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NEW IEEE693 SEISMIC QUALIFICATION PROCEDURE OF SEISMICALLY PROTECTED HIGH-VOLTAGE SUBSTATION EQUIPMENT BY TESTING AND ANALYSIS IN A DETAILED CASE STUDY

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ABSTRACT

The use of seismic protective devices in the electric power industry to improve seismic resiliency of high-voltage substation equipment is increasing worldwide. Seismic isolation represents one of the most common approaches used in the industry to reduce the seismic demand by driving the natural frequency of the system into the low frequency range where demand is low and incorporating some supplemental damping. This study is focused on an experimental evaluation of the new IEEE693 qualification procedure by analysis of substation equipment with a seismic protective system. A high-voltage equipment protected by full-scale friction pendulum bearings is the focus of the study. The seismically isolated equipment is experimentally studied on a long-stroke uniaxial shaking table to evaluate the response of the isolated system to the strong motion time histories recommended in the new draft of IEEE693. In addition, the friction pendulum bearing is studied in a component testing setup to evaluate its performance under relatively small vertical loads. A numerical model of the isolator is calibrated based on the results of the component tests. The isolator's numerical model is incorporated in the finite element model of the system, which was subjected to the same strong motions used in the shaking table tests. The results of numerical simulations are being compared to those of the shaking table tests to evaluate the new IEEE693 procedure of seismic qualification of seismically protected equipment by analysis.

INTRODUCTION

Seismic isolation is a common technique used for the protection of structures and equipment from earthquakes. There are several types of devices providing seismic isolation. One of the most popular and commonly used is a friction pendulum bearing (FPB). The main idea behind a FPB is based on sliding movable spherical surfaces in respect to fixed spherical surfaces. A slider in between the surfaces makes this possible.

SOME EXAMPLES OF SEISMIC ISOLATION BY FPBS

Bonneville Power Administration (BPA) (BPA, 2013) was the first United States electric utility to use base isolation with an existing high voltage transformer. The friction pendulum bearings were selected as suitable isolation devices. Four FPBs were used to isolate the existing 460-kV transformer. The total weight of the transformer in service was about 500-kips. The design work included a bi-linear hysteretic model for determining design parameters of the isolation system. Once the parameters were determined, a dynamic response history analysis according to ASCE 7-10 was used to determine the displacement capacity of the isolation bearings. The analysis confirmed that the demands on the equipment could be reduced by approximately 50%. The photos of the FPBs applications in this project are presented in Figure 1. The displacement capacity was about ±20-inches.

a) Overall view b) Close view of a FPB

Figure 1. 460-kV transformer isolated by four FPBs at BPA's substation (courtesy BPA).

Another similar and more recent application of the FPBs is described by Cochran (2015). Four FPBs were used to reduce the seismic demand on a 120-kV transformer at one of the substations of Seattle City Light utility company. The total weight of the transformer was about 400-kips. The photos taken by one of the authors during the site visit of the substation are presented in Figure 2. The displacement capacity was about ±20-inches.

c) Overall view of the transformer d) Close view of FPB at the corner

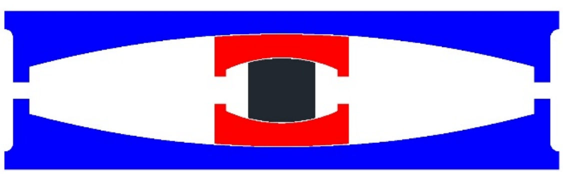
Figure 2. 120-kV transformer isolated by four FPBs at Seattle City Light's substation.

As described above the FPBs are most often used for isolating transformers, which represent a relatively heavy equipment. This study, results of which are presented herein, had two objectives. First, this study was undertaken to evaluate the performance of FPBs when the vertical load on the isolator is relatively low. Second objective was to evaluate a seismic qualification guidelines for isolated high-voltage equipment published in the new version of the IEEE693 document (IEEE, 2018). Four full-scale FPBs with a displacement capacity of ±32-in were used in this study. They were provided by Earthquake Protection Systems.

