HIGH VOLTAGE TRANSFORMER BASE ISOLATION

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ABSTRACT: The Bonneville Power Administration (BPA), USDOE, has conducted research on base isolation technology and its application to electric power high voltage transformers. Power transformers are the most important component of a transmission line system. They are also one of the most vulnerable substation equipment as demonstrated by past and recent earthquake damage. The question is why not base isolate this critical piece of equipment? BPA conducted an extensive research project to address this question. The research included analysis of base isolated transformers and scale model shake table tests. A base isolated system was selected and the first base isolated high voltage transformer installation in the United States was completed. This paper will present the results of the research and details of the base isolation transformer installation.

1. Introduction

High voltage power transformers are the most critical component of the transmission system. They have been identified as one of the most seismically vulnerable pieces of substation equipment. Current seismic hardening of transformers is to anchor them to the foundation. This solution allows the ground motions to be directly transferred into and through the transformer. These ground motions are amplified as they move up the transformer to areas were the bushings, arresters, and conservators are mounted. This results in these components experiencing high accelerations which can cause subsequent failures. Because transformers are large and heavy, it is not economical to shake table test the complete transformer unit. Therefore, typically the transformer is seismically evaluated using static finite element analysis, and in a few cases dynamic analysis. The individual components (i.e. bushings and arresters) are usually qualified by shake table tests, but not in their installed configuration on the transformer. In the US, the IEEE 693 analysis qualification procedure is used to seismically qualify high voltage transformers, yet the industry is still experiencing transformer component failures.

To better understand the seismic performance of high voltage transformers an analytical study was performed, Reference 7. A production, static analysis model evaluation of a 230kV transformer was used to compare with a dynamic analysis assessment. The dynamic model was used to investigate the seismic response of a 230kV high voltage transformer and identify the critical parameters and component interactions affecting the response. Modeling options were studied to determine their sensitivity to the seismic performance of the different transformer components. The analytical results from this study were also used to investigate base isolation options for high voltage transformers.

Base isolation technology applied to high voltage transformers was investigated. From the base isolation options investigated, a triple friction pendulum was selected for developing a base isolation solution for a 460 kV and 500 kV transformer. Reduced scale model shake table testing demonstrated that the selected base isolation devices can be used to reduce the seismic vulnerability of transformers. A simplified analysis procedure was developed to help the utility engineer select the appropriate base isolation design parameters. The design for an installation demonstration for the 460kV transformer was developed and installed.

2. **Transformer Seismic Vulnerability**

High voltage transformers are critical for the operation of the power grid. Transformers allow the transformation of different voltage levels, which is essential for electrical transmission and distribution delivery. The basic transformer is a steel box which houses the internal components, coils and core. Attached to the box are the basic external components consisting of the oil conservator, radiators, and bushings. In addition to these components, some transformers may have surge arrestors and tap changes mounted to the transformer. Figure 1 shows a high voltage power transformer.

The current industry practice is to anchor the transformer to the concrete foundation. This prevents the transformer from sliding or overturning during an earthquake. With the transformer anchored to the foundation the earthquake ground accelerations are directly transferred to these components, both internal and external. As the accelerations move up the transformer they can be amplified, by as much as 2 times, and greater, than the input ground accelerations. Assuming that the transformer is anchored, the amplified accelerations can damage both the external and internal transformer components.

Past and recent earthquake events have demonstrated the seismic vulnerability of transformer mounted surge arrestors and bushings, and in some cases the radiators. There also has been a few earthquake events were the transformer has failed internally a short time period after the earthquake, caused by possible shifting of the internal components.

Figure 1, High Voltage Power Transformer

3. **Seismic Qualification Procedures**

In the US, the industry standard IEEE 693 provides the seismic qualifications requirements for substation equipment, including high voltage transformers. The current industry practice for seismic qualification of transformers attempts to mitigate the vulnerability of this critical equipment. Because high voltage transformers are expensive, large, heavy, and usually unique to the power grid that they are used in, it is not practical to shake table test a production transformer. Therefore, current qualification procedures use analytical methods, typically static analysis, to evaluate the transformer. The transformer external components, surge arrestors and bushings, are seismically qualified independent of the transformer by shake table testing, for higher voltage units. There is a disconnect between the individual qualification of the external components and their dynamic behaviour in the transformer system. The current IEEE 693 qualification procedure has not provided transformer systems with the necessary seismic capacity to prevent damage.

