A qualified dry-type transformer under the combined seismic conditions

ABSTRACT

This article presents the design, seismic simulation, and seismic testing of a 2500 kVA 36 kV 7.7-ton dry-type transformer designed to withstand the rigorous IEEE693-2018 moderate-level seismic test involving dynamic forces in the range of 0-55 Hz and 0.5 g acceleration. The testing was conducted at IAGB Test Company in Munich, Germany, and we are pleased to report that the test was successfully completed. Remarkably, the transformer design eliminates the need for additional consoles or supports, achieving stability solely through the use of eight M24 fasteners for secure grounding. This innovative approach ensures the transformer's resilience under seismic conditions, addressing critical considerations for power infrastructure in earthquake-prone regions. The results and implications of this seismic testing contribute valuable insights to the field of transformer design and seismic resilience.

KEYWORDS:

Seismic, Dry-type transformer, Finite element method, IEEE693, Kocaeli-Gebze Seismic Condition, Simulation, ANSYS

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> **The mechanical integrity of a 2500 kVA, 36 kV transformer under both static and dynamic loading conditions is verified for seismic loads in accordance with the IEEE693-2018 standard**

1. Introduction

The mechanical integrity of a 2500 kVA, 36 kV transformer under both static and dynamic loading conditions is verified using the ANSYS Mechanical software. Microsoft Excel and Mathcad will be employed to create design response spectra and any necessary graphs or tables. Seismic loads are considered in accordance with the IEEE693-2018 standard for the Seismic Design of Substations [1].

A 3-D solid finite element analysis is conducted in four steps. These steps are defined as follows:

- The application of gravitational dead loads to the entire model.
- Utilizing linear perturbation analysis to extract the natural frequencies and modal shapes of the entire model.
- Applying seismic loads (using linear perturbation) to the model, accompanied by appropriate response spectrum analysis.
- This analysis will provide insights into the mechanical stresses affecting critical components, such as clamps, U-profiles, winding supports, connecting bolts, and more. The final results will be presented in units of MPa for stresses and mm for displacements.

Guo-Liang, Ma, and Qiang, Xie recount a sobering incident wherein a 500 kV power transformer bore the brunt of an earthquake's fury. The aftermath was disastrous, marked by fractured bushings, sheared-off oil conservator supports, and a consequential fire fueled by leaked transformer oil. A finite-element model of the power transformer was meticulously developed, and modal and response-history analyses were conducted to discover the reasons behind this seismic catastrophe. [2]

Ersoy, Selahattin, et al. introduce us to the concept of the Friction Pendulum System (FPS), an innovative isolation technology that intertwines the principles of sliding bearings and pendulum motion. The paper delves into a parametric study evaluating the effectiveness of FPS bearings under various seismic parameters. Notably, it ponders over the suitability of response combination rules, such as SRSS and CQC, in estimating total responses under orthogonal motions. [3]

Nobuo, Murota, Maria, Q. Freng, and Gee, Yu Liu take us to the world of seismic isolation, focusing on two distinct systems: sliding bearings combined with rubber bearings and segmented high-damping rubber bearings. This study involves triaxial earthquake simulator testing and reveals the efficacy of base isolation systems in reducing response acceleration. It also highlights the intricate dynamics of vertical ground motion on bushings and the impact of bushing connecting cables on response in the base-isolated system. [4]

Seyed, Alireza Zareei, Mahmood, Hosseini, and Mohsen, Ghafory-Ashtiany shift the focus to seismic vulnerability

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> **The analysis accounts for seismic loads in accordance with the IEEE693-2018 standard, considers the vertical ground acceleration as two-thirds of the horizontal component**

evaluation, primarily discussing power transformers (PTRs) in electrical substations. The paper reviews the seismic vulnerability of PTRs in the wake of past earthquakes and delves into detailed 3D finite element modeling and time-history analysis. The results present seismic analytical fragility curves for PTRs, emphasizing the importance of specific seismic considerations. [4]

Shoma, Kitayama, et al. embrace a probabilistic approach, offering a detailed assessment of seismically isolated electrical transformers. It explores various parameters, including ground motion characteristics, displacement capacity of isolation systems, and transformer configuration. The findings underscore the potential of seismic isolation systems to enhance performance, especially when isolating in both horizontal and vertical directions. [5]

These references collectively underscore the critical importance of seismic resilience in power transformer design and provide a rich tapestry of research and insights that inform our exploration into the seismic response of electrical transformers in this article.

2. Description of the dry-type transformer and mounting

The general dimensions of this transformer at the 36 kV voltage level are 2.25 m x 2.47 m x 2.00 m, with a total weight of 7.7 tons. Its center of gravity is located 1.5 m from the floor.

The transformer was securely attached to the test table using fasteners appropriate for regular operation. This attachment was achieved using eight M24 screws, each tightened to a torque of 350 Nm.

