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# Seismic performance of instrument transformers

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**SUMMARY**

Seismic events around the world can be identified as one of, if not the most unpredictable events affecting modern society and all of its aspects, including the power grid. In order to be able to understand the impact of this natural phenomenon on the power grid, it is necessary to systematically conduct research on high voltage equipment and, in accordance with new knowledge, adjust the design of critical components.

The main purpose of this paper is to present the experiences with seismic qualification of instrument transformers for different seismically active regions, corresponding FEM analyses and how they affect the final design of the instrument transformer.

All of the shake table tests and FEM analyses are performed in accordance with IEEE 693 standard which is found to be the most complete and demanding standard. Other available standards are compared to the latest version of IEEE 693 to give a complete overview. These standards are: IEC 61869 (current draft 38/652/CD), ETGI 1.020 and IEC 62271-300.

The use Finite Element Method (henceforth FEM) is proposed not only as a tool for pre-test analyses, which are intended for design optimization, but also for obtaining comparable results to actual testing, which makes it a reliable tool for actual transformer qualification.

All results, analyses and conclusions in this paper are based on actual data from tests performed on two distinct instrument transformers of different types, with different critical materials, tested according to different versions of IEEE 693 standard in different laboratories.

The aim of this paper is to provide insight and recommendations on seismic qualification of instrument transformers, serving as a well-rounded basis for further research and discussions on the topic.

**KEYWORDS**

Seismic performance, FEM analyses, Instrument transformers, Shake-table testing, Seismic qualification

## 1. INTRODUCTION

In the several past decades there has been a significant emphasis on overall requirements for seismic performance in the power sector. Damage due to earthquakes in seismically active regions over the last few decades was a big motivation for development of seismic standards in the US and the rest of the world [1]. The primary goal of seismic requirements for high-voltage equipment is to ensure that the entire transmission system is either unaffected or in a working state as fast as possible after a seismic event. That being said, the increased stringency of seismic standards transfers the pressure to individual component manufacturers.

In instrument transformer world, there has to be a delicate balance between the unit being designed to withstand the worst possible seismic stresses and remaining economically viable. To satisfy both ends of that spectrum, products need to be thoroughly optimized, which is a task that is difficult to perform without extensive application of FEM analysis.

This paper explains the standard seismic qualification procedure of instrument transformers and attempts to show the benefits of FEM analysis in modern product design. The usual and the widely recognized method is Response Spectrum Analysis combined with Modal Analysis [2]. Combined together, they are powerful tool for fast and efficient assessing of seismic performance.

For the purpose of this paper, two seismic qualification reports were examined, and relevant results measured during the tests were compared to the results of FEM analysis. Both analyses were done in accordance with the IEEE 693, one was made according to 2005 version of the standard and the other to 2018 version of standard. To emphasize one of the main goals of this paper, additional FEM analysis was performed with the units mounted on the support structure and with the support structure omitted (units mounted directly to the ground).

The main contribution of this paper is that it determines a solid foundation for seismic qualification of instrument transformers and practical considerations and recommendations that should be taken into account to make the entire process valid, adequate and economically feasible.

## 2. COMPARISON OF RELEVANT SEISMIC STANDARDS

It should be noted that all considered standards basically use the same terminology. Some of the more relevant terms are listed, discussed, and described in this chapter, while some of the relevant ones will be shortly discussed. *RRS (Required Response Spectrum)* is the required level of input motion for the shake table. *ZPA (Zero period acceleration)* is the largest peak value of ground acceleration and is the key parameter for determining qualification level, and for comparing different standards. *SML (Specified Mechanical Load)* is a load rating for composite insulators and one of the main criteria for acceptance of mechanical integrity in most of seismic standards. This is a maximum load which the composite insulator has to withstand for one minute [3].

There are several seismic standards available worldwide. Probably the most well-rounded and the most demanding is the IEEE 693, which is still present in the market in its 2005 and 2018 variants [4], [5]. It covers a wide range of high voltage equipment, including instrument transformers. It is applied mostly in North America and approved in numerous countries across the world.

IEC 62271-300 is primarily intended for circuit breakers and is found to be one of the less demanding standards [6]. This fact was taken into account and addressed by a new revision of IEC 61869-1 (current draft 38/652/CD), which will contain a specific annex for seismic qualification of instrument transformers, due to their specific design [7].

ETGI and ETGA are Chilean engineering standards [8]. Due to very high seismic hazards and the strongest recorded earthquakes, Chile is one of the most seismic active regions of the world. For ETGI and ETGA there is only one qualification level. As an alternative standard in Chile, there is a recommendation to use high performance level of IEEE 693 [8].

**Table I** provides an overview of the most commonly used seismic standards. Furthermore, **Figure 1** shows the comparison of RRS for ZPA = 0,5g, which in this case corresponds to IEEE 693:2018 High design level [3], [4]. Based on this, it immediately evident that IEEE 693:2018 is the most demanding standard with the greatest accelerations which should result with the biggest loads applied on the tested equipment.

