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Failure Analysis of High Voltage Disconnector Under Seismic Load

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Abstract

A disconnector is a mechanical switch that isolates the essential part of the circuit where the repair/replacement of equipment is planned. High voltage disconnectors used in substations are fragile to earthquake events. Mechanical dynamics of the disconnector switch change with a change in the position of the main and earth-moving contact. Hence seismic performance evaluation of disconnectors is highly complicated, seismic behavior should be evaluated under all possible disconnector positions. High voltage disconnectors located in seismic Zones IV and Zone V of India are vulnerable to seismic events. Seismic performance evaluation of high voltage disconnectors, transformer bushings, instrument transformers, circuit breakers etc., along with interconnection of equipment and anchoring will prevent failure in the event of an earthquake. Hence, demand for safe and uninterrupted electrical service in a post-earthquake environment can be maintained. Tri-axial shaker system of Central Power Research Institute (CPRI) can simulate realistic earthquake vibration simultaneously in two horizontal and one vertical direction. Failure analysis of 245 kV disconnectors subjected to seismic loading by the shake table method is presented in this paper.

Keywords: High Voltage Disconnector/Isolator, Resonance Frequency, Seismic Qualification

1. Introduction

An earthquake is the sudden release of energy from the rupture of geological faults in the earth's crust in which elastic strain has been accumulating. The seismic waves that radiate from the rupture arrive at the earth's surface as a complex multi-frequency vibratory ground motion. Earthquake vibration has two horizontal and vertical components, acting simultaneously. Vibration due to earthquakes is random with dominating low-frequency content. This will result in high displacement, causing massive destruction to civil structures and electrical substation equipment. Predicting the time of earthquake occurrence is not possible, which makes it more devastating. The level of earthquake vibration for any given location can be evaluated scientifically.

Electrical equipment should be designed for seismic loading in addition to its basic functional design parameters. Equipment andstructures can be protected from earthquake natural disasters by designing them to the required seismic loading based on location. Failure of equipment and structures due to earthquake events causes huge financial loss and more time is required for restoring the facilities. Failure also causes hindrances in rescue operations, resulting in the loss of human and animal life.

The performance of high voltage[1] substation equipment during previous earthquakes is not good. The design of electrical equipment and their supporting structures for earthquake loading is unique and complex. The seismic design of electrical equipment cannot be compared with civil structure design. The scope for altering the geometry of electrical equipment is very much limited dueto functional and safety requirements. Highly brittle ceramic insulators are used as insulators in electrical equipment and damping of equipment with a support structureis low. Also, electrical functional capability isthe major requirement in addition to structural integrity in the event of an earthquake. Electrical equipment is interconnected, relative movement of interconnected equipment should be considered to avoid failure during seismic dynamic conditions.

The seismic qualification level is decided based on the criticality of equipment and geographical location. The

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probability of any equipment being subjected to intense earthquakes is low. Normally substation equipment is designed for moderate earthquake levels. Moderate-level generalized response spectrum recommended in the relevant standards is used for seismic performance evaluation. Highly critical nuclear power plant equipment is designed for the maximum expected level of earthquake, and a site-specific response spectrum is used for qualification. Each country has its seismic zone mapping with defined acceleration levels for each zone. Seismic zones of India are defined in IS 1893: Part 1: 2016[2], India is classified into four seismic zones Zone II, Zone III, Zone IV and Zone V. In the event of earthquakes, regions under Zone II will experience low acceleration levels and Zone V will have the highest level of ground acceleration. Himalayan region, Northeast states, part of Gujarat and part of Maharashtra fall under Zone V. Earthquakes with zero period acceleration of 0.2 g can cause damage to high voltage substation equipment. Substations located in Zone III, Zone IV and Zone V are prone to failure, hence seismic loading factors should be part of the design. Failure analysis of 245 kV disconnectors when subjected to seismic loading by the shake table method is presented in this paper.