Technical drawings are attached to show the location/position of the accessories and the foundation plan. The foundation plan will be used as a reference drawing when applying boundary conditions to the

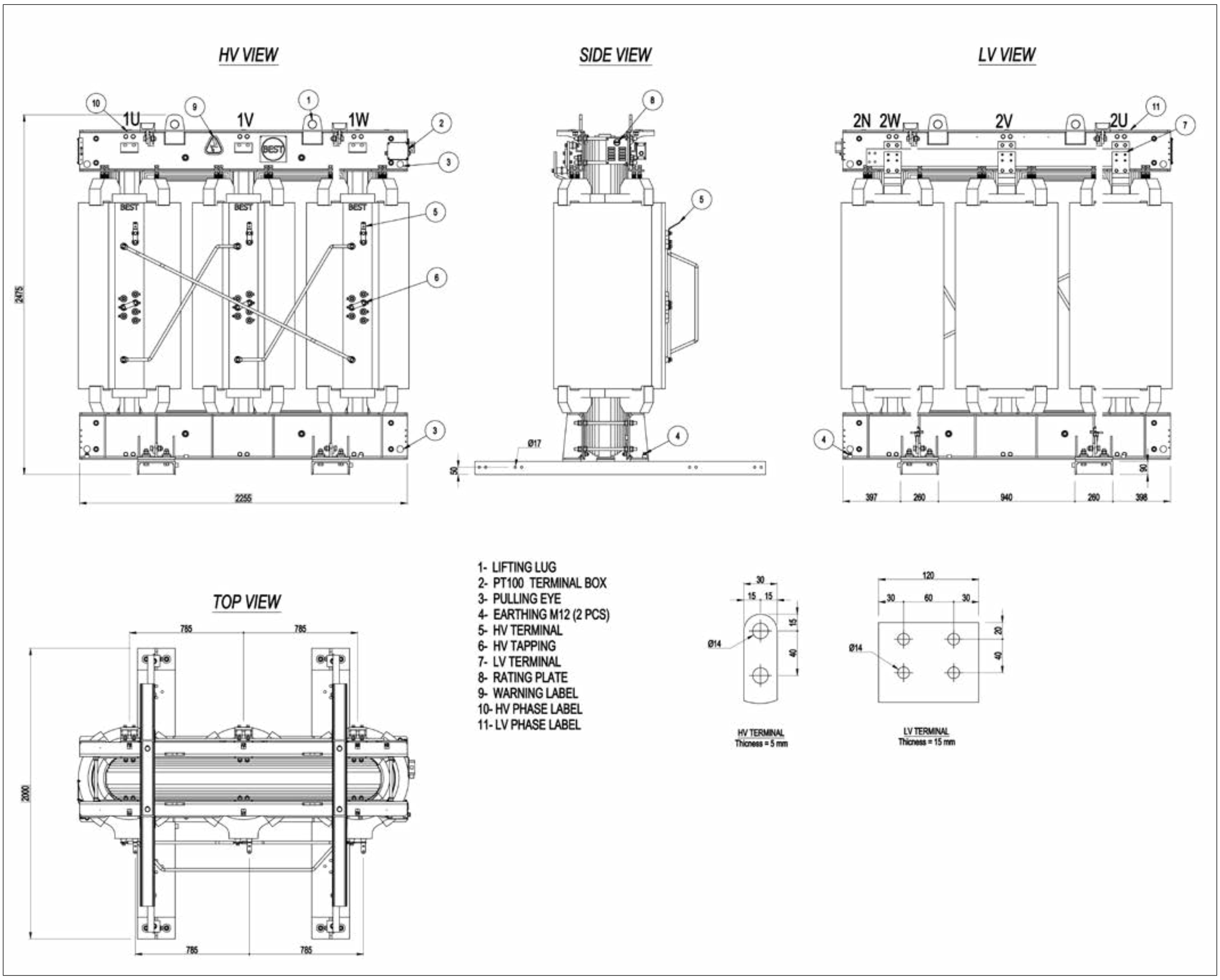

Figure 1. Technical drawings of the dry-type seismic transformer

> **Using dynamic analysis, the equipment, its appendages, and any support structure will first be modeled as an assemblage of discrete structural elements interconnected at a finite number of points called nodes**

Finite Element (FE) model. This drawing shows which portion of the transformer base will be in contact with the foundation.

3. Seismic condition

The analysis accounts for seismic loads in accordance with the IEEE693-2018 standard, referred to as IEE693 hereafter. It considers the vertical ground acceleration as two-thirds of the horizontal component. In two orthogonal horizontal directions, ground accelerations are equal, and these collective ground accelerations are depicted through a response spectrum.

3.1 Earthquake level

The following earthquake level is considered in this study.

Moderate seismic qualification level: Qualifications to the moderate seismic qualification level will meet the relevant requirements given in Annex A of IEEE693-2018 in conjunction with the spectrum depicted in Figure A.2. Relevant requirements shall be as stated in the applicable equipment-specific annex (Annex C through Annex P, Annex V, and Annex W of IEEE693-2018) when the equipment being qualified can be categorized into an equipment specific annex (as defined by operation and configuration). If the equipment being qualified cannot be categorized into an equipment-specific annex (as defined by operation and configuration), then the relevant requirements will be as given in Annex B of IEEE693-2018 [1].

