REAL-TIME HYBRID SIMULATION ON A LONG-STROKE HIGH-VELOCITY SHAKING TABLE CONFIGURATION AS A VALUABLE TOOL FOR IEEE693 STANDARD DEVELOPMENT

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ABSTRACT

This paper presents extensive discussion on seismic qualification of substation equipment in conventional shake table tests and its comparison to real-time hybrid simulation (RTHS). The hybrid simulation technique is based on a sub-structuring idea where a portion of a test specimen with well-predicted performance can be replaced by its finite element model. The rest of the test specimen is experimentally studied as part of the coupled system, where the test object and the mathematical model are interacting with each other in real time. The real-time hybrid simulation technique has a strong potential of complementing and in some cases replacing seismic qualification testing. In addition to that, it has a strong potential as a comprehensive and reliable tool for IEEE693 standard development, where code provisions can be developed from parametric hybrid simulation studies of actual pieces of substation equipment which are otherwise difficult to model. As a typical example of successful application of hybrid simulation, a comprehensive study related to RTHS of electrical disconnect switches is discussed in the paper. First, the RTHS system developed for this purpose is described and the results of a RTHS test are compared with a benchmark conventional shaking table test as a validation of the system. Second, effect of the support structures of the disconnect switches on the global and local responses of different insulator types is evaluated using the results of a series of RTHS tests. Third, the paper investigates the advantages of using a sophisticated control approach for RTHS conducted on a long-stroke high-velocity shaking table.

INTRODUCTION

Disconnect switches constitute a crucial component of power transmission and distribution systems. They are used to control the flow of electricity between all types of substation equipment. Electrical insulator posts and a metallic tube that resides between the top of the insulator posts comprise a typical disconnect switch. In the field, disconnect switches are generally mounted on support structures, which are typically steel frames or columns with well-defined geometry. IEEE693-2005 (IEEE, 2006) requires seismic qualification verification of the disconnect switches by conducting shaking table tests. According to this requirement, a disconnect switch and its accompanying support structure is constructed, mounted to a shaking table and tested as shown in Figure 1.

Structural configuration of the support structures have considerable effect on the response of the disconnect switches. Therefore, there may be a need for an iterative shaking table test scheme based on the modification of the structural configuration of the support structure until the acceptable performance of the tested disconnect switch is achieved. However, conducting a series of this type of conventional shaking table tests is time-consuming and economically unfeasible. In that regard, hybrid simulation (HS), which allows representation of support structures with well-defined material and geometrical properties as analytical substructures, comes forward as a cost effective and efficient testing method alternative to the conventional shaking table testing of the disconnect switches. The rate-dependent nature of some types of insulators, e.g. polymer composite insulators, mandates the use of real-time hybrid simulation (RTHS). The distributed mass of the insulators limits the practical use of actuators at concentrated locations along the height of the insulator and necessitates RTHS to be conducted on smart shaking table configurations. Therefore, a RTHS system is developed for testing insulator posts of the disconnect switches to fulfill the above mentioned objectives. An experimental parametric study, which investigates the effect of support structures on the response of disconnect switches, is conducted with the developed system. Furthermore, potential improvements to the practice of RTHS on shaking tables are investigated through the use of a combined acceleration, velocity and displacement control.

Figure 1. Seismic qualification shaking table tests of 550 kV (left) and 230 kV (right) disconnect switches

RTHS SYSTEM

Components of the developed RTHS system, namely the shaking table, controller, data acquisition (DAQ) system and the specimen (insulator), are shown in Fig. 2.1. As marked in the figure, the DAQ system also contains the computational platform through the DSP I/O module. The shaking table employed as a part of the RTHS system is a small (1.22 m x 1.22 m [4 ft × 4 ft]) high fidelity shaking table at the UC-Berkeley structural testing laboratory, which can reproduce the target accelerations accurately up to 20 Hz frequency. The shaking table is composed of a steel platform moving on supporting rollers. The platform is attached to a 111.2 kN [25 kip], ±127 mm [5 inch] dynamic actuator which can accommodate velocities up to 889 mm/sec [35 in./sec]. Two steel beams placed close to the ends of the platform are used as hold down systems to prevent the uplift due to overturning moments caused by the inertia force of the physical specimen.

Development of the RTHS system consists of the following four steps: 1) formulation of the governing equation of motion and corresponding computational algorithm, 2) implementation of the computational algorithm in the computational platform, 3) setting up the proper communication between the components of the system, and 4) adoption of a feed-forward error compensation scheme to minimize the time delay in the actuator response. The key features related to these steps are discussed in the following sub-sections.