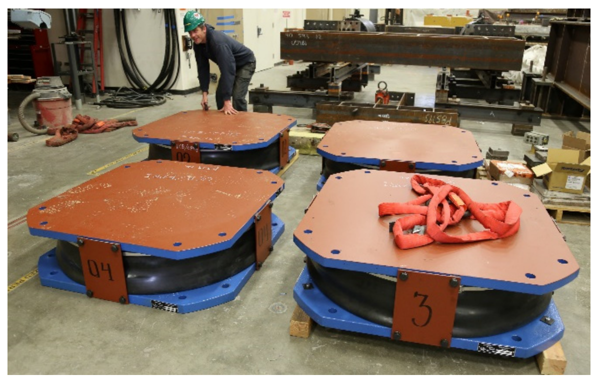
COMPONENT TESTING OF FPB

Details of FPB used in the study. There are several types of seismic isolation. One of the most commonly used is the Friction Pendulum Bearing (FPB). In the most basic case, the FPB consists of a spherical surface on which a slider slips. Since the radius of the spherical surface is predefined by the design requirement of the isolator, it controls the resonant frequency of the isolator, which is based on a pendulum theory (see Timoshenko (1937), for example).

There are several implementations of this basic idea, and the FPB studied in this paper was a representative of the so-called triple FPBs (EPS, 2019). It consists of two dishes with polished concaved spherical surfaces and a slider pack between them as presented in Figure 3a. In addition, the slider pack consists of two concaved spherical surfaces with a rigid slider inside. This type of isolation provides several advantages. A few advantages are listed here. First, triple FPB is more compact than FPB with a single sliding surface designed for the same seismic displacement demand. Second, due to the presence of several surfaces there is a possibility of having several resonant frequencies of the isolator depending on which surface is involved in the sliding action. Third, due to the presence of several contact surfaces, the overall damping depends on the friction of the slider's liner, which can be selected in the most beneficial way to meet the design requirements of the isolator. The full-scale isolators used in this study are shown in Figure 3b.



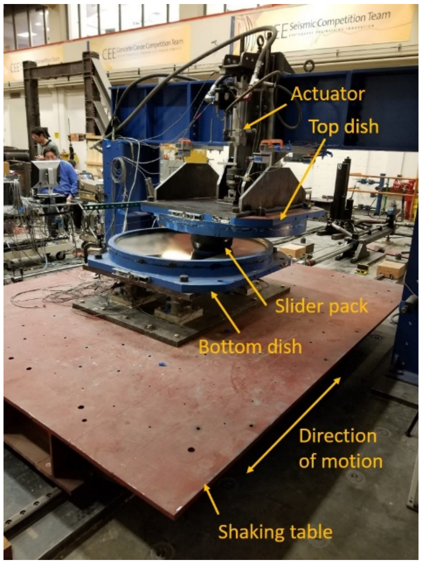
a) Schematic drawing



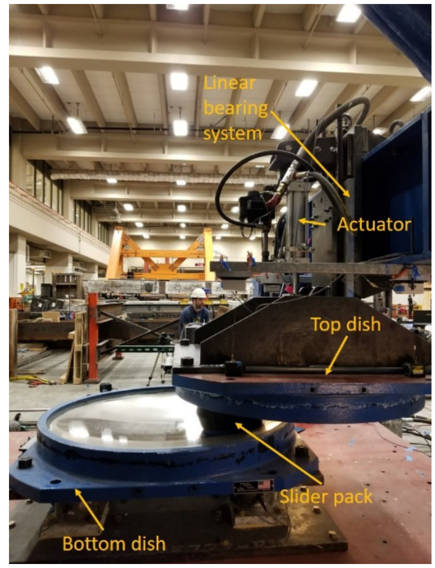
b) Photo of FPBs used in the study

Figure 3. Triple FPBs were used in this study.