Since ETGI standard allows equivalent qualification according to IEEE 693 and IEC 62271-300 will soon be superseded by the new revision of IEC 61869-1, which will specifically cover instrument transformers, it makes sense to focus further on comparison between these two standards. The comparison of different RRS requirements is shown in **Figure 2**. As a first remark in the comparison of those two standards, it has to be noted that the new revision of IEC will use the same RRS as IEEE. The biggest difference between IEEE and IEC is that IEEE in its latest revision from 2018 makes it mandatory to use the three axes in testing and dynamic analysis while IEC doesn't. Furthermore, what can be seen in the **Figure 2** is that the IEEE standard does have a 1,0g level and with 2018 revision, this becomes the golden standard for testing, while IEC only have up to 0,5g. The corresponding test levels specified by the IEEE 693 standard are more stringent than those proposed in IEC 61869-1. The only moot point is the 0.3g level according to IEC, which is theoretically more demanding than moderate design level, based on RRS alone. This fact is analysed in more detail and presented in **Table II**, which presents the proposed equivalency levels from IEEE 693:2018 which can be inherently applied to IEC required levels, but not vice versa.

IEC does not require qualification for voltage levels below 72,5 kV, so any existing qualification according to IEEE 693 should be ineherently valid. Similarly, any qualification performed for units that are of 245 kV voltage level or higher, should be done by actual seismic testing, according to IEEE 693:2018 [4]. That leaves only units that are rated between 72,5 and 170 kV which should be qualified by dynamic analysis according to IEEE, while IEC allows both static and dynamic analysis. That being said, the only range where IEEE is not obviously applicable is for units rated between 72,5 kV and 170 kV for required level of 0,3g. However, since the IEC standard has different requirements that are much more lenient than IEEE, such as aforementioned two axes instead of three, 0,5g instead of 1,0g, lower vertical acceleration factor (0,5 vs 0,8), superelevation factor (1,5 vs. 2,5), no requirement on conductor load, no additional tests for insulators required (e.g. shed seal test for composite insulators) and a lower safety margin on the insulators, it can be concluded that it is universally less stringent than IEEE 693:2018. Furthermore, today there are not many customers who want to have the equipment that can fulfill 0,3g or lower accelerations, almost everyone will demand the 0,5g whether they need it or not. This leaves manufacturers with no choice but to fulfill the most stringent requirement. On 0,5g level, there is no doubt that IEEE is more demanding and better rounded standard than IEC. A couple of published papers thematizes the need for harmonization between different seismic standards and recognizes the IEEE in general as the most demanding standard [14], [15].

*Table I* **Comparison of the most used seismic standards**

| Standard | Qualification level [g] | Acceptance Criterium | Safety factor |
|---|---|---|---|
| IEEE 693-2018 | Design Level:<br>1. Low: ZPA≤0,1<br>2. Moderate: ZPA=0,3<br>3. High: ZPA=0,5 | Ductile materials:<br>≤ yield strength/ Ω<br>(AISC 360, ASD)<br>Brittle materials: ≤ 50% breaking strength<br>(SML) | 1,67<br>2,0 |
| | Performance Level:<br>1. Low: ZPA≤0,1<br>2. Moderate: ZPA=0,5<br>3. High: ZPA=1,0 | Ductile materials:<br>≤ yield strength / Ω<br>(AISC 360, ASD)<br>Brittle materials: ≤ 100% breaking strength (SML) | 1<br>1 |
| IEC 62271-300 | Low: ZPA≤0,2<br>Moderate: ZPA=0,3<br>High: ZPA=0,5 | Ductile and Brittle materials: ≤ 100% Yield strength | 1 |
| IEC 61869-1 38/652/CD | Very light: ZPA=0,1<br>Light to medium: ZPA=0,2<br>Medium to strong ZPA=0,3<br>Strong to very strong: ZPA=0,5 | Ductile materials: ≤ 100% yield strength<br>Brittle materials: ≤ 100% breaking strength | 1 |
| ETGA (ETGI) 1-0.20 | 0,5 | Ductile materials: ≤ 80% yield strength<br>Brittle materials: ≤ 50% breaking strength | 1,25<br>2 |