Equation of Motion and Computational Algorithm

In the developed RTHS system, a single insulator post used in 230-kV disconnect switches is tested as the experimental substructure on a shaking table and a single degree of freedom (SDOF) system representing the support structure is employed as the analytical substructure. It should be noted that testing of a single insulator represents the testing of the disconnect switch in an open configuration where the experimental element is the jaw post as identified by an ellipse in the right-hand side photograph of Figure 2.

According to Figure 3, the governing equation of motion of the mass m can be written as follows,

$$m\ddot{u} + c\dot{u} + ku - f = -m\ddot{u}_g \tag{1}$$

where m, k, and c are respectively the mass, spring stiffness, and damping coefficient of the SDOF analytical substructure that represents the support structure, u, $\dot{u}$, and $\ddot{u}$ are the displacement, velocity and acceleration of the mass with respect to the fixed base of the spring (i.e. base of the support structure), $\ddot{u}_g$ is the ground acceleration time history and f is the internal force at the base of the insulator acting on the mass m, which is obtained by using load cell measurements during the test. It is worth noting that the force f includes the inertial and damping forces acting on the insulator since the hybrid simulation is conducted in real time. RTHS is conducted by solving equation (1) numerically with explicit Newmark integration (Newmark, 1959). Sequence of computations is adjusted to comply with the required HS communications between the experimental and analytical substructures.

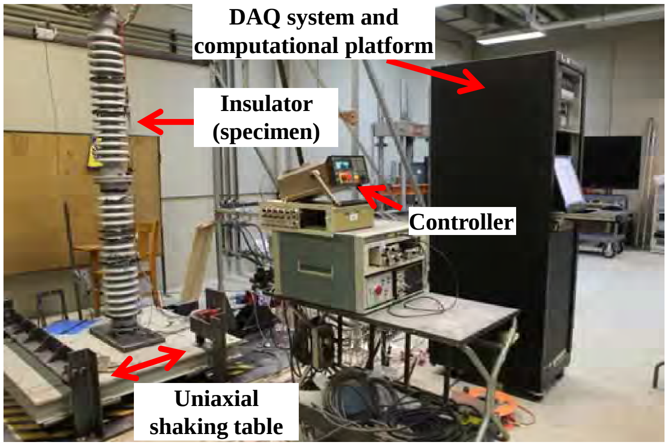

Figure 2. Components of the developed RTHS system

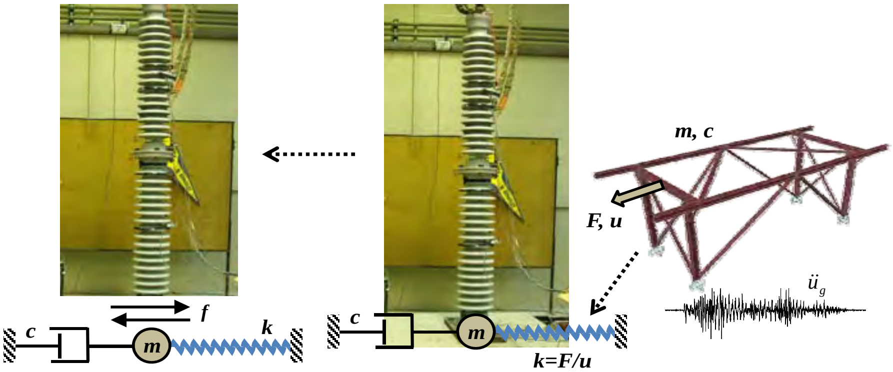

Figure 3. Schematic representation of the experimental substructure (insulator jaw post) and SDOF analytical substructure representing the support structure

Integration Time Step and Feed-forward Error Compensation

With the developed RTHS system, it is possible to conduct RTHS using an integration time step as small as 1 millisecond. Hence, in this case, an integration step is physically completed in 1 millisecond when the integration time step is chosen to be as such. This fast execution time of an integration step is realized by a combination of the computation power introduced by the DSP card, the physical cable transfer between the computational platform and the controller, and the real-time compatible PID control technology of the controller and the servo-hydraulic system. The number of iterations used in RTHS should be constant and small in order to be able to allocate a definite and practically applicable time for the completion of each iteration. Moreover, the displacement increments in all the iterations of an integration time step should be as close as possible to each other to avoid velocity and acceleration oscillations within the integration time step. Hence, explicit integration schemes are the most suitable integration methods for RTHS, since they do not require iterations. A limiting factor which restricts the applicability of explicit integration is the conditional stability criterion requiring the integration time step to be smaller than a certain fraction of the period of the highest mode of the structure. In that regard, the ability to use integration time steps as small as 1 millisecond allows the use of real-time compatible explicit integration in a broad range of structures.