3.2 Seismic loading

Analysis, as required in this recommended practice, will be performed using the design level seismic loads corresponding to 50% of the performance level loading defined by the elastic response spectra of Figure A.1 and Figure A.2 of IEEE693-2018, which is shown in Figure 2 for the high and moderate performance levels. [1]

3.3 Dynamic response spectrum analysis

Using dynamic analysis, the equipment, its appendages, and any support structure will first be modeled as an assemblage of discrete structural elements interconnected at a finite number of points called nodes. The number, location, and properties of elements and nodes will be such that an adequate representation of the modeled item(s) is obtained in the context of a seismic analysis.

3.4 Response spectrum

The input motion time history for all time history tests shall satisfy the requirements given below. This recommended practice principally uses response spectra to establish the characteristics of the time histories used to seismically qualify substation equipment.

All theoretical and table output motions cited below refer to accelerations or signals that ultimately will be evaluated as accelerations. Also, all acceleration will be recalculated according to the title of "seismic loading" for modal response spectrum analysis.

The elastic response spectrum representing the horizontal component of earthquake ground motion is defined as follows (Figure 3):

3.4 Response spectrum

$$S_a(f) = 1.144\,\beta\,f \qquad 0.0 \le f \le 1.1) \qquad (1.1)$$

$$S_a(f) = 1.25\,\beta \qquad (1.1 \le f \le 8.0) \qquad (1.2)$$

$$S_a(f) = \frac{(13.2\beta - 5.28)}{f} - 0.4\beta + 0.66$$

$$(8.0 \le T \le 33) \qquad (1.3)$$

$$S_a(f) = 0.50 \qquad 33 \le f \qquad (1.4)$$

$$\beta = (3.21 - 0.68.\ln(d))/2.1156$$

g: Acceleration due to gravity that is 9.81 m/s^2

Where S_a represents spectral acceleration, f stands for frequency, g is for gravity and d denotes the damping ratio.

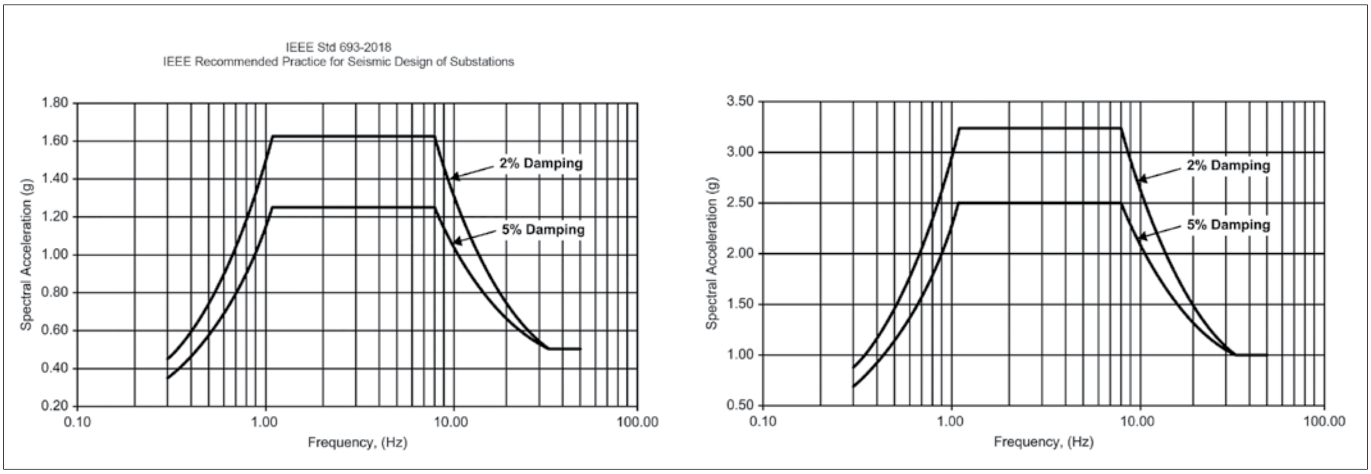

Figure 2. Elastic response spectrum for high level (left) and moderate level (right)

