

A FUNDAMENTAL STUDY OF WIDE-AREA DAMPING CONTROLLERS WITH APPLICATION TO FUZZY-LOGIC BASED PSS DESIGN FOR DYNAMIC SHUNT COMPENSATORS

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Abstract – Despite the high level of activity in recent years on wide-area control, many aspects of it remain poorly understood because of the difficulty in performing the relevant analytic or parametric study on a large power grid. We have therefore set up a small four-machine two-area test system in Matlab SimPowerSystems to perform a set of controlled experiments addressing most of the challenging issues facing wide-area control. A linearized analysis is first applied to understand its performance sensitivity with respect to factors such as number of tie-lines, sending- or receiving-end location, power flow direction and levels, etc. Then, a new concept of fuzzy-logic PSS, able to perform equally well with either local or wide-area input signals, is proposed. Nonlinear simulations are further used to demonstrate the superior performance of wide-area controllers under nearly all conditions studied. To confirm some of the test system conclusions, similar fuzzy PSSs have been developed and implemented on a full Hydro-Québec network and the initial results are very encouraging. On a set of 30 standard fault events applied to 60 network configurations, wide-area fuzzy PSSs achieved a 53% reduction in the number of cases violating a voltage criterion, while the local fuzzy PSSs reduced this number by only 9%. Regarding the loss-of-synchronism events, the improvement was 24% for global PSSs versus 16% for local PSSs.

Keywords: *Inter-area oscillations, power system stabilizer, observability, controllability, residues, wide-area control, dynamic shunt compensators, system stability, PMU, SVC, PSS, power grid control*

1 INTRODUCTION

The last decade has seen a tremendous increase in the interest in stabilizing the control of power grids using wide-area measurements [1-7]. This attempt to move from local to global signal-based control is motivated by the rapid adoption of PMU technology by utilities around the world. Numerous academic studies have demonstrated the feasibility and substantial benefits of wide-area stabilizing control on large-scale realistic power grid models in terms of damping improvement and power transfer capability increase [5,6]. Moreover, in its road-map, the NASPI organization (<http://www.naspi.org/>) has identified wide-area control as one of the most promising long-term applications of advanced PMUs in the context of the smart transmission grid being deployed in the USA, thanks to the so-called

stimulus grants (<http://www.sgiclearinhouse.org/>). Although some initial open-loop experiments have been reported in China [7], in most other places wide-area damping controllers are still under detailed design and engineering, at a more or less advanced stage of laboratory or network simulator testing [7].

Many aspects of wide-area control remain poorly understood because of the difficulty of performing the relevant analytic or parametric study on a large power grid such as the Québec interconnection. The sensitivity of wide-area control during a reversal of the power transfer direction on the monitored line and the impact of the location of the control device as a function of the power flow direction (sending- or receiving-end sitting, for instance) are among the challenging issues. A fair comparison of local and global control loops is also very complicated on large systems due to the wide range of available local signals, each with its own scaling and dynamic characteristics (current, power, bus voltage magnitude and frequency, etc.).

In this context, in order to better understand the underlying mechanisms of the variety of factors that may influence the performance of a wide-area controller without delving with too many details, we set up a small four-machine two-area test system in Matlab SimPowerSystems [8,9] to perform a set of controlled experiments addressing most of the issues. Given two configurations with one or two tie-lines, a SVC is tentatively installed at various locations along the corridor. A linearized analysis is first applied to understand the performance sensitivity of the wide-area damping controller with respect to factors such as number of tie-lines, sending- or receiving-end location, power flow direction and levels, etc. Then a new concept of fuzzy-logic PSSs, able to perform equally well with either local or wide-area input signals, is proposed [4,11-13]. It has only three degrees of freedom and is therefore intrinsically easy to tune whatever the type of input signal. Nonlinear simulations are further used to demonstrate the superior performance of wide-area controllers under nearly all conditions studied. Although they are sensitive to measurement time delays, it is shown on the test system that, with fuzzy logic-based controller design, it takes a very large delay (exceeding 300 ms) to destabilize the fuzzy PSS-based closed-loop system. To confirm some of the test system conclusions, fuzzy PSSs were

developed and implemented on a full Hydro-Québec network. To this end, four control loops involving one synchronous condenser and three SVCs were selected for their high joint observability-controllability indices in order to compare local and wide-area control configurations as equitably as possible [14]. Thirty standard fault events were applied to 60 network configurations, resulting in a total of 780 different cases from which the control system statistics, including those for the wide-area control schemes and communication time delays varying from 50 to 200 ms, were determined with respect to the base case without supplementary voltage modulation. The behavior of the stabilizers was then compared using two statistical indicators: the number of voltage and/or frequency criteria-violation cases within the 20-s simulation time-frame and the number of loss-of-synchronism cases.

