gradient of the transformer tank.

3. SIMULATION BY NUMERICAL METHOD

In this section, the paper will simulate and calculate the forces and stresses acting on the 500kV HVT tank with a capacity of 3x300MVA in two cases: when the transformer is transported without oil and when it is transported fully filled with oil.

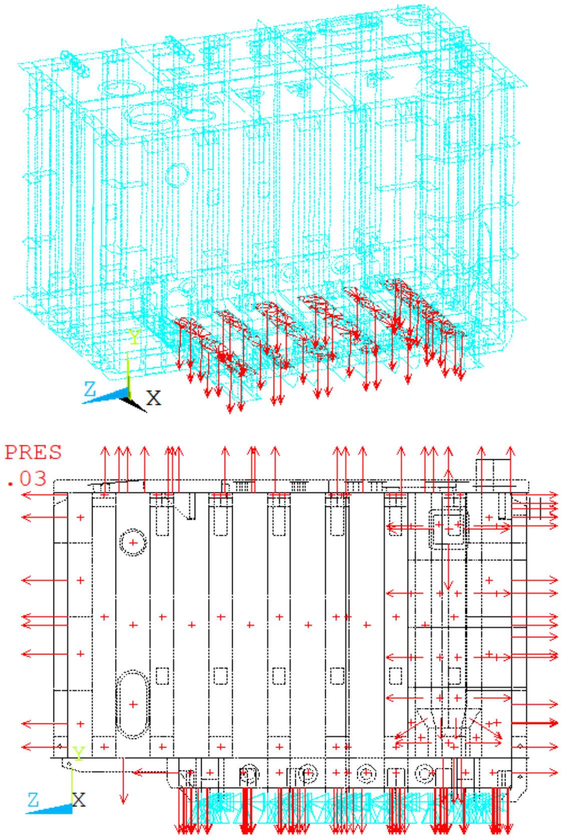


Figure 1. Force distribution during transformer movement along the Z direction "Z"

- ***Case of transformer transported without oil:*** In this case, the transformer tank is filled with nitrogen gas at a pressure of 30kPa. Figure 1 illustrates the distribution of forces on the transformer tank during movement, subjected to a longitudinal acceleration of "3g" in the "Z" direction. It can be observed that the force distribution is mainly concentrated at the bottom and at the corner joints between the tank body, the cover, and the base. These are areas with a high risk of local deformation, especially under oil-free conditions where the internal pressure is maintained by nitrogen gas at 30kPa.