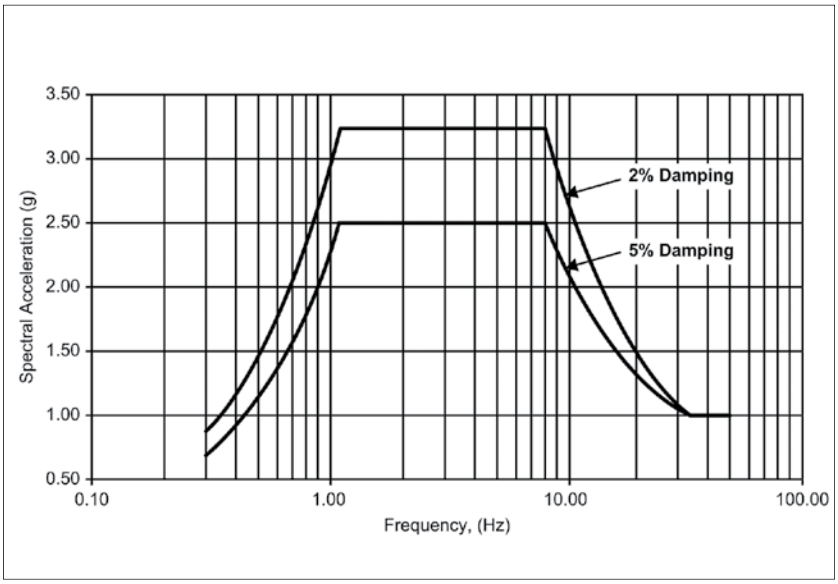

Figure 3. Elastic response spectrum for moderate level

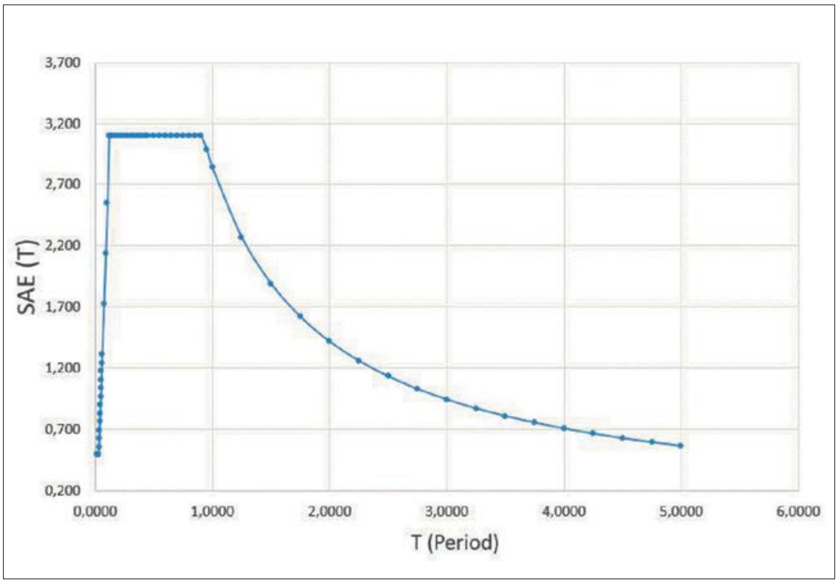

Figure 4. Spectrum coefficients determining the shape of the elastic spectrum (IEEE693-2018)

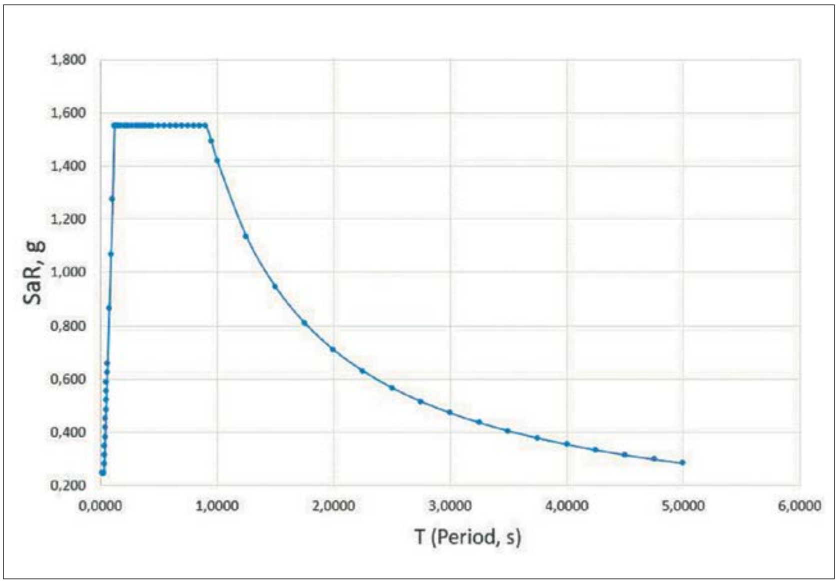

Figure 5. Reduced Elastic Response Spectrum Curve

In [1], the methodology to determine the response spectrum for IEEE693-2018 IEEE Recommended Practice for Seismic Design of Substations is given. Mathcad and Microsoft Excel were utilized to determine the shape and the values of the spectrum, and they are provided in IEEE693-2018 of this document using [1]. This document also provides spectrum curves for IEEE693-2018, and a curve considers the maximum values of these spectra as IEEE693-2018, which is dominant at different periods or frequencies. Elastic Spectrum (SAE(T)) is given in Figure 4 for IEEE693-2018.