Another advantage introduced by the 1 milisecond integration time step is the assurance of continuous movement of the actuator of the smart shaking table, since a command is sent to the controller in every millisecond. It is noted that the controller operates in a rate such that it expects a command in every millisecond. Since the developed RTHS system is capable of executing integration time steps equal to a millisecond, the calculated displacement is directly sent to the controller as the command without a predictor-corrector smoothing algorithm, e.g. Mosqueda et al. (2005).

Considerable research has been conducted about the effect of errors on HS. Among the various sources of errors, the problem of phase lag or time delay of the hydraulic actuators is particularly important for RTHS. Phase lag induces not only errors but also negative damping which may lead to instability during RTHS. A simple feed-forward error compensation scheme is implemented in the developed RTHS system in order to overcome the time delay problem. This feed-forward error compensation scheme, which is a simplified version of the scheme that is proposed by Elkhoraibi and Mosalam (2007), consists of adding the estimated error to the command signal as a function of the actuator velocity. The error function in this study is obtained from the RTHS runs conducted on the bare shaking table. A substantial improvement in the displacement tracking of the shaking table is observed after the implementation of the feed-forward error compensation scheme, Fig. 2.3. It is theoretically possible to achieve a similar error reduction by adjusting the feed-forward gain on the controller. However, this option was not applicable since the feed-forward gain of the utilized controller was limited to 40 miliseconds, which was not sufficient to eliminate the time delay.

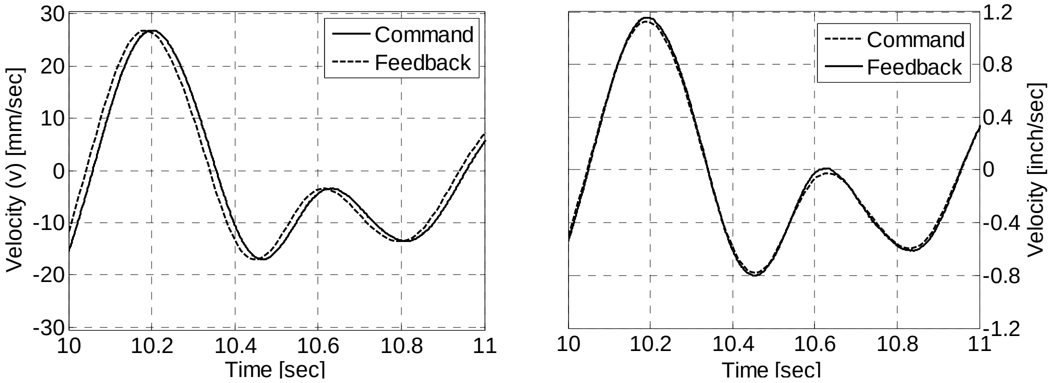

Figure 4. Displacement tracking without (left) and with (right) feed-forward error compensation

COMPARISON WITH CONVENTIONAL SHAKING TABLE TESTS

The results of a conventional shaking table (CST) test, conducted on the PEER shaking table for a vertical-break 230-kV disconnect switch in open main blade configuration together with its support, Figure 1, are compared with those of the corresponding RTHS test. An identical insulator post to the one identified with an ellipse in the right photograph of Figure 1 is used in the RTHS. It is to be noted that the response of the single insulator post is independent from the rest of the disconnect switch in the open blade configuration. Therefore, the response of the marked insulator is compared with the response of the insulator tested with RTHS for validation of the developed RTHS system. The lateral stiffness and total mass of the support structure tested on the CST is used as the stiffness and mass of the analytical SDOF substructure in RTHS. The employed stiffness, k = 9.63 kN/mm [55 kip/in], and mass, m = 2.63 tonnes [163.3 slug], values are validated by comparing the natural period of the SDOF system (0.104 sec) with the identified period of the support structure during the CST tests (0.106 sec). A damping ratio of 1%, identified from sine sweep tests on the CST, is employed in the analytical substructure. The input excitation employed in the tests is an artificially generated excitation from an acceleration record of the 1992 Landers earthquake to match the response spectrum required by IEEE 693 (Takhirov et al., 2005).

Accelerations measured on top of the support structure are and the strains measured at the two sides of the insulator base are plotted in Figure 5 and Figure 6, where the strain gage locations are indicated with circles.