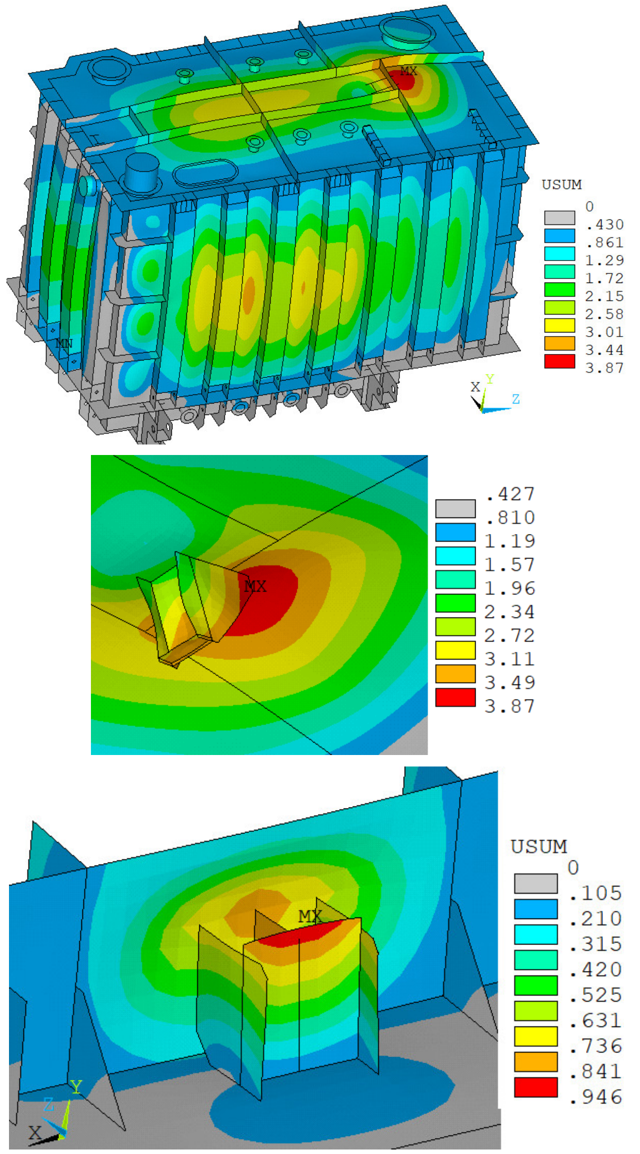


Figure 2. Deformation of the transformer tank due to force acting in the "Z" direction

Similarly, the deformation diagram of the transformer tank due to "Z-directional" force is shown in Figure 2. The results indicate that deformation mainly occurs in the central area of the tank body, where the surface area is large and there are fewer stiffening ribs. The maximum deformation remains within allowable limits, demonstrating that the design can withstand loading conditions during oil-free transportation. Figure 3 illustrates the deformation of the transformer tank due to stress in the Z direction. Compared to the deformation caused by external forces in Figure 2, this stress-induced deformation provides a more detailed representation of the stress concentration zones particularly along weld edges and at the joints between shell plates. This result is crucial for improving welding structure and reinforcement design. The force distribution when the transformer moves in the "*X direction*" is shown in Figure 4. It can be seen that lateral acceleration causes significant inertial forces acting on the side walls of the transformer tank. The asymmetric force distribution reflects the complex influence of geometry variations and the arrangement of stiffening ribs. Figure 5 shows the deformation of the oil-free transformer tank under stress when moving along the X-axis. Large deformations are concentrated on the side plates, especially near bolt holes or rib cut-out positions. These are critical areas where welding quality and reinforcement must be carefully controlled during manufacturing.

- Case of transformer transported fully filled with oil: In this case, the transformer is transported with oil, resulting in additional internal pressure from the oil inside the tank. This pressure is distributed along the height of the tank, acting on the cover, body, and bottom in accordance with the law of hydrostatic pressure. During transportation, the boundary conditions with fixed bottom beams have also been taken into account in the calculations.

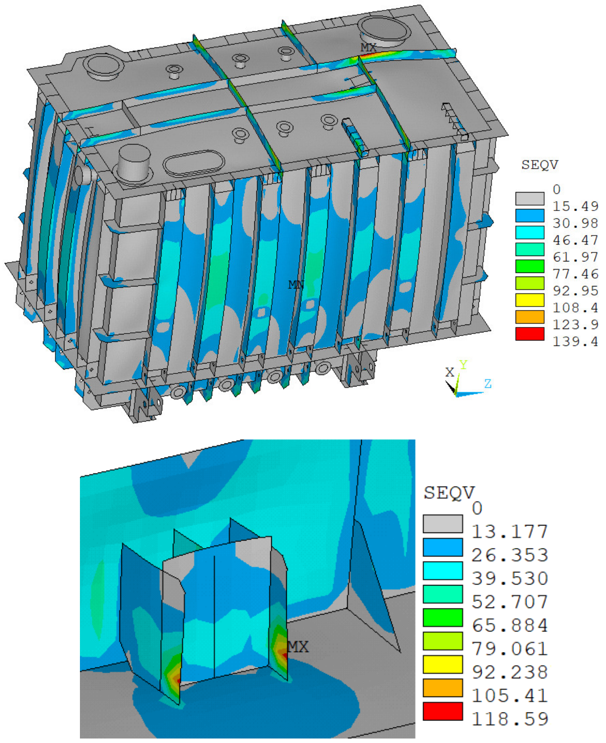


Figure 3. Deformation of the transformer tank due to stress acting in the "Z" direction