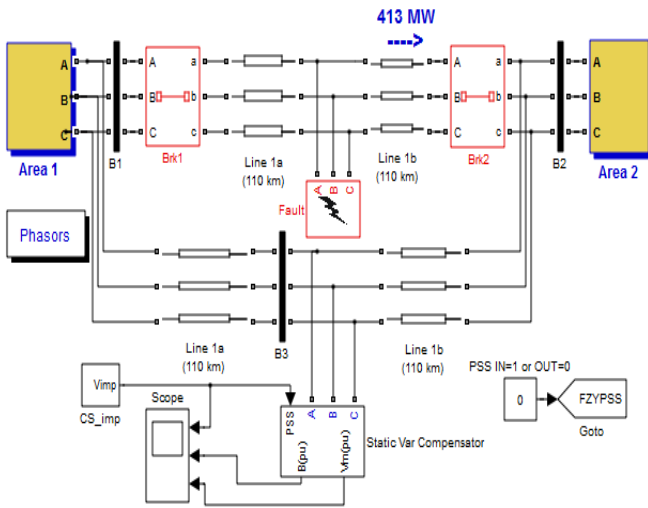
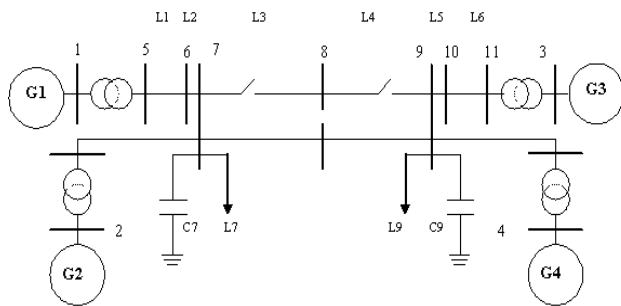


Figure 1: Four-machine two-area Kundur test system

2 UNDERSTANDING WIDE-AREA CONTROL OF THE KUNDUR FOUR-AREA TEST SYSTEM

2.1 Test system

The Kundur test system, shown in Fig.1a, consists of two fully symmetrical areas linked together by two 230-kV lines, 220 km in length. The grid modeled in Matlab SimPowerSystems (SPS) is illustrated in Fig.1b, assuming a static var compensator (SVC) at the mid-point of the second tie-line. This SVC has a zero var contribution to the grid in steady state (i.e. it is in floating mode).

2.2 Small-Signal Analysis of the Wide-Area Control Structure

The linearized state-space model is obtained in Matlab Simulink using the built-in linear analysis tool [9] with the following conventions:

1. Model input: SVC voltage reference
2. Model outputs : local and wide-area angle shifts defined as follows :

$$\begin{cases} \theta_{Local} = \theta_{Remote} - \theta_{SVC} \\ \theta_{Global} = \theta_5 - \theta_{10} \end{cases} \quad (1)$$

where θ_5 and θ_{10} are the bus 5 and 10 voltage phasor angles, as in Fig. 1a. In addition, θ_{Remote} is measured at the bus nearest to the studied SVC, while moving farther away from the area where this SVC is located. By convention, when the SVC is at the mid-point of the tie-line (bus B3 in Fig.1b), the so-called ‘remote’ bus corresponds to bus 7 in Fig. 1a (bus B1 in Fig. 1b). Figures 2 and 3 summarize the controllability/observability structure [11] of the inter-area mode assuming a two (K2L) - or one (K1L)-tie-line network configuration respectively. For each configuration, x-axis represents the three power flow direction and y-axis the observability /controllability measures and shapes. The measures are used to quantify the observability /controllability of the modes whereas the shapes are used to see if the locations are coherent in the swing. Finally, for each configuration and power flow, three location of SVC are considered: mid-point (SVC-C, bus B3) and receiving or sending end of the corridor power transfer direction (SVC-D and SVC-G, buses B2 and B1).

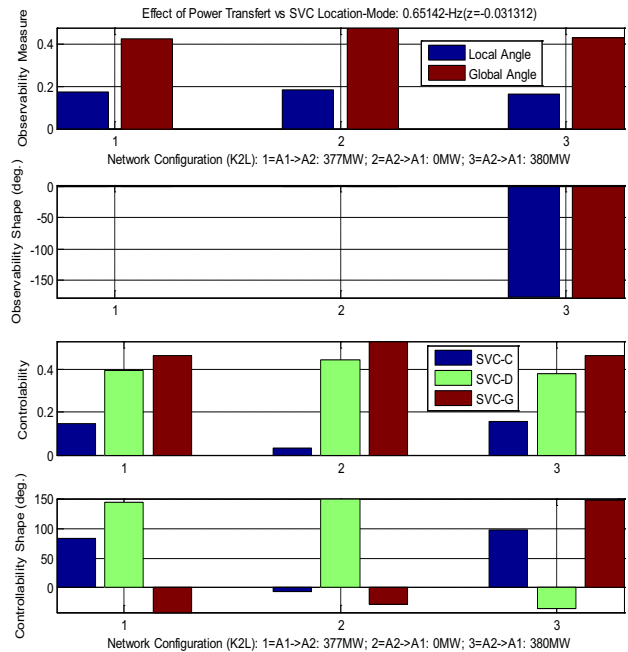


Figure 2: Controllability/observability of the inter-area mode with respect to the SVC location on the Kundur test system with 2 tie-lines (C=center; D=right; G=left).