2. Tri-Axial Shaker Facility

CPRI is equipped with state-of-the-art facilities for seismic and dynamics qualification of equipment as per National and International standards. The shake table is 3mx3m in size with a maximum payload of 10,000 Kg. The frequency range of vibration is 0.1 to 50 Hz and the acceleration limit is 1g. This facility caters to the requirements of National and International customers. CPRI has been involved in seismic qualification of electrical equipment for the past two decades. Equipment tested included 800/400 kV transformer bushings, 420/220/145 kV instrument transformers, 220/145 kV disconnectors, 800/400/220 kV surge arrestors and Medium/Low voltage switchgears.

3. Disconnectors/Isolators

3.1 Types of Disconnectors

Disconnectors or Isolators are generally usedon both ends of breakers for safe repair/replacement of equipment. Construction and operating mechanisms vary based on the voltage rating.

Types of disconnectors:

a. Horizontal Break
b. Double Break disconnector
c. Single Break Isolator (center break)
d. Vertical Break
e. Pantograph type Isolator.

3.2 Dynamics of Disconnectors

Three possible positions of isolator with ground switch:

a. Disconnector closed and ground switch in open condition,
b. Disconnector open and ground switch in closed condition and
c. Disconnector open and ground switch in open condition.

The mechanical dynamics of the disconnector are different in all three possible positions. Figure 1 shows a 245 kV vertical break disconnector with the disconnector in the closed position and the ground switch open. Under this position, the disconnector closing rod acts as a link between two post insulators. The entire disconnector will have cantilever action along the widthwise which is weak. Figure 2 shows a 245 kV vertical break disconnector with the disconnector in the open position and ground switch closed condition. Under this position, both post insulators will act as cantilevers. Post insulator with disconnector rod extended vertically is a slender and weak structure. Input acceleration will be amplified to a very high value, which may fail. Under disconnector, open and ground switch open condition post insulator with disconnector rod extended will be more vulnerable compared to ground switch closed condition. Change in mechanical dynamics with change in positions of disconnectors is applicable for all types of disconnectors.

Figure 1. 245 kv disconnector mounted on tri-axial shaker system: Disconnector closed and ground switch open.

Figure 2. 245 kv disconnector mounted on tri-axial shaker system: Disconnector open and ground switch closed.

4. Failure Analysis

4.1 Vertical Break Disconnector

4.1.1 Vertical Break Disconnector Details

Table 1. Disconnector details

Voltage rating, kV	245
Current rating, A	3150
Total height (disconnector in closed position), mm	5200
Total height (disconnector in open position), mm	8246
Support structure height, mm	2500
Weight, Kg	1450

4.1.2 Dynamic Properties

Dynamic characteristic of the disconnector was evaluated with the main contact in closed condition and the earth switch in open condition. The disconnector was subjected to low-level sinusoidal sweep vibration with constant acceleration. Response accelerometers are mounted at critical locations. The resonance frequencies of disconnectors are shown in Table 2.

Table 2. Resonance frequencies

Direction	Resonance frequency, Hz
Along width	2.19, 8.97 and 21.05
Along length	3.11 & 11.16
Vertical	31.98

The minimum value of damping evaluated based on the resonance search test is 3.74%. Figure 3 shows the typical resonance search test plot.Input acceleration is amplified by 20 times at resonance frequency[3] of 2.19 Hz. At resonance frequencies, structures behave in a non-linear manner resulting in amplification of input motion. Damping[4] is the controlling factor for amplification, but electrical equipment has low damping.

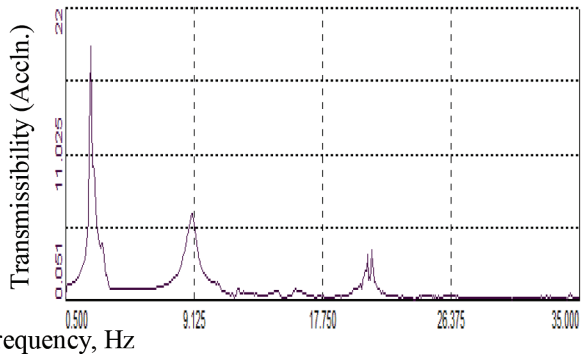

Figure 3. Resonance search test plot, resonance frequencies: 2.19 hz, 8.97 hz and 21.05 hz.