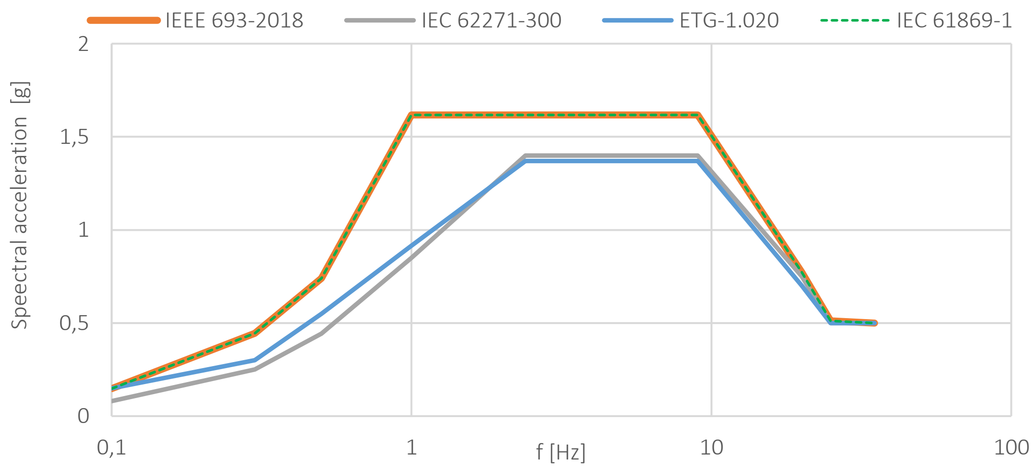


**Figure 1** **Comparison of RRS present in different standards for ZPA = 0,5g**

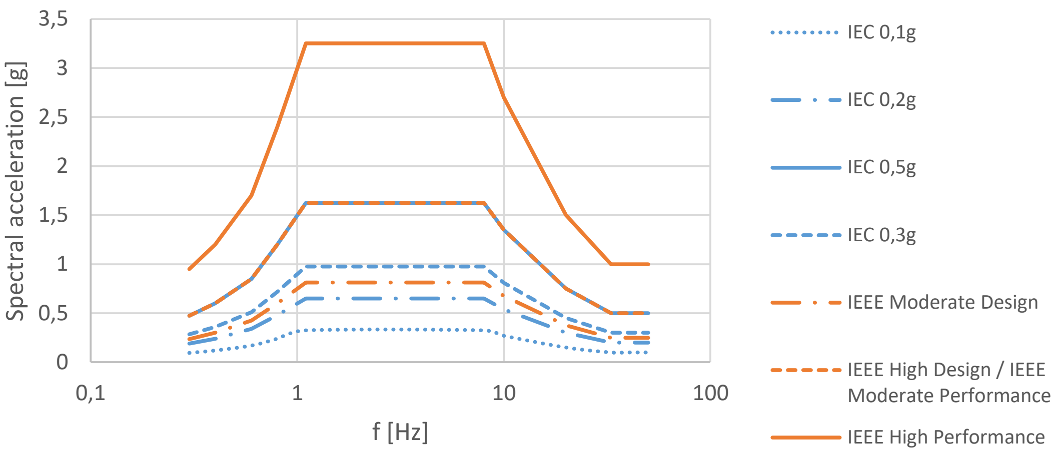


**Figure 2 Comparison of RRS between IEEE 693:108 and IEC 61869-1 (38/652/CD)**

***Table II*** **Qualification equivalency between IEEE 693:2018 and IEC 61869-1**

| Voltage class [kV] | IEC Seismic level [g] | | | |
|---|---|---|---|---|
| | 0,1 | 0,2 | 0,3 | 0,5 |
| < 72,5 | IEEE Low | IEEE Moderate | IEEE Moderate | IEEE High |
| 72,5 – 170 | IEEE Low | IEEE Moderate | IEEE Moderate | IEEE High |
| ≥ 245 | IEEE Low | IEEE Moderate | IEEE Moderate | IEEE High |

Based on the comparison presented in this chapter, it can be stated that instrument transformers which satisfy the IEEE 693 standard, at the same time satisfy standards IEC 62271-300, IEC 61869-1 and ETG-1.020 (High Performance level), which is a very important conclusion, crucial for recognition and approval of existing test reports, especially because instrument transformers are the type of equipment that is not economically justifiable to be tested for the same requirement due to a cosmetic difference between available standards.

## 3. UNITS CONSIDERED AND TESTING PERFORMED

There has to be made some clarifications about the process of the qualification according to IEEE 693. Both 2005 and 2018 versions require shake table test during which strains has to be measured on the critical points of structural components. The test itself has some specifics, there has to be certain enveloping of the spectra which requires testing starting at a lower percentage of the RRS and going up to the 100% of required RRS. The number of these steps can vary between different testing laboratories and their best practice. The danger in doing to many steps and repettions is that the test object can be unnecessarily loaded, increasing the risk of damage before the main test itself. The authors strongly recommend only the necessary steps before the main test itself. Main test is performed only once and maximum strains, accelerations and deflections are measured during this main test.

All further analysis performed take two distinct transformers into account. The first one is a combined instrument transformer type VAU-245 [9]. Transformer base assembly is made from structural steel and the insulator material is porcelain. The transformer VAU-245 was tested in IZIIS, Skopje, per IEEE 693-2005 standard, mounted on a steel support structure. The unit contained a porcelain insulator. Transformer has successfully been qualified to the High Seismic Qualification Level with ZPA=0,5g of RRS according to the IEEE 693-2005. Since the laboratory is equipped with bi-axial shaking table (one horizontal and one vertical axis), and during bi-axial test, it was shown that a significant coupling exists and the transformer was tested with horizontal acceleration increased by a factor of 1.4, according to IEEE 693-2005 A.1.1.2.2. [5]

The test method consisted of resonant frequency search tests and bi-axial time history shake table testing. Bi-axial time history tests were carried out with simultaneous but independent inputs into the horizontal Y and vertical Z axes, each producing the High Required Response Spectrum (RRS). Results are shown and compared with FEM analysis in the next chapter. **Figure 3** shows the applied TRS (Test Response Spectrum) against the RRS.

