Seismic qualification and time history shake-table testing of high voltage surge arrester under seismic qualification level moderate

Noman Ullah1*, Syed Mohammad Ali2, Rahman Shahzad3 and Faisal Khan1

Abstract: Earthquakes are one of the deadliest forces of nature that can shake structures to their limits. No comprehensive study has been done in Pakistan on seismic performance of electric supply substations and requires immediate attention as Pakistan is one of the highly seismic area in the world with potential of large earthquakes. Seismic qualification of electric supply substation equipment (132 kilo Volt surge arrester) by time history shake-table testing is presented in this paper. This equipment was tested under “Seismic Qualification Level Moderate” that is according to earthquake input requirements of this region. An artificial time history was generated that qualifies the Required Response Spectrum of Pakistan Electrical and Telecom Safety Code (PETSAC-2014) and IEEE Recommended Practice for Seismic Design of Substations (IEEE Std. 693-2005). Two types of measurements (displacement and acceleration) were recorded during time history shake-table testing at four different points using six accelerometers and four displacement transducers. Seismic qualification of electric supply substation equipment is totally a new dimension in Pakistan's electrical power system.

Subjects: Structural Mechanical Engineering; Structural Engineering; Georisk & Hazards; Life-Long Design; Power Engineering

Keywords: time history shake-table testing; required response spectrum; seismic qualification level moderate; pakistan electrical and telecom safety code; high voltage electrical equipment

ABOUT THE AUTHORS

Noman Ullah is serving as lecturer at Electrical Engineering Department, COMSATS Institute of Information Technology, Abbottabad, Pakistan. He earned BS in Electrical (Power) Engineering from COMSATS Institute of Information Technology, Abbottabad, and Masters in Electrical (Power) Engineering from University of Engineering & Technology, Peshawar in 2012 and 2015, respectively. His research interest includes design, analysis, seismic testing, and seismic qualification of high voltage electrical equipment, their concrete foundations and supporting steel structures. In design process, while following guidelines illustrated in IEEE Std. 693-2005 can reduce fatal and nonfatal accidents and ensure safety of assets of the related entities.

PUBLIC INTEREST STATEMENT

8 October 2005 earthquake was one of devastating earthquake in the history of Pakistan, seriously damaged electrical power transmission system, distribution systems, and hydropower generating stations with an estimated damage of Rs. 641.8 million. Objective of this research is to reduce fatal and nonfatal accidents of employees and general public and ensure safety of assets of the related entities. If electrical power system equipment ceases to fulfil its function and needs replacement then it would have two major impacts on the society; one would be direct cost related to power system equipment and second but most expensive and costly would be the indirect cost for the entire downtime. Thus accurate performance of power system is essential before, during and after natural disasters such as earthquakes.
1. Introduction
Safety of employees and general public from electrocution and allied hazards, and safety of utility assets shall be top priority of all utility companies (transmission and distribution) in Pakistan (Pakistan Electrical & Telecom Safety Code [PETSAC], 2014). Electric supply substations are vital component of electrical power system. In case of a natural or manmade disaster, if electric supply substations cease to fulfil its function, it can further exacerbate an emergency situation and impede provision of much needed emergency services, such as, in hospitals and emergency shelters. Apart from their functional and strategic importance, electric supply substations are expensive infrastructure assets whose survival in an extreme event is highly desirable, as replacement costs are high and social and economic costs during the downtime can be significant. Thus, ensuring safety of electrical power distribution network and facilities under extreme events is essential.

Earthquakes are one of the deadliest forces of nature that can shake structures to their limits. The term used to define the potential of earthquakes is “Seismic Hazard”. Different areas would have different seismic hazard based on the studies of past earthquakes by means of geological and seismological studies done by researchers dealing with earth sciences and seismology.

The IEEE Std. 693-2005 “Recommended Practices for Seismic Design of Substations” (IEEE Std. 693-2005, 2005) provide comprehensive set of guidelines for the seismic design of substation buildings, structures, and equipment. IEEE Std. 693-2005 (2005) is intended to establish standard methods of providing and validating the seismic withstand capability of electrical equipment. It provides detailed test and analysis methods for each type of major equipment. It establishes standard methods of verifying seismic withstand capability, which gives the designer the ability to select equipment from various manufacturers, knowing that the seismic withstand rating of each manufacturer’s equipment is an equivalent measure. Significant portion of the guidelines is devoted to the requirements for “Seismic Qualification” of substation equipment. “Seismic Qualification” of equipment may be defined as “A process which consists in establishing the appropriate withstand capabilities of an equipment against seismic forces that are considered appropriate for the class of equipment being considered, assuring that the equipment being qualified shall function after a seismic event and its service life is not compromised”.

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 method. The various methods recognized by IEEE Std. 693-2005 (2005) for carrying out seismic qualification of electrical equipment (Surge arrester) include qualification by: Inherently acceptable, static coefficient analysis, dynamic response spectrum analysis, and time history shake-table testing.