Experimental setup. A special experimental setup was developed at the University of California, Berkeley to conduct component testing on seismic isolators (Takhirov, 2019). A full-scale triple FPB was studied in this setup by imposing incrementally increasing cyclic horizontal displacements while keeping the vertical load constant. The setup was intended for the performance evaluation of FPBs under relatively low vertical load and feasibility study of their application as a seismic isolation of high-voltage equipment. The setup is presented in Figure 4a. To mimic a real-life installation, where the top and bottom dishes remain parallel to each other, a special linear bearing system was introduced to keep the top dish horizontal while allowing its movement up and down as shown in Figure 4b. The bottom dish was attached to a shaking table platform capable of delivering ±32-in displacement.



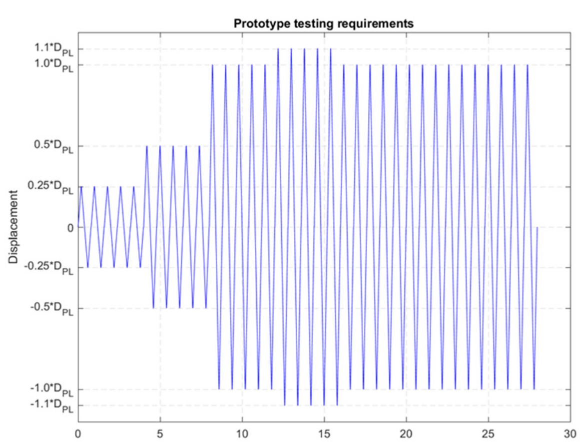
a) Setup



b) Top dish remains parallel to bottom one during large displacement

Figure 4. Experimental apparatus for component testing of full-scale FPBs.

Results of Component Testing. The component testing protocol recommended by (IEEE, 2018) for seismic protection devices was used in the study. At the beginning of this study, the cycles prescribed by the IEEE693-2018 document were generated as a combination of ramps up and ramps down as presented in Figure 5a. Due to stick and slip action in the isolator's sliding system the horizontal force had significant spikes in vicinity of points where the direction of loading reverses as presented in Figure 5b. It was related to the fact that these points correspond to the points of very high accelerations where velocity nearly instantaneously changes its sign while the value remains the same. Typical test results with no additional vertical load are presented in Figure 5b. The total vertical load acting on the slider pack was a sum of self-weight of the top dish and the weight of the upper parts of the test setup. In the next steps of testing, additional weights were applied by adding lead blocks or using an actuator.

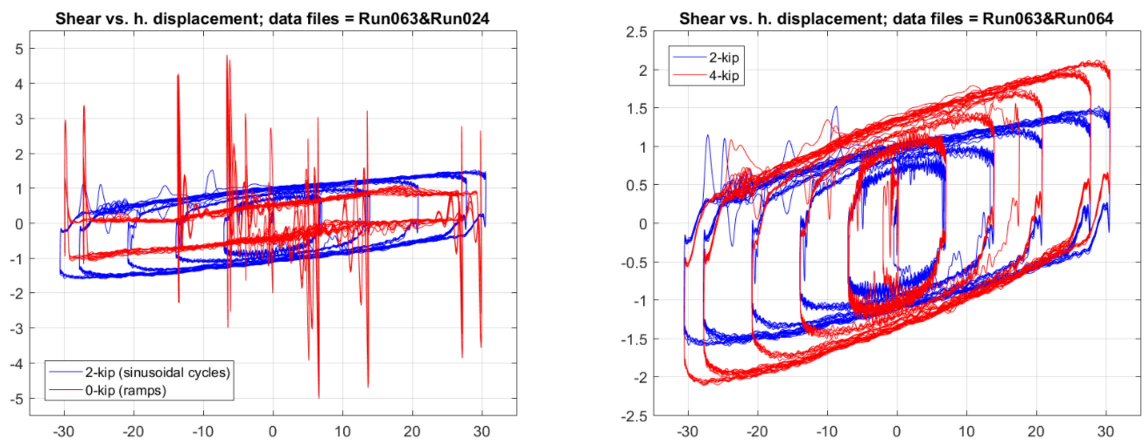


a) Component testing protocol based on ramps up and ramps down

b) Force vs. displacement curve for ramps

Figure 5. Component test protocol and test results for ramps.

