Experimental study of Dynamic Characteristics of 63kV & 132kV Post Insulators with Flexible Conductors

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SUMMARY:
Recent Earthquakes have shown that the electrical substations are very vulnerable, and direct and indirect losses resulting from their damages are highly considerable. Post Insulators in substations are usually used as support for the Bus bars or flexible conductors. According to their height, low lateral stiffness and brittle materials used, they have shown very poor seismic performance. In this paper, the dynamic characteristics of two 63kV and 132kV PIs with flexible connections to their top are studied. The experimental program consisted of tests of individual Post Insulators mounted directly on the simulator platform followed by tests of Post Insulators mounted on the lattice steel structure. Insulators were subjected to a set of sine sweeps and earthquake time histories. The results show that they have very high frequencies and hardly can get damaged, but the lattice steel structure decreased the natural frequencies by almost 70%, which amplifies the acceleration.

Keywords: Substation, Seismic Behavior, Post Insulator, Shake Table Test

1. INTRODUCTION

Earthquakes usually cause extensive direct and indirect losses to the built environment, and among various damages those imposed to lifeline systems are more critical. Electric power network and its complex components have a key role among all other groups of lifelines such as transportation networks, pipelines, communication networks, etc. to vast usage of electrical energy in different industries and its vital role in the industrial production of countries on the one hand, and the dependence of functionality of almost all other lifelines to the electric system saving the flow of the electric energy during and after an earthquake could prevent extensive direct and indirect losses, such as physical vulnerability and severe damages of electric equipment which are very expensive, or business interruption losses due to the electricity outage. This is particularly important in the aftermath of big earthquakes, when all lifelines should be operational, and even present extra services, for successful response activities.

Substations are among the most important parts in electric power networks, and play a vital role in stability, controllability and serviceability of electric energy, yet the experiences gained from the past earthquakes have shown that they are very vulnerable and the direct and indirect losses resulting from their damages are sometimes really considerable. This is due to using of brittle materials such as porcelains, using massive elements with a non-proper distribution of mass in height of the equipment, interaction of adjacent equipment, rigid connections, poor anchorage, insufficient lateral stiffness and strength and so on. Although several studies have been done with regard to seismic risk evaluation and mitigation of electric power systems, very few cases have discussed specifically the substations.
Hwang and Chou (1998) have evaluated the seismic performance of an electric substation using event tree/fault tree technique. They have established event trees / fault trees to delineate interrelationships of the equipment. Using the fragility data of each component and the chosen technique, they have determined the probabilities that the substation, as a whole, fails at various levels of ground shaking, and have displayed the results as the substation fragility curves. Furthermore, in their study, the most critical and vulnerable component in the substation can be identified.

Anagnos (1999) has developed a database that documents the performance of substation equipment in twelve California earthquakes. The purpose of the database is to provide a basis for developing or improving equipment vulnerability functions. Data have been summarized by earthquake, site, and equipment type. Probabilities of failure are calculated by dividing the number of damaged items by the total number of items of that type at the site. Using peak ground accelerations as the ground motion parameter, failure probabilities have been compared with opinion-based fragility curves for a few selected equipment classes. The comparisons have indicated that some of the existing fragility curves provide reasonable matches to the data, and others should be modified to better reflect the data.

Andrew Whittaker et al. (2007) have evaluated the seismic performance of high voltage substation disconnect switches through shake table tests. Several studies regarding the seismic behavior of substations have been performed in PEER at Berkeley. Amir Gilani and his colleagues(1999,1998) have studied the 196kV, 230kV and 550kV porcelain transformer bushings, and Takhirov and his colleagues (1999) have performed the seismic qualification and fragility testing of 550kV line break disconnect switches.

As it is seen, none of the studies mentioned above have focused on the post insulators as common equipment in substations. Therefore, in this paper the main goal is to study the seismic behavior of post insulators and the dynamic characteristics of these elements by the means of shake table tests. The data gained from the tests were used to verify the numerical model. These models are used to evaluate the seismic performance of the elements.

In the following sections of the paper, at first, a brief description is presented about post insulators. Then the test procedure is described, next the results of the experiment are discussed.