3.5 Reduction of elastic seismic loads

Elastic seismic loads determined in terms of spectral accelerations defined in section 4.4 are divided into below-defined seismic load reduction factors to account for the ductile behavior of the structural system during the earthquake.

$$SAR(T) = \frac{SAE(T)}{q} \tag{1.5}$$

SAR(T): Reduced seismic load

q: ratio of reduction factor

Power transformers are made of mild steel with high ductility within a certain temperature range. The ductility of the steel used in the 2500 kVA transformer retains its ductility at -25°C according to Charpy Test results. We will use the value of 2 for the parameter “q” in this analysis. The design spectrum can be easily calculated by dividing the elastic response spectrum to . For IEEE693-2018, the calculation method is provided in Appendix A and will not be repeated here. Final response spectrum curves and reduced spectral acceleration for IEEE693-2018 are given in Figure 5 below.

The curve will be considered in the simulation when finding the response of a 2500 kVA transformer to seismic-type loading.

4. Description of the seismic simulation

Due to the complexity of the full model of the transformer, parts that are not subject to mechanical or seismic loading are not included in the model to save

> **We subjected all bolt connections to stringent static hand calculations, affirming their structural robustness and cementing the foundational stability of the entire system**

computation time, allowing the use of highly refined mesh density in critical areas.

4.1 Simulation model

In our analytical framework, we applied distinct modeling methodologies and made specific suppositions to underpin a thorough comprehension of the system's dynamics. To optimize computational efficiency while preserving precision, steel components were represented as surfaces using shell modeling techniques. The core assembly, on the other hand, was simplistically approximated as a solid. In addressing both low and high-voltage connections, we judiciously selected beam elements to strike an equilibrium between computational economy and precise representation. Furthermore, we subjected all bolt connections to stringent static hand calculations, affirming their structural robustness and cementing the foundational stability of the entire system. These modeling strategies and validation protocols constituted pivotal elements in our strategy for assessing the transformer's performance under diverse loading conditions.

4.2 Modal analysis

Up to 55 Hertz, we extract natural frequencies, considering the cumulative effects of prior steps, including gravitational loading. The extraction begins with the lowest mode and proceeds to the highest. Initially, we present some noteworthy natural modes, while a comprehensive table of all extracted modes will be provided in the subsequent chapter. To enhance clarity, we adjust the deformation scale differently for each mode, allowing for a clear distinction between deformed and undeformed shapes.

The initial excitation sequence starts with the upper portion of the entire transformer, followed by the U-profile and other associated equipment. Notably, due to their high stiffness-to-mass ratio, the windings are relatively robust and compact compared to other transformer compo-