4. **Base Isolation**

One option to improve the seismic performance of high voltage transformers is the use of base isolation technology. Base isolation technology is not new, it have been applied to buildings, bridges, and other structures for earthquake protection. There had been a number of times that the question has been asked by non-utility engineers, why high voltage power transformers are not protected by this type of technology. The answer to this question has been “I do not know why”, other than the electric power transmission line industry is conservative/cautious when it comes to applying new civil/structural technologies to the most important electrical equipment in the power grid. To be able to provide a better answer to this question, a research project was started at the Bonneville Power Administration to investigate the application of this technology applicable to high voltage power transformers.

5. **History Of Base Isolation Research For Transformers**

There have been a number of researchers that have investigated base isolation technology for transformer applications [Cao M., 2012, Ersoy S., 2002, Houtman N., 2013, Murota N., 2003, Saadeghvaziri M. A., 2001, 2007, 2010, Selahattin E., 2001, and Suzuki H.,1992]. Investigations using analytical and experimental methods have been performed. References Cao M., 2012, Murota N., 2003, and Suzuki H.,1992 investigated high damping (3.5% natural rubber and 12% ferrite rubber) laminated elastomeric rubber isolator. Murota N., 2003, used a combination of rubber isolators (also referred to as bearings) and sliding bearings. The sliding bearings carried the weight of the transformer and the rubber bearings provided horizontal restoring force without sustaining any vertical load. The sliding bearing coefficient of friction varied from 0.04 to 0.16. The equivalent damping ratio for the system was 27%.

Cao M., 2012, discusses shake table testing of a mock-up transformer. This was a very unique research project that used a test specimen that looks like a single phase transformer with 500kV and 230kV bushings, conservator, and simulated iron core. The model transformer length was 3.524 m, width of 2.242 m, and height of 3.172 m. The modelled transformer was filled with water and weighed 45,315 kg. The base isolation system used laminated rubber bearings with an effective damping range of 15% – 25%. The result of this investigation demonstrated the importance of selecting the appropriate isolation parameters: damping and stiffness.

References Ersoy S., 2002, Saadeghvaziri M. A., 2007, and Selahattin E., 2001, investigated friction pendulum base isolation systems (FPS). This isolation system consists of a polished stainless steel spherical concave surface, articulated slider, and low friction composite liner. During an earthquake, the articulated slider moves relative to the concave surface(s). The period of oscillation is independent of the weight of the supported structure and dependent on the radius of the concave surface. A typical damping value for a FPS device ranges between 10% - 30%. The FPS was demonstrated to be effective for protecting power transformers using analytical and scale model testing.

The research results obtained from the referenced investigations demonstrate the effectiveness of base isolation systems for protecting high voltage transformers. These base isolation systems can reduce the input accelerations on the transformer and external components. The disadvantage of these devices is that they increase the displacement response of the transformer.

The next phase applying base isolation systems to power transformers is implementation on actual transformers to address the associated design issues. Xie, Q., 2013, discusses the installation in China of a laminated rubber bearing isolation system applied to a 220 kV transformer. This installation uses both elastomeric rubber bearings, and lead-core elastomeric rubber bearings. Another application of base isolated transformers is Transpower’s, NZ, new HVDC facility. They use base isolation technology to protect HVDC transformers.

6. **Bonneville Power Administration's Base Isolation Project**

The Bonneville Power Administration (BPA) initiated a research project to investigate the application of base isolation technology. This was a three year project with the University at Buffalo (UB), the State University of New York, USA. UB was selected because of their state-of-the-art three dimensional shake table test facility. The objective of the investigation was to develop a seismic isolation system appropriate for low weight and potentially high asymmetric high voltage transformers. BPA specified that the isolation system should have a displacement limit of 30.48 cm in a strong seismic event. This research included both analytical and experimental testing.