2. POST INSULATORS IN SUBSTATIONS AND THEIRVULNERABILITY

The electric power networks usually consist of three basic parts:
1- Generation (i.e. power plants)
2- Transmission (i.e. transmission lines and substations between the cities having high voltages)
3- Distribution (i.e. distribution lines and substations in cities which have low voltages)
All of these components are vulnerable to earthquakes, which may result in significant disruption of power supply. Among these facilities, substation has a critical situation. An electrical substation is a facility that serves as a source of energy supply for the local area and has the main following functions:
- Changing the voltage level
- Providing network operation safety by eliminating the lightning and surges
- Providing power line control by means of measuring instruments

Substations consist of different equipments, the most important of which are:
- Power Transformers (TR)
- Current Transformers (CT)
- Voltage Transformers (CVT)
- Circuit Breakers (CB)
- Disconnect Switches (DS)
-Post insulators (PI)
- Lightning and Surge Arresters (LA)

These equipments are usually in the switch yard. The control panels and the battery room are located in the Control Building which is near the yard. These substations are classified according to their voltage. The high-voltage substations are 400 kV and 230 kV ones. The above-mentioned equipments are shown in Figure (1), from left to right after the guyed tower the equipments are LA, CVT, DS, CB, CT, PI and TR respectively.

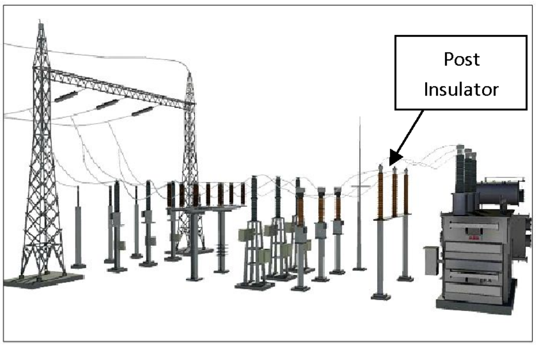


Figure1. Typical substation configuration

The recent earthquakes have proved that substations are very vulnerable, even to moderate earthquakes. There are some obvious reasons for the observed such as:

- Use of brittle materials as the main part of several equipments
- Inadequate anchorage to the base
- Insufficient lateral stiffness and strength
- Low redundancies
- Low level of damping
- Interaction between adjacent equipments
- Interaction between the equipment and its contents
- Having heavy mass
- Improper mass distribution at the height of some equipments
- Poor installation and maintenance besides their remarkable ages in some cases.

It can be seen that most of the imperfections and shortcomings mentioned above can be removed and fixed with an easy attempt. However, as long as these remedies and their implementation have not been studied, the substations are considered high vulnerable and therefore, evaluation of their seismic vulnerability is of great importance. Post insulators are widely used in substations and are commonly used as a support for the rigid aluminum bus bars or flexible conductors in order to maintain the specified height for the conductors connected to adjacent equipments. In this study, the post insulators with flexible conductors connected to the top flange are evaluated, also the slack of the connected cables to the top is assumed to be enough in order to eliminate any possible interactions between adjacent equipments. PI's usually consist of a solid porcelain core with a small diameter in similar parts that are connected to each other by cast iron flanges. According to their voltage, this may lead to a large height for the PI and when they become tall, their lateral stiffness decreases significantly. Also, according to the weakness and brittleness of the used ceramics they will experience sudden cracks and damages.

3. TEST SPECIMENS CHARACTERISTICS

In the test procedure two post insulator specimens 63kV and 132kV were taken, the specimens were provided by an Iranian manufacturer which is the main supplier of the substations in the country.

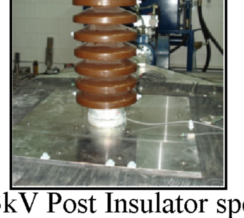


Figure2. 63kV Post Insulator specimen

Figure3. 132kV Post Insulator specimen

The 63 kV post insulator weighs 42 kg and the 132 kV specimen weighs 100 kg. The dimensions of these two specimens are given in table1.

Table1. Dimensions of the test specimens

Dimension (mm)	63 kV	132 kV
Total height	770	1500
Ceramic part height	610	1320
End flange height	80	90
Core diameter	130	135
Total diameter	260	260
Flange diameter	160	260

4. SHAKE TABLE TEST SETUP

The shake table tests were performed in two different stages. At first, the Post insulators were mounted on the table and were shaken separately. In order to mount the specimens on the shake table a solid 700*700*25 mm base plate made of ST-53 steel was designed to withstand the overturning moment and to prevent any damage to the shake table surface, which its details are illustrated in Figure (4).