1.1. Inherently acceptable
Neither a seismic report, a nameplate, nor a seismic outline drawing is required. However, calculations that demonstrate the following anchorage requirements shall be provided to the user or user’s agent. The equipment anchorage shall be capable of withstanding at least 1.0 times the equipment weight applied in one horizontal direction combined with 0.8 times the weight applied in the vertical direction at the center of gravity of the equipment and support. The resultant load shall be combined with the maximum normal operating load and dead load to develop the greatest stress on the anchorage. Both orthogonal directions shall be checked, and the greatest stresses shall be used in the design of the anchorage.

This is only valid for surge arrester having duty cycle voltage rating less than 35 kV DCV.

1.2. Static coefficient analysis
The acceleration response of the equipment shall be determined using the maximum peak of the Required Response Spectrum (RRS) at a damping value of 2%, unless a higher value for damping is justified by a test. The seismic forces on each component of the equipment are obtained by multiplying the values of the mass times the maximum peak of the RRS times the static coefficient. A static
coefficient of 1.0 or 1.5 shall be used, with 80% of the horizontal value being applied in the vertical axis. The resulting force shall be distributed over the components in a manner proportional to its mass distribution. The stress at any point in the equipment shall be determined by combining the three orthogonal directional stresses (at that particular point) by the square root of the sum of the squares (SRSS) method at that point and combining all dead and normal operating stresses in such a manner to obtain the greatest stress at the point.

This is only valid for surge arrester having duty cycle voltage rating greater than 35 kV DCV and less than 54 kV DCV.

1.3. Dynamic response spectrum analysis
Using dynamic analysis, the equipment and any support structure shall first be modelled 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 shall be such that an adequate representation of the modelled item(s) is obtained in the context of a seismic analysis. The resulting system is called a finite element model. The finite element model shall be dynamically analyzed using a “modal spectrum analysis,” as described, for example, by Chopra (1980) and Gupta (1992). In general, the modal responses of the finite element model to the dynamic analysis shall have three translational and three rotational components in and about the defined orthogonal axes system.

This is only valid for surge arrester having duty cycle voltage rating greater than 54 kV DCV and less than 90 kV DCV.

1.4. Time history shake-table testing
Seismic qualification by time-history testing of the equipment using a shake table is a rigorous test method which is considered to provide clear evidence of the capability of equipment to withstand seismic forces. Seismic qualification by time-history testing can be divided into two steps; namely, (1) Resonant frequency test (Free vibration test), and (2) Time history shake-table testing.

The resonant frequency search test is for determining the resonant frequencies and damping of equipment. The data obtained from the test are an essential part of an equipment qualification; however, the test does not constitute a seismic test qualification by itself. 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, in the two horizontal axes and the vertical axis to determine the resonant frequencies and the damping. The amplitude shall be no less than 0.05 g. It is suggested that an amplitude of 0.1 g be used. Damping may be found using the half-power bandwidth method. A frequency search above 33 Hz is not required. White noise may be used in lieu of the sine sweep, provided damping is found and the amplitude of the white noise input is not less than 0.25 g.

The equipment and supporting structure shall be subjected to at least one time history test. The input motion time history for Seismic Qualification Level Moderate shall satisfy the requirements of RRS shown in Figure 1. IEEE Std. 693-2005 (2005) principally uses response spectra to establish the characteristics of the time histories used to seismically qualify electric supply substation equipment. A time history may be such that its response spectrum envelops the RRS, but the energy content in certain frequency ranges will be low, so that equipment that has important natural frequencies in that range may not be adequately excited. This result can occur because of the design of the time history or the interaction of the equipment and the shake-table that is exciting it. There is a need to balance the concern that the equipment be adequately excited, with the desire to avoid over-testing equipment during its qualification. Although imposing a power spectral density requirement on the input time history can assure an acceptable distribution of energy over the frequency range of interest, this has proved problematic in attempting to address this issue (Kennedy, 2004). If the response spectrum of a time history is reasonably smooth, a reasonable distribution of the energy in the record is also assured (Kennedy, 2004).
Critical locations on the surge arresters and the supporting structure shall be monitored for maximum displacement, maximum accelerations, and maximum stresses. Monitoring requirements are illustrated as following:

1. Maximum displacement: Top of equipment.
2. Maximum accelerations: Top of equipment (vertical and horizontal).
3. Maximum stresses: Bottom end of porcelain surge arrester, bottom metal end fitting, and base of supporting structure.

The equipment shall undergo standard electrical production tests as defined by IEEE Standard for Metal-Oxide Surge Arresters for Alternating Current Power Circuits (IEEE Std C62.11-1999, 1999) after the completion of the shake-table tests. In addition, devices that are pressurized or sealed against atmospheric contamination shall be tested to ensure seal integrity.

This type of test is valid for surge arrester having duty cycle voltage rating of 90 kV DCV and above.

Various literature research articles are reviewed in order to summarize aforementioned seismic qualification techniques for electric supply substation equipment. Authors of Ala Saadeghvaziri, Feizi, Kempner, and Alston (2010) explains the seismic performance of electric supply substation transformer and bushings. An actual case study of 433.3-MVA transformer, results of fixed base case and isolated base case are compared and discussed. Authors modelled the transformer data and extracted results through Finite-element analysis (Figure 2). Mohammadi and Pourkashani Tehrani (2013) explains the seismic behaviour of three interconnected pieces of electric supply substation equipment using shake-table testing and discussed that although electric supply substation equipment are designed according to seismic requirements but when they are interconnected to each other they show poor performance.