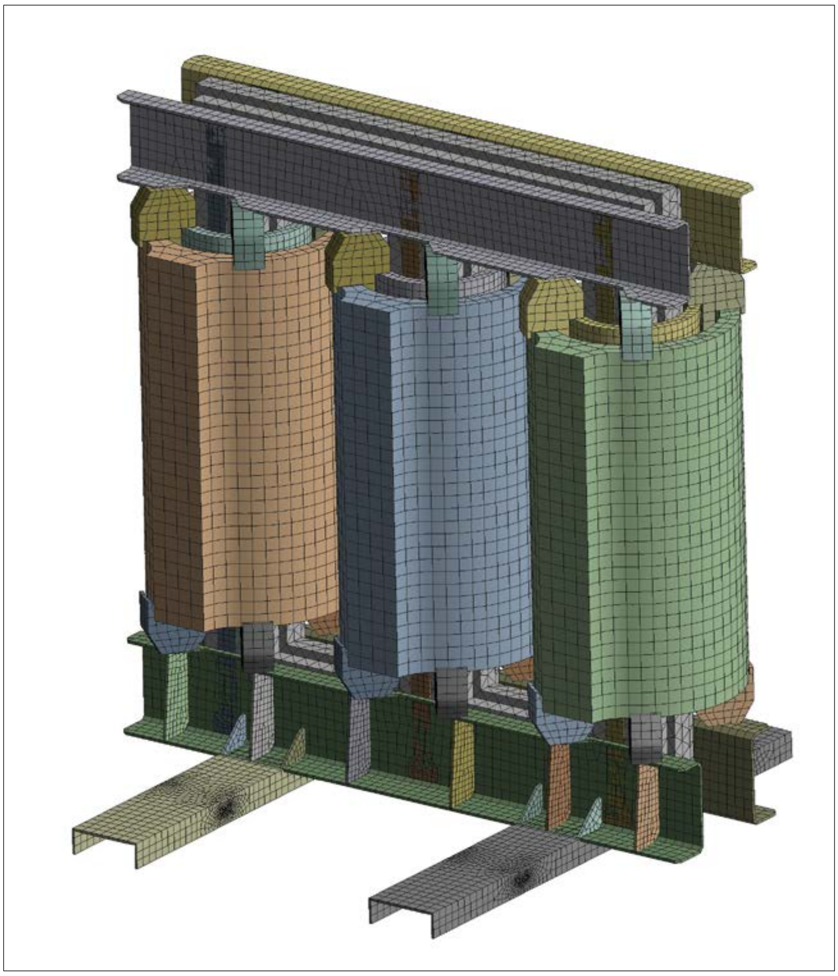

Figure 6. Finite element model of transformer

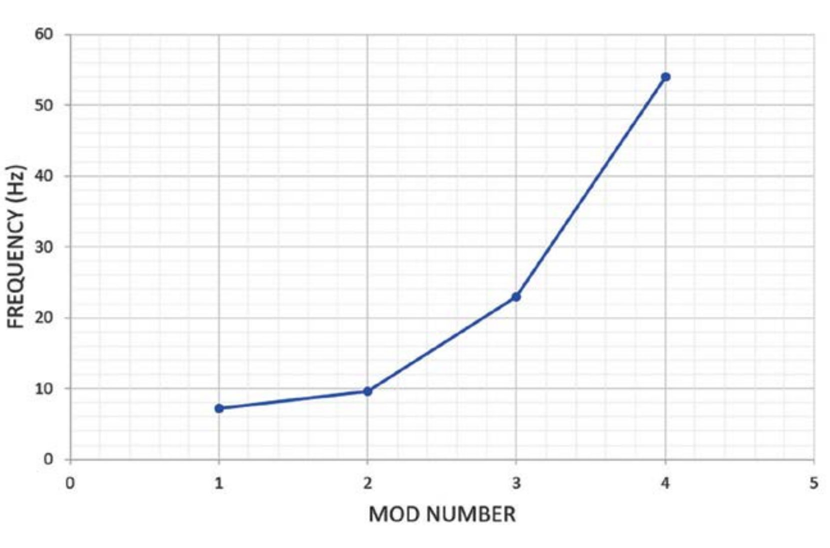

Figure 7. Mode number vs. natural frequency of a 2500 kVA dry-type transformer

> **Through the simulation, we gain invaluable insights into the structural response of the transformer under varying seismic conditions**

nents, leading to their excitation at higher modes.

To account for scenarios where other parts may be more severely excited during the response spectrum analysis, we consider modes up to 55 Hertz, even though the contribution of higher modes may have a limited impact on the overall behavior.

4.3 Response spectrum analysis

The seismic response spectrum simulation, conducted in strict accordance with the IEEE693-2018 standard, is a pivotal component of our study. This simulation entails the application of a range of ground motions to the transformer model, meticulously replicating the seismic forces it might face during an earthquake. Adherence to the IEEE693-2018 standard ensures that our simulation aligns with industry-leading practices in the realm of seismic design for substations.

Through this simulation, we gain invaluable insights into the structural response of the transformer under varying seismic conditions. This data serves as the foundation for a comprehensive assessment of its resilience. Notably, through post-response spectrum analysis, we ascertain that the worst-case scenario for the transformer pertains to its bottom clamps and U profile. This discovery informs our design decisions and mitigation strategies, allowing us to tailor the transformer's construction for optimal performance and safety in regions susceptible to seismic activity.

Additionally, Figure 9 displays the response spectrum deformation results, providing a visual representation of the transformer's behavior under seismic stress. This graphical representation is instrumental in comprehending the dynamic response of the transformer, further aiding our efforts to enhance its seismic resilience. In essence, the seismic response spectrum simulation, conducted in alignment with the IEEE693-2018 standard, empowers us to create a transformer that excels in seismic resilience, ensuring its reliability and safeguarding it in earthquake-prone areas.

5. Conclusions

In conclusion, the journey of designing, testing, and validating the 2500 kVA 33/0.4 kV dry-type transformer has been a testament to the commitment to safety and reliability in the face of seismic challenges. The seismic simulations conducted in accordance with the IEEE693-2018 standard were instrumental in shaping the design of this transformer, ensuring that it could withstand seismic forces effectively.

Following the meticulous design phase, the transformer was brought to life, manufactured, and subsequently transported to the IAGB test laboratory in Munich, Germany. In a rigorous examination of seismic resilience, the transformer encountered the ultimate test by undergoing a seismic assessment that amalgamated the stringent criteria of the IEEE693-2018 standard with the formidable challenges posed by the Kocaeli seismic conditions. Notably, the Kocaeli seismic conditions surpass both standards in terms of their intensity and complexity. In this context, the