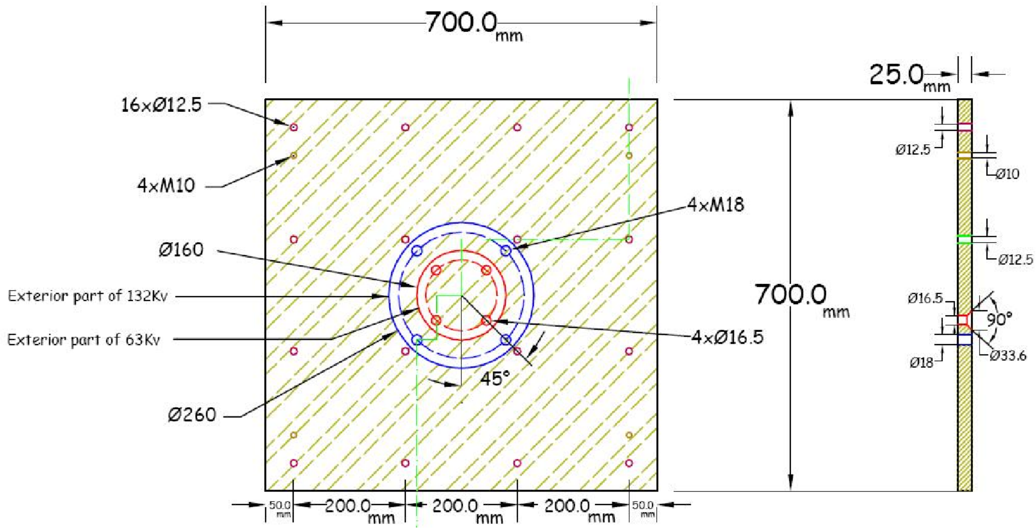
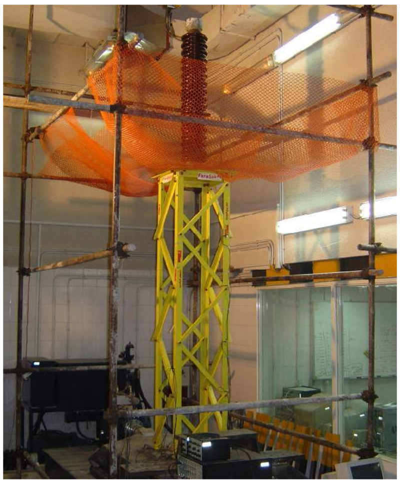


Figure4. The base plate prepared for test

Post insulators are commonly mounted on a lattice steel structure. In order to simulate the actual conditions, in the second part of the test procedure a steel structure within the actual scale and dimensions was used as a support for the PIs. The height of support structure was 2.45m and the vertical members were made of L60*60*6 angles, while the diagonal members are made of L40*40*4 angles. The PI's are mounted on the top plate of the structure by four bolts. The thickness of top plate is 15 mm and the bolts are M16 for the 63kV PI and M18 for the 132 PI. The supporting structure was then welded to the thick base plate mentioned above.

The shake table facility at IIEES structural department has a unidirectional longitudinal plus vertical movement. The dimensions of the table surface are 1200*1450 mm, and the maximum movement amplitude and load capacities are 35mm (on each side) and 2000 Kg respectively.



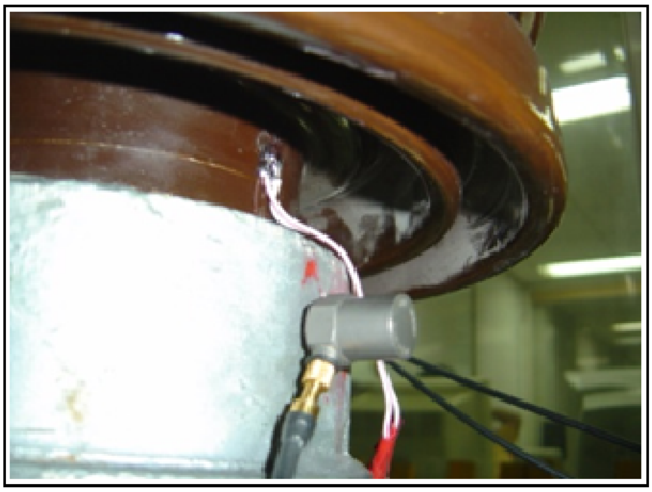


Figure5. The 132kV PI mounted on the support structure **Figure6**. The strain gauge and B&K transducers

According to different types of the transducers, two different data loggers were used in the test. One type of the transducers were TML strain gauge type transducers with two 2g and 5g capacities and the other type were piso-electric B&K high capacity (up to 100g) transducers. In addition to the acceleration sensors two FLA6-11strain gauges were used at the bottom of the ceramic part close to the flange connection at both sides in order to record the strains' history at the most critical section of the specimens.

