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Performance of High-Voltage Electrical Equipment Seismic Connection with Rigid Bus Conductor

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ABSTRACT

A seismic evaluation study was completed on a high-voltage (500 kV) electrical substation equipment Seismic Connection of a 12.7 cm (5 inch) diameter Aluminum Rigid Bus Conductor. The Seismic Connection is made with three semi-rigid aluminum alloy conductors running parallel with each other and positioned to provide vertical support. T-shape plates are welded to the top and bottom of the conductors for the connection to the Rigid Bus. Bonneville Power Administration (BPA) initiated this study for the purpose of assessing the dynamic stability, connection loads, and jumper damage to the Seismic Connection during a seismic event. This study determined the performance of the Seismic Connection, and investigated the capability of the 12.7 cm (5 inch) Rigid Bus Connection to resist loads induced by seismic forces when subjected to various stiffness boundary conditions of a Disconnect Switch (DS) and Power Circuit Breaker (PCB).

INTRODUCTION

Earthquake experiences have shown that high-voltage electrical substations are vulnerable to equipment damage. In the past and for some time into the future, high-voltage electrical equipment will continue to use porcelain components as an insulating material. Porcelain components not designed to resist earthquake forces are vulnerable to damage. The earthquake design of porcelain components should take into account the material strength and interaction between the connected high-voltage electrical equipment. The interaction between the equipment is dependent on the method of connection. Typically high-voltage equipment is connected using either flexible conductor or rigid bus connections. When either of these connection systems are used adequate flexibility must be provided to minimize equipment interaction.

There are advantages and disadvantages for both flexible conductor and rigid bus connections. Flexible conductor connections allow for adequate slack, but require higher profile substations. A rigid bus connection allows lower profile substations, but provides the design challenge of including adequate equipment interaction flexibility (Figure 2.). BPA has traditionally used the rigid bus connection method.

The vulnerability of high-voltage electrical equipment and the potential of damage as a result of equipment interaction are a major concern to electric utilities in both the United States of America (USA) and Canada. Portland State University (PSU) is working with BPA in the evaluation of a seismic connection rigid bus system (Albi 1999 and Starkel 1998). Research is also being conducted at the Pacific Earthquake Engineering Research (PEER) Center, University of California – Berkeley on high-voltage electrical equipment connection interaction. This project includes both analytical and experimental studies. In Canada, both B.C. Hydro (Opsetmoen 1992) and Hydro Québec (Dastous 1995) have studied interaction parameters for flexible conductor connections. The USA and Canadian researchers are sharing information on the results of their investigations.

In the late 1970's BPA (Aguilar 1976) started investigating methods for providing rigid bus equipment connections with adequate slack to minimize earthquake ground motion-induced interaction of high-voltage electrical equipment. This paper discusses the latest effort being conducted at PSU to provide a rigid bus design with adequate seismic slack. The rigid bus connection discussed in this paper is being used to connect D-T 500 kV Power Circuit Breakers to Vertical Break Disconnect Switches.

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SEISMIC SHAKE TABLE

The single degree-of-freedom (SDoF) Shake Table at PSU, Civil Engineering Department has a 3 m x 3 m [9.842 ft x 9.842 ft] steel platform and weighs 60,051 KN [13,500 lbs.]. A 222.4 KN [50,000 lbs.] hydraulic actuator moves the Shake Table horizontally with a maximum velocity of 0.9 m/s (2.95 ft/s), 3g bare table acceleration, or 1+g acceleration with an 89 KN (20,000 lbs.) specimen. The Shake Table is attached to four hydraulic bearings located at the corners of the table, which provide a near friction-less surface on which the table glides. The usable stroke of the table is 30.48 cm (12 in.). MTS System Corporation, Minneapolis, Minnesota, manufactured the Shake Table and actuator.

The instrumentation used included accelerometers, strain gages, and load cells. Specifically, seven Setra Systems High Output Linear Accelerometers Model 141, four Measurements Group EA-Series Strain Gages Model EA-13-250BG-120, and three Kulite Semiconductor Load Cells Model LE-754(755)(756)-TC-2000 were used during testing.

TEST CONFIGURATION

The Rigid Bus Seismic Connection tested is shown in Figure 1. The total length of the rigid bus system was 7.6 m (25 ft.). The 12.7 cm (5 inch) diameter rigid aluminum bus is made of 6061-T6 aluminum alloy. The three conductor end supports are 33.02 mm (1.3 inch) diameter Hood conductors (AAC/TW), 914.4 mm (36 inches) in length, shown in Figure 2. The conductor ends are welded to aluminum T-shape plates. The T-plates are 304.8 mm (12 inches) by 228.6 mm (9 inches) and 38.1 mm (1.5 inch) thick. The 12.7 mm (5 inch) rigid bus is attached directly to the top of the Power Circuit Breaker bushing. The bottom T-shape plate of the three Hood conductors is attached to the Disconnect Switch.