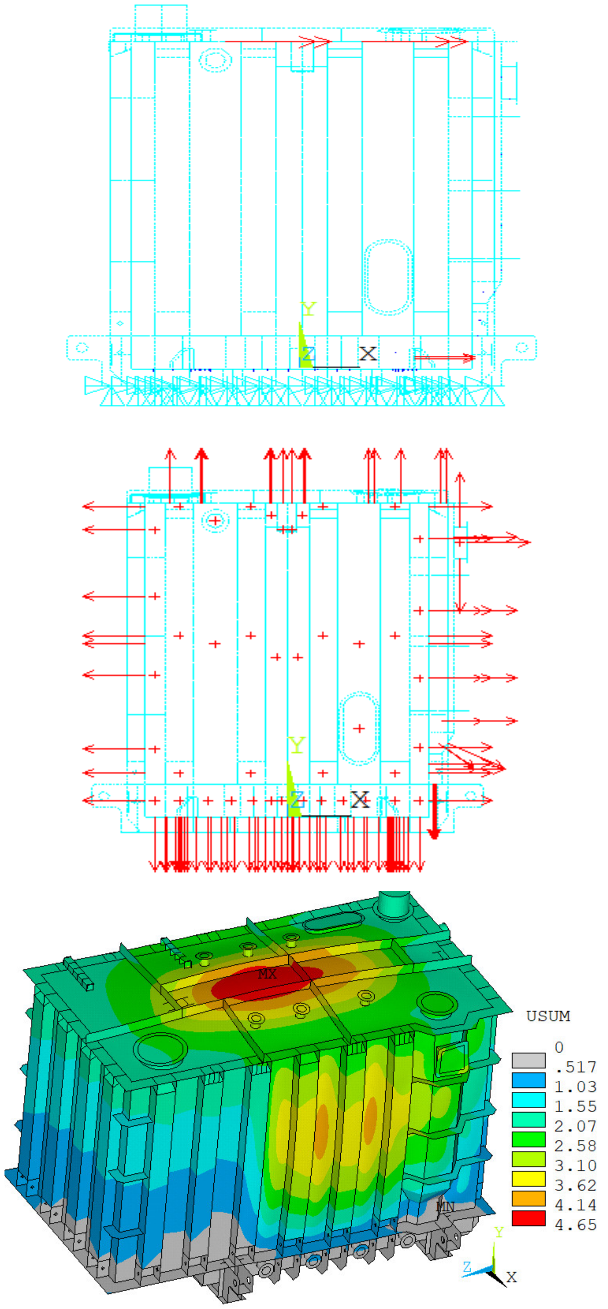
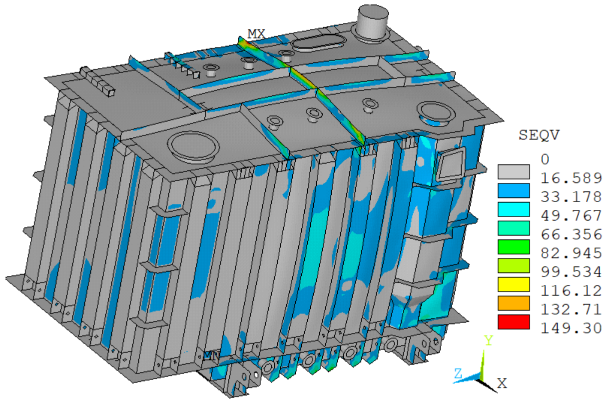
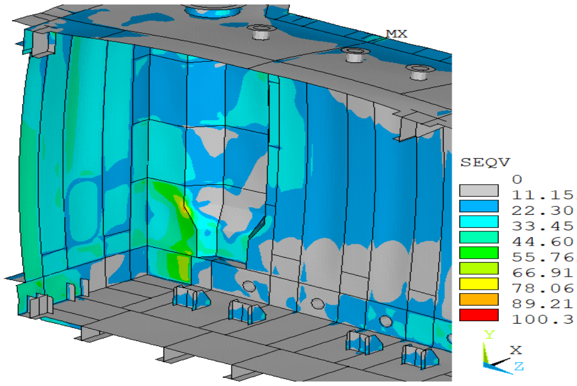


Figure 4. Force distribution during transformer movement in the "X" direction





Fiugre 5. Deformation of the transformer tank due to stress during movement in the "X" Direction (N/mm^2)

Figure 6 illustrates the deformation of the transformer tank during oil-filled transportation in the "Z direction". Due to the oil pressure, an additional hydrostatic pressure distribution is generated along the tank height. It can be observed that deformation increases significantly, especially on surfaces with large areas. This demonstrates the considerable impact of oil weight on the overall mechanical behavior of the tank structure. The deformation caused by stress in the "Z direction" with oil present is shown in Figure 7. The stress concentration increases significantly at interface corners and the cover region. These points could be potential crack initiation sites if not properly designed or reinforced.

