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Seismic Effects of Flexible Conductors Between Substation Equipment

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ABSTRACT

The effects of connections made of flexible conductors must be included in the seismic design of substation equipment. This paper presents the approach and results of studies made at Hydro-Québec to investigate the significance of the dynamic behavior of connections and to take account of their effects in the design. It is found that connections can be excited in resonance and generate significant forces on the equipment to which they are connected, even when sufficient slack is provided. The study shows that the dynamic reactions of connections must be considered for the proper design of substation equipment. A connection design methodology in development at Hydro-Québec is presented.

INTRODUCTION

The 1988 Saguenay earthquake of magnitude 6.2 caused major damage to three Hydro-Québec substations (Pierre 1991). Among the different units of apparatus affected, those connected with flexible conductors (Fig. 1) were the most severely damaged. The earthquake prompted recommendations that the effects of connections be investigated, since Hydro-Québec suspected the fact that they might have played a major role in the destruction of the equipment. Similar conclusions were also drawn after earlier earthquakes. For example, during the Miyagi earthquake in Japan in 1978, many units of interconnected equipment failed, even though individually qualified to withstand the effects of an event of this magnitude (Okada et al. 1986).

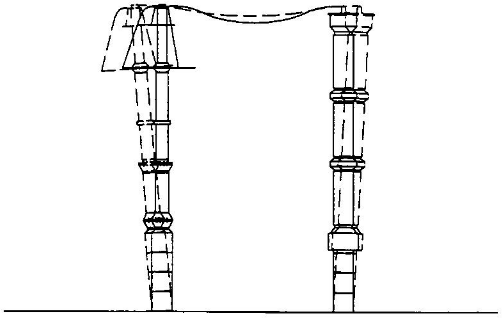

Figure 1: Interconnected equipment experiencing a differential displacement during an earthquake

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At the present time, substation equipment is generally qualified on an individual basis to withstand the loads generated by an earthquake, with the effect of flexible conductors taken into account as a static force; a static force of 1000 N/conductor is currently used in Hydro-Québec's specification on the seismic qualification of substation equipment (Hydro-Québec 1990). It is also a primary requirement that all interconnections between equipment be able to accommodate the large relative displacements that might occur (Fig. 1), without generating impact forces, as specified in many standards (Hydro-Québec 1990, IEEE 1984, IEEE 1990).

A study performed in Japan after the Miyagi earthquake established some criteria for determining the required conductor length for differential displacements to have no impact (Okada et al. 1986). The results of this study were based mainly on computer simulations of interconnected equipment using the finite-element method, without any mention of the dynamic behavior of the conductors.

However, in a general guideline for the seismic design of substations (Clarenne 1984), it is mentioned that the dynamic reactions of connections might generate additional forces on equipment. It is pointed out that connections must therefore be designed not only to permit relative displacement between equipment, but also to avoid dynamic interaction. The latter is achieved by ensuring the connections have natural frequencies different from those of the interconnected equipment, thus avoiding possible resonances between the two. Experimental measurements of the natural frequencies rather than analytical studies are recommended, because of the difficulty in determining the mechanical properties of short conductors.

This paper presents the approach and results of studies made at Hydro-Québec to investigate the significance of the dynamic behavior of connections and to take account of their effects in the design. We first present the results of a study performed to determine whether typical connections made of flexible conductors have natural frequencies likely to be excited during an earthquake, and to obtain insight into their dynamic behavior during such an event. The results demonstrate that dynamic phenomena and conditions, such as resonances, might cause significant forces during such an event, even when sufficient slack is provided to accommodate the differential displacement. The paper then briefly presents a design methodology being developed at Hydro-Québec to take into account the dynamic effects of connections.

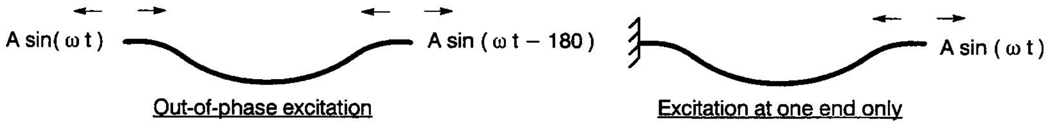
EXPERIMENTAL STUDY OF CONNECTIONS

Approach used

The natural frequencies of connections are difficult to determine analytically for different reasons. One is that these structures are geometrically nonlinear, that is their behavior and properties depend on their configuration; a connection subject to differential displacement of its ends has natural frequencies that will vary during motion. Another is the difficulty in assessing their mechanical properties, such as axial and bending stiffness, which may vary according to the level of tension in the conductor, the geometry and during motion (Scanlan and Swart 1968); since connections are made up of short conductor lengths (a few metres), their tension can change significantly during a differential displacement. It would therefore be hazardous to try to determine their natural frequencies analytically with techniques such as the finite-element method. It is advisable rather to determine them experimentally, with consideration given to their variation during motion.