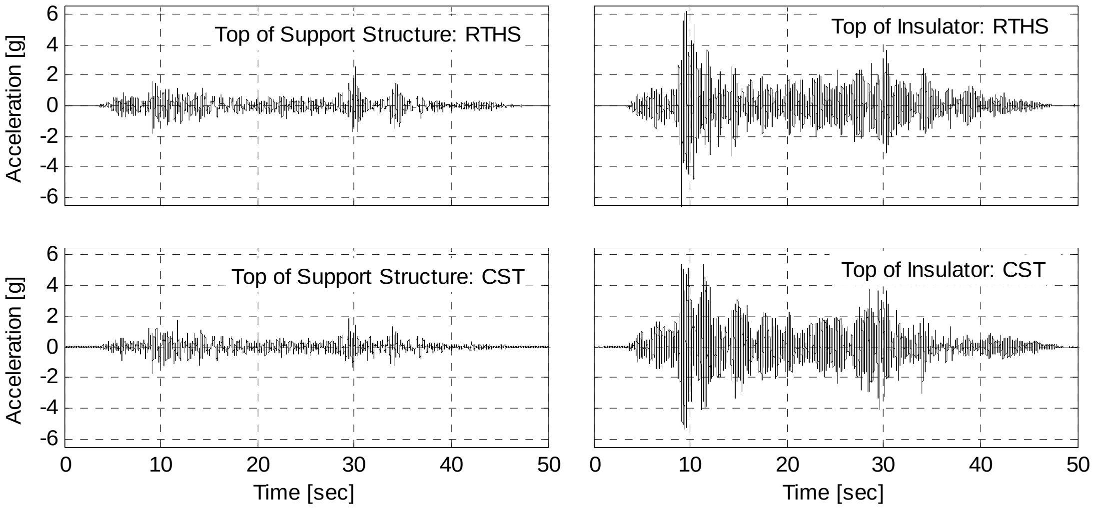

Figure 5. Comparison of the accelerations from the CST and RTHS tests

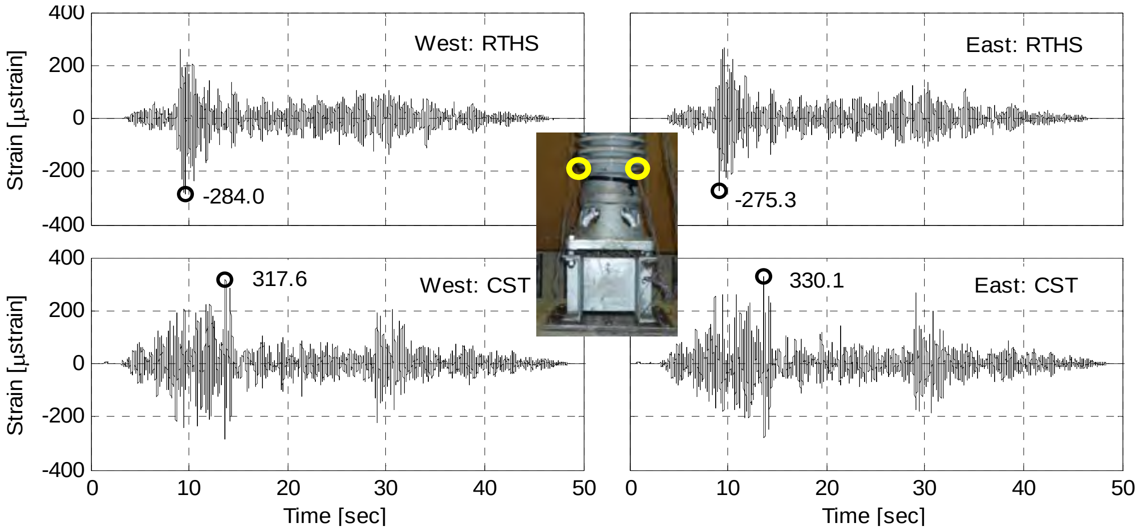

Figure 6. Comparison of the strains from the CST and RTHS tests

Accelerations and displacements (not shown here due to space limitations) measured from the CST and RTHS tests are in good agreement. Identical stiffness and mass properties of the insulators tested using both the RTHS and the CST and the resemblance of the boundary conditions at the base of the insulator posts are confirmed from the similar natural frequencies identified for the insulator posts from both tests. Although these frequencies are reasonably close (5.13 Hz and 4.87 Hz from the RTHS and the CST test, respectively), the small difference between them is most probably the reason for the small differences in the acceleration responses. The largest deviation between the results of the RTHS and the CST tests is in the strains although the peak values are close Figure 6. The differences between the measured strains between the two tests are attributed to the difference in the utilized ground motion components. The CST tests involve three ground motion components, while the RTHS tests involve a single horizontal component. The vertical component of the ground motion that is not included in the RTHS tests affects the strains by providing additional axial strains to those due to bending from the horizontal component. Furthermore, considering that the local response measured by a strain gage can be affected by various conditions including the location and orientation of the gage, local impurities at the cross-section where the strain gage is located, etc., the agreement in the strain gage history shown in Figure 6 and the close estimation of the peaks are considered as a reasonably accurate overall match.

