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EXPERIMENTAL AND ANALYTICAL STUDY OF A HIGH VOLTAGE INSTRUMENT TRANSFORMER

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SUMMARY

Based on the current state of knowledge on earthquake hazards and vulnerability of electrical transmission and distribution system several issues need investigation. This paper focuses on the equipment performance and as a special case on a current transformer (CT). They usually have a narrow long porcelain insulator, which is the most vulnerable part subjected to earthquake. The paper deals with theoretical and experimental studies on dynamic behavior of one such electrical equipment, namely 132 kV CT model pc-65 from Mitsubishi Factory. A large number of tests have been performed with shaking table facility to determine seismic performance of models for structures and equipment. The results of shaking table tests and those obtained from analytical models have been compared for the CT to develop the analytical model for different height and stiffness cases. Comments for decreasing the fragility and retrofit practice are introduced in the paper as well.

INTRODUCTION

The vulnerability of high voltage substation, particularly narrow slender ones, has been the main cause of power grid failure in the past earthquakes in Iran. Based on the current state of knowledge on earthquake hazards and vulnerability of electrical transmission and distribution system several issues need investigation. Ground motion data base, electrical substation equipment performance, earthquake fire safety associated with gas and electrical systems, vulnerability of equipment-housing buildings, and finally vulnerability of underground cables are among the important ones [1]. Of particular interest is current transformer (CT), which had

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many cases of damage in past and recent earthquakes, especially during Manjil earthquake of 1990 and Bam earthquake of 2004. The support mounting of this equipment plays an important role as it changes the dynamic characteristics of the equipment. During Manjil earthquake, with maximum horizontal acceleration of 0.3g and the maximum vertical acceleration of 0.15g, both equipments and building damages was seen in Loshan power plant [2]. Also in the substation at Bam city many Baleteau CTs got severely damaged.

A large number of tests have been performed with shaking table facilities to determine seismic performance of models of structures and equipment, and for assuring compliance with relevant specifications, including most existing and proposed seismic standards [3]. Seismic interaction in interconnected electrical substation equipment has been also studied by several researchers, including Der Kiureghian [4, 5] and also Filiatrault [6]. Seismic evaluation and analysis of 132 kV disconnect switches and 550 kV bushing been performed by Gilani [7, 8], as well as Anagnos [9], who has obtained the fragility curves using a data base gathered in the US. James Wilcoski and Steven Smith have also done some shake table studies to define the capacity of transformer bushing [10].

In Iran the manufacturer of the main electrical equipment have no responsibility for the design of the mounting support, because it is done by different agencies and are usually of different types. Therefore, the equipment should be tested in the laboratory for the response which may cater for different types of support mountings, even though the manufacturers are asked to certify an earthquake time history/spectra at the base of the equipment.

This paper focuses on the equipment performance and as a special case on a current transformer (CT). Current transformer, magnetic voltage transformer and capacitor voltage transformer are different types of Instrument Transformer (IT). They usually have a narrow long porcelain insulator, which is the most vulnerable part subjected to earthquake. The paper deals with theoretical and experimental studies on dynamic behavior of one such electrical equipment, namely 230 kV CT, model pc-65 from Mitsubishi Factory. This is a cascade electromagnetic transformer type used for measuring the Amperage, and consists of a top oil chamber located in a conidial porcelain column which is supported by a four leg oil container, as shown in Figure 1.

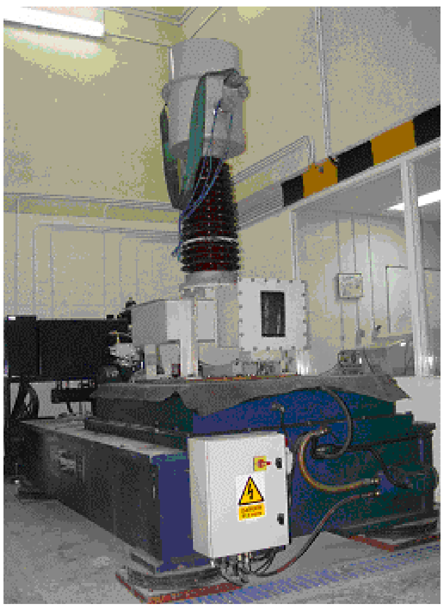

Figure 1- 132 kV current transformer mounted on shake table

Tests have been done in accordance with the shaking levels used in the industry qualification standards for substation equipment, Std693-1997, published by Institute of Electrical and Electronics Engineering (IEEE) [11]. The results of shaking table tests and those obtained from analytical models have been compared for the CT to develop the analytical model for different height and stiffness cases. Comments for decreasing the fragility and retrofit practice are introduced in the paper as well.