For this study, the natural frequencies likely to be excited were determined by means of a sine-sweep test. Such a test is generally performed at low amplitude but, since the natural frequencies of connections depend on the amplitude of vibration because of their nonlinear properties, the tests were performed at amplitudes representative of those expected during an earthquake. The natural frequencies corresponding to the horizontal excitation of a connection along its span were studied.

Two variants of excitation were used (Fig. 2), the first corresponding to the extreme case, where a connection is installed between two units of equipment oscillating out of phase, the second to conductor(s) connected between units of oscillating equipment and equipment that is rigid or not excited by the earthquake. During the tests, the horizontal forces applied at the ends were measured together with the frequency of excitation.



Out-of-phase excitation

Excitation at one end only

Figure 2: Variants of excitation used

One advantage of this approach is that it also permits a qualitative characterization of the actual horizontal excitation that might be transmitted in practice. In fact, the excitation applied at the ends of a connection is the motion at the top of the interconnected equipment excited at their base by the ground motion. Since a large proportion of substation equipment can be considered analytically as linear single or multi-degree-of-freedom models, the ground motion is filtered and vibration is predominantly at the fundamental frequency (or those excited by the frequency content of the earthquake) (Fischer 1971). The motion at the top of the equipment is therefore close to a sinusoidal excitation of varying amplitude.

Thus, a sine-sweep test at realistic amplitudes also allows the dynamic behavior of connections during an actual earthquake and possible resonances to be investigated. However, continuous excitation at constant amplitude during this test might magnify the response during resonance at levels higher than those expected in practice. The forces measured during the sweep tests therefore provide an upper-bound estimate of those expected in reality. However, to obtain a first estimate of the severity of the results obtained during the sweep tests, we also performed sine-start tests, consisting in the sudden application of a sinusoidal excitation of constant amplitude and fixed frequency, to evaluate the number of cycles required to obtain the same level of forces as measured during the sweep tests.

Test parameters

The sine-sweep tests were performed at selected amplitudes on frequency bands whose upper frequency was related to the amplitude used. The amplitudes and corresponding upper frequencies were determined using Hydro-Québec's seismic response spectrum for substations, for an acceleration of 0.34 g. Generally, the expected value of ground acceleration throughout the province of Québec is 0.23 g, except in the Charlevoix region where it reaches up to 0.7 g. The value of 0.34 g corresponds to 0.23 g multiplied by a factor of 1.5, taking account of potential site effects. A value of 2% was assumed for the critical damping ξ.

The displacements obtained from a response spectrum correspond to the maximum values expected for a single-degree-of-freedom oscillator. In the case of a specific unit of substation apparatus modeled in this way, such a value would correspond to the displacement at its mass center, whose proximity to the top depends on its mass distribution. Since substation equipment may possess a few modes that lie in the frequency band of an earthquake, the top displacement would be better approximated by normal-mode analysis, summing up the contribution of each relevant mode in a statistically meaningful way, e. g. the square root of the sum of the squares method (SRSS). However, the diversity of equipment in a substation led us to make direct use of the displacements obtained from the response spectrum. This approach was consistent with our goal, to perform the tests with realistic amplitudes. Nevertheless, this approach led to good approximations, as can be seen from Figure 3 where displacements for different circuit breakers computed by the normal-mode method are compared to those retained for the tests.

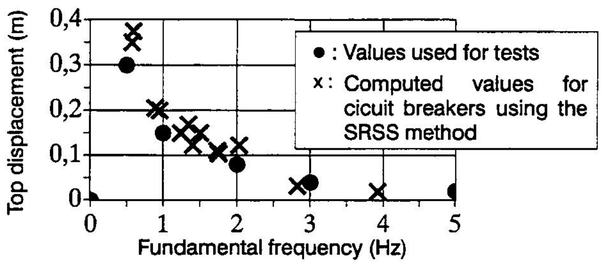


Figure 3: Expected displacements for circuit breakers (0.34 g)

The fundamental frequencies of interconnected substation equipment generally vary between 0.5 and 10 Hz and rarely exceed 5 Hz (Ushio et al. 1972). Furthermore, the corresponding displacements at frequencies higher than 5 Hz are negligible; consequently the higher upper-band frequency used for the sine-sweep tests was limited to 5 Hz. The lowest frequency for each band was chosen as 0.5 Hz. The frequency bands and corresponding amplitudes chosen for the tests are presented in Figure 4.