4.1.3 Seismic Qualification

Evaluation of functional and structural capabilities of equipment by mounting on the tri-axial shake table and simulating the earthquake environment is a seismic qualification. Seismicqualification by shake table is a more realistic method. Mounting of test samples during seismic qualification should simulate actual field mounting conditions.

The seismic performance of the disconnector isevaluated as per IEEE standard 693 - "IEEE recommended practice for seismic design of substations"[5]. The disconnector was subjectedto seismic loading under all possible combinations of the main switch and earth switch position. Disconnector is qualified for moderate performance level, 5 m/s^2 zero period acceleration. Required Response Spectrum (RRS) and achieved Test Response Spectrum (TRS) are shown in Figure 4.

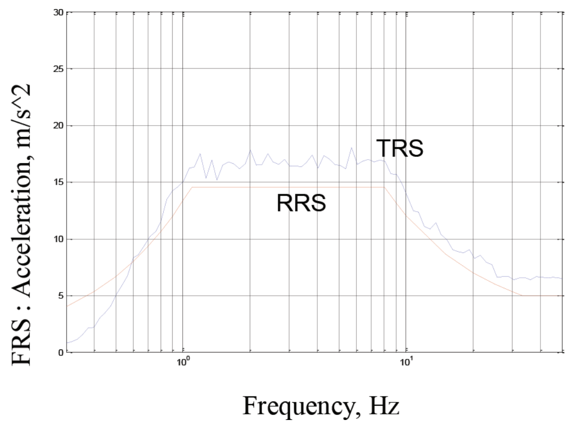

Figure 4. RRS and TRS

A disconnector in the open position is highly critical concerning the seismic performance of a vertical break disconnector. The height of the sample with the disconnector in the closed position is 5200 mm and in the open position is 8246 mm, height is increased by 3046 mm due to the opening. The main switch is a metal tube fixed on the moving mechanism of the disconnector without any support. Input acceleration to the table was 5 m/s^2 zero period acceleration. Due to the tall slender structure acceleration measured at the top of the metal tube was +111.77 and -81.86 m/s^2. Figure 5 shows the time history[6,7] of response acceleration. The amplification of acceleration at the top of the metal tube is around 22 times. This resulted in the failure of the welding joint between the main contact tube and moving mechanism and the main contact tube dislocated, refer Figure 6 for a photograph.

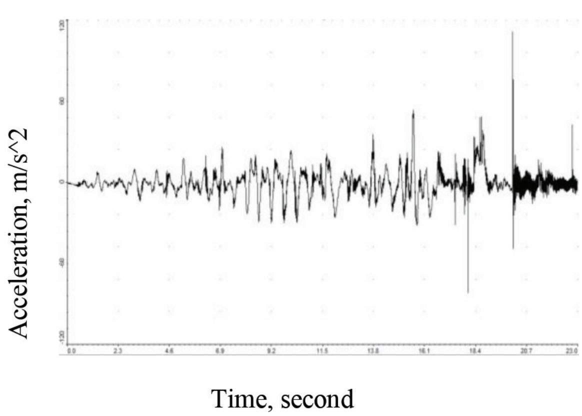

Figure 5. Time history of acceleration, peak value: +111.77 & -81.86 m/s^2.