THE EMPLOYED SEISMIC QUALIFICATION PROCEDURE

The porcelain insulator is the most delicate and important part which is not supposed to sustain even hair cracks. The properties of the porcelain have been obtained from free vibration test as well as static lateral load test. Dynamic analysis of the CT has been carried out by two methods. In the first one, the CT was analyzed as an assemblage of a rigid beam element which is connected to the flexible mounting frame with a torsion spring. In the second one, finite element analysis was done wherein actual shape of the petticoat was preserved. Both results were compared to the results obtained from shake table tests.

It is believed that seismic qualification should demonstrate the ability of equipment to withstand seismic stresses and to maintain its required function without failure, during and after earthquake of a specified severity. On the other hand, the ground acceleration depends upon the site where the apparatus is to be located. When it is known, it should be prescribed by relevant specification; otherwise the severity level should be selected from tables (IEC-1463) [12]. The ground motion can be described by actual time histories when known, or by artificial time histories which should comply with the required response spectra (RRS). In some cases the severity of earthquake for which the equipment has been designed may be available by manufacturer in terms of RRS or maximum peak acceleration. In order to qualify equipment to withstand earthquakes, the following dynamic problems should be considered:

- the expected magnitude of excitation
- the equipment configuration, and
- the functional aspects of the equipment during and after earthquake.

The use of seismic response spectra as a means for qualifying equipment, either by calculation or by test has become the most widely accepted and powerful methods. The amplified acceleration response of equipment is due to its modes having frequencies in range of 1.1 Hz to 33 Hz as indicated in IEEE Std694-1997 spectra, shown in Figure 2, [11].

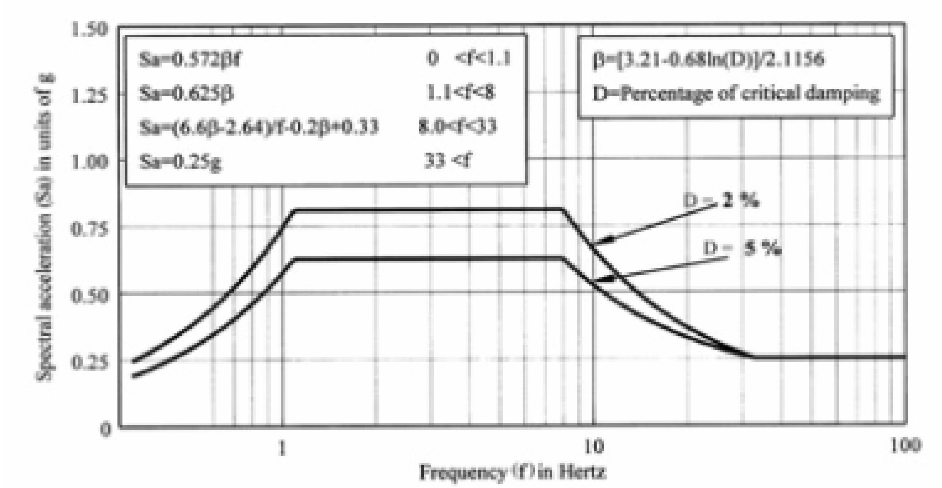

Figure 2- IEEE Std693-1997 test response spectrum for high level qualification

RESULTS OF ANALYSES AND TESTS

Static Coefficient Analysis

This type of analysis usually applies to equipments which have a few important modes in the seismic range. 1.5 times of the peak values obtained from the required response spectra, applied according to the mass distribution in the direction of each of principal axes, are required to account for the multimode effects. From a mathematical point of view, an instrument transformer can be studied as a single degree of freedom (SDOF), that's to say a mass M (total mass of transformer) concentrated at the height H (height of center of gravity). It is also represented by two factors, namely the natural frequency, f, and the damping ratio, ζ, which both can be easily measured during a free oscillation test in which the head of the unit is slowly moved apart from its originals position and then suddenly released. The obtained values for natural frequency and damping ratio of the CT under study are 5 Hz and 3% respectively.