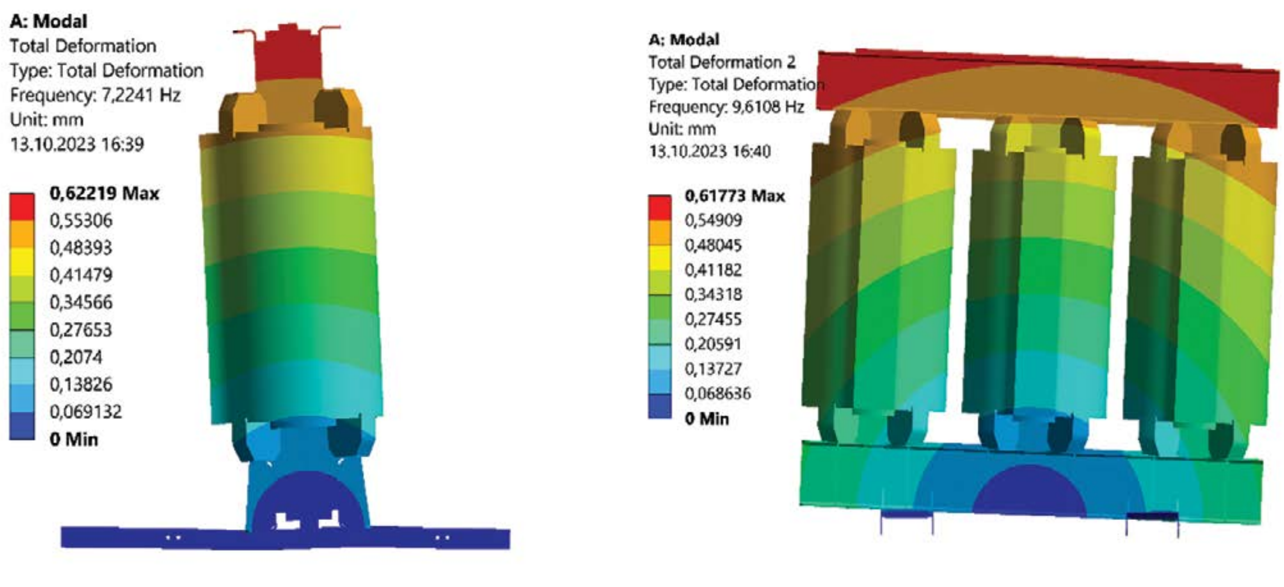

Figure 8. The first two mods of dry-type transformer. 1. Mod 7.22 Hz (left) and 2. Mod 9.61 Hz. (right)

concept of the Combined Reduced Response Spectrum (RRS) was introduced, signifying the superimposition of the maximum values derived from both the IEEE693 and Kocaeli seismic standards. This approach provided a comprehensive understanding of the transformer's response under the combined influence of these demanding seismic scenarios, ensuring a robust evaluation of its seismic resilience and readiness for real-world seismic challenges.

We are delighted to report that the seismic test was not only successfully completed but also confirmed the transformer's robustness in the face of demanding seismic conditions. This is a testament to the effectiveness of the design, manufacturing, and testing process. It signifies that the 2500 kVA 33/0.4 kV 7.7-ton dry-type transformer, developed and tested based on the results of comprehensive seismic simulations, is a reliable and resilient piece of engineering, well-prepared to safeguard critical infrastructure in regions susceptible to seismic events.