In this paper, results of time-history shake table testing of a high voltage surge arrester are presented. Shake table (Model: R141) having table top of 1.5 × 1.5 m with 1DOF and maximum payload capacity of eight (8) tons with maximum acceleration of ±1.1 g and maximum velocity of ±1.1 m/s manufactured by ANCO Engineers Inc. USA is used for seismic qualification (details are illustrated in Table 1). To the best of the authors’ knowledge, this test is the first such test of its kind performed in
Pakistan, as in the past it has been a practice to have such tests conducted abroad due to lack of testing facilities.

2. Technical background

2.1. Electric supply substation

General layout of step-down electric supply substation is shown in Figure 3. The high tension transmission line is received by isolator; isolator is a no-load operating device and can be only operated when the high tension transmission line is de-energized. After that current transformer is installed and is used for metering and protection purposes. Circuit breaker is the equipment that can be used to disconnect and isolate the circuit under loaded/energized conditions. Lightening/Surge arrester is used to protect the transformer from lightening and over-voltage damages. Transformer is the most important and costly equipment used in electric supply substation, it is used to step-down or step-up voltage level. Once the voltage level is decreased, the power circuit can be distributed through underground cables to the control panels of electric supply substation.

### Table 1. Seismic simulator specification

| Name                      | R141       |
|---------------------------|------------|
| Manufacturer              | ANCO Engineers Inc. USA |
| Table Top                 | 1.5 × 1.5 m |
| Type                      | 1DOF       |
| Maximum Payload Capacity  | 8 tons     |
| At 4 tons                 |            |
| Acceleration              | ±1.1 g     |
| Velocity                  | ±1.1 m/s   |
| Displacement              | ±125 mm    |
| Frequency                 | 0–50 Hz    |
| Over turning movement capacity | 10 ton-m   |
2.2. Seismic zones of Pakistan

Building Code of Pakistan – Seismic Provisions (2007) provides the seismic zoning map of Pakistan, which is shown in Figure 4. Pakistan has been divided into five zones. These zones are based on the peak ground acceleration ranges summarized in Table 2. The zoning map shows that significant area of Pakistan has moderate to high seismic hazard associated to it: the areas falling under Seismic Zone 2A are considered to be moderate seismic hazard areas, whereas, areas falling in Seismic Zone 2B or above are considered to be high seismic hazard areas. It is worth mentioning that the seismic zoning map of Pakistan as given in the Building Code of Pakistan (Figure 4) is based on a seismic event with a probability of exceedance of 10% in 50 years, which corresponds to an earthquake with a return period of 475 years.

2.3. Damages of earthquake and ground motions

The most vulnerable elements in electric supply substation are bushings made by porcelain used for circuit breaker, disconnect switch, circuit switcher and lightning arrester (Takada, Bastami, Kuwata, & Javanbarg, 2004). Table 3 summarizes the damages to the substation equipment due to Bam Earthquake in Iran (Takada et al., 2004). 8 October 2005 Kashmir Earthquake was one of most devastating earthquake in the history of Pakistan. A damage assessment report (Asian Development Bank & World Bank, 2005) estimated that the damages just to the electricity production and distribution sector attributable to this earthquake were about Rs. 641.8 million.

A series of three earthquakes (Kwasinski, Eidinger, Tang, & Tudo-Bornarel, 2014) that occurred in New Zealand between 2010 and 2011. The first event (the Darfield event) of M 7.0 occurred on 4 September 2010, second M 6.1 event occurred on 22 February 2011 and third event of M 6.0 occurred on 13 June 2011. Figure 5 shows the power transmission infrastructure around Christchurch, Epicenters of three seismic events and surface rupture of 4 September 2010 earthquake. During the 4 September 2010 earthquake, a rapid increase in New Zealand’s South Island grid frequency was observed due to sudden load loss, frequency of New Zealand’s South Island grid briefly exceeded the prescribed upper limit of 50.75 Hz until power generation actuators were able to compensate.

2.4. Related work to seismic qualification of electrical equipment

Shanfa, Meiying, Miaolin, Xiaofeng, and Jiyong (2009) investigated the seismic capacity of high-voltage electric switchgear cabinet under a magnitude 8 earthquake by shake-table test. The high voltage electrical switchgear cabinet was tested on a shake table by shaking in both X- and Y-directions.
Figure 6 shows electrical switchgear cabinet fixed on the shake-table for seismic testing. Koliou, Filiatrault, and Reinhorn (2011) discussed seismic response of transformer bushing system in both mounted on rigid base and “as installed” situation. Parise et al. (2013) explains different seismic qualification categories of electrical equipment and also defined equipment seismic levels.