EXPERIMENTAL PARAMETRIC STUDY

After validation of the developed RTHS system, an experimental parametric study is conducted to investigate the effect of support structure stiffness and damping on the insulator response, using three damping ratios assigned to the dashpot (*c* in Figure 3) of the analytical SDOF system (representing the support structure) and 12 stiffness values assigned to the spring (*k* in Figure 3) of the analytical SDOF system, for each damping ratio. Employed damping ratios are 1%, 3%, and 5%, the typical range for steel structures, while the employed stiffness values range between 0.039 kN/m [2.2 kip/in] and 1.051 kN/m [60 kip/in]. Peak strains measured at the insulator base are plotted against the support structure frequency, f_{ss}, (bottom axis) and f_{ss} normalized by the insulator frequency, f_{ss}/f_{ins}, (top axis) in Fig. 4.1. Tested porcelain insulators possess a very brittle mode of failure with almost linear elastic response until failure. Therefore, peak strain demand is a very convenient indicator for evaluating the insulator seismic response. Maximum value of peak strain is observed for f_{ss}/f_{ins} close to 1.2 and decreases on both sides of this value. The minimum peak strain occurs for the flexible support structures ($f_{ss} < 4$ Hz). It is observed that the effect of the damping ratio of the support structure is highest for f_{ss}/f_{ins} ratios between 0.8 and 1.2 and decreases as this frequency ratio increases or decreases outside this range. In particular, the damping ratio of the support structure has negligible effect for stiff support structures ($f_{ss} > 9$ Hz). The measured peak strain normalized by the failure strain, determined from static pull-over tests, is also indicated on the right axis of Figure 7. Detailed information about the parametric study can be found in Günay and Mosalam (2013).

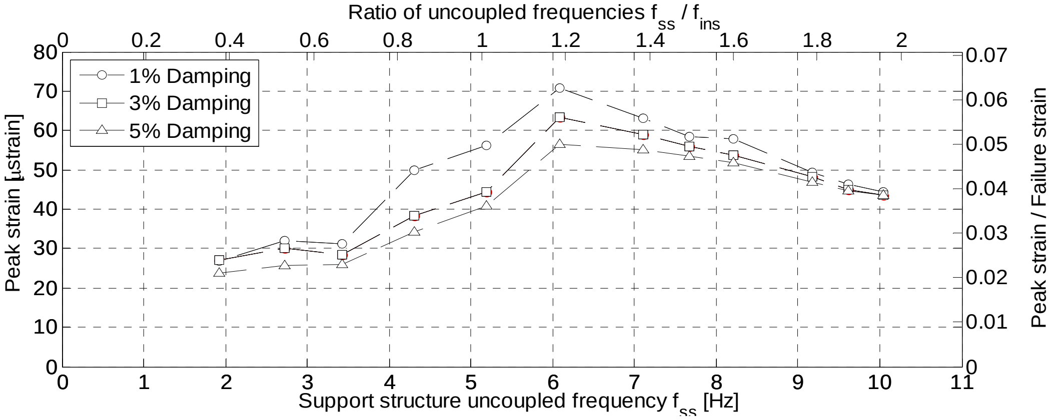

Figure 7. Variation of peak strain with damping and frequency of the support structure

THREE VARIABLE CONTROL

Although conventional shaking table testing is well established in many laboratories around the world and there is considerable accumulated experience on RTHS in the recent years, research and developments on the combination of these two, RTHS on a shaking table, is limited. Therefore, RTHS on shaking tables can still be considered in the development stage, where potential problems may be discovered and solutions to these problems may need to be developed. One of the existing problems related to the current practice of RTHS on shaking tables is as follows: Conventional hybrid simulation is based on the accurate tracking of the imposed displacements, where a considerable amount of research has been conducted on the effect of the inadequate tracking on the results of hybrid simulation, and on the methods to improve the tracking. As a result of these research and the advances in control theory, displacement tracking performance is currently at acceptable levels for a broad range of test configurations and velocities. However, in an RTHS conducted on a smart shaking table by imposing displacement commands to the actuator(s) of the shaking table, a small error in the displacement may translate into larger errors for high frequencies.