The open-loop natural frequency is shown on the top of each figure, i.e. 0.65 Hz and 0.48 Hz, with a negative damping of -0.35 and -0.035 respectively. Therefore,

short of PSSs on its generators, the test system is intrinsically unstable without supplementary modulation of the SVC. The main observations arising from these figures follow:

1) Observability

- a) The wide-area signal has twice the observability of the inter-area mode compared to the local signal whatever the number of tie-lines, the power transfer level and the SVC location
- b) Reversal of the power transfer results in signal phase inversion as well.

2) Controllability

- a) When the power transfer is not zero ($x=1$ or 3), the inter-area mode controllability by the SVC is relatively insensitive to its location at the receiving or sending ends of the corridor, whatever the number of tie-lines. However, the controllability is twice as low when the SVC is at the mid-point.
- b) When there is no inter-area power flow ($x=2$), the inter-area mode controllability by the SVC is still good if the SVC is located either at the receiving or the sending end of the corridor but it decreases to zero when the SVC is moved to the tie-line mid-point.
- c) Reversing the power flow direction makes it necessary to change the sign of the control-signal phase.

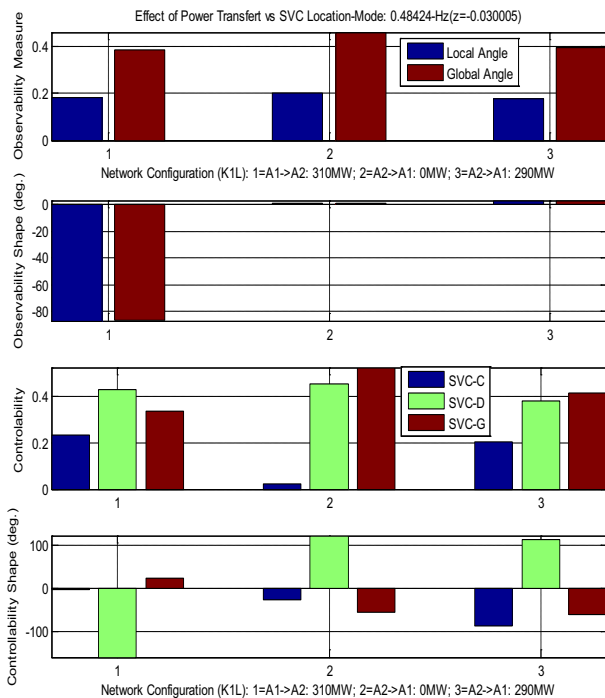


Figure 3: Observability/governability of the inter-area mode as a function of the location of the SVC on the Kundur system with one tie-line

From the analysis above, it appears that the mid-point is not the best location for sitting an SVC-based, dynamic shunt modulator scheme aimed at damping the inter-area mode, especially at low power transfer. In addition, wide-area control demonstrates twice the potential of the equivalent local control, whatever the operating scenario considered.

3 DAMPING IMPROVEMENT USING A FUZZY-LOGIC PSS

At this point it is interesting to see how the local signal-based and the wide-area signal-based PSSs compare with each other. However, for a fair comparison, the two controllers should have the same structure and settings with the only difference being the gain. For this purpose, we decided to use a fuzzy-logic PSS (FLPSS) described recently in [14,11-13], and whose architecture is given in Fig. 4.