Table 2. Seismic zones of Pakistan

| Seismic zone | Peak horizontal ground acceleration |
|--------------|------------------------------------|
| 1            | 0.05–0.08 g                        |
| 2A           | 0.08–0.16 g                        |
| 2B           | 0.16–0.24 g                        |
| 3            | 0.24–0.32 g                        |
| 4            | >0.32 g                            |

Table 3. Damage rate information of 230 kV substation—Bam earthquake

| Type of equipment | Total EQUIPMENT | Damaged EQUIPMENT | Damage percentage (%) |
|-------------------|-----------------|-------------------|-----------------------|
| Current transformer | 18              | 12                | 67                    |
| Disconnector       | 12              | 4                 | 33                    |
| Surge arrester     | 18              | 2                 | 11                    |
| Circuit breaker    | 24              | 6                 | 25                    |

Figure 4. Seismic zoning map of Pakistan.
2.5. Seismic qualification of electrical equipment

In order to design structures and seismically qualify electrical equipment, three qualification levels are defined, which are: “low”, “moderate” and “high” (IEEE Std. 693-2005, 2005). Correlation of these seismic qualification levels to Building Code of Pakistan – Seismic Provisions (2007) is defined by Pakistan Electrical and Telecom Safety Code (2014) and are illustrated in Table 4.
3. Description of test specimen

The electrical equipment selected for seismic qualification in the present investigation was a “132 kV Metal-Oxide Gapless Surge Arrester”, Type: Y10 W-120/295, manufactured by “Wenzhou Yikun Electric Company, Ltd, China”. According to IEEE standards, surge/lightning arrester is a protective device for limiting surge voltages on the equipment by diverting surge current and returning the device to its original status. Surge arresters are usually installed between phase and earth/neutral, parallel to the equipment that is to be protected against over-voltages. Surge arrester was selected for seismic qualification test because it is used to protect transformer; transformer is the most important and costly equipment in electric supply substation.

The surge arrester unit is supported by a steel frame, composed of angle sections. Detailed drawing of steel structure is shown in Figure 7. Base steel plate of supporting structure is bolted at twelve points on the shake table. Figure 8 shows sketch of surge arrester mounted on the steel support

Table 4. Seismic zoning and corresponding qualification levels for substation equipment

| Seismic zoninga | Ground acceleration | Qualification level |
|-----------------|---------------------|---------------------|
| Zone-1          | 0.05–0.08 g         | Low and medium voltage Low |
| Zone-2A and Zone-2B | 0.08–0.24 g       | Low/Moderateb Moderate |
| Zone-3 and Zone-4 | 0.24– > 0.32 g      | Low/Moderateb High |

or

>0.24

aThese seismic zonings are taken from Table 2.2 Building Code of Pakistan-Seismic Provisions 2007.

bThe owner shall decide the qualification level depending on the rating of substation.

Figure 7. Detail design of steel structure.
structure and locations for instrumentation. Approximate weight of steel support structure was about 200 kg (440 lbs.) and approximate weight of surge arrester unit was about 350 kg (770 lbs.).

The surge arrester assembly was fitted with six accelerometers at four points, namely Point A, Point B, Point C and Point D. Point A is located at the top of the surge arrester and two accelerometers are installed to examine force in both X-direction and Y-direction, point B is located at the middle of the surge arrester, point C is located at the base of the surge arrester and two accelerometers are installed to examine accelerations in both X-direction and Y-direction, point D is located at the bottom-most part of the steel structure as shown in Figure 8. The surge arrester assembly was fitted with four displacement transducers at four different locations, namely Point A, Point B, Point C and Point D. Figure 9 shows surge arrester assembly mounted on the shake-table for seismic qualification test.
4. Analysis and equations

Three types of tests were performed on the surge arrester assembly. Free vibration test was conducted to find damping ratio and natural frequency of the assembly Chopra (2001). Natural frequency of assembly indicates the stiffness of structure. As explained by (1).

$$f = \frac{1}{2\pi} \times \sqrt{\frac{k}{m}}$$  \hspace{1cm} (1)

where

- $f$ is frequency of the structure
- $k$ is stiffness of the structure
- $m$ is mass of the structure.

Equation (1) can be written as,

$$f \propto \sqrt{k}$$  \hspace{1cm} (2)

Equation (2) illustrates that frequency is directly proportional to the square-root of the stiffness of the structure. If stiffness decreases frequency will decrease and vice versa. This type of test is conducted to examine the stiffness of the structure and ultimately examine its mechanical strength.

Figure 9. Surge arrester assembly mounted on shake-table for seismic qualification.
Any mechanical damage or loss of stiffness as a result of subsequent testing can be evaluated by comparing the natural frequency of the damaged system to the natural frequency of the undamaged system.

For measurement of natural frequency and damping ratio, whole assembly is subjected to free vibration test and data of accelerometers was recorded. Natural frequency and damping ratio were calculated by using (3), (4) and (5).

\[ T = \frac{X_{i+N} - X_i}{N} \]  
(3)

where

\( T \) is time period

\( X_{i+N} \) is final value of X-axis (time in seconds)

\( X_i \) is initial value of X-axis (time in seconds)

\( N \) is the total number of peaks

Equation (4) is used to calculate natural frequency of the structure.

\[ f = \frac{1}{T} \]  
(4)

Equation (5) given below is used to calculate damping ratio of the structure.

\[ T = \frac{1}{2\pi N} \ln \left( \frac{Y_i}{Y_i + N} \right) \]  
(5)

where

\( \xi \) is damping ratio

\( Y_i \) is initial value of Y-axis (Acceleration in g)

\( Y_i + N \) is final value of Y-axis (Acceleration in g)

\( N \) is the total number of peaks

By utilizing these basic formulae and data of accelerometers, natural frequency and damping ratio is calculated as 2.5 Hz and 1% respectively.