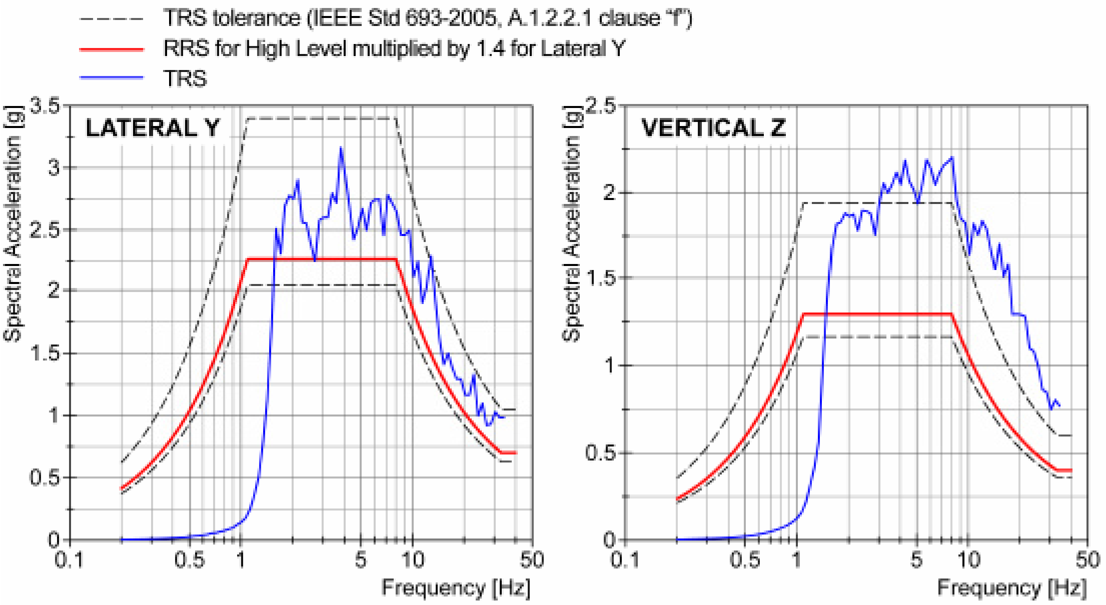


**Figure 3 Input time history (Random) and TRS vs RRS for VAU-245**

**Figure 4** shows the seismic outline drawing made for the tested transformer with all relevant data.

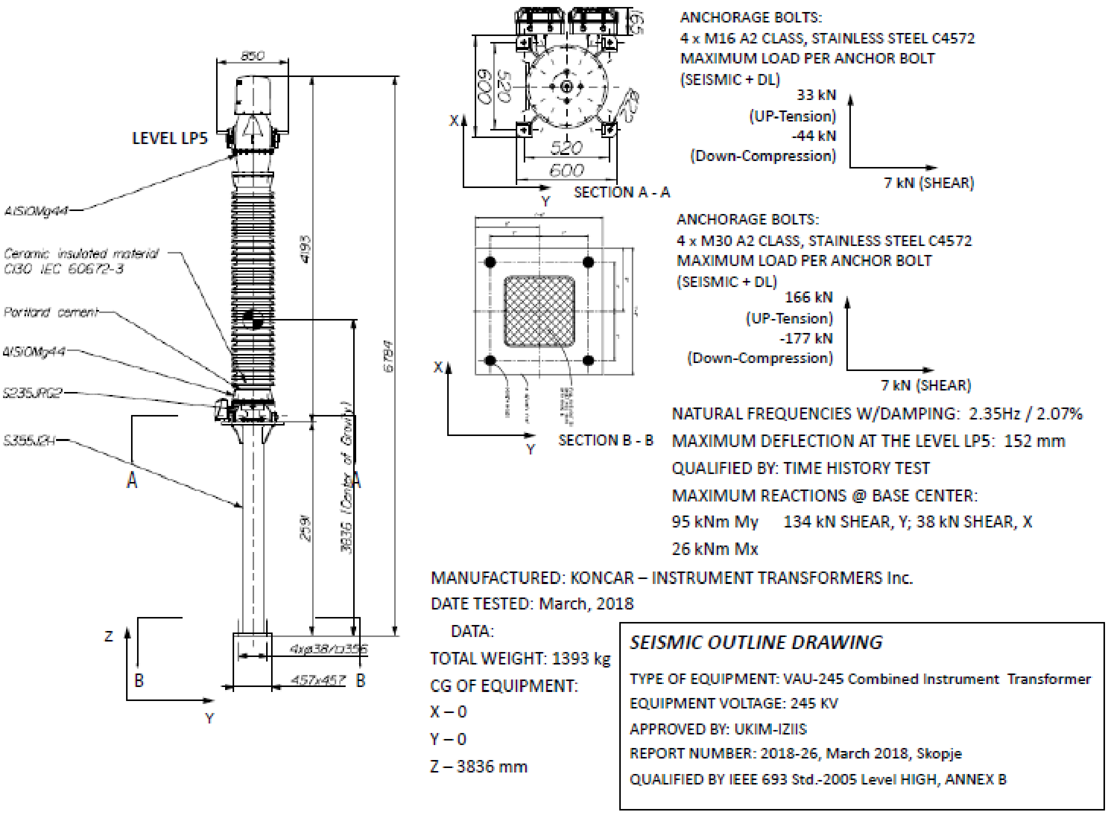


**Figure 4 Input time history (Random) and TRS vs RRS for VAU-245**

The second tested transformer was an inductive voltage transformer type VPU-145 [10]. The transformer was tested in CESI laboratory, Italy per IEEE 693-2018. The unit had a composite insulator and was tested mounted on a steel support structure. Transformer has been qualified to the High Performance Seismic Qualification Level with ZPA=1g of RRS according to the IEEE 693-2018.

Laboratory is equipped with tri-axial shaking table. The test method consisted of resonant frequency search tests and tri-axial time history shake table testing. Tri-axial time history tests were carried out with simultaneous but independent inputs into the horizontal X and Y, and vertical Z axes, each producing the High Required Response Spectrum. Results are shown and compared with FEM analysis in the next chapter. **Figure 5** shows the applied TRS (Test Response Spectrum) against the RRS.