There were four accelerometers mounted on the body of each PI specimen as shown in Figure (7) at the first part of the test. Two sensors were mounted at each end and two others at the 1/3 and 2/3 of the post insulators height. At the second stage of the test in which the specimens were mounted on the supporting structure, one of the sensors on the body of specimens was dismounted and only one sensor was mounted at the mid height of each specimen. In order to achieve the table accelerations, a transducer was mounted on the rigid base plate on the shaking table as shown in Figure (8), though this data could be taken as the input motions of the test.

The supporting structure was also tested in two stages. In the first part of the test, the lattice structure was shaken alone, and the data were taken to study this structure. In this part, there were eight transducers mounted on the structure as shown in Figure (9). Two sensors at each end and four other transducers at almost four equally divided sections on the height. As shown in Figure (10) three transducers were mounted on the top plate of the structure in vertical directions in order to record any probable torsions of the structure during the test. At the second stage of the test, the specimens were mounted on the top plate of the structure and the sensors on the height of the structure were dismounted and only one sensor was fixed at the mid height of the structure.

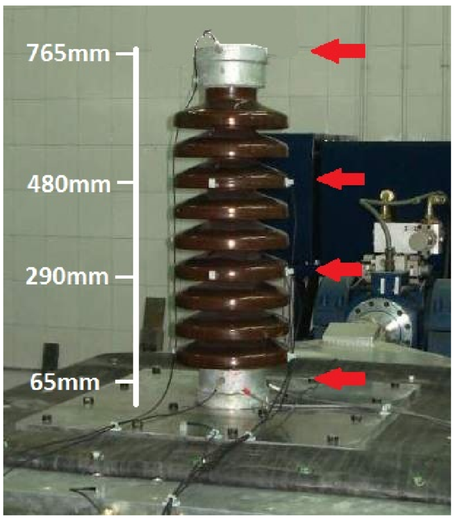


Figure 7.the position of transducers on the 63kV specimen **Figure 8**.the position of transducer on base plate

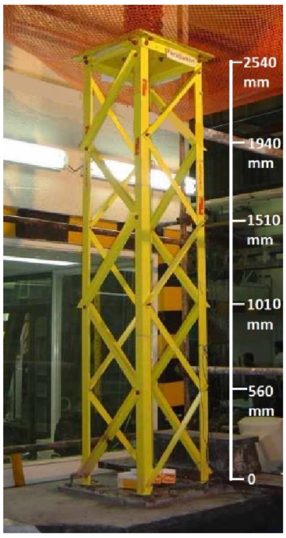


Figure 9.position of transducers on the lattice structure

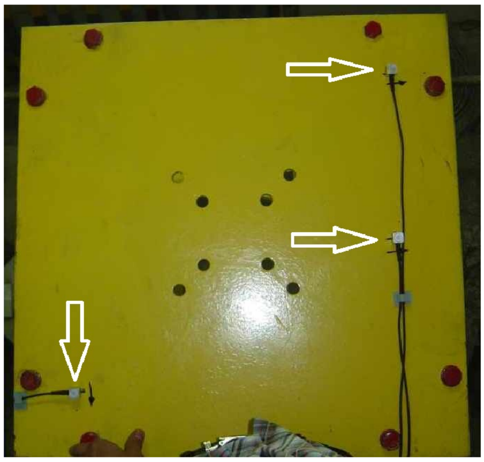


Figure 10.position of transducers on the top plate

5. TEST PROCEDURE, INPUT MOTIONS AND TEST RESULTS

The input motions of the test consist of two different parts. At first, the sine sweep frequency search test was performed in order to derive the natural frequency of the test specimens. The sine sweeps were produced according to IEEE 693-2005 recommendations. Some important notes are as below:
1-A sine sweep frequency search shall be conducted at a rate not greater than one octave per minute in the range for which the equipment has resonant frequencies but at least from 1 Hz.
2-The amplitude shall be no less than 0.05g. It is suggested that amplitude of 0.1g be used.
3-No resonant frequency search in the vertical axis is required.