Modal Dynamic Analysis

The use of seismic response spectra as a means for qualifying equipment either by calculation or by test has become the most widely accepted method. Another important point related to this method is its simplicity thanks to the fact that all CTs have basically one resonance frequency in the frequency range of seismic spectra (typically 0.5-33 Hz). The most stressed area in an instrument transformer subjected to an earthquake is the bottom part of the insulator. As a matter of fact, a seismic load induces an horizontal force, located at the gravity center for a SDOF model which cause a maximum bending moment at the bottom of insulator. The stress evaluation scheme is presented in Figure 3.

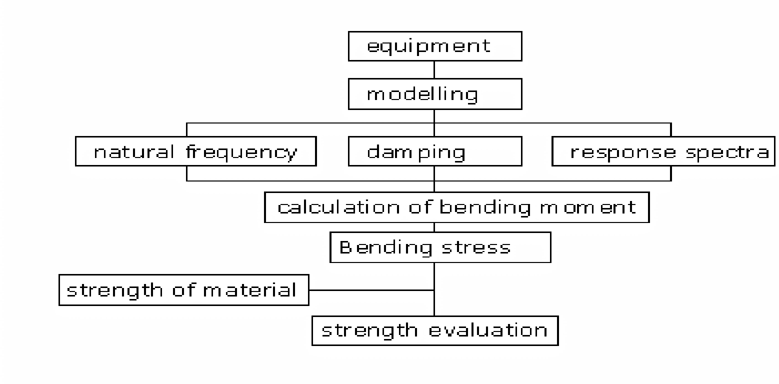

Figure 3- Stress evaluation scheme for the CT

Having the values of natural frequency and damping ratio the response spectrum gives the maximum acceleration and displacement of the CT center of gravity, then calculation of bending moment and corresponding bending stress is possible respectively by Equations (1) and (2).

$$M = \sum_i (m_i * H_i) * Acc \qquad (1)$$

In this equation M is the moment value at the bottom of CT base, m_i is the mass of i^{th} part above the oil container, and H_i is the height of i^{th} mass center of gravity as given in Table 1.

$$\sigma = M / S \qquad (2)$$

In Equation (2) S is the section modulus given by $\pi*(D^4-d^4)/32$, where d is the inner diameter, which is 26.2 cm, and D is the outer diameter, which is 29.2 cm. The values of S is calculated as 25099 cm^3.

Table 1- Masses and heights of CT parts

Item	Mass (kg)	Height (cm)	Moment value (kgf*cm)
Top oil	196.25	124.5	855.16
Top container	108.34	115.5	437.98
Porcelain	51.05	50.5	90.24
Oil inside porcelain	118.46	50.5	209.38
Top flange	19.89	87.0	60.58
Bottom flange	37.98	5.0	6.65

Based on the values of moments given in Table 1, the maximum tensile stress at the bottom section of the CT is obtained as 9.92 kgf/cm^2. Except for indoor or very particular equipment, the Instrument Transformers are always placed on a pedestal or on a frame made by angles, so the center of gravity is in a higher location, and this results in the lower natural frequency, therefore, according to response spectra the acceleration increases and so does the stresses in transformer insulator. So, it is allowed to calculate the flexural stresses at the ground level for all types of CT, as it gives the conservative results compared with the actual situation in substations. Tables 2 and 3 show the porcelain material properties.

Table 2- Minimum flexural strength for two types of porcelain (IEC 60672-3 (1997-01))

IEC Group	Glazed	Unglazed
C110	50 N/mm^2	60 N/mm^2
C120	90 N/mm^2	110 N/mm^2

Table 3- Porcelain properties used by ABB Company

			Type of ceramic materials		
			C110	C120	C130
Property (Minimum Values)	Unit	Test condition	Siliceous porcelain	Aluminous porcelain standard strength	Aluminous Porcelain high strength
Bulk density	g/cm^3	-	2.2	2.3	2.5
Tensile strength	MPa	Glazed	30	50	70
Bending strength	MPa	Glazed	60	100	160
Impact resistance	kJ/m^2	Unglazed	1.8	2.2	2.5
Module of elasticity	MPa	Unglazed	60000	80000	100000