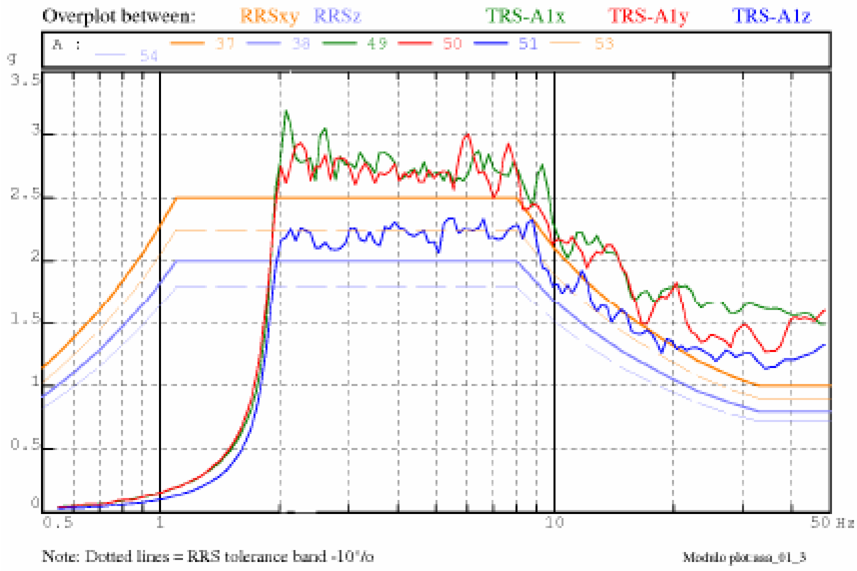


**Figure 5 Input time history (Random) and TRS vs RRS for VPU-145**

**Figure 6** shows the seismic outline drawing made for the tested transformer with all relevant data.

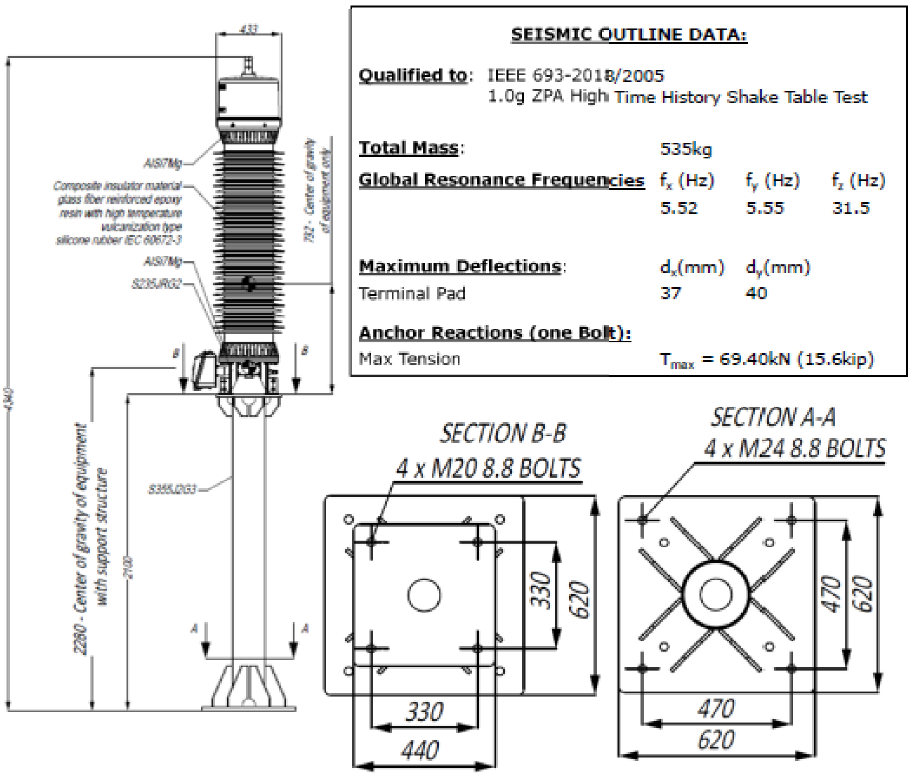


**Figure 6 Input time history (Random) and TRS vs RRS for VPU-145**

## 4. FEM ANALYSIS AND RESULTS COMPARISON

FEM analysis is advised to be used both as pre and post analysis of shake table tests. In both cases, the main goal is a better understanding of instrument transformers' dynamic behaviour. As a powerful tool, FEM analysis provides an opportunity for design iterations which can result in a well-optimized product. The main goal of this paper was to present the results from seismic shake table testing for two different instrument transformers with different insulator material and compare them with the FEM analysis performed on those two transformers. As mentioned earlier, Response Spectrum method in combination with Modal analysis was used [3].

The comparison of results from FEM analysis and shake table tests are shown in **Table III**. As it can be seen, there is a good relation between the test shake table results and FEM analysis, with the maximal difference within 15%. Furthermore, and adequate matching of natural frequencies in both transformers is observed, which is typically an indication of a correctly implemented model.