In order to overcome this problem related to the amplified accelerations, an advanced control approach is implemented in the hybrid simulation system at nees@berkeley laboratory (which is a different system from the RTHS system described above) via a MATLAB/Simulink (2009) model to be employed in the RTHS tests. It is to be noted that a similar but separate implementation is conducted for dynamic tests that include harmonic or ground motion excitations. This advanced approach, developed by MTS Systems Corporation and so-called the "three variable control", TVC, includes acceleration and velocity control in addition to the traditionally employed displacement control. A modified version of the original scheme documented in Thoen (2010), as adopted for the implementation mentioned herein, is shown in Figure 9. There is considerable improvement of the acceleration response after the implementation of TVC as demonstrated in Figure 10. The left-hand side plot of this figure presents the use of the TVC for RTHS, where the error due to time delay is minimized by adjusting the tuning parameters. Elimination of the time delay requires the feed-forward gains to be increased which results in slight displacement overshooting. Accordingly, for the "non-hybrid" dynamic tests, where the elimination of time delay is not required, even more improved acceleration response is obtained as shown in the right-hand side plot of Figure 10.

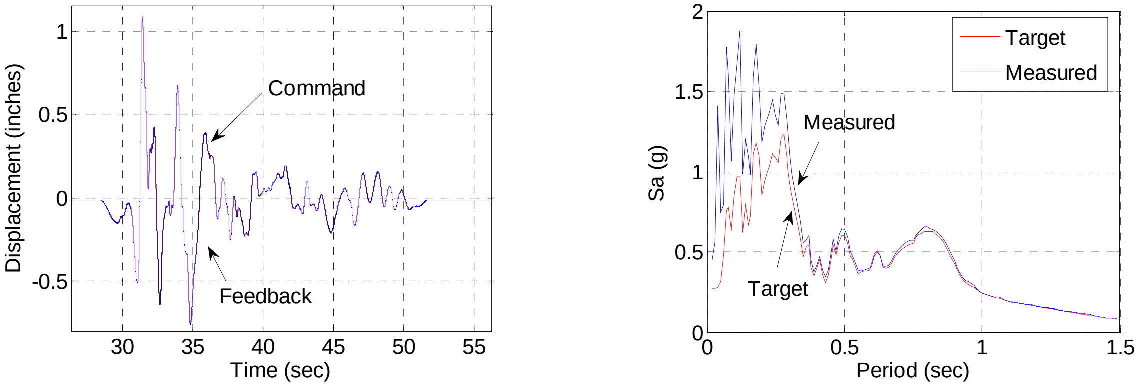

Figure 8. Mismatch in spectral acceleration at small periods (right) despite adequate displacement tracking (left)