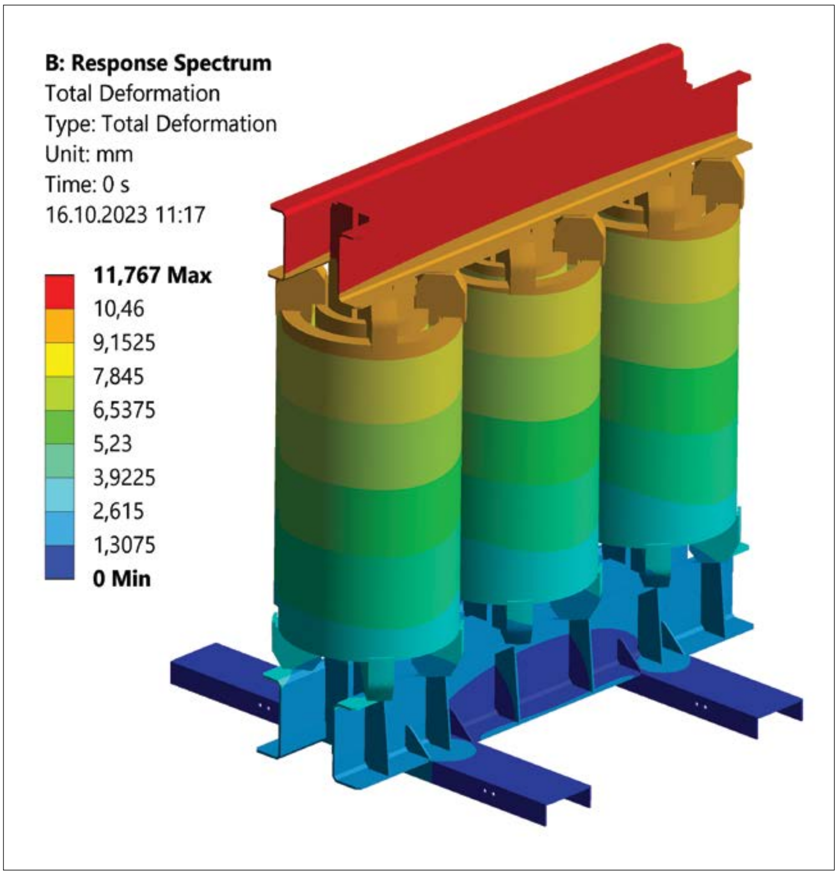

Figure 9. Deformation results of response spectrum analysis

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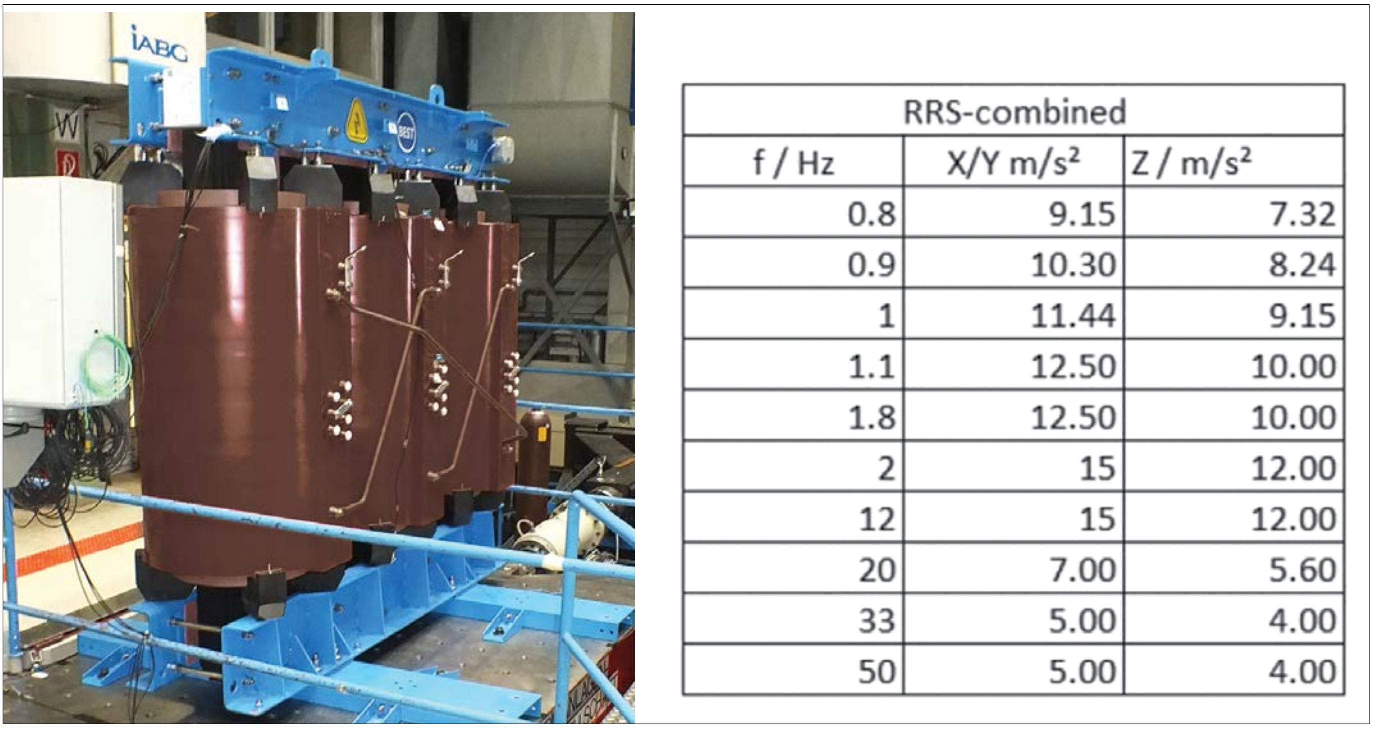

RRS-combined		
f / Hz	X/Y m/s²	Z / m/s²
0.8	9.15	7.32
0.9	10.30	8.24
1	11.44	9.15
1.1	12.50	10.00
1.8	12.50	10.00
2	15	12.00
12	15	12.00
20	7.00	5.60
33	5.00	4.00
50	5.00	4.00

Figure 10. Seismic test and table of the combination of seismic conditions

This achievement reaffirms the significance of rigorous seismic testing in the development of critical equipment and serves as an exemplary model for enhancing the seismic resilience of power infrastructure worldwide.

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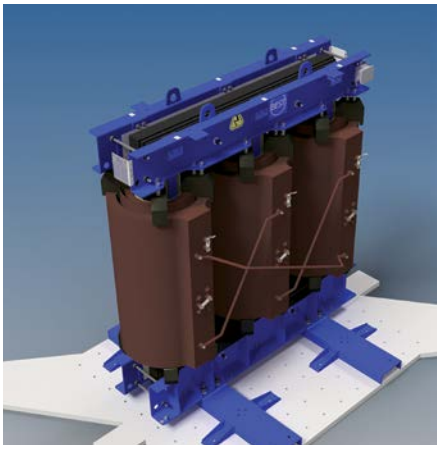

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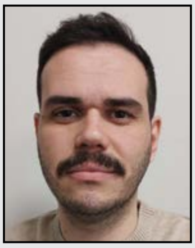

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