4.1. Generation of response spectrum matched time-history

Electrical equipment is to be qualified for the Peshawar (Khyber Pakhtunkhwa, Pakistan) region, and is subjected to “Qualification Level Moderate”. According to PETSAC (2014), Required Response Spectrum for damping ratio of 1% is calculated and plotted, as shown in Figure 10. After many attempts and iterations a time history was finalized, shown in Figure 11 that has time span of thirty second and is matched to the Required Response Spectrum.
The response–spectrum matched time-history was generated using Spectime Version 1.0 software, developed by ANCO Engineers USA. The response spectrum matched time-history was further validated by three types of tests to check whether the developed time-history indeed corresponded to the prescribed response spectrum. These tests are:

4.1.1. Seismo-signal software
Seismo-Signal software was used to validate that developed time-history indeed corresponded to the prescribed response spectrum.

4.1.2. Bare shake table tests
Accelerometers was installed on bare table top and the time history was run. Data of accelerometers was recorded and accordingly Response Spectrum was re-plotted and was found to be reasonable matched with Required Response Spectrum.

4.1.3. Validation test by installing concrete slab on shake table
In order to further verify the generated time history, a weight of 1600Kgs was installed on shake table to ensure that table can simulate the desired time history in reasonable fashion. Again accelerometers was installed on concrete slab and the time history was run. Data of accelerometers was recorded and accordingly Response Spectrum was re-plotted and was found to be reasonable matched with Required Response Spectrum.

The results of the above three tests validated that the developed time-history indeed corresponded to the Required Response Spectrum.
5. Results of time-history tests

Multiple time-history shake-table tests were conducted on surge arrester assembly, free vibration test were conducted initially, in middle and after time-history shake-table tests. Test protocol is summarized, as shown in Table 5.

Time-history shake-table tests with 50% intensity were conducted first to simulate the effect of mechanical aging of the assembly. Time-history shake-table tests with 100% intensity can be conducted prior to 50% intensity tests, results obtained from direct 100% intensity represent means strength of freshly installed structure. The purpose is to qualify the equipment for life-time, therefore time history shake-table tests with 50% intensity are conducted before 100% intensity test to demonstrate that the equipment was installed a long time before and experienced mechanical aging and then the earthquake struck the structure.

Time history shake-table tests with 100% intensity will actually explains that whether the surge arrester assembly is able to withstand strong ground motions and can perform correct operational state during and after seismic event or its supporting structure design should be updated.

Test results are discussed according to location of instruments, for example, results of accelerometers and displacement transducer installed at the top of surge arrester assembly (Point A) are discussed firstly, and so on.

5.1. Recorded data at point A

Point A is located at top of surge arrester assembly as shown in Figure 8. Two accelerometers and one displacement transducer was installed at this location. These instruments are named as “Accelerometer No. 1”, “Accelerometer No. 2” and “Displacement transducer No. 1”. Accelerometer No. 1 is in the direction of shaking and accelerometer No. 2 is perpendicular to accelerometer No. 1, displacement transducer No. 1 is also installed in the direction of shaking at this point.

Values recorded from Point A accelerometers during all the above mentioned time-history shake-table tests are tabulated in Table 6, absolute maximum displacements at Point A are tabulated in Table 7 and relative maximum displacements between Point A and other points are tabulated in Table 8.

| Table 5. Time-history shake table test protocol |
|-----------------------------------------------|
| **S. No.** | **Type of test**                               |
| 1          | Free vibration test no. 1                     |
| 2          | Free vibration test no. 2                     |
| 3          | Time-history shake-table test no. 1 with 50% intensity |
| 4          | Free vibration test no. 3                     |
| 5          | Time-history shake-table test no. 2 with 50% intensity |
| 6          | Time-history shake-table test no. 3 with 50% intensity |
| 7          | Time-history shake-table test no. 4 with 50% intensity |
| 8          | Time-history shake-table test no. 5 with 50% intensity |
| 9          | Free vibration test no. 4                     |
| 10         | Time-history shake-table test no. 6 with 100% intensity |
| 11         | Free vibration test no. 5                     |
### Table 6. Point A acceleration values

| Test/Accelerometer | Maximum acceleration (g) | Time of maximum acceleration (s) | Sustained maximum acceleration (g) |
|--------------------|---------------------------|-----------------------------------|-----------------------------------|
| Test No. 1-Accelerometer No. 1 | 0.52 | 14.40 | 0.50 |
| Test No. 1-Accelerometer No. 2 | 0.13 | 26.33 | 0.12 |
| Test No. 2-Accelerometer No. 1 | 0.47 | 18.95 | 0.45 |
| Test No. 2-Accelerometer No. 2 | 0.13 | 20.27 | 0.12 |
| Test No. 3-Accelerometer No. 1 | 0.50 | 26.22 | 0.46 |
| Test No. 3-Accelerometer No. 2 | 0.15 | 20.32 | 0.14 |
| Test No. 4-Accelerometer No. 1 | 0.50 | 26.25 | 0.42 |
| Test No. 4-Accelerometer No. 2 | 0.14 | 14.01 | 0.13 |
| Test No. 5-Accelerometer No. 1 | 0.50 | 26.32 | 0.44 |
| Test No. 5-Accelerometer No. 2 | 0.14 | 15.06 | 0.13 |
| Test No. 6-Accelerometer No. 1 | 0.80 | 20.15 | 0.66 |
| Test No. 6-Accelerometer No. 2 | 0.24 | 26.60 | 0.22 |

