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Performance of 420 kV Instrument Transformers under Earthquake

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Abstract

Seismic performance of substation equipment during past earthquakes is poor. In addition, requirement of electric power during post-earthquake led to an increased focus on the earthquake survivability of substation equipment. Equipment installed in the substation is vulnerable to earthquakes by virtue of its geometry and configuration. Interconnection between equipment further aggravates the problem. Failure of substation equipment results in financial loss and considerable time is required to repair/replace the equipment to restore power supply. Earthquake vibration level can be evaluated based on site/location but predicting time of occurrence of earthquake is not possible. High voltage substation equipment shall be designed for seismic loading. Foundation, anchoring, installation and interconnection between equipment also need to be engineered according to the seismic load based on location of installation of equipment. Seismic qualification of various substation equipment as per National and International standard is performed using tri-axial shake table facility of Earthquake Engineering and Vibration Research Centre. Performance of 420kV instrument transformers under earthquake environment is presented in this paper.

Keywords: Damping, Resonance Frequency, Substation Equipment, 420kV Instrument Transformer

1. Introduction

Earthquakes are caused by the sudden rupture of geologic fault. Shock waves released due to earthquake causes strong ground vibration. Shock waves during an earthquake result in a complex multi-frequency ground vibration, having two horizontal and one vertical component. Earthquakes can cause substantial damage to structures and electrical equipment. Data obtained from the substations based on past experiences of earthquake indicates high voltage substations are not safe even for low severity of seismic event. Earthquakes with 0.2 g Zero Period Acceleration (ZPA)[1] can cause severe catastrophic damage to substation equipment. Simultaneous tri-axial vibration with high energy content in low frequency region attributes to failure of tall substation equipment. The reliability of substation after an earthquake depends on the seismic behaviour of each high voltage substation equipment such as isolator, instrument transformer, surge arrester, switchgear, transformer etc. Data from past earthquake experiences of substations which experienced also reveals failure of equipment can also happen due to improper interconnection of equipment or failure of anchorage. Hence equipment, support structures, interconnection and anchorage shall be designed for substations placed in sensitive seismic areas.

Designing equipment and base structures for earthquake load is unique to each type of equipment. The load experienced due to a strong earthquake is irregular and unpredictable. However, statistically the probability of any given equipment experiencing high intensity earthquake during its lifetime is low. Hence, only the critical equipment and structures are designed to withstand high intensity earthquake. Other

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electrical equipment is designed to withstand moderate earthquakes. Equipment used in nuclear power plants is responsible for handling nuclear material and nuclear waste material. Equipment in nuclear power plant are designed for intense earthquakes to ensure safe shutdown condition[2]. Substation equipment are normally designed for moderate earthquakes.

2. Seismic Qualification

Demonstration of ability of equipment to perform its intended functions during and after it is subjected to the forces originating from earthquake motions is called seismic qualification. Seismic qualification involves choice of acceptance criteria, method of qualification, selection of earthquake level and demonstration of structural capability. Qualification criteria will depend on type of equipment and its application. Seismic qualification by analysis using software and seismic qualification by shake table test are most popular methods. Analysis method cannot provide documentary evidence related to functioning of equipment during and after the earthquake. In case of substation equipment, evaluating functional capability is very important in addition to evaluation of structural integrity. Hence, standards recommend shake table method of qualification for substation equipment. Due to shake table size and payload limitation combination of analysis and shake table test are also used for seismic qualification. For example, weight of high voltage power transformer is huge and cannot be qualified by shake table method. Hence, transformer is qualified by analysis method and transformer fragile bushing part is subjected to seismic event and qualified by shake table method. Equipment can be qualified to the generalized level of response spectrum specified in the standards or to the site specific response spectrum. Usually substation equipment is qualified to the generalized response spectrum based on respective qualifying standard.

Tri-axial shaker system capable of generating vibrations in all six degrees of freedom is available in Central Power Research Institute (CPRI) for seismic qualification of substation equipment. Tri-axial shake table is 3m x 3m in size and maximum payload capacity is 10,000 Kg. Frequency of vibration ranging from 0.1 Hz to 50 Hz can be simulated. The control system of this facility can generate earthquake ground vibrations with high accuracy. The control system is capable of simulating three-dimensional random ground vibrations. These vibrations are simultaneous but statistically independent of each other. Earthquake conditions can be simulated using synthesized time history which is compatible with the response spectrum or compatible to the real time history recorded during past earthquakes.

Qualification of 420 kV dead tank and live tank instrument transformer with porcelain insulators under seismic load is presented in this paper.

3. High Voltage Substation and Seismic Event

Substation equipment is fragile when subjected to seismic forces due to its geometry and configuration. Behaviour analysis of high voltage substation equipment is complex in nature. Substation equipment is placed on support structures and is interconnected to each other which changes the dynamic behaviour of equipment completely. Hence, study of seismic testing of substation equipment shall be performed with support structures. Effect of interconnection shall also be considered for earthquake resilience for establishment of safe high voltage substations. Voltage rating of substation equipment and height of substation equipment are directly proportional to each other. Increase in voltage rating will increase the height of equipment to have safe ground clearance which increases its fragility to seismic loads.