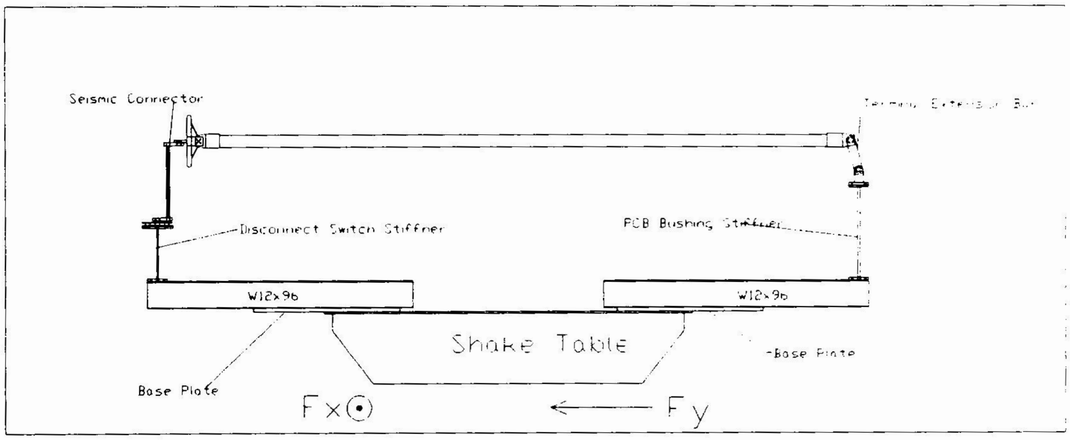

Figure 1.

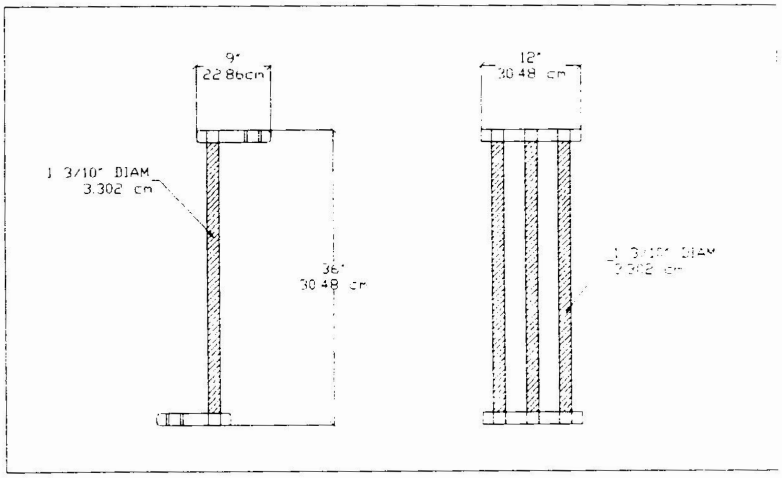

Figure 2

The test configuration is designed to simulate flexible, semi-rigid and rigid 500 kV PCB bushing to DS end connection boundary conditions used. The end connection boundary conditions were designed using information provided in IEEE Std 693, Section 6.9.2, on estimated displacements for typical equipment response from a 0.3g peak ground acceleration. Based on an estimated fundamental natural frequency, Table 1 of IEEE Std 693, Section 6.9.2, was used to obtain estimated equipment connection displacements of 101.6 mm [4 in.] to 203.2 mm [8 in.] for a 500 kV Dead-Tank PCB bushing and 203.2 mm [8 in.] to 609.6 mm [24 in.] for the DS.

The end connection boundary condition stiffnesses within the test load range for the Dead-Tank PCB bushing were 0.17 kN/cm (95 lbs./in), referred to as B1, and 2.2kN/cm (1250 lbs./in.), as B2. For the DS the stiffness ranges were 0.12 kN/cm (74 lbs./in.), referred to as D1, 0.25 kN/cm (141 lbs./in.) as D2, 0.50 kN/cm (278 lbs./in.) as D3, and 8.75 kN/cm (5000 lbs./in.) as D4. The results from the D1 stiffness are reported in Seismic Evaluation Part I (Starkel, 1998).

The load limit criteria for the PCB bushing is set at 2.22 – 2.45 kN (500-550 lbs.) based on information obtained in IEEE/ANSI C57.19.01 (1991) and IEEE PC57.19.100/D11 (1994). The PCB bushing seismic load is approximately 50 percent of the cantilever load test requirement, which was selected as 4.45 – 4.89 kN (1000 – 1100 lbs.). The DS load limit criteria is 0.67 kN (150 lbs.) which is obtained from IEEE/ANSI C37.32 (1990).