Calculation shows that the flexural stress in porcelain is very little compared with allowable stress based on the porcelain properties, that is:

Tensile Stress = 1.5*9.92*9.81 = 145.97 N/cm^2 << 6000 N/cm^2

Shaking Table Test

As shown in figure 1 eight TML-ARLF acceleration sensors were used for data gathering during time histories, random vibration, and swept frequency tests. The arrangement of sensor is shown in Figure 4, sensors 1, 2, 5, and 6 were used for gathering horizontal acceleration, and sensor 3, 7 and 8 were use for vertical acceleration, and finally sensor 4 was used for strain value at the base of porcelain. El Centro, Tabas, Abbar and Naghan accelerograms were the time histories used in these tests. Sine sweep tests were carried out at four different frequency domains, including 2-4 Hz, 4-8 Hz, 8-16 Hz and 16-32 Hz.

The random vibration tests were also carried out in different types, including random band-width, normal random, random using power spectral density and uniform random. The difference between these random vibrations is in the way they are produced. N-sine wave (10 sinusoidal waves with 2.0 mm amplitude) was also done for comparison. To achieve the noise level, the data were gathered with ambient vibration to estimate the accuracy of digits.

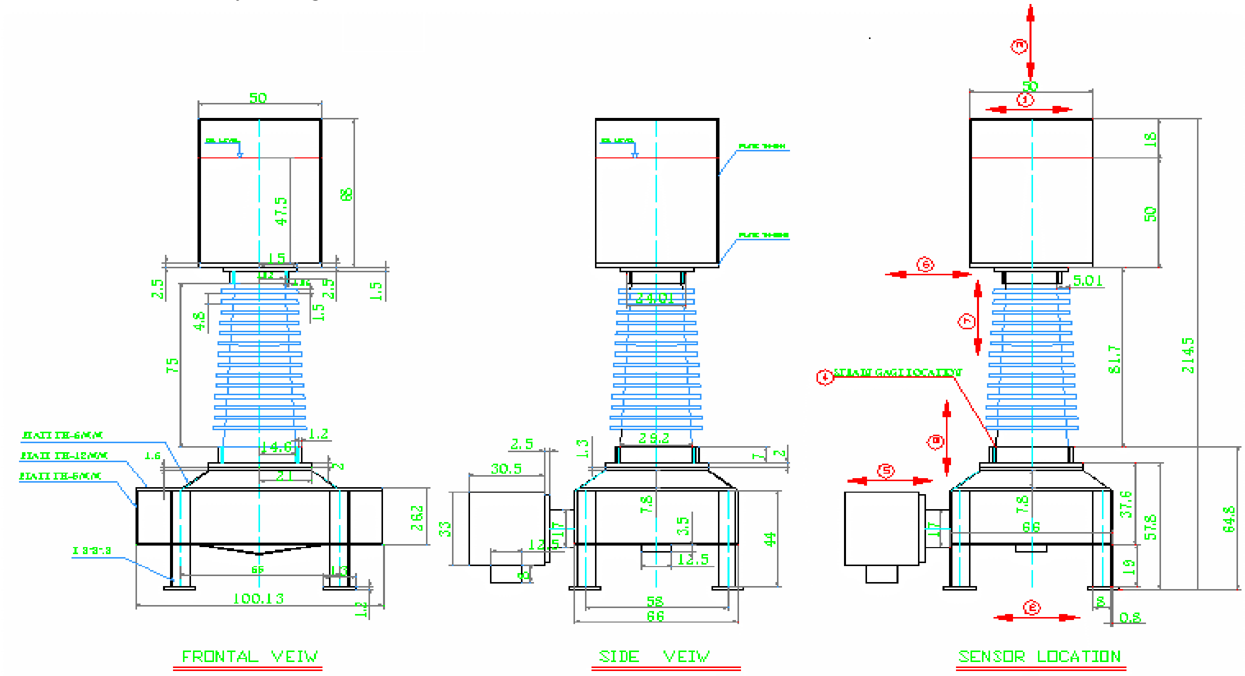

Fig 4- Frontal and side view of the CT

Because of the limitation in number of sensor and also in the shaking table capabilities, each input record has three amplitude levels, but less than *g*. The strain at the base of porcelain and the accelerations in the specified position were recorded. Using MATLAB software the signal processing was done. The acceleration amplification factor was calculated and the stress at the base of porcelain was plotted during the record applications.