Porcelain insulators used in HV substation equipment have high compression strength but low tensile strength. Hence, porcelain insulators are chosen for this study. Resonant phenomenon under seismic loading can cause immense dynamic forces and, due to its weight and brittle nature, porcelain is susceptible to destructive harmonic frequencies. Seismic events cause bending moment which induces both compression and tensile stress. Tensile stress is amplified by lever action with the height of insulator. Refer Figure 1. Maximum stress is expected at bottom porcelain and metal flange cementing joint.

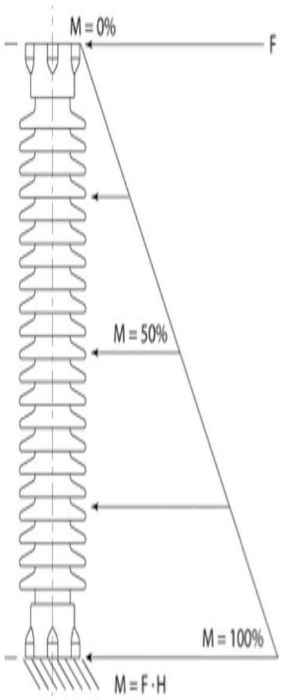

Figure 1. Lever action in tall insulators.

4. Performance of Instrument Transformers

Current transformers, voltage transformers and capacitive voltage transformers used in high voltage substation for measuring and protection of equipment are vulnerable to seismic forces. Failure analysis of live tank instrument transformers and dead tank instrument transformers is carried out with 420 kV porcelain based instrument transformers.

Seismic performance shall ensure that the instrument transformers shall not have any structural failure and shall perform its electrical function after seismic event simulation.

Seismic performance of instrument transformer is evaluated as per IEEE standard 693 – "IEEE recommended practice for seismic design of substations"[3]. Generalized frequency response spectrum for high performance level with 10 m/s 2 Zero Period Acceleration (ZPA) and moderate performance level with 5 m/s 2 ZPA are recommended in the standard. Instrument transformer was subjected to resonance search test to determine natural frequency and damping. Resonance search test is carried out by base excitation method with sinusoidal swept at constant acceleration and varying frequency at 1octave/minute. Damping of structure is computed by half-power method. Frequency response spectrum corresponding to the evaluated value of damping is used for seismic testing. Seismic qualification level (ZPA) will depend on level of earthquake anticipated at the mounting location of equipment. After seismic test, instrument transformers are subjected to resonance search test again. Change in resonances frequency after seismic test indicates reduction in structural integrity. A change of more than 20% in the resonant frequencies as a result of seismic test corresponds to 36% reduction in stiffness[4]. This is also one of acceptance parameter when qualification of instrument transformer is carried out. Instrument transformer is subjected to routine test before as well as after seismic test for evaluating its functional capability.

4.1 Live Tank Instrument Transformer

Windings and core of live tank instrument transformer are housed in live tank at the top of transformer. Performance of 420 kV, 2000A live tank current transformer was evaluated by shake table method. Photograph showing live tank current transformer on shake table is shown in Figure 2. Current transformer was 5300 mm high and weighed 1670 Kg with porcelain insulator. Tubular support structure (Height - 3500 mm and Weight 600 Kg) was used to simulate actual field mounting condition on shake table.

Resonance search test was conducted with 19 mm peak displacement/0.075 g acceleration in the frequency range of 0.1 to 50 Hz[5]. Observed natural frequency after resonance search test of live tank current transformer is 0.75 Hz. Vigorous vibration was noticed at and close to natural frequency of instrument transformers leading to its failure. Crack was seen near cementing joint at the base of porcelain insulator. Base of porcelain near metal cementing joint was the weakest point. Stress developed at this point due to seismic loading was higher than yield stress resulting in its failure. Since live tank current transformer failed during resonance search test seismic performance evaluation for multi-axis time history test could not be carried out.

In case of live tank insulator transformers, higher mass is located at the top; centre of gravity is close to top live tank. This results in high moment during seismic event and makes its highly vulnerable to seismic forces.

Figure 2. Live tank current transformer on shake table.

Figure 3 and Figure 4 show photographs of equipment captured after failure.

Figure 3. Live tank current transformer on shake table after failure.

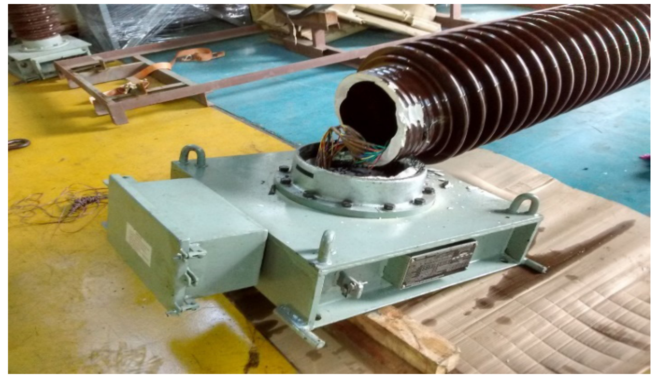

Figure 4. Close view of insulator after failure.