The Bonneville Power Administration's high voltage power grid is potentially subject to a M8 – 9 subduction zone earthquake, Houtman N., 2013. This earthquake source is similar to earthquakes experienced by Japan, Indonesia, and Chile. The return periods for subduction zone earthquakes in the BPA service region are 240 years for M_w 7.4 -8.4, 320 - 430 years for M_w 8.4 – 8.5, and 500 years for M_w greater than or equal to 9. The last subduction zone earthquake, M_w 9^+, in the BPA service region occurred in 1700.

The application of modern seismic isolation systems to electrical power transformers presents several challenges. The relatively small weight, compared to traditional applications to buildings and bridges, of a power transformer limit the use of elastomeric systems for isolation through significant shifting of the effective structural period, without compromising the vertical stability of the isolators. Additionally, the asymmetric mass distribution of the transformer and the high vertical stiffness of the transformer tank can cause strong torsional response in an elastomeric bearing isolation system. Base isolation sliding systems, such as friction pendulum devices, are ideal for low weight applications as the effective period is independent of the supported weight. These systems should be designed to limit the displacements, such as the 30.48 cm specified limit, in order to avoid overstressing the connections to external components (surge arrestors, bushings, and control cables).

The base isolation devices studied were a stiff and highly damped Lead Rubber bearing, and a Triple Friction Pendulum (TFP) bearing, Figure 2. A series of tests were carried out on a three dimensional shake table in order to investigate the effectiveness of the selected base isolated systems. This paper only discusses the triple friction pendulum system selected for a three phase 460 kV power transformer. Additional information on this research can be obtained in Oikonomou K., 2012.

Figure 2, Triple Friction Pendulum, Earthquake Protection Systems, Inc., Zayas, 2006

The 460 kV power transformer is used for high voltage fog chamber testing. It is a General Electric transformer that weighs 1690 kN, and is 963 cm in length, 355.6 cm wide and 458.5 cm tall, Figure 3.

Figure 3, 460 kV Power Transformer

A series of tests were conducted on a three dimension shake table. Because the actual transformer could not be tested, a transformer model and TFP isolators at a reduced scale length of 1:3 was used. The model accounted for the asymmetry of the transformer mass distribution, allowance for symmetric and non-symmetric bushing installations, and appropriate transformer tank cover plate flexibility using a flexible plate for the bushing-mounting interface. The scaling weight of the model was 209 kN's, representing a transformer weight of 1890 kN's. Figure 4 shows one of the model configurations. The 230 kV bushing was used for testing.

The triple friction pendulum parameters, Figure 5, used for the reduced model tests were: R_1 (radius) = R_4 = 43.5 cm, R_2 = R_3 = 5.31 cm, d_1 = d_4 = 5.89 cm, d_2 = d_3 = 1.32 cm, u_1 (friction coefficient) = u_4 = 0.13, and u_2 = u_3 = 0.4. Figure 6 show the displacement pattern and typical hysteresis loop for a TFP device.

The shake table tests demonstrated the effectiveness of the Triple Friction Pendulum to reduce the ground motion acceleration into the high voltage power transformer system. The base isolators act as a filter between the ground and the transformer superstructure. The TFP system demonstrated negligible torsional response due to the model mass eccentricity. For the Lead Rubber bearings isolators the torsional response was significant.

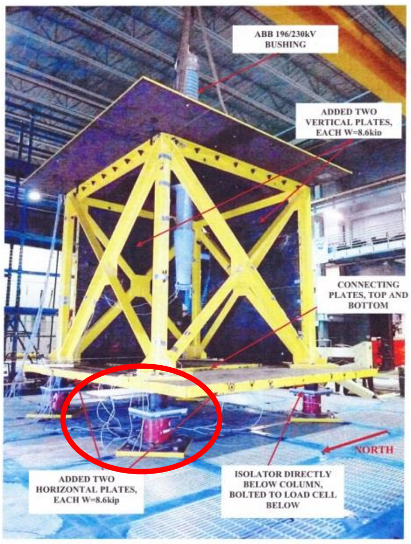

Figure 2 Model Used in Shake Table Testing with Added Mass in Symmetric Bushing Configuration