Using system identification toolbox, the natural frequencies and damping ratios were calculated with different methods, and compared with the results from free vibration test. The stress time histories were also plotted during the application of records. The results show that during the earthquake, the tensile stress is far from the allowable stress and the equipment, without interaction with other equipments does not have any damage. The amplification factor varies from one record to another; also it changes with the intensity of records. The amplification at the top of CT is greater than the amplification on the bottom container except for the random vibration with low amplitude. A finite element method (FEM) analysis has been also performed for calculating the fundamental frequency of the CT. Tables 4 to 9 show some of the obtained results.

Table 4- Frequency and damping obtained for the CT by tests and FEM analysis

Method	Damping (%)	Frequency (Hz)
Free vibration	3.5	5.0
Shaking table (sine sweep)	4.0	5.1
FEM	----	5.2

Table 5- Maximum acceleration and amplification along the obtained by random vibration tests

Type of random vibration	Max hor. acc. @ top	Max hor. acc. @ frame	Max acc. @ table	Amplification @ top	Amplification @ container
ba100	2.3274	1.523	1.2775	1.8218	1.1922
ba75	1.6368	1.094	0.866	1.8883	1.2621
ba50	0.9988	0.6873	0.5455	1.831	1.26
no30	1.5844	1.4985	1.2125	1.3067	1.2358
no25	1.2648	1.2611	0.9856	1.2833	1.2796
no20	0.9785	0.9577	0.734	1.3331	1.3048
psd20	0.9664	0.9568	0.6301	1.5337	1.5184
psd25	1.2558	1.2302	0.8094	1.5515	1.5198
psd30	1.5425	1.4352	0.975	1.5821	1.472
uni15	0.9645	1.1075	0.8424	1.1449	1.3147
uni20	1.4438	1.4912	1.2607	1.1453	1.1829
uni25	1.8518	1.8322	1.5956	1.16	1.1483

Table 6- Maximum acceleration and amplification along the CT obtained by sine sweep test

Sweep (Hz)	Max hor. acc. @ top	Max hor. acc. @ container	Max acc. @ table	Amplification @ top	Amplification @ container
Sine 2-4	0.155	0.126	0.111	1.399	1.137
Sine 16-32	1.071	0.352	0.236	4.530	1.489
Sine 4-8	0.901	0.326	0.239	3.766	1.361
Sine 8-16	2.978	0.407	0.311	9.567	1.306

Table 7- Maximum acceleration and amplification along the CT obtained by 10 sine waves tests

Record	Max hor. acc. @ top	Max hor. acc. @ container	Max acc. @ table	Amplification @ top	Amplification @ container
10 sine 2.0 mm	1.685	0.951	0.611	2.757	1.557

Table 8- Maximum acceleration and amplification along CT for ambient noise test in laboratory

Input	Max hor. acc. @ top	max hor. acc. @ container	max acc. @ table	Amplification @ top	Amplification @ container
Noise	0.00273	0.0032	0.00135	2.01E+00	3.75E-01

In Table 9 the following abbreviations have been used:

ab: Abbar record
el: El Centro record
na: Naghan record
tab: Tabas record

For better comparison of the obtained results they have been also shown in Figures 5 to 9.

Table 9- Maximum acceleration and amplification along the CT obtained by time histories with different amplitudes