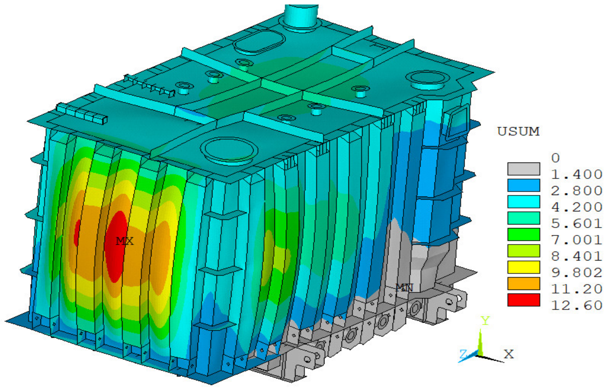
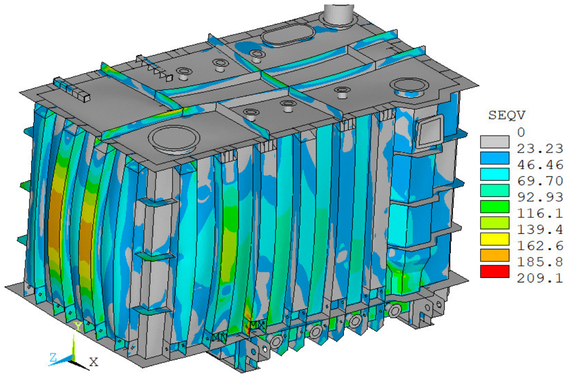


Figure 6. Overall tank deformation due to force during oil-filled movement in the "Z" Direction (mm)



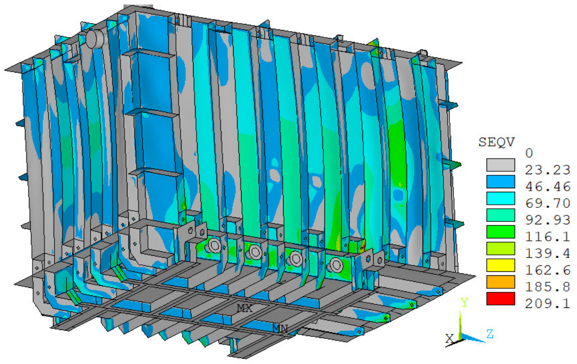


Figure 7. Deformation of the transformer tank due to stress during movement in the "Z" Direction (mm)

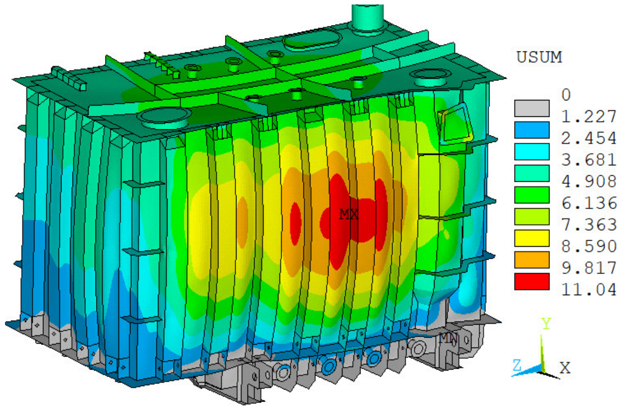


Figure 8. Deformation of the transformer tank due to force during movement in the "X" direction (mm)