Figure 12 View Model with Full Size Triple Friction Pendulum Bearings on Shake Table

Figure 4, Reduced Transformer Model

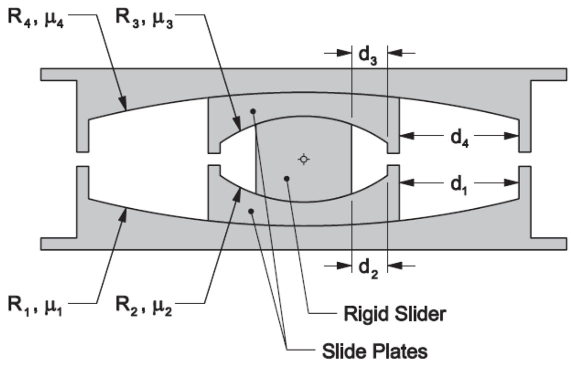

Figure 5, Triple Friction Pendulum Parameters

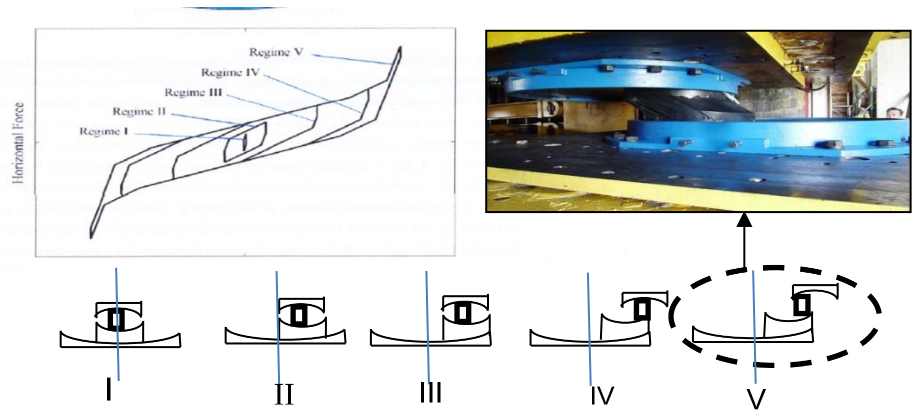

Figure 6, Triple Friction Pendulum Displacement Pattern and Hysteresis Loop

7. **Bonneville Power Administration's Demonstration Project**

Based on the research results, BPA completed a demonstration project installing a Triple Friction Pendulum system for a three phase 460 kV high voltage transformer. Figure 7 shows the design concept used for this installation. Because the transformer was not design to support a four point load base isolation system, a concrete support pad was design to support the transformer between the concrete foundation and the TFP devices. Dimensions for the concrete support pad are 648 cm in length, 401 cm in width, and 45.7 cm thick. The design parameters for the demonstration project TFP device are R_1 (radius) = R_4 = 99.1 cm, R_2 = R_3 = 20.3 cm, d_1 = d_4 = 17.8 cm, d_2 = d_3 = 2.54 cm, u_1 (friction coefficient) = u_4 =0.12 to 0.15, and u_2 = u_3 = 0.06 to 0.07. The height of the TFP isolator is 22.9 cm. Figure 8 shows the completed installation.

The connections (cabling) to the transformer need to have sufficient slack. The connection to the voltage regular is similar to a station service tertiary connection. These bushing have minimum phase spacing and can be subject to high current, therefore high short circuit forces. To address the possible high short circuit forces and the displacement demand of the base isolated system a flexible copper bus was used for this connection. An alternate to a copper cable is a thin copper bus with an S-shape and thermal expansion devices at both ends. Fortunately this type of connection is not typical in the BPA power system. The control cable is a corrugated aluminum sheath cable, Figure 8. The control cable has large loop located between the concrete foundation and transformer concrete support pad.