Time history	Max hor. acc. @ top	Max hor. acc. @ container	Max acc. @ table	Amplification @ top	Amplification @ container
ctab100 (x-x)	0.1809	0.1291	0.1181	1.532	1.0936
ctab75	0.1237	0.0956	0.0883	1.4019	1.0834
dctab50	0.0821	0.0688	0.0611	1.344	1.1265
ctna50	2.9673	1.1368	0.9919	2.9916	1.146
ctna40	2.4774	0.8096	0.7417	3.34	1.0916
ctna30	1.8584	0.5705	0.5106	3.64	1.1175
ctta100	0.1552	0.1145	0.083	1.87	1.38
ctta75	0.1068	0.0832	0.0592	1.8055	1.4065
ctta50	0.0721	0.0519	0.033	2.1845	1.5728
ctab100 (y-y)	0.1613	0.1214	0.1097	1.4707	1.1064
ctab75	0.1138	0.0935	0.0847	1.3438	1.1044
ctab50	0.0782	0.0681	0.059	1.3242	1.15
ctel100	0.0863	0.0924	0.0639	1.1923	1.4438
ctel75	0.0535	0.0679	0.0464	1.154	1.4558
ctel50	0.0331	0.0405	0.0301	1.1	1.349
ctna40	1.4617	0.6197	0.6413	2.27	0.966
ctna30	1.1072	0.4967	0.4377	2.5299	1.135
ctna20	0.7199	0.3101	0.2848	2.527	1.089
ab017l100	0.768	0.677	0.515	1.493	1.315
ab017l75	0.191	0.143	0.140	1.366	1.023
ab017l50	0.141	0.107	0.100	1.405	1.071
ab017t100	0.951	1.241	0.893	1.065	1.390
ab017t75	0.541	0.680	0.557	0.972	1.221
ab017t50	0.336	0.482	0.361	0.931	1.336
ab030l100	0.283	0.267	0.234	1.210	1.139
ab030l75	0.208	0.249	0.200	1.041	1.243
ab030l50	0.154	0.195	0.142	1.081	1.375
na0l100	0.241	0.245	0.162	1.485	1.514
na0l50	0.317	0.172	0.165	1.927	1.045
na0l30	0.583	0.529	0.366	1.592	1.444
na0t100	0.383	0.348	0.287	1.332	1.211
na0t75	0.278	0.282	0.247	1.125	1.143
na0t50	0.255	0.388	0.304	0.838	1.277
ta0t100	0.089	0.042	0.061	1.453	0.692
ta0t75	0.058	0.070	0.054	1.069	1.300
ta0t50	0.035	0.049	0.038	0.941	1.314
tab0l100	0.436	0.394	0.326	1.336	1.209
tab0l50	0.084	0.049	0.037	2.280	1.337
tab0l75	0.277	0.261	0.238	1.164	1.096