To address the issue of large force spike, the combinations of ramps up and ramps down were replaced by sinusoidal cycles. The resulted performance of FPB was much smoother as presented in Figure 6a. Figure 6b shows the difference between performance of the FPB with 2 kip and 4 kip preloads. These results were obtained for the IEEE693 component testing protocol generated from sinusoidal cycles. Since the force versus displacement curves are much smoother, it is recommended to use sinusoidal cycles for the component testing, especially when the seismic protective device is very sensitive to large peaks in accelerations. The results of the component tests are used in modelling of the equipment isolated by the FPBs, which is discussed below.



a) Ramps compared to sinusoidal cycles

b) Sinusoidal cycles

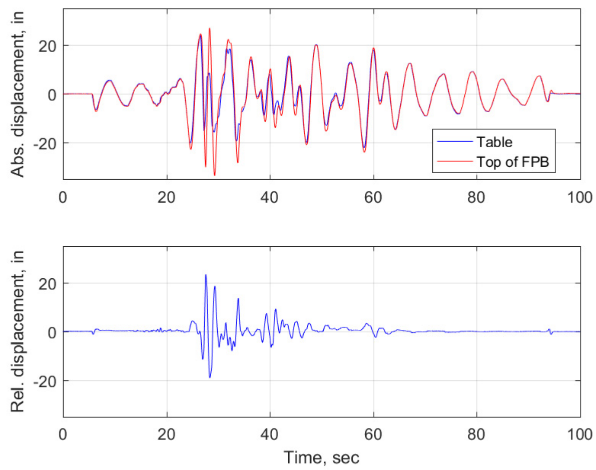
Figure 6. Component test results for ramps and sinusoidal cycles with different preload.

SHAKING TABLE TESTING OF FPBS

A long-stroke and high-velocity uniaxial shaking table was used for the seismic evaluation of the full-scale FPBs. The stroke of the shaking table is ±32-in and the table is capable of delivering 100-in per second peak velocity. All four FPBs were used in the shaking table tests. The bottom dishes of all FPBs were firmly attached to the shaking table and the top dishes were attached to a stiff frame ensuring that all top dishes move together. The overall weight of the stiff frame was very slow and as such, this configuration was representing a limit case with no weight on top of the isolation. The FPBs ready for testing on the shaking table is presented in Figure 7.

Figure 7. All four full-scale FPBs on uniaxial shaking table.

TestQke4IEEE5-4 (Takhirov et al, 2017), one of the time histories recommended for seismic qualification per IEEE693 (IEEE, 2018), was used as an excitation signal to the shaking table. The level of shaking was incrementally increased from 25% to 95% of the High Performance Level (PL) testing anchored at 1.g. Due to the size limitations of this paper, only the results for the last test at 95% of High PL are discussed herein. The relative displacement between the top and bottom dishes were quite large as expected and exceeded 23-in as presented in Figure 8.