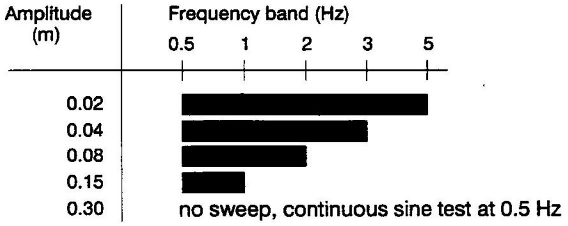


Figure 4: Frequency bands for sine-sweep tests

The two types of aluminum conductors most commonly found in Hydro-Québec substations were used for the tests (1796-MCM, 4000-MCM). Depending on the power to be transmitted, connections comprise one conductor or two conductors with spacers. The tests were therefore performed for these respective configurations; catenary types with ends clamped horizontally were utilized.

The spans in substations vary from 3 to 6 m generally. Spans in the intervals 3.2 to 3.6 m and

5.0 to 5.6 m were selected for the tests. The effect of the sag/span ratio on the natural frequencies and the dynamic behavior was studied. Ratios of 0.08, 0.12, 0.16 and 0.20 were used by varying the span for conductors of fixed lengths; for example, with the 5.52 m 1796-MCM conductor, ratios of 0.08 and 0.20 correspond to spans of 5.4 and 5.0 m respectively (Fig. 5).

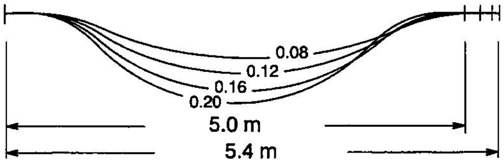


Figure 5: Configurations for different sag/span ratios

Main test results

For a given sag/span ratio, the sweep tests were performed only for bands that allowed the corresponding differential displacement without generating impact forces at the utmost stretched position. The minimum and maximum values of horizontal forces attained during a cycle of oscillation were retained, along with the corresponding frequency, thus providing a response spectrum for each of these two quantities. The resonant frequencies, or those likely to be excited during an earthquake, were then identified using these spectra. Two of the predominant behaviors observed during the sweep tests will now be discussed.

1) Dynamic stability

This behavior characterizes a connection which oscillates in a stable way around its equilibrium position, without any sudden change of amplitude or forces observed during resonances. The forces measured at a given frequency vary cyclically between two extremes, corresponding to the minimum and maximum spans attained for a given amplitude of oscillation. During the tests, the forces measured during dynamic stability were smaller than those developed during resonances.

Typical spectra exhibiting dynamic stability over the complete test bandwith indicate that no natural frequencies are significantly excited, even though some are present within the frequency band tested. Hence for given configurations, connections may be excited at one of their natural frequencies without resonance or any of the corresponding damaging effects. It was also observed that the level of forces developed dynamically can be considerably higher than those developed statically; for example, during a given test, a force of 1600 N was generated at an amplitude of 0.02 m and a frequency of 5 Hz, compared to a force of 124 N statically for the same displacement. It was observed that the highest forces are generally developed at low amplitudes, at frequencies close to the upper limit of the test band, from which we can conclude that dynamic effects may play an important role in the traction generated, even with sufficient slack provided to accommodate the differential displacement.

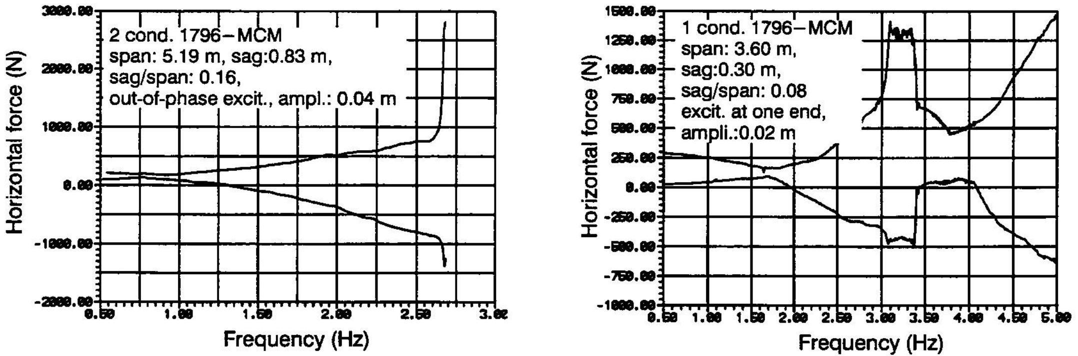
For the configurations tested, dynamic stability was observed on the complete test frequency band but only for high sag/span ratios. In the case of out-of-phase excitation, dynamic stability was observed mostly for a ratio of 0.20, whereas in the case of excitation at one end only, it was observed mostly for ratios of 0.20 and 0.16. Hence, a high sag/span ratio favors dynamic stability over a broader range of amplitudes and frequencies.

2) Resonance

During the resonances observed, there was a sudden amplification of the forces at the connection ends and, correspondingly, of the displacement amplitude. In many cases, the resonances observed led to an erratic motion of the conductor(s), which oscillated at large amplitudes, often lashing back and forth generating large impact forces; the motion observed in most cases was closely related to a dynamic instability rather than following a vibration mode of characteristic shape.