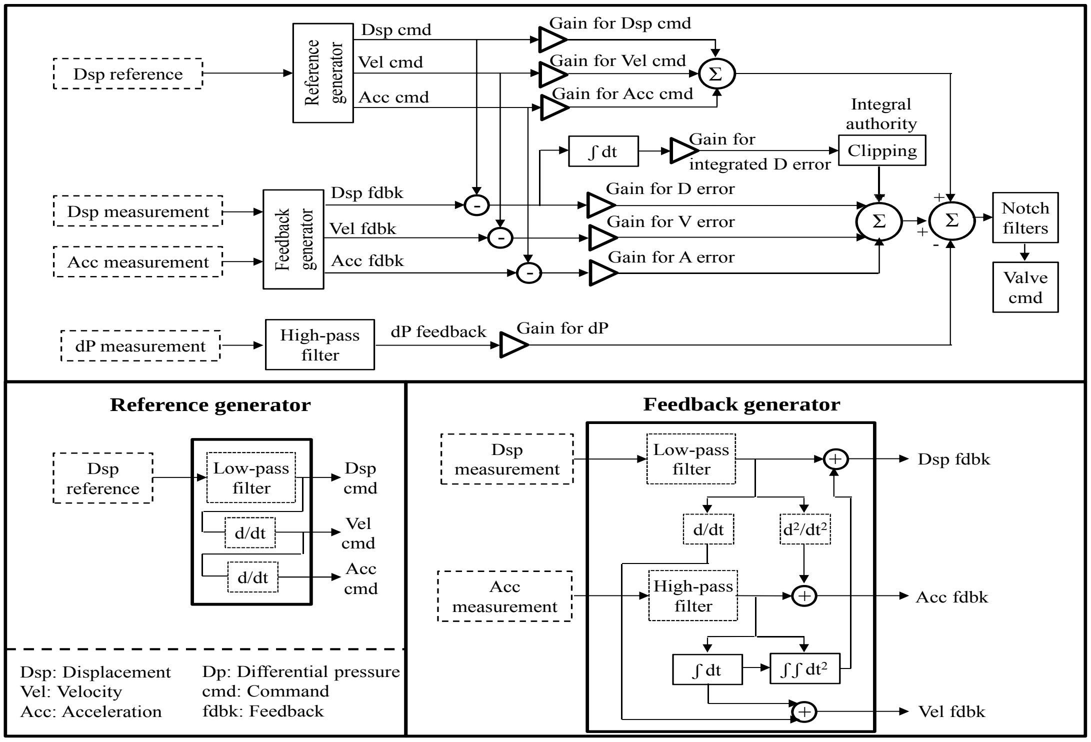

Figure 9. Schematic of TVC as implemented at nees@berkeley laboratory

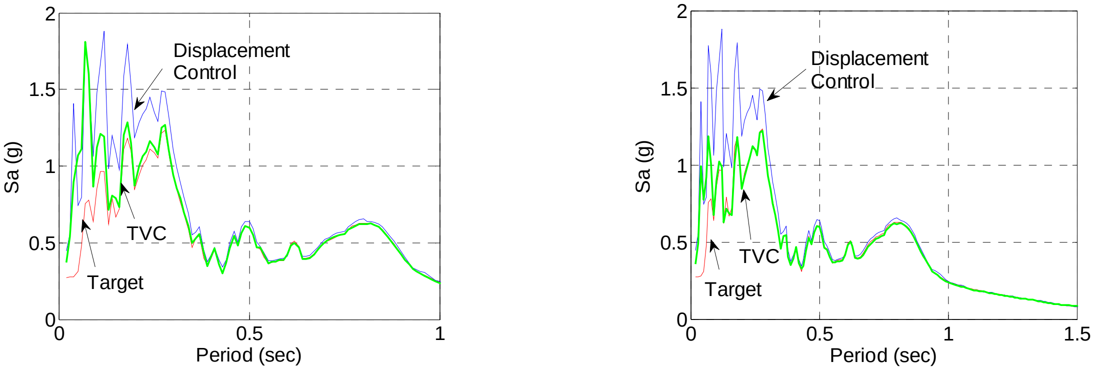

Figure 10. Improved acceleration response due to TVC; Tuning for RTHS: time delay minimized (left), Tuning for shaking table: time delay allowed (right)

HYBRID SIMULATION PLATFORM: PERFORMANCE AND POTENTIAL USAGE FOR IEEE693 DEVELOPMENT

In addition to hybrid simulation capability that can imitate equipment's interaction with its support structure, the real-time hybrid simulation platform described earlier is a high-performance long-stroke uniaxial shake table. When it used in a shake table configuration the test response spectrum envelops the IEEE693 High Performance Level (PL) from about 0.5 Hz as shown in Figure 11 with peak displacement of about 11.5-in and peak velocity of about 52.6-in/sec. Peak table acceleration exceeds 1.0 g as required by IEEE693-2005 (IEEE, 2006). The platform is powered by a 150-kip actuator that can provide large payload capacity. The size if the platform is 7-ft by 20-ft that can be extended to accommodate equipment with a larger footprint. The platform has large clearance above it that can accommodate tall electrical substation equipment. This unique capability combination turns the platform into a strong potential tool for IEEE693 standard development especially for the cases of seismically isolated equipment when long-stroke and high-velocity performance is essential. A schematic drawing of an isolated and a fixed base equipment on the platform is shown in Figure 12. In addition to possibility of coupled testing of substation equipment supported on structures, the hybrid simulation can be utilized for IEEE693 standard development of interconnected equipment. In this case, the most complicated element of the interconnected system – a flexible cable – can be tested as a physical object that will interact via hybrid simulation with finite element models of the connected equipment on both sides.

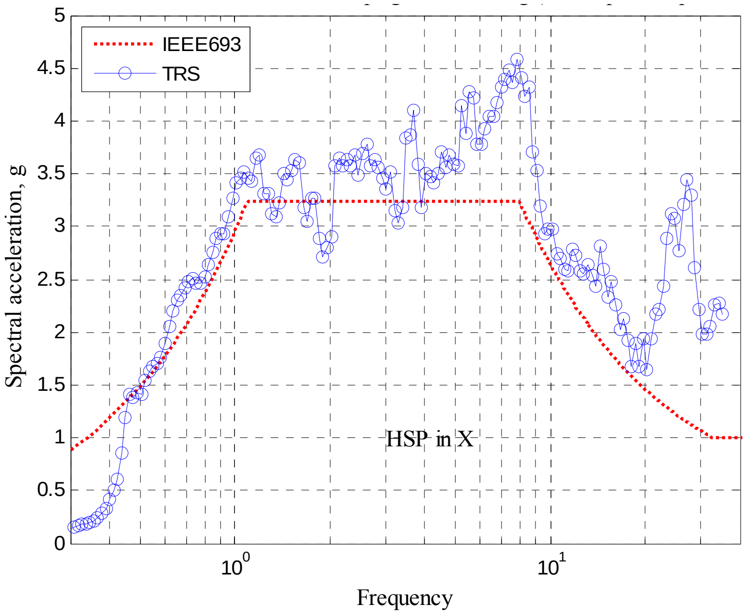

Figure 11. Test response spectrum of real-time hybrid simulation platform at nees@berkeley laboratory when used in shake table configuration