The Shake Table testing sequence had four operations utilizing three types of signals: sine sweep, transient time history, and sine beat. The sine sweep was used to determine the resonant frequencies of the rigid bus configuration for all boundary conditions. A sine sweep is obtained by continuously varying the frequencies of a sine wave over time. The frequency change is measured in octaves and was varied at 1 oct/min. The complete sine sweep specifications are as shown in Table 1. Following the sine sweep a transfer function is calculated for the response time histories to obtain the resonant frequencies. The outputs of the transfer function are frequency in Hertz (Hz) and amplitude gain, which is unitless.

Table 1. Sine Sweep

Complete Frequency Range: 0.25 Hz - 25.0 Hz

0.25 Hz - 1.50 Hz	0.01 g	Constant Acceleration
1.50 Hz - 2.50 Hz	0.01 g - 0.10 g	Varied Acceleration
2.50 Hz - 25.0 Hz	0.10 g	Constant Acceleration

The structure was then subjected to a transient time history as specified by the IEEE Std 693 (1997) High Required Response Spectrum (RRS) at 2% damping. This acceleration time history was synthesized to envelop the maximum response of typical earthquakes and soil site conditions. Due to the size of the rigid bus connection, it was desirable to get both the longitudinal and transverse responses during one test. This was accomplished by orienting the rigid bus at 45° to the table motion and overdriving the table to a level of 177%, which produced a zero period acceleration of 0.65g in both directions.

The sine beat is defined by IEEE Std 693 (1997) as a continuous sinusoid of one frequency, amplitude modulated by a sinusoid of another frequency. When the Transient Response Spectrum (TRS) does not envelop the RRS at a certain frequency, a sine beat is used to test at that frequency. Some of the boundary conditions required a sine beat at 1.2 Hz.

TEST RESULTS

Depending on the end connection boundary conditions, the Rigid Bus system experienced up to seven natural frequencies during the sine sweep, as shown in Table 2. At no time during the transient test, with any boundary conditions did the structure become dynamically unstable. With six accelerometers it was possible to measure the different accelerations and displacements at various points in the structure. The peak acceleration was 5.55g and occurred at the center of the Rigid Bus with the rigid-rigid (B2-D4) boundary condition. Maximum displacements of the Seismic Connection were 71.91 cm (28.31 in.) globally, during flexible-flexible (B1-D2) test, and 67.26 cm (26.48 in.) relatively, during the flexible-rigid (B1-D4) test. During the test with the rigid PCB bushing (B2) and semi-rigid DS (D2) the maximum load limit criteria was exceeded with loads in the bushing exceeding 4.45 kN (1,000 lbs.), see Table 3. No damage occurred during any individual test, however over many tests (more than 50) the braiding on the seismic connector began to show a slight separation between the individual conductor strands (birdcage).

Table 2. Resonant Frequencies

	Vibration Modes	Frequencies[5]
1	Transverse to Rigid Bus	~1.00 Hz
2	Torsion	~3.00 Hz, 9.20 – 10.20 Hz
3	Longitudinal to Rigid Bus	3.50 – 3.75 Hz
4	Transverse of Disconnect	6.60 – 6.75 Hz
5	Vertical Bus	7.40 – 9.50 Hz
6	Longitudinal of Disconnect	~12.00 Hz
7	Vibration	~18.50 Hz

Table 3. Max Loads kN (lbs. = 0.225 kN)

Boundary Condition	Disconnect Switch			Power Circuit Breaker Bushing		
	Max F_x	Max F_y	Resultant	Max F_x	Max F_y	Resultant
B1D2	0.43	-0.12	0.45	1.23	-0.72	1.43
B1D3	0.55	-0.12	0.56	1.21	-0.72	1.41
B1D4	0.89	-0.11	0.90	0.93	-0.68	1.15
B2D2	0.22	-0.11	0.24	3.21	3.22	4.55
B2D4	-0.62	-0.11	0.63	1.76	-2.91	3.40

CONCLUSION

The purpose of this study is to assess the dynamic stability, connection loads, and jumper damage of the 500 kV electrical substation equipment Seismic Connection during an earthquake event under varying end boundary conditions. The test results demonstrate that a Rigid Bus connection with adequate slack/flexibility can be used to limit high-voltage electrical equipment connection loads. Rigid/stiff end connections resulted in seismic loads that exceeded recommended values. At 500 kV the tested rigid/stiff boundary conditions are not realistic. The results demonstrate that the higher flexibility of non-ceramic Dead-Tank Power Circuit Breaker bushings will help to minimize end connection loads using BPA's rigid bus seismic connection. Future research will include the study of flexible bus systems.

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[5] '~' is 'about equal to'

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