There were some limitations to the test facility which the important ones are:
1-The maximum displacement of the table is 30 mm.
2- At low frequencies, the maximum applicable acceleration could not exceed 1g.
3-The shake table input is in displacement format.
According to the above limitations and IEEE recommendations, 11 sweeps from 1 Hz to 151 Hz were produced. These sine sweeps apply the amplitude variation versus time, and the acceleration during each sweep is constant. Full descriptions of sine sweeps are given in Table 2.

Table2. Input sine sweeps characteristics

Sweep	Start frequency	End frequency	Acceleration(g)	Maximum amplitude (mm)	duration (sec)
Sweep 1	1	1.6	0.1	24.85	45
Sweep 2	1.5	2.5	0.1	11.04	45
Sweep 3	2.4	4	0.1	4.31	45
Sweep 4	3.9	6.5	0.1	1.63	45
Sweep 5	6	10	0.25	1.72	45
Sweep 6	9	15	0.25	0.77	45
Sweep 7	14	23.5	1.0	1.27	45
Sweep 8	22	36	1.0	0.51	45
Sweep 9	34	57	2.0	0.42	45
Sweep 10	55	92	4.0	0.33	45
Sweep 11	90	151	4.0	0.12	45

After the sine sweep tests, a set of ground motions were applied to the specimens to observe the seismic behavior of the test specimens under earthquake simulation. According to the displacement limitations of the shake table, three input ground motions were scaled down. The ground motions' specifications are presented in table 3. The first record is the IEEE spectrum compatible time history ground motion which is provided by the IEEE 693.

Table3. Input ground motions characteristics

Name	PGA(g)	PGD(cm)	Duration(sec)	Scale factor
IEEE compatible	0.0604	2.98	39.99	0.065
Imperial Valley	0.0716	2.99	39.99	0.23
Tabas	0.133	2.99	23.82	0.39
Northridge	0.562	2.91	39.98	1.0
Coalinga	0.605	2.32	39.99	1.0

In order to validate the acceleration transducers, at first, the transducers were mounted on the table individually and the recorded data were compared with the table input motions. As mentioned before, each specimen was tested in two stages. At first, they were tested individually, and then the test was repeated after mounting the specimen on the lattice steel structure support. The eleven prepared sweeps and five earthquake simulations were applied to the specimens respectively. After each test, the specimens were inspected precisely in order to evolve any probable cracks and minor damages.

According to light weight of the specimens in comparison to 230kV and 400kV Post Insulators and low frequency content of ground motions applied, no cracks and damages were observed. The main results of the tests are recorded acceleration time histories at the points where the sensors were mounted. By computing the FFT of the response of the specimens to each sweep the natural frequency of the PI is derived using Peak Picking Method (PPM).

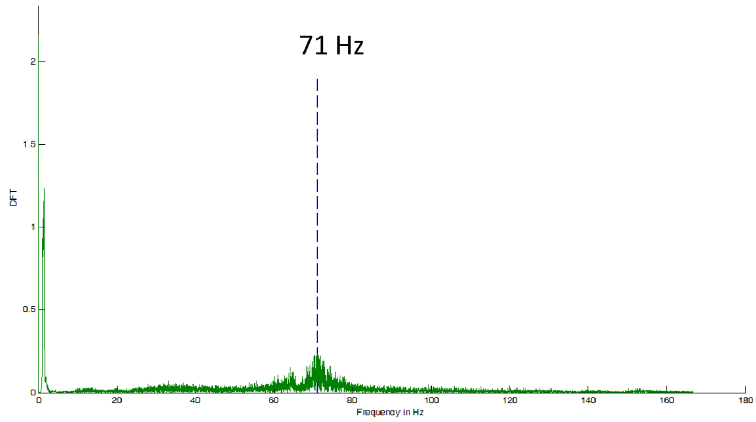


Figure11. Response of the top flange to the first sweep

Peak Picking Method is based on the fact that absolute value of the Fourier transform of a structure response will usually have peaks at the modal frequencies and perhaps also at the input frequencies. The plot of the absolute value of the discrete Fourier transform (DFT) as a function of frequency which is called periodogram for the response of the top flange to sweep 1 is presented in figure (11) as an example. As it is obvious the first mode frequency is about 70 Hz. The frequencies gained by the test are given in Table 4. According to very high values of the frequencies of higher modes, they could not have been evolved by the test and were calculated by the finite element modeling and modal analysis of the numerical model. As it is seen in Table 4, the lattice support structure has a noticeable effect on reducing the natural frequency of the Post Insulators, in some cases the reduction is almost 75%. This will lead to higher responses and seismic demands of the equipments.