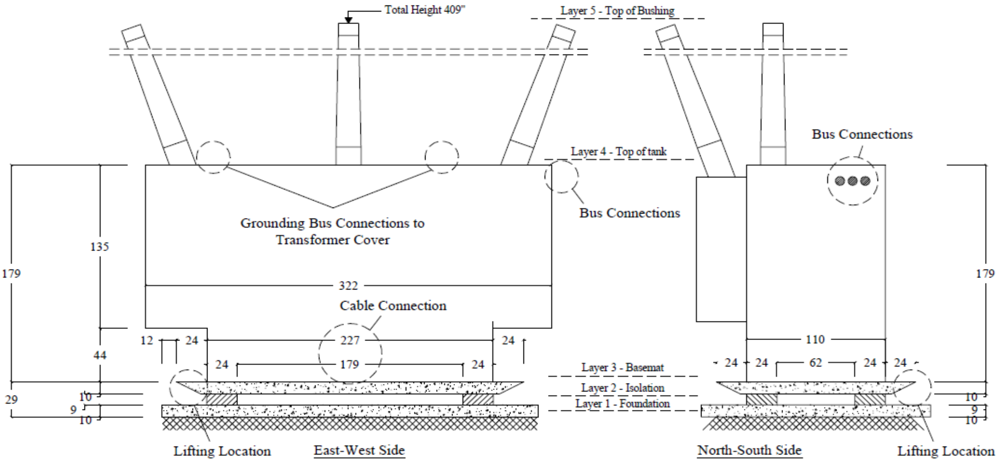

Figure 7, Base Isolation Design

Figure 8, Completed Base Isolation Installation

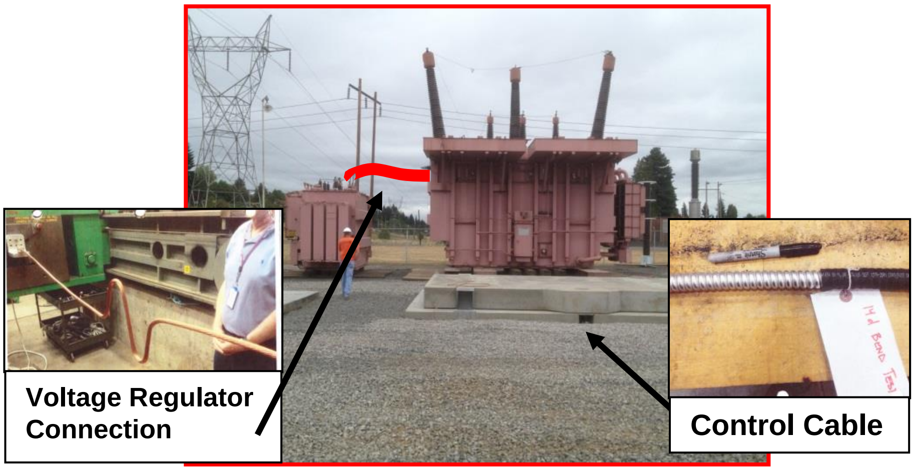

Figure 8, Cable Connections

This demonstration project was constructed to provide an example of applying base isolation technology to high voltage power transformers. For future installation, the design of the intermediate support pad will consider using structural steel or composite support systems, with ballast weights. The use of the intermediate support is important to provide additional weight to the low weight of the transformer relative to the performance of the TFP system. This alternate method is required for retrofitting existing transformers were minimizing the outage time of the transformer is critical to implementing this technology. Since the installation of BPA's transformer and presentations by BPA at IEEE 693 and Inter-Utility meetings, this technology is now being considered by California Utilities. Seattle City Light visited the demonstration project, and has subsequently base isolated a 115 KV transformer using TFP, and plan to base isolate the remainder of their units. There are now two transformers in the US base isolated and more to follow. The answer the question "Why not base isolate power transformer" has been answered "Yes we can do it".

8. **Conclusions**

Mitigating the seismic vulnerability of high voltage transformers is very important to the Bonneville Power Administration. BPA's service region has the potential for a M9+ earthquake. Base isolation is a proven technology for other important facilities, such as buildings and bridges, and should be investigated for high voltage power transformer applications. This research project provides additional information and a demonstration project to support base isolation technology for high voltage power transformer application.

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