### Table 7. Absolute maximum displacement of Point A

| Test number | Displacement transducer number | Absolute maximum displacement (mm) |
|-------------|--------------------------------|-----------------------------------|
| 1           | 1                              | 54.05                             |
| 2           | 1                              | 60.13                             |
| 3           | 1                              | 58.97                             |
| 4           | 1                              | 63.72                             |
| 5           | 1                              | 60.84                             |
| 6           | 1                              | 140.34                            |

### Table 8. Relative maximum displacements between Point A and other points

| Relative maximum displacement (mm) |
|-----------------------------------|
| Test number | Point A – Point B | Point A – Point C | Point A – Point D |
|-------------|-------------------|-------------------|-------------------|
| 1           | 7.77              | 14.76             | 23.80             |
| 2           | 10.11             | 18.46             | 27.96             |
| 3           | 8.84              | 15.73             | 24.98             |
| 4           | 8.41              | 16.37             | 25.64             |
| 5           | 9.37              | 17.38             | 27.27             |
| 6           | 21.03             | 43.19             | 77.22             |
5.2. **Recorded data at point B**

Point B is located at the middle of surge arrester as shown in Figure 8. One accelerometer and one displacement transducer is installed at this point. These instruments are named as “Accelerometer No. 3” and “Displacement transducer No. 2”, both of these instruments are installed in the direction of shaking at this point.

Values recorded from Point B accelerometer during all afore mentioned time history shake-table tests are tabulated in Table 9, absolute maximum displacements at Point B are tabulated in Table 10 and relative maximum displacements between Point B and other points are tabulated in Table 11.

5.3. **Recorded data at point C**

Point C is located at top of steel structure and at the base of surge arrester as shown in Figure 8. Two accelerometers and one displacement transducer is installed at this point. These instruments are named as “Accelerometer No. 4”, “Accelerometer No. 5” and “Displacement transducer No. 3”.

| Table 9. Point B acceleration values |
|-------------------------------------|
| Test/Accelerometer | Maximum acceleration (g) | Time of maximum acceleration (s) | Sustained maximum acceleration (g) |
| Test No. 1-Accelerometer No. 3 | 0.30 | 25.94 | 0.27 |
| Test No. 2-Accelerometer No. 3 | 0.32 | 26.17 | 0.27 |
| Test No. 3-Accelerometer No. 3 | 0.32 | 26.23 | 0.27 |
| Test No. 4-Accelerometer No. 3 | 0.33 | 26.26 | 0.26 |
| Test No. 5-Accelerometer No. 3 | 0.33 | 26.35 | 0.26 |
| Test No. 6-Accelerometer No. 3 | 0.50 | 26.07 | 0.38 |

| Table 10. Absolute maximum displacement of Point B |
|-----------------------------------------------|
| Test number | Displacement transducer number | Absolute maximum displacement (mm) |
| 1 | 2 | 49.18 |
| 2 | 2 | 55.21 |
| 3 | 2 | 56.84 |
| 4 | 2 | 58.40 |
| 5 | 2 | 58.78 |
| 6 | 2 | 127.39 |

| Table 11. Relative maximum displacements between Point B and other points |
|--------------------------------------------------------------------|
| Relative maximum displacement (mm) |
| Test number | Point B – Point C | Point B – Point D |
| 1 | 8.41 | 17.66 |
| 2 | 8.80 | 18.18 |
| 3 | 9.18 | 18.35 |
| 4 | 8.72 | 18.37 |
| 5 | 8.73 | 18.44 |
| 6 | 22.71 | 56.71 |
Accelerometer No. 4 is in the direction of shaking and accelerometer No. 5 is perpendicular to accelerometer No. 4, displacement transducer No. 3 is also installed in the direction of shaking at this point.

Values recorded from Point C accelerometers during all afore mentioned time history shake-table tests are tabulated in Table 12, absolute maximum displacements at Point C are tabulated in Table 13 and relative maximum displacements between Point C and Point D are tabulated in Table 14.