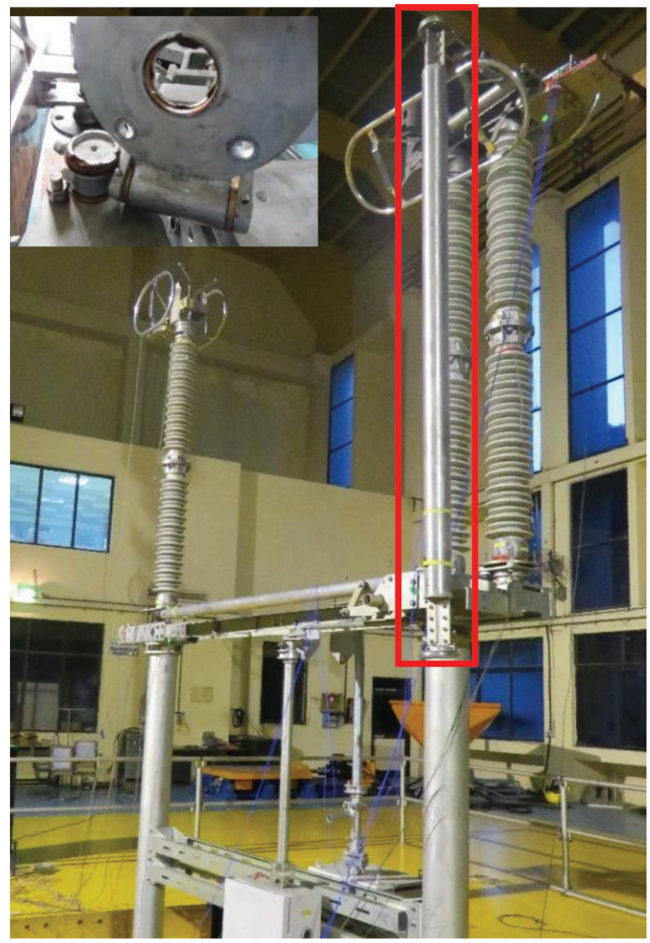

Figure 6. 245 kv disconnector main contact tube dislocated.

4.2 Horizontal Center Break Disconnector

4.2.1 Horizontal Center Break Disconnector Details

Table 3. Disconnector details

Voltage rating, kV	245
Current rating, A	2000
Total Height, mm	6100
Support structure height, mm	3200
Weight, Kg	1350

Figure 7 shows a 245 kV Horizontal centre break disconnector with the disconnector in the open position and the ground switch closed. Disconnector in the open position and ground switch in open condition will result in higher dynamic loading on post insulators compared to the other two operating conditions.

Figure 7. 245 kv horizontal centre break disconnector: Disconnector open and ground switch closed.

4.2.2 Failure During Seismic Qualification

In the horizontal centre break disconnector, both the post insulators are mounted on a moving mechanism and are attached with horizontal main contact of length 1325 mm each. Disconnectors in open conditions are the most critical concerning seismic performance, compared to other operating positions. During seismic loading, post insulators attached with main contact at the top and extending horizontally will be subjected to huge strain at the base of the post insulator, near the bottom cementing joint. Figure 8 shows the time history of strain developed during seismic loading.

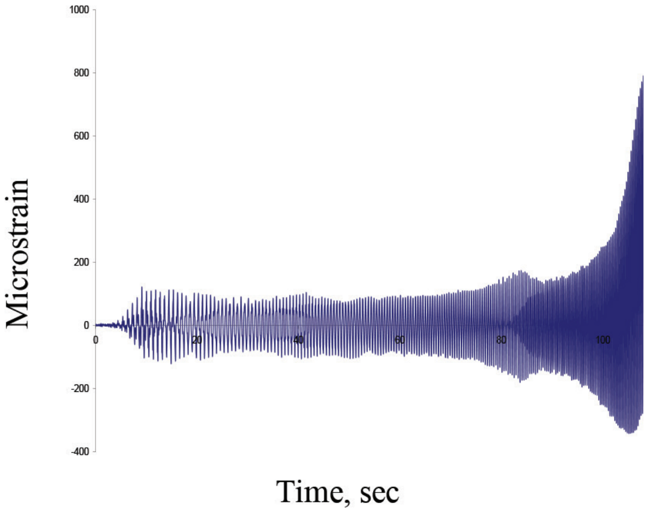

Figure 8. Time history of strain gauge, peak value: + 790.437 and -342.163 microstrain.