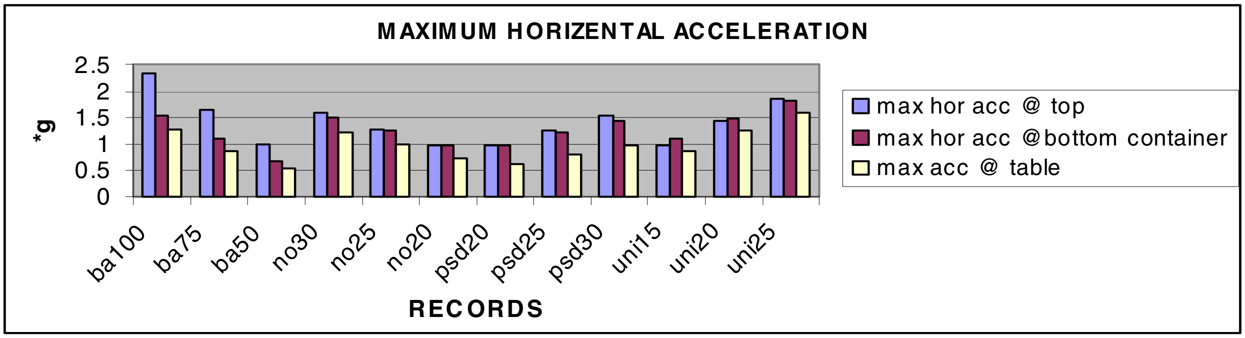

Figure 5- Maximum acceleration along the CT obtained by random vibration tests

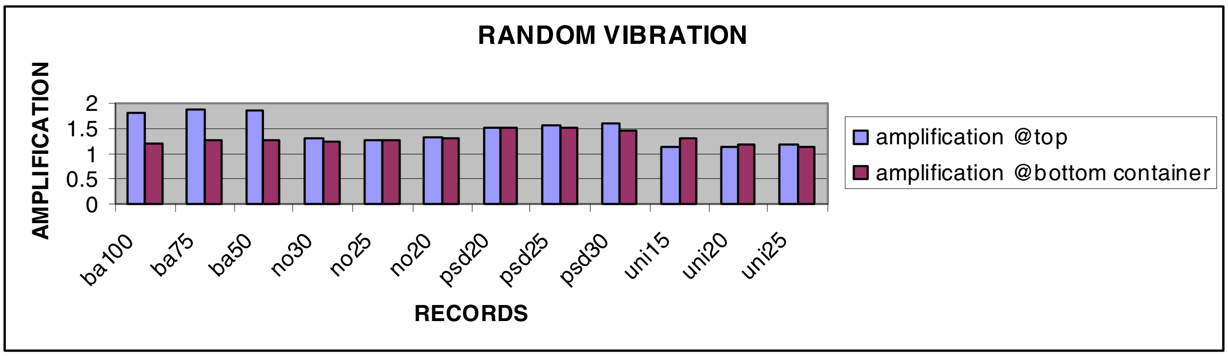

Figure 6- Amplification along the CT obtained by random vibration tests

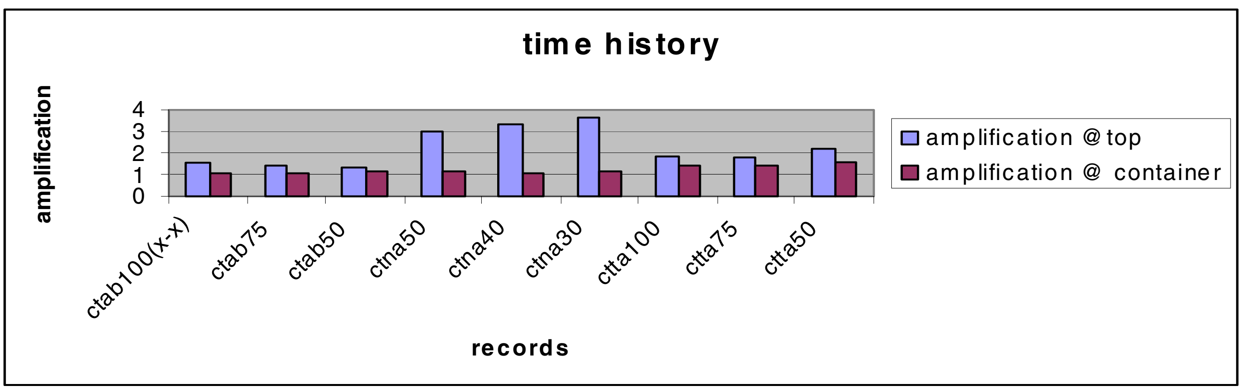

Figure 7- Amplification along the CT obtained by time histories tests

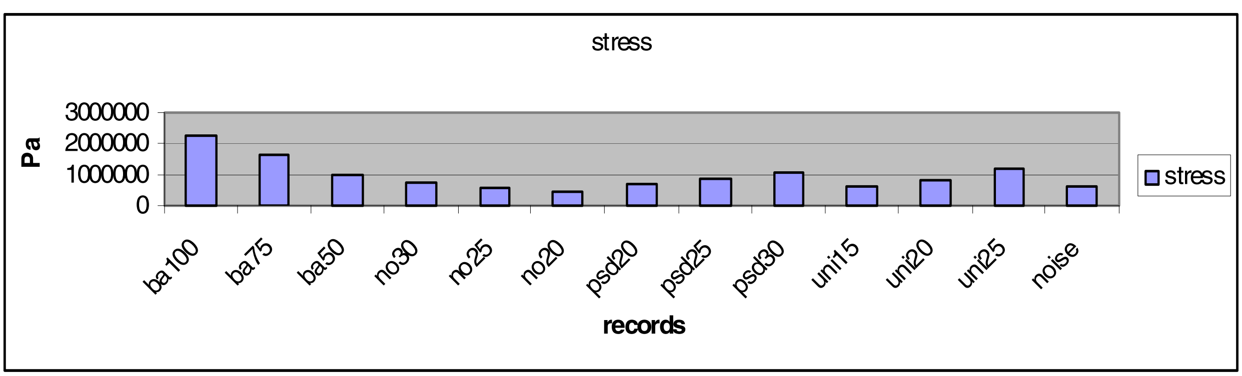

Figure 8- Stress values at the base of the CT obtained by random vibration tests

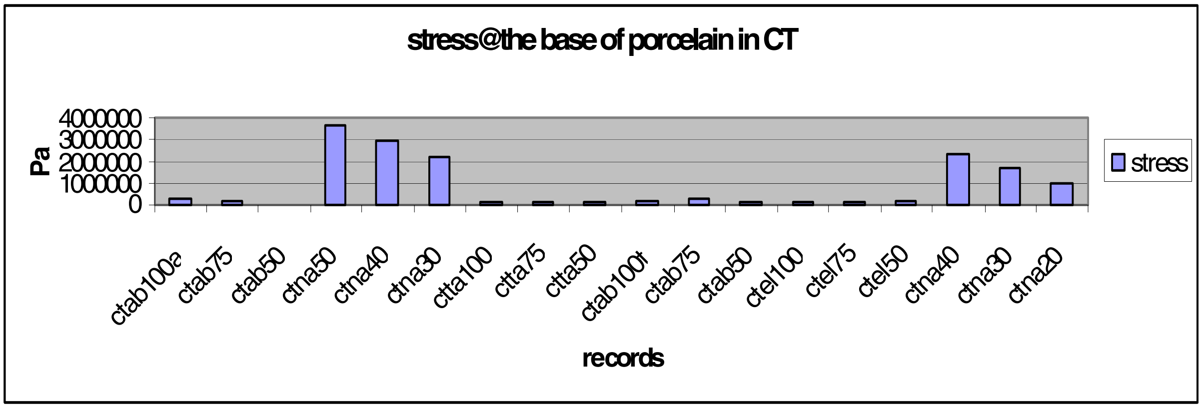

Figure 9- Stress values at the base of the CT obtained by time histories tests

Tests Considerations

There are some consideration for performing the tests, based on which the test results would be accepted as reliable results. These considerations are listed below.

- For porcelain component, the total stress shall not exceed 50% of the porcelain ultimate strength.
- The total stresses in steel component shall not exceed the allowable stress specified in the latest revision of AISC.
- The total stress in a ductile aluminum component shall not exceed the allowable stress specified in aluminum design manual.
- For the cast aluminum or other brittle component the seismic stress shall not be exceed 50% of the ultimate strength.
- Composite components shall not be damaged.
- There shall be no leaks or observable offset of the porcelain on its base, no movement of the porcelain relative to the gasket, and no movement of the gasket

These considerations have been observed in the tests discussed in this paper.

CONCLUSIONS

The 132 kV CT was qualified by test and analysis. The following conclusions can be stated based on this study:

- Both results show that the CT without interaction with other equipment is safe. As shown in Figures 8 to 9 the maximum stress at the base is far from the 50% of allowable stress (25 MPa). The conical shape of CT cause more rigidity than the ordinary ones, and the stiffness of porcelain used in the CT is greater than the ordinary one.