4.2 Dead Tank Instrument Transformer

Core and secondary winding are located in dead tank near the bottom of current transformer. 420 kV, 2000A Dead tank current transformer performance was evaluated by shake table method. Photograph of 420 kV Dead tank current transformer mounted on shake table is shown in Figure 4. Current transformer was 5528 mm high and weighed 2100 Kg with porcelain insulator. Tubular support structure of (Height - 3330 mm and Weight - 550 Kg) was used for seismic performance evaluation.

Natural frequency of dead tank current transformer was investigated by base excitation method with 19 mm peak displacement/0.075 g acceleration in the frequency range of 0.1 to 50 Hz[5]. Resonance frequency found is given in Table 1. From the results of resonance search data damping of equipment was compute. It was 2.31%. Typical resonance plot is shown in Figure 5.

Table 1. Resonance frequency

Direction	Location	Resonance frequency, Hz
Horizontal Direction 1	Top of Transformer	2.00
	Centre of Gravity	2.00
Horizontal Direction 2	Top of Transformer	2.00
	Centre of Gravity	2.00
Vertical	Top of Transformer	No resonance
	Centre of Gravity	No resonance

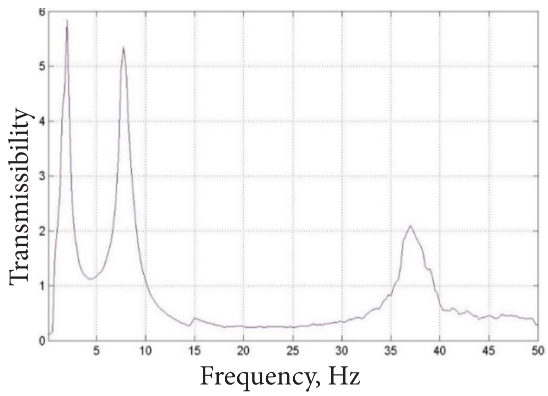

Figure 5. Results of resonance search test.

Dead tank current transformer has centre of gravity close to dead tank. Hence, bending moment developed during seismic event is less when compared to live tank current transformer. Successful seismic qualification of dead tank instrument transformer was carried out by shake table method[6]. Stress observed during multi-axis shake table test near cementing joint is shown in Figure 6. Dead tank current transformer will be a preferred choice for highly active seismic regions.

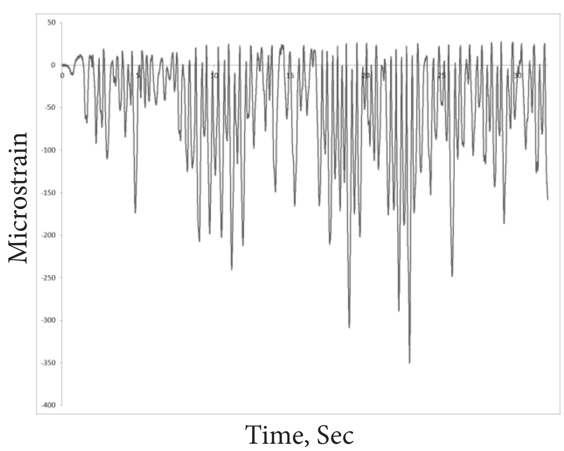

Figure 6. Strain measured at the bottom of insulator near cementing joint.

Peak value = + 27.541 & -350.375 microstrain

5. Summary

Live tank current transformers have better electrical performance than dead tank. However, when seismically compared it is more vulnerable than dead tank current transformers. This behaviour is due to heavy mass concentration at the top of the transformer which increases the bending moment experienced during a seismic event near the base the insulator. 420 kV live tank current transformers with porcelain insulator are fragile; failure rate is very high even for low seismic levels of qualification.

For dead tank instrument transformers, mass is concentrated at the base of transformer and centre of gravity is closer to tank. Based on resonance search test results and stress measured in multi-axis shake table test, it is observed that dead tank current transformers have better seismic performance than live tank current transformers.

6. Future Scope of Research

Earthquakes are natural calamity which can cause huge damage to equipment and structures, especially in highly populated country like ours. Performance of high voltage equipment placed in the substations is not satisfactory during earthquakes. Based on shake table tests; performance evaluation of 420 kV instrument transformers with porcelain insulators is carried out. It is found that 420 kV live tank current transformer with porcelain insulator are more susceptible to failure even for low level of earthquake.

Study to evaluate seismic performance of instrument transformers and ways to improve its seismic behaviour is in progress. Under this study, performance of live tank and dead tank current transformers with composite insulators will be carried out. Dynamic properties required for ideal support structure will be investigated. Feasibility of using commercially available anti-vibration dampers and their effects will be studied.

This study will be helpful in ensuring the safety of high voltage instrument transformers in substations, making them more dependable during earthquakes. This will help in assuring continuous power supply during and after earthquakes in the country.

7. Acknowledgement

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