Due to high strain near post insulator bottom cementing joint, the insulator sheared (Figure 9).

Figure 9. Disconnector post insulator shear.

4.3 Change in Status of Main Contact

Disconnectors are meant for operation under no-load conditions, they are not manufactured either for breaking or making a circuit with load current. Changes in the status of the main contact of disconnectors are also noticed during seismic qualification in addition to physical damage. This means the disconnector is breaking and making the circuit when the current is flowing, which will damage the disconnector. Change in status of contact can occur irrespective of type.

The disconnector main contact was monitored by passing a low-voltage DC supply and monitoring the DC voltage using a high-speed data logger. Continuous change in the status of the disconnector main contact was observed during seismic loading and resulted in the opening of contact. The monitoring graph with continuous change in status and resulting in the opening of contact is shown in Figure 10.

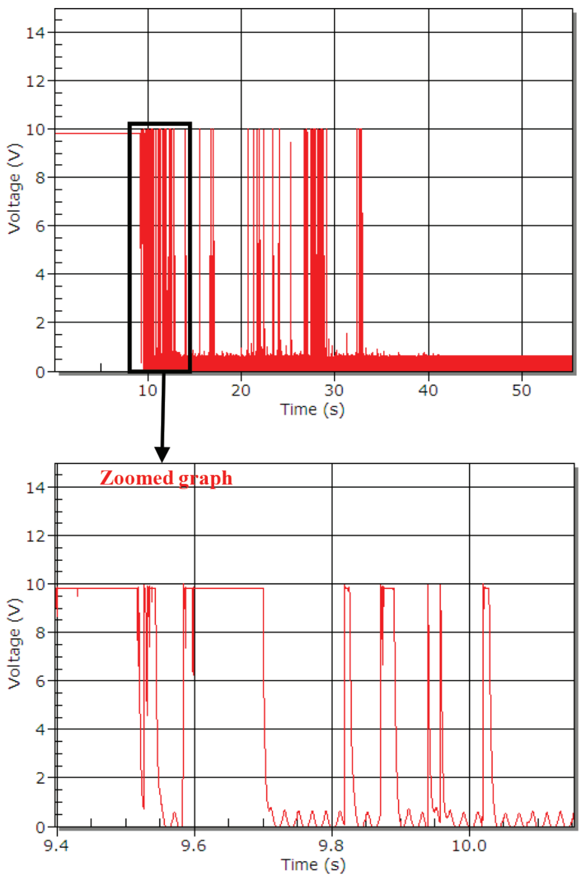

Figure 10. Contact monitoring graph.

5. Conclusions

The nature of high voltage disconnector failure due to earthquake loading is presented in the paper and contributing factors to failure are discussed. Possible failures that are; welding failure, post-insulator failure and functional failure (change in status of main contact) are discussed with case studies. Failures are noticed near critical locations. Amplification of input acceleration at natural frequencies and low damping causes failure. Evaluation of local natural frequencies at critical locations and evaluation of stress concentration while designing can prevent failure. The local natural frequency of the main contact closing rod with high amplification has failed welding under open conditions. Improving the quality of welding and strengthening to the required dynamic load can prevent failure. Stress concentration is high near the bottom cementing joint of the post-insulator. Stress should be evaluated at the critical location and it should be less than the material allowable limit.

In the case of electrical equipment, mechanical integrity and functional capability are to be checked for seismic qualification. Finite element analysis using software will give information about the structure at the initial design stage. Stress concentration and resonance can be evaluated using finite element analysis. Design validation and function capability evaluation should be carried out by the shake table method.

Designing equipment, interconnection and mounting configuration considering failure patterns can prevent failures and ensure the reliability of equipment. Power utilities and manufacturers may utilize the state-of-the-art facilities available at CPRI to ensure a reliableand safe power supply during earthquakes.

6. Acknowledgement

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