Table4. Post Insulators 1st. mode frequencies

Specimen	With out Structure	Mounted on Structure
63 kV	70 Hz	19 Hz
132 kV	28 Hz	9 Hz

6. SEISMIC EVALUATION OF INSULATORS

In order to evaluate the seismic response of the specimens, the acceleration response of the top and bottom flanges of PI and the base plate are plotted. Figures 12 to 14 present responses of the 63kv Post Insulator mounted on the structure to Sweep 1.

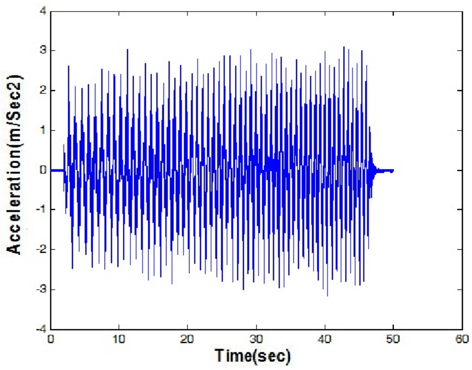


Figure12. Experimental top flange acceleration

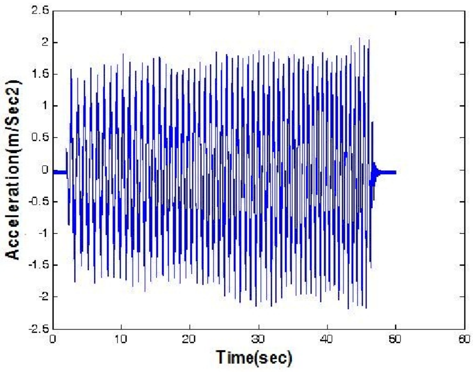


Figure13. Experimental bottom flange acceleration

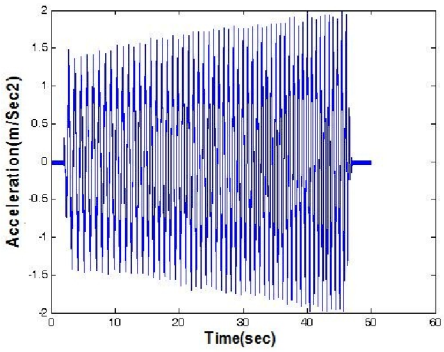


Figure14. Experimental base plate acceleration

The base plate acceleration could be taken as input for the specimens. As it is seen the response of the bottom flange is maximum 2.2 m/s^2 which is very close to the base plate acceleration (i.e. 2.05$m/s^{2)}$, this means the structure is rigid enough, but the top flange response of the PI reaches to 3.1 m/s^2 that is almost 40% more than bottom flange and 50% more than the base acceleration.

The Figures 15 to 17 present responses of the 63kv Post Insulator mounted on the structure to the IEEE proposed ground motion input. As it is seen, the maximum response of the bottom flange is 9.6 m/s^2 that is almost 41% greater than the base plate acceleration which is 6.8 m/s^2, but the top flange response reaches to 13.1 m/s^2 that is 92% more than base plate acceleration. This means that the amplification of the response acceleration is about 1.92.

Figures 18 & 19 illustrate the maximum experimental strains at the sensors mounted on the base of the specimens. The maximum strain at the specimen with structure is 5.02Micro m/m and the specimen without structure is 4.30Micro m/m which is increased by 17%.