***Table III*** **Comparison of shake-table testing and performed FEM analyses for both units**

| | VAU-245 | | | | VPU-145 | | | |
|---|---|---|---|---|---|---|---|---|
| | Natural frequency [Hz] | Base assembly stress [MPa] | Insulator stress [MPa] | Directional deformation [mm] | Natural frequency [Hz] | Base assembly stress [MPa] | Insulator stress [MPa] | Directional deformation [mm] |
| Shake table test | 2,35 | 21 | 14,3 | 152 | 5,55 | 74,4 | 10,93 | 37 |
| Response Spectrum method | 2,27 | 24 | 14,8 | 158 | 5,61 | 68,2 | 9,5 | 32 |
| Difference [%] | 3,5 | 14,2 | 3,5 | 3,3 | 1 | 9,1 | 15 | 15,6 |

One of the results that attention should be paid to is the stress on the insulator, which exhibited good correlation for both considered cases. Porcelain is a brittle material and mechanical properties are determined by the manufacturer technology. Generally speaking, the more controlled and automated the production process is, the more predictable the properties of porcelain are [11]. This is extremely important since IEEE 693 and other standards define safety factors for porcelain insulators based on standard deviation of the breaking force. If the standard deviation is high, achieving certain force results with the higher insulator mass and it affects the behaviour of whole transformer.

Both materials are anisotropic, so to reduce the computing time a homogenous material must be created. For composite insulators, different moduli of elasticity for all three different axes were implemented. All data used in the analyses was supplied by the manufacturer, obtained on similar insulators, which could lead to certain discrepancies between shake table tests and FEM analyses. Still, those discrepancies are well within acceptable limits.

The comparison of actual test to the calculated data for combined unit type VAU-245 and inductive voltage transformer VPU-145 is shown in **Figure 7** and **Figure 8**, respectively.