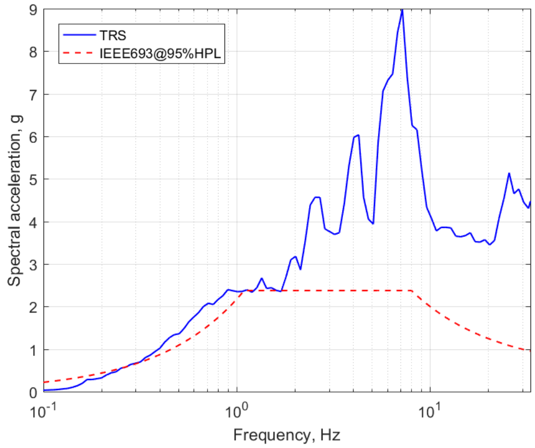


a) Absolute (top) and relative (bottom) displacements

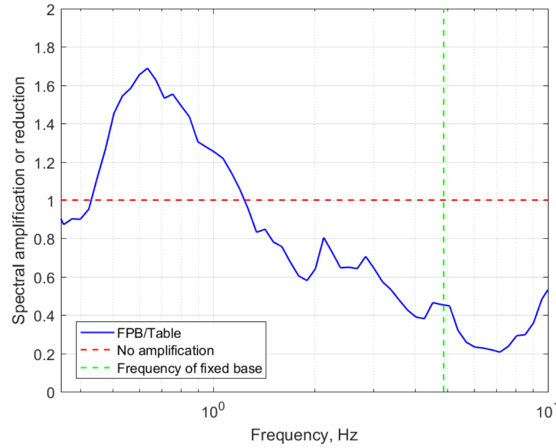
b) A movie frame showing large relative displacements during seismic tests

Figure 8. Displacements of the FPBs in shaking table tests.

The test response spectrum (TRS) computed from the table acceleration is presented in Figure 9a. It worth noting that TRS is compared against the IEEE693 spectrum at 5% damping, which is a change to the required damping value for spectral matching incorporated in the latest version of the IEEE693 document (IEEE, 2018). The ratio of spectral accelerations of the spectral acceleration on top of the FPBs to that of the shaking table is presented in Figure 9b. The latter plot clearly shows that there is a spectral reduction in the high frequency region which is beneficial for the deduction of the seismic demand. For example, for the equipment with the resonant frequency of about 5 Hz which studied below in the section related to the numerical simulations the demand on the equipment is expected to be reduced by about 50%. The latter frequency is shown by a green line in Figure 9b.



a) Test response spectrum (TRS)

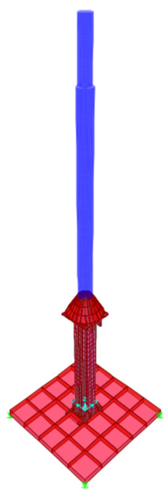


b) Spectral amplification

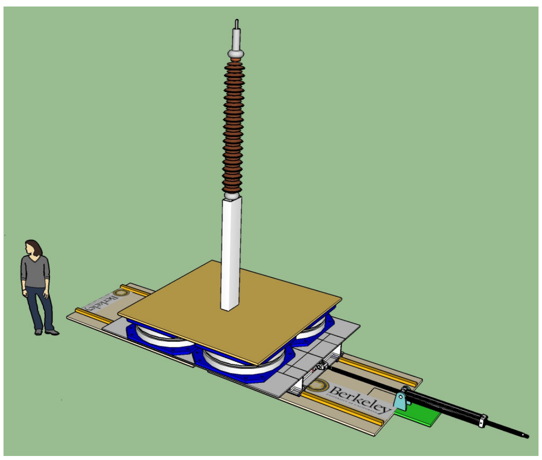
Figure 9. TRS and reduction in spectral demand.

NUMERICAL SIMULATIONS

The numerical modelling is conducted in SAP2000 CSI, 2011). The finite element model of the equipment isolated by four FPBs is presented in Figure 10a, which a sketch shown in Figure 10b. The numerical modelling is still in progress and is not presented herein. The results of the FE analysis compared with the test data of the actual equipment will be presented in the future in the extended version of this paper.



a) FE model



b) 3D sketch

Figure 10. FE model and its sketch.

CONCLUSIONS

1. Since the force versus displacement curves are much smoother, it is recommended to use sinusoidal cycles for the component testing instead of ramps, especially when the seismic protective device is very sensitive to large peaks in accelerations.

2. The shaking table tests of the four FPBs without any additional payload at about ±30-in peak displacements have shown the benefit of the base isolation that reduced the spectral demand by a factor of two at the resonant frequency of fixed based equipment.
3. The shaking table tests of the equipment isolated by four seismic isolators are in progress. The results will be compared to the results of the numerical simulations, which are also ongoing.

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