In the case of connections comprising only one conductor, there was often a lateral motion coupled with the transversal one, illustrating the fact that modes in two orthogonal directions can be coupled during dynamic excitation in only one direction. Connections with two conductors are more rigid laterally due to the spacers and no significant motion was observed in that direction.

In many instances, the resonances were so severe that the tests were stopped to prevent damage to the load cells and the setup; the response spectra from one such test are shown in Figure 6a, where the sudden amplification of force is manifest. In other cases, the test was not interrupted and the resonance was seen to last during a certain frequency interval and then the behavior changed to dynamic stability again; a typical case is shown in Figure 6b. This behavior indicates that the natural frequencies of a connection change during motion, so that a given configuration can be excited in resonance over a range of frequencies rather than at one specific frequency alone.



a) test stopped b) test pursued

Figure 6: Response spectra exhibiting resonance conditions

The strongest resonances were for small amplitudes of excitation (0.02 and 0.04 m). It was observed that a high level of forces is reached during resonance, with a measured maximum force of 4044 N; in fact, in some instances, we believe that higher levels could have been reached if the test had not been stopped during resonance. It was also observed that the level of forces reached for both types of excitation is of the same order of magnitude. Excitation at one end only is less idealistic than out-of-phase excitation, which means that significant forces can be generated in resonance, even if only one end of a connection is excited in the proper frequency range. Since a connection might be attached to units of equipment of different natural frequencies, there is a strong possibility that it may be excited in resonance. The frequencies at which resonances occurred varied according to the sag/span ratio, as well as the amplitude of excitation. In general, higher frequencies were excited at smaller amplitudes and inversely, lower frequencies at larger amplitudes.

A few sine-start tests at given frequencies were also performed to investigate the number of cycles of oscillation required to obtain the same level of horizontal forces measured during the sweep tests. The tests were performed at the frequencies at which dynamic stability was observed, as well as at resonant frequencies. In both cases, for all tests performed, the same level of force obtained during the sweep tests was reached quickly, usually in 3 to 5 cycles. The few results obtained tend to demonstrate that the level of forces obtained during the sweep tests could be attained during an earthquake, when the equipment is excited for a few cycles only. However, further research work is required to assess the severity of the forces measured during the sweep tests in relationship to a real earthquake excitation, and would be welcome in order to investigate this aspect more thoroughly and generalize the results.

CONNECTION DESIGN METHODOLOGY AT HYDRO-QUÉBEC

The main observations from the dynamic tests led to the following conclusions:

- Connections used in substations possess natural frequencies likely to be excited in resonance in the range 0.5 to 5 Hz during an earthquake; large forces can develop at the ends of connections excited in resonance and combine with large amplitudes of displacement.
- The maximum forces measured in resonance occurred for small amplitudes of excitation, indicating that it is not enough to design connections on a static basis, merely in terms of allowing for the differential displacement expected at their ends.
- A large sag/span ratio tends to promote the dynamic stability of connections and thus avoids the risk of resonances and dynamic effects. Since the required distance of electrical insulation must be considered, geometries other that those with horizontally clamped ends might be interesting alternatives (vertically clamped ends, for example).
- It is important to design connections in such a way that the range of natural frequencies at which they can be excited are different from those of the equipment to which they are interconnected, which avoids the risk of dynamic interaction and resonance between them.

Based on these conclusions, a connection design methodology is presently in development at Hydro-Québec. It can be summarized by the four following steps for two given units of equipment to be interconnected:

1 Identify the natural frequencies of the equipment to be interconnected and estimate the maximum differential displacement (D_{max}).

2 Develop a design providing sufficient slack to allow for D_{max} without impact forces, while meeting the insulation distance requirements.

3 Perform sine-sweep tests to verify that the connection resonant frequencies are significantly different from the natural frequencies of interconnected equipment; if this is not the case, modify the design while respecting step 2.

4 Perform 3 cycles sine-beat tests on connection around the natural frequencies of the interconnected equipment to ensure the dynamic reactions at connection ends are lower than the force permitted; if this is not the case, modify the design while respecting steps 2 and 3.

CONCLUSIONS

The results of dynamic tests on connections demonstrate the significance of the latter's dynamic behavior in response to the excitation generated by an earthquake. Sine-sweep tests at realistic amplitudes on selected frequency bands have been presented as an appropriate way to establish the natural frequencies of connections likely to be excited during such an event, as well as a way to study their dynamic behavior.

Based on these results, a connection design methodology is presently in development at Hydro-Québec. It takes into account the importance of designing connections in such a way that the range of natural frequencies at which they can be excited will differ from that of the equipment to which they are interconnected, to avoid the risk of dynamic interaction and resonance between them.

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