### Table 12. Point C acceleration values

| Test/Accelerometer | Maximum acceleration (g) | Time of maximum acceleration (s) | Sustained maximum acceleration (g) |
|--------------------|--------------------------|----------------------------------|-----------------------------------|
| Test No. 1-Accelerometer No. 4 | 0.36                      | 14.88                            | 0.27                              |
| Test No. 1-Accelerometer No. 5 | 0.10                      | 16.57                            | 0.09                              |
| Test No. 2-Accelerometer No. 4 | 0.28                      | 14.11                            | 0.25                              |
| Test No. 2-Accelerometer No. 5 | 0.10                      | 8.48                             | 0.09                              |
| Test No. 3-Accelerometer No. 4 | 0.27                      | 8.36                             | 0.25                              |
| Test No. 3-Accelerometer No. 5 | 0.11                      | 15.13                            | 0.09                              |
| Test No. 4-Accelerometer No. 4 | 0.26                      | 7.33                             | 0.25                              |
| Test No. 4-Accelerometer No. 5 | 0.09                      | 25.46                            | 0.09                              |
| Test No. 5-Accelerometer No. 4 | 0.23                      | 25.52                            | 0.24                              |
| Test No. 5-Accelerometer No. 5 | 0.10                      | 8.47                             | 0.09                              |
| Test No. 6-Accelerometer No. 4 | 0.66                      | 26.00                            | 0.48                              |
| Test No. 6-Accelerometer No. 5 | 0.22                      | 26.77                            | 0.18                              |

### Table 13. Absolute maximum displacement of Point C

| Test number | Displacement transducer number | Absolute maximum displacement (mm) |
|-------------|--------------------------------|-----------------------------------|
| 1           | 3                              | 45.72                             |
| 2           | 3                              | 50.97                             |
| 3           | 3                              | 52.72                             |
| 4           | 3                              | 54.39                             |
| 5           | 3                              | 54.84                             |
| 6           | 3                              | 113.35                            |

### Table 14. Relative maximum displacements between Point C and Point D

| Test number | Relative maximum displacement (mm) | Point C – Point D |
|-------------|------------------------------------|-------------------|
| 1           | 9.57                               |                   |
| 2           | 9.96                               |                   |
| 3           | 10.06                              |                   |
| 4           | 10.38                              |                   |
| 5           | 10.36                              |                   |
| 6           | 34.33                              |                   |
5.4. Recorded data at point D

Point D is located at the base of surge arrester assembly as shown in Figure 8. One accelerometer and one displacement transducer is installed at this point. These instruments are named as “Accelerometer No. 6” and “Displacement transducer No. 4”, both of these instruments are installed in the direction of shaking at this point.

Values recorded from Point D accelerometer during all afore mentioned time history shake-table tests are tabulated in Table 15 and absolute maximum displacements at Point D are tabulated in Table 16.

Comparison of Required Response Spectrum, Response Spectrum recorded at accelerometer No. 6 location and the response spectrum associated with 100% intensity time-history shake table test (Test No. 6) is shown in Figure 12. Comparison of Required Response Spectrum, Response Spectrum recorded at accelerometer No. 6 location associated with 50% intensity time-history (Test No. 1 to Test No. 5) is shown in Figure 13 and illustrates that values of acceleration for 50% Intensity tests are lower than Required Response Spectrum for almost all the frequency range. This type of response is desired from 50% intensity tests because these tests are conducted to include the factor of mechanical aging.

Five free vibration test are conducted. They are conducted before, in middle and after time history shake-table tests. These tests are conducted to find natural frequency of the structure and helps us to evaluate the stiffness of the structure. Natural frequency of the structure is measured at the top of whole assembly (Point A).

| Test/Accelerometer | Maximum acceleration (g) | Time of maximum acceleration (s) | Sustained maximum acceleration (g) |
|--------------------|--------------------------|-------------------------------|----------------------------------|
| Test No. 1-Accelerometer No. 6 | 0.24 | 25.61 | 0.22 |
| Test No. 2-Accelerometer No. 6 | 0.24 | 14.99 | 0.20 |
| Test No. 3-Accelerometer No. 6 | 0.24 | 15.04 | 0.21 |
| Test No. 4-Accelerometer No. 6 | 0.24 | 0.21 | 0.21 |
| Test No. 5-Accelerometer No. 6 | 0.24 | 26.00 | 0.21 |
| Test No. 6-Accelerometer No. 6 | 0.36 | 25.64 | 0.30 |

| Test number | Displacement transducer number | Absolute maximum displacement (mm) |
|-------------|-------------------------------|----------------------------------|
| 1           | 4                             | 39.66                           |
| 2           | 4                             | 44.45                           |
| 3           | 4                             | 46.19                           |
| 4           | 4                             | 47.64                           |
| 5           | 4                             | 48.06                           |
| 6           | 4                             | 96.92                           |
6. Interpretation of test results

Time history shake table testing using RRS for seismic qualification of high voltage electric supply equipment has become the most widely accepted and powerful method. Response spectrum of artificial earthquake must satisfy RRS spectrum for specific electrical equipment (Test specimen: 132 kV Surge arrester) shown in Figure 12 throughout the frequency range and must be equal or above at value of natural frequency viz. 2.5 Hz for appropriate seismic qualification. As if researcher chose artificial earthquake that have overall response spectrum values greater that RRS, the test may fail due to overload at point of natural frequency.