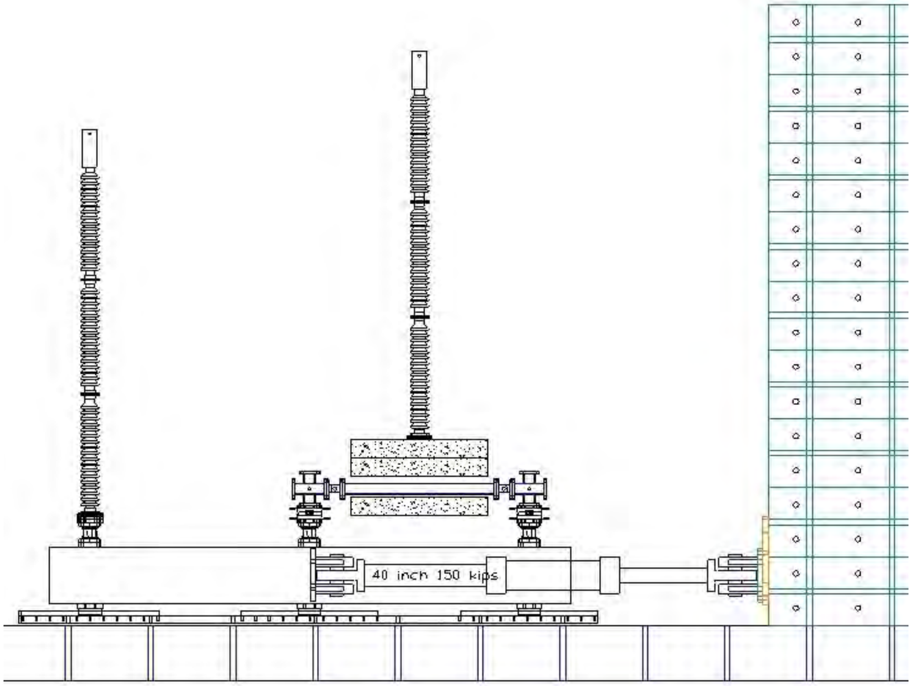

Figure 12. Schematic drawing of isolated and fixed base equipment on the platform

CONCLUSION

A stand-alone RTHS system is developed for cost effective and timely efficient dynamic testing of electrical insulator posts. Two of the unique features of the developed RTHS system are the application of a simple feed-forward error compensation scheme and the ability to perform RTHS with integration time steps as small as 1 milisecond. The developed RTHS system is validated by comparing the RTHS test results with the results of a conventional shaking table test. After validation of the developed RTHS system, a parametric study is conducted to investigate the effect of support structure stiffness and damping on the porcelain insulator response. Such an investigation would require construction and testing of many different support structures, which would probably be practically impossible to realize on a conventional shaking table. Accordingly, the RTHS system summarized in the first part of the study can be stated to fulfil the intended objective of cost effective and timely efficient dynamic testing of insulator posts. The improvements on the acceleration tracking response due to the implementation of the advanced TVC approach are presented in the last part of the paper. This development, which is one of the very first applications of TVC in RTHS, contributes to the improvement of the accuracy of RTHS conducted on shaking tables.

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REFERENCES

Elkhoraibi, T. and Mosalam, K.M. (2007). Towards error-free hybrid simulation using mixed variables. Earth. Eng. & Str. Dyn. 36:11, 1497-1522.

Günay S. and Mosalam, KM. Seismic performance evaluation of high voltage disconnect switches using real-time hybrid simulation: II. Parametric Study. submitted to Earthquake Engineering and Structural Dynamics

IEEE Standard 693-2005. (2006). Recommended Practice for Seismic Design of Substations. New York, NY.

Mathworks Inc., 2009, Matlab Version 2009a, www.mathworks.com.

Mosqueda G, Stojadinovic B, and Mahin S. (2005). Implementation and Accuracy of Continuous Hybrid Simulation with Geographically Distributed Substructures, EERC 2005-02, University of California, Berkeley.

Newmark, N.M., (1959). A method of computation for structural dynamics. ASCE J. Eng. Mec. 85:EM3, 67-94.

Takhirov, S., Fenves, G., Fujisaki, E. and Clyde, D. (2005). Ground Motions For Earthquake Simulator Qualification Of Electrical Substation Equipment. PEER Report. PEER 2004/08.

Thoen, Bradford K., 2010, 469D Seismic Digital Control Software, MTS Systems Corporation.

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