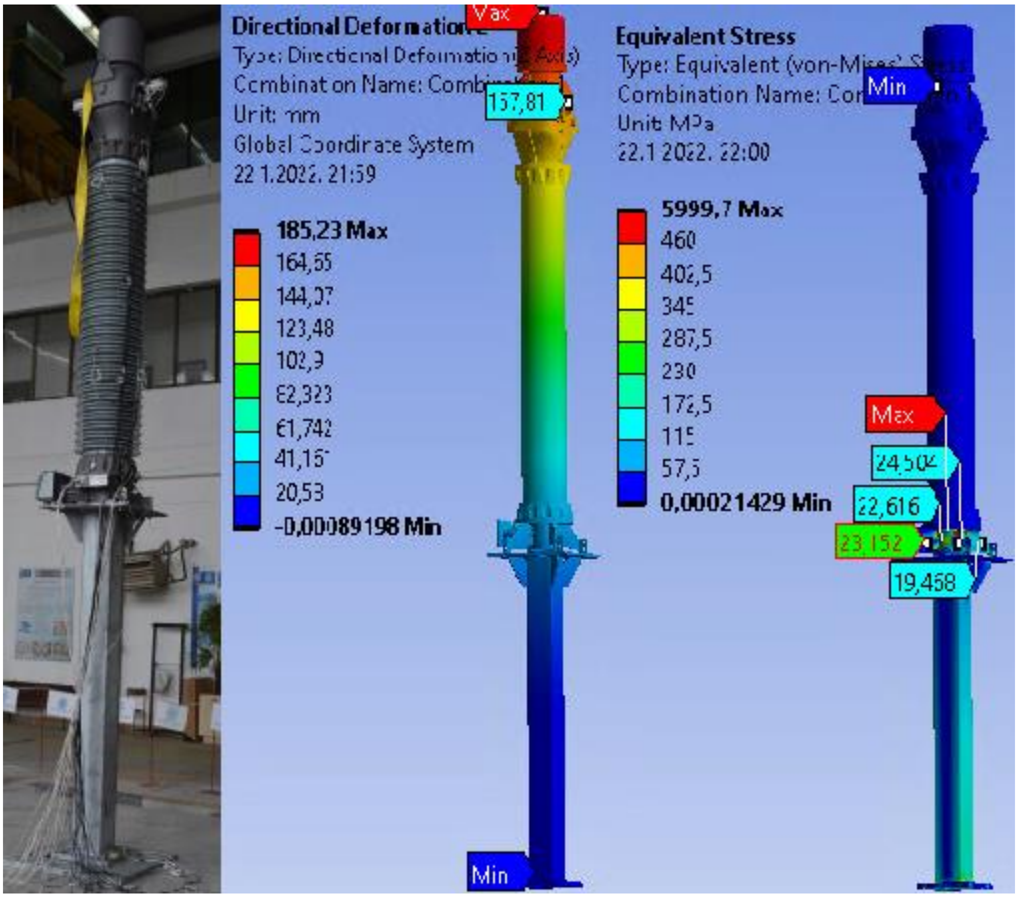

**Figure 7** VAU-245 in test and FEM analysis

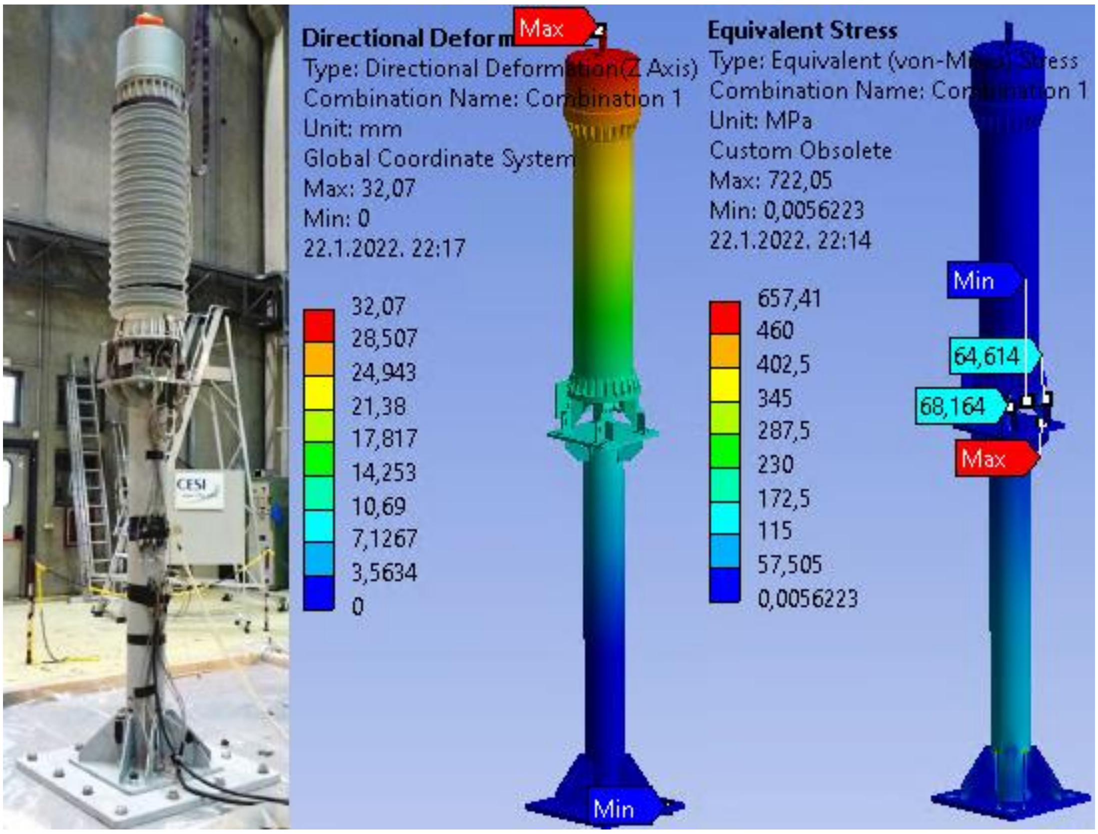

**Figure 8** VPU-145 in test and FEM analysis

One of the main points of this paper is to suggest that any unit should be qualified with an included support structure. It is clear that in some cases the actual structure it will be mounted on is not known at the time of design. Even then, a more realistic representation of the unit's behaviour will be obtained if it is considered with a default structure than no structure at all. The same recommendation is corroborated by data shown in **Figure 9**.