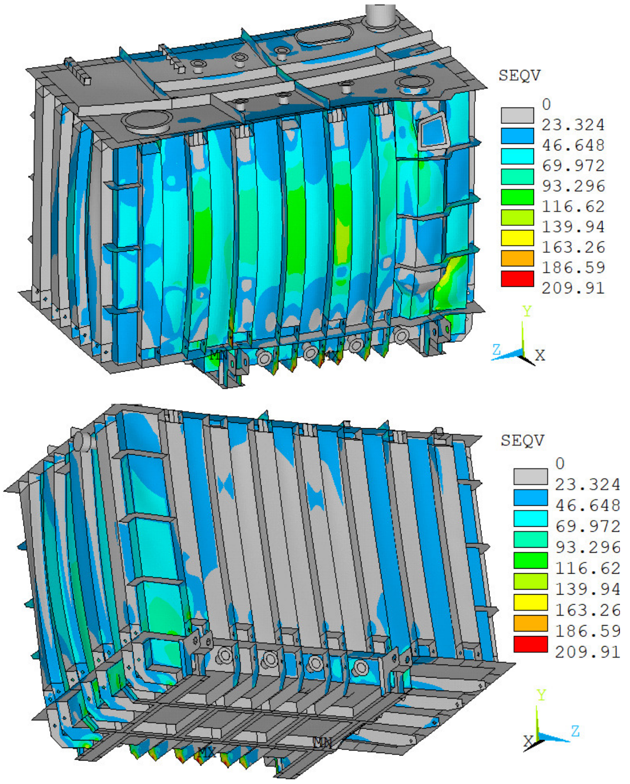


Figure 9. Deformation of the transformer tank due to dynamic stress during movement in the "X" direction (mm)

Table 1. Stress and deformation of the transformer tank under different test conditions

Test Conditions	**Deformation (mm)**	**Stress (N/mm^2)**	**Allowable Stress (N/mm^2)**
Transportation mode with longitudinal ("Z") acceleration and vertical acceleration without oil	3.87	139.4	$\sigma_{test} = 0.75\sigma_y = 176$
Transportation mode with lateral ("X") acceleration and vertical acceleration without oil	4.65	149.3	
Transportation mode with longitudinal ("Z") acceleration and vertical acceleration with oil	12.6	209.1	
Transportation mode with lateral ("X") acceleration and vertical acceleration with oil	11.04	209.91	

Figure 8 shows the deformation due to force when the oil-filled transformer is moved in the X direction. The combination of lateral impact and internal oil pressure causes asymmetric deformation, leading to a risk of structural warping if no proper anti-torsion mechanisms are implemented. This figure is essential for evaluating stability during real transport conditions. The deformation caused by dynamic stress in the X direction with oil is presented in Figure 9. Similar to Figure 7, stress is highly concentrated at intersections and weld joints, especially under the combined effect of lateral loads and oil weight. This must be strictly controlled in the structural design and material selection for the tank. The maximum calculated stress in the structural components under different loading conditions does not exceed the allowable stress and is summarized in Table 1.

4. CONCLUSION

The numerical simulation results show that under the condition of transporting the transformer without oil, the stresses generated in the tank shell remain within the allowable material limits, ensuring operational safety. Conversely, when transporting the transformer fully filled with oil, the maximum stress at certain locations exceeds the allowable threshold, posing a risk of local failure if not addressed with appropriate reinforcement measures. A detailed analysis of the results reveals:

Stress tends to concentrate at the junctions between the body, cover, and bottom, as well as at welds, which are structural weak points;

The presence of oil inside the tank significantly increases hydrostatic pressure, leading to greater deformation and stress, especially during transportation;

The stiffening rib system effectively limits local deformation and enhances the mechanical stability of the tank shell.

Based on the above analysis, it can be concluded that transporting the transformer in an oil-free state is the optimal option to ensure mechanical safety. At the same time, the study highlights the essential role of the FEM in evaluating the mechanical behavior of structures subjected to complex loads, contributing to design optimization, cost savings in prototype manufacturing, and improving the competitiveness of domestic products. The obtained results demonstrate Vietnam's capability to master the technology of SHV transformer design and manufacturing, laying the groundwork for developing local technical standards and promoting the application of numerical simulation in the industrial electrical equipment sector.

ACKNOWLEDGMENT

The research content of this paper was supported by the results of the state-level project coded: **DAĐL.CN-05/21.**

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THÔNG TIN TÁC GIẢ

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