- Static and resonance search tests were conducted to determine the properties of the substation equipment and to assist in preparing simple analytical models. Sine sweep tests show that there are three peaks, one between 4-8 (5.1 Hz), another between 8-16 (9.8 Hz), and the last one between 16-32 (18.0 Hz). Also from free vibration test the natural frequency is obtained as 5.0 Hz, and the damping ratio as 3%.
- As shown in the Tables (5-7); 10sinewave produce higher acceleration than random vibrations at the top of CT and container level, so it is a good tool for qualification.
- Since the porcelain is fixed to the steel container by a flange, the flexibility of container cause an amplification factor of about 1.57 for time histories and 1.52 for random vibrations.

- The maximum amplification factor at the top of the CT is about 1.89 for random vibration and 3.0 for time histories. So it seems that in modal analysis a safety factor is needed to amplify the accelerations more than 1.5.
- Shaking table test and related analysis of CT lead to improved fragility models and identify areas for improving design or retrofit practice. The results from single degree of freedom model were also compared with a three dimensional finite element method and the accuracy of simple method was checked. Consequently, for Instrument Transformers, which have identical structure, supplementary shake table tests are not necessary, since a similar stress distribution for different voltage classes occurs. This allows a valuable prediction of their behavior, confirmed by former actual table tests on the greatest units and presents calculated values for each unit supplied in a seismic zone. This study showed that results from shake table are very close to analytical methods.
- All parts of Instrument Transformer are firmly fixed together and are not moving, so there are four solutions to retrofit the porcelain insulator:
  - Increasing the bottom diameter to increase the section modulus
  - Keeping the same dimension, but taking an insulator with an intrinsic higher strength
  - Providing the transformer with additional dampers.

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