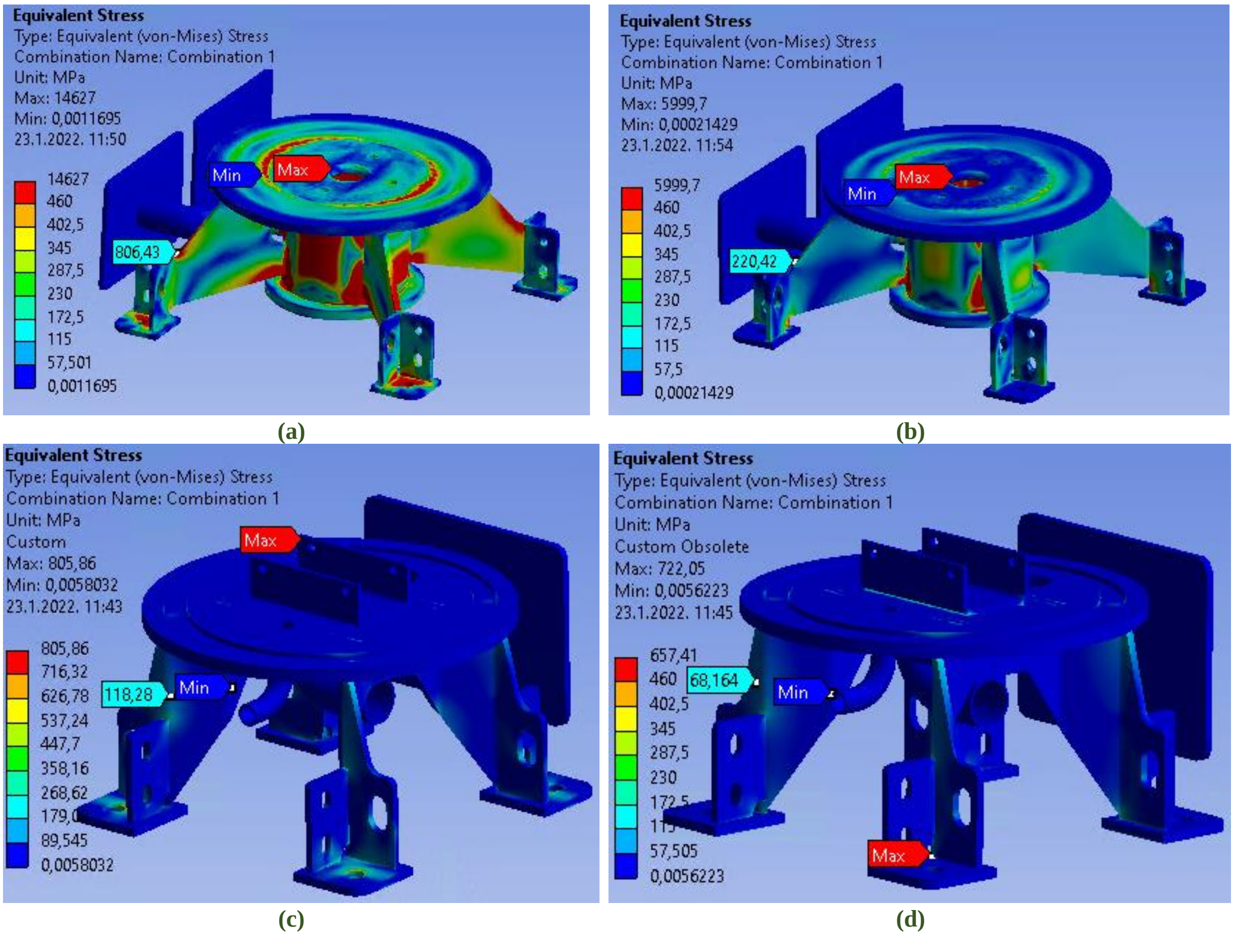


**Figure 9 Comparison of equivalent stress for CTVT Type VAU-245: (a) CTVT Type VAU-245 without steel support structure (b) CTVT Type VAU-245 with steel support structure (c) VT Type VPU-145 without steel support structure (d) VT Type VPU-145 with steel support structure**

As it can be seen in **Figure 9**, in a critical area in VAU-245 base assembly exhibited a stress concentration which is two times higher than ultimate tensile stress and in terms of absolute change at this point, stress is almost four times higher than in analysis with support structure. In case of VPU-145, there is similar relation between results. This only means that the design of the unit has to be overdimensioned in a location that would not be exposed to this type of stress in actual operating conditions (i.e. with the unit mounted on a support structure).

Moreover, per clause 5.10.4 of IEEE 693-2018 standard, when tests or analyses must be carried out without support structure, the input accelerations have to be multiplied with a factor of 2,5 [4]. **Table III** shows the comparison of results of FEM analysis with and without support structure, obtained at the same measurement points in order to see how it affects the whole structure, not just steel base assembly. As expected, there is a huge difference between results with support structure and without.

Almost all calculated values for VAU-245 mounted directly without a support structure present are more than two times higher than those with support structure. VPU doesn't follow the same relations since it has much lower weight, center of gravity and a composite insulator. However, there are also visible increases in stress, especially in the base assembly. For those reasons, the authors strongly recommend that testing should be done with the support structure in order to avoid such situations.

***Table IV*** **Comparison of FEM results with and without support structure for both units**

| | **VAU 245** | | **VPU 145** | |
|---|---|---|---|---|
| | Base assembly stress [MPa] | Insulator stress [MPa] | Base assembly stress [MPa] | Insulator stress [MPa] |
| FEM with support structure | 52 | 14,8 | 68,2 | 7,15 |
| FEM without support structure | 24 | 33,5 | 118,3 | 7,7 |
| Difference [%] | 217 | 226 | 173 | 7,7 |

It should be mentioned that the comparison of test results and Response Spectrum method does introduce some uncertanties, primarily due to a different nature of testing and Response Spectrum method. Tests can be considered as a nonlinear transient real-life analysis while Response Spectrum method is a linear method derived from time history analysis [12]. It uses input as a maximum response of SDOF (Single Degree of Freedom) systems of time dependent loads [13].

In addition, shake tables are enormously complex and massive hydraulic systems, with obvious tolerances and limitations on their performance, which can result in different TRS (Test Response Spectrum) than expected one which can over test the transformer (it is usual to have rises and drops of signal which results with non-uniform time history plot).

Consequently, it is expectable to have certain deviations between the shake table tests and Response Spectrum method. As another way to ensure the reliability of the results, there is a nonlinear Time History method which can deliver even better results than Response Spectrum [3].

## 5. CONCLUSION

There are three main conclusions to this paper, which were corroborated by comparisons of different standards, tests and FEM calculations.

The first conclusion is that the preferred standard for seismic qualification should be IEEE 693:2018 as it gives the most well-rounded, stringent requirements and recommendations as well as standardized requirements on documentation and contents of each report. The upcoming revision of the IEC 61869-1 standard (i.e. 38/652/CD) introduces a worthwhile approach where all requirements are included in a product-specific standard. However, it is lacking in many areas, compared to the IEEE 693. For that reason, any qualification performed according to IEEE 693 should be inherently applicable to the requirements of the IEC standard, which will hopefully be recognized by the international experts.

The second conclusion is that FEM analysis can be used as a reliable tool both for design qualification and design optimization. Actual testing results obtained for two units with different parameters, materials and testing standards were compared to FEM analysis and displayed a good correlation.

The final conclusion of the paper is that instrument transformers should always be qualified with support structures. If actual support structures are not known or available, the units should be qualified with default, manufacturer-recommended structures. The rationale is, even with a different support structure, the results and stress distribution are more representative to actual operating conditions than units tested directly on the ground surface with a superelevation factor applied. In laymans terms, qualification without a support structure places an inappropriate amount of stress where it normally would not be.

This paper is aimed to serve as a fundamental guideline for adequate interpretation of different standard requirements and a basis for further research in seismic performance of instrument transformers, which is a fast-evolving topic in the e xpert community in recent years.

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