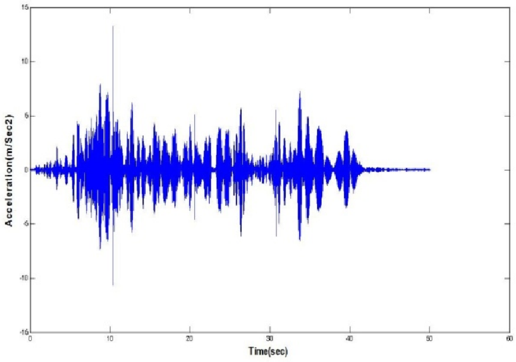


Figure15. Experimental top flange acceleration

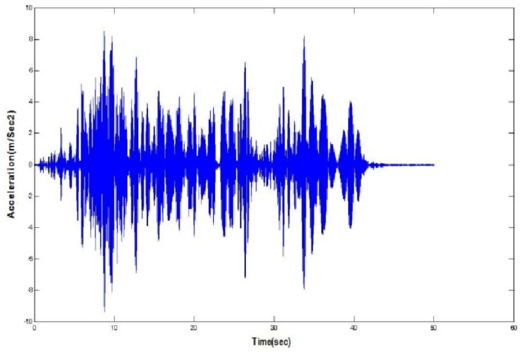


Figure16. Experimental bottom flange acceleration

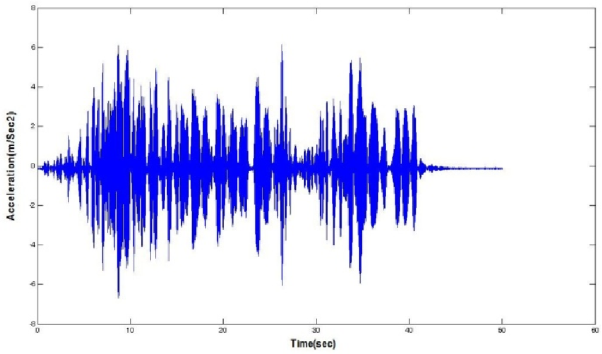


Figure17. Experimental base plate acceleration

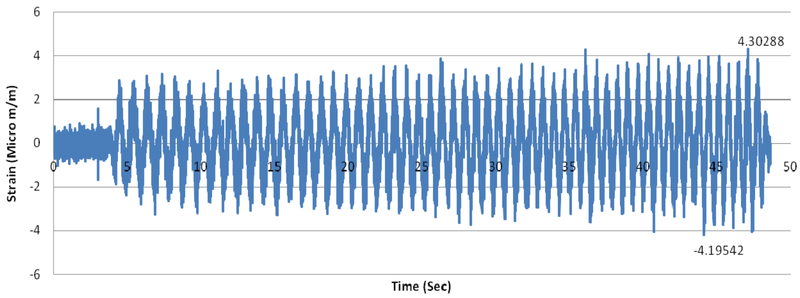


Figure18. Experimental strain at the base of the 63kV specimen mounted directly on the table

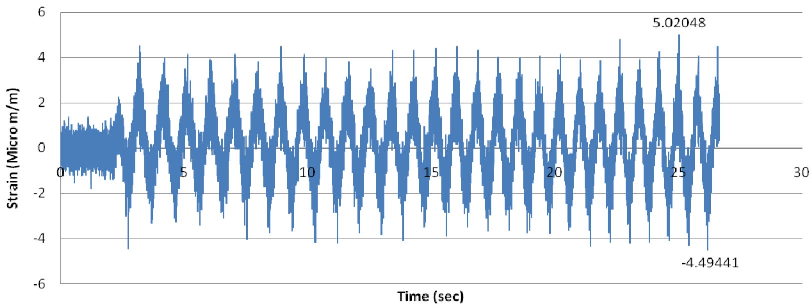


Figure19. Experimental strain at the base of the 63kV specimen mounted on the structure

7. CONCLUDING REMARKS

Based on the experimental studies it can be concluded that:

- The most considerable result of the test was that there were no significant responses from the specimens, and not any damages were observed during the earthquake simulation tests. This is because of the high-frequency content of these equipments that are much greater than that from ground motions, which is usually about 3 to 10 Hz ,and their lower weights.

- Natural frequencies of insulators without supporting structure are very higher than conventional structures due to their high stiffness and low weight.
- The effect of supporting structure on the natural frequencies of insulators mounted on the supporting structure was evaluated. The natural frequencies decrease by almost 70%.
- Effect of the supporting structure on the amplification of the experimental top flange acceleration shows that the kind of structure used amplifies the acceleration by 1.25 compared to the PI without structure.
- Effect of the supporting structure on the amplification of the strains at the base of the specimens shows that the structure amplifies the strains by 1.17.

8.ACKNOWLEDGEMENTS

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