While following test protocol, time history shake tables test results are analyzed. Acceleration values at bottom of whole structure is less than values at top which validates the theory proposed in Parise et al. (2013). Parise et al. (2013) explains that seismic accelerations produced by earthquake linearly increase along the height of the supporting structure. Measured values of accelerometers installed at orthogonal axes to motion are recorded as very low compared to values of accelerometers installed in parallel to the direction of motion. Absolute maximum displacement also follow decrement pattern while comparing top and bottom displacement transducer measurements, this type of behaviour is due to damping ratio and elastic nature of steel structure. Upon successful completion of shake table test, free vibration test is conducted and natural frequency is calculated.
Table 17. Summary of structure frequency through-out free vibration tests

| Free vibration test number | Frequency (Hz) |
|----------------------------|----------------|
| 1                          | 2.52           |
| 2                          | 2.54           |
| 3                          | 2.53           |
| 4                          | 2.53           |
| 5                          | 2.50           |

Table 17 summarises the natural frequency of the structure calculated from free vibration test’s data (conducted before, in middle, and after time history shake table test).

According to Table 17 slight change in frequency is observed which may be due to noise generated by the instrument or may be due to other electrical interferences. This slight change is in the acceptable limits and is neglected.

7. Conclusion
Seismic qualification of electric supply substation equipment by time history shake-table testing was presented in this paper. Surge arrester was mounted on top of steel frame composed of angle sections. Height of steel structure is 3.7 m and height of surge arrester equipment is 2.45 m. Design and height of the whole assembly was same as that of the installed equipment in the field. Surge arrester assembly was subjected to strong ground motions of “Seismic Qualification Level Moderate” because this equipment was installed in Peshawar (Khyber Pakhtunkhwa, Pakistan) region and according to study about seismic qualification levels, electrical equipment of this voltage ratings that is to be installed in Peshawar (Khyber Pakhtunkhwa, Pakistan) region shall be seismically qualified under “Seismic Qualification Level Moderate”. Six accelerometers and four displacement transducers are used to measure acceleration and displacement during time history shake-table testing at four different points.

No degradation or mechanical damage was observed visually in the whole surge arrester assembly. Moreover, free vibration test shows slight frequency variations that may be due to noise in the electrical circuit or other electrical interferences. This slight change is in the acceptable limits and is neglected. As the natural frequency of the surge arrester assembly is almost constant which means that stiffness of the structure is not changed and is same as it was before shake-table testing. This helps us to conclude that surge arrester assembly was perfectly intact with shake-table before and after time history shake-table testing. It is concluded that surge arrester assembly of this design is “Seismically Qualified” for “Seismic Qualification Level Moderate”.

Acknowledgments
Authors are thankful to University of Engineering & Technology Peshawar staff for their help and consistent support throughout the research period. Authors are also thankful to Pakistan Engineering Council, they have provided national platform for seismic qualification criteria through Pakistan Electric and Telecom Safety Code (PETSAC-2014).

Funding
The authors received no direct funding for this research.

Author details
Noman Ullah¹ E-mail: engrnomankundi@gmail.com
ORCID ID: http://orcid.org/0000-0002-9506-7907
Syed Mohammad Ali² E-mail: bridge_doctor@yahoo.com
Rahman Shahzad¹ E-mail: rahman.shahzad@gmail.com
Faisal Khan¹ E-mail: faisalkhan@cit.net.pk
¹ Electrical Engineering Department, COMSATS Institute of Information Technology, Tobe Camp, Abbottabad, Pakistan.
² Civil Engineering Department, University of Engineering & Technology, Peshawar, Pakistan.
³ National Engineering Services of Pakistan (NESPAK), Lahore, Pakistan.

Citation information
Cite this article as: Seismic qualification and time history shake-table testing of high voltage surge arrester under seismic qualification level moderate, Noman Ullah, Syed Mohammad Ali, Rahman Shahzad & Faisal Khan, Cogent Engineering (2018), 5: 1431375.

References
Ali Saadeghvaziri, M. A., Feizi, B., Kempner, L., & Alston, D. (2010). On seismic response of substation equipment and application of base isolation to transformers. IEEE
incorporating flexural stiffeners. In 8th international conference on structural dynamics (pp. 227–233). Leuven.
Kwasinski, A., Eidinger, J., Tang, A., & Tudo-Bornarel, C. (2014). Performance of electric power systems in the 2010–2011 Christchurch, New Zealand, earthquake sequence. Earthquake Spectra, 30(1), 205–230.
https://doi.org/10.1193/022813EQS056M
Mohammadi, R. K., & Pourkashani Tehrani, A. (2013). An investigation on seismic behavior of three interconnected pieces of substation equipment. IEEE Transactions on Power Delivery, 29(6), 1613–1620.
Pakistan Electrical and Telecom Safety Code. (2014). Islamabad: Pakistan Engineering Council.
Parise, G., Martirano, L., Parise, L., De Angelis, M., Perno, S., & Reggio, A. (2013). Seismic qualification categories (EQC) of electrical equipment. In Industry applications society annual meeting (pp. 1–7). Lake Buena Vista, FL: IEEE.
Shanfo, R., Meijing, W., Miaolin, D., Xiaofeng, F., & Jiyong, Z. (2009). The study on a seismic test of high-voltage electrical switch cabinet. Power and Energy Engineering Conference, Asia-Pacific, Wuhan, 1, 1–6.
Takada, S., Bastani, M., Kuwata, Y., & Jovanbang, M. B. (2004). Performance of electric power systems during the Bam earthquake and its fragility analyses. Memoirs of Construction Engineering Research Institute, 46, 161–152.