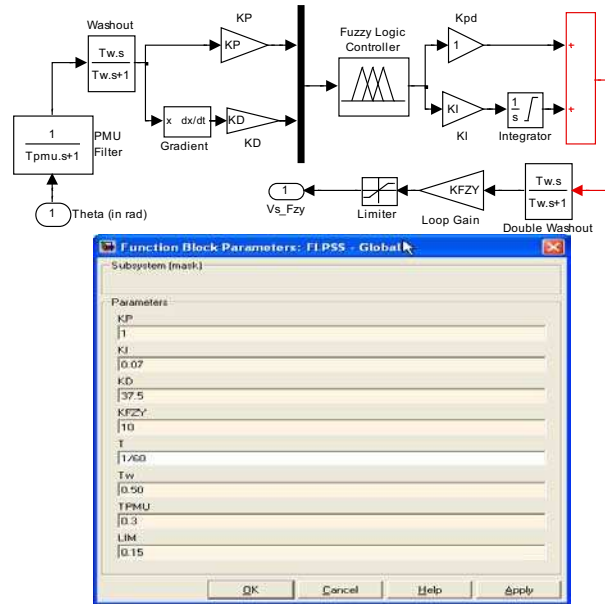


Figure 4: PID-type fuzzy-logic PSS model

The core of the FLPSS is a fuzzy-logic controller (FLC) [12]. Gains KD, KI, KP and KFZY were added outside the FLC, on the one hand, to normalize the input variables of the fuzzy-logic controller and, on the other hand, to achieve the PID function. It should be noted that the addition of these gains outside the fuzzy-logic controller means that the structure can be kept simple. The FLC uses the angle shift (in radians) and its derivative (in radians/cycle) as inputs.

The design process of the fuzzy-logic controller may be split into five steps [11-13]: selection of the control variables, definition of the membership function, creation of the rules, selection of the fuzzy-inference method and the defuzzification strategy. The fuzzy-inference method is the minimum-maximum type (Mamdani) with a fuzzy-centroid defuzzification strategy. The membership functions of the input variables were chosen identical because of the normalization achieved on the physical variables using KD and KP. Normalization is important because it allows the controller to associate an equitable weight with each rule and, therefore, to correctly calculate the stability signal. Each input variable is classified by seven trapezoidal fuzzy membership functions. The following fuzzy sets were chosen: **BN** = [-5.0 -1.0 -0.2 0.1], **MN** = [-1. -0.2 -0.1 0.2], **LN** = [-1.0 -0.1 -0.03 1], **Z** = [-1.0 -0.03 0.03 1], **LP** = [-1 -0.03 0.1 1], **MP** = [-0.2 0.1 0.2 1.] and **BP** = [-0.1 0.2 1.0 5.0].

The output variable is classified by triangular fuzzy membership functions: **BN** = [-1.0 -0.515 -0.439], **MN** = [-0.515 -0.439 -0.302], **LN** = [-0.439 -0.302 0.], **BZ** = [-0.302 0. 0.302], **LZ** = [-0.0015 0.0 0.0015], **LP** = [0.0 0.302 0.439], **MP** = [0.302 0.439 0.515], **BP** = [0.439 0.515 1.].

$\Delta\theta/\Delta\theta/dt$	BP	MP	LP	Z	LN	MN	BN
BN	BZ	LN	MN	MN	BN	BN	BN
MN	LP	BZ	LN	MN	MN	BN	BN
LN	MP	LP	BZ	LN	LN	MN	BN
Z	BP	MP	LP	LZ	LN	MN	BN
LP	BP	MP	LP	LP	BZ	LN	MN
MP	BP	BP	MP	MP	LP	BZ	LN
BP	BP	BP	BP	MP	MP	LP	BZ

Table 1: Fuzzy-logic PSS decision table.

The inference mechanism of the FLC is presented by a 7x7 decision table. The entire set of rules (49 if-then rules) is presented in Table 1. The output signal was obtained using the following principles:

- If the angle shift is large but tends to decrease, then the control must be moderated. In other words, when the areas in opposition come close to each other, even though the frequency shift is considerable, the system is capable, by itself, to return to steady state.
- If the angle shift is weak but tends to increase, then the voltage signal must be significant. This means that the opposite areas tend to separate more and the control must reverse the trend.

A1>A2 MW	2L 377	1L 310	2L 0	1L 0	2L -380	1L -280
C-Global	+1	+1	±1	±1	-1	-1
C-Local	+2	+2	±2	±2	-2	-2
D-Global	-1	-1	-1	-1	-1	-1
D-Local	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5
G-Global	+1	+1	+1	+1	+1	+1
G-Local	+1.5	+1.5	+1.5	+1.5	+1.5	+1.5

Table 2 : Ratio of Local to global gain of the SVC based PSS at location (C, D and G)

4 FUZZY LOGIC-BASED WIDE-AREA CONTROL OF THE KUNDUR TEST SYSTEM

Given that the wide-area signal is twice as large in the inter-area frequency mode (i.e. twice the observability), it is tempting to apply a twice-higher KFZY gain to the local signal-based PSS to achieve a similar control effort. However, such an amplification of the loop gain could result in the local mode (in which the local SVC bus may be participating) becoming unstable. Table 2 presents the compromised gains of the local PSS, when assuming a unit gain for the wide-area PSS. Since the

same settings (c.f. section 3) are used for all local/global PSS configurations, it should be understood that the sign of the gain in Table 2 defines the required modifications when changes are made to the SVC location and the number of tie-lines of the power transfer level. The main conclusions from Table 2 follow:

1) When the SVC is located at the ‘sending’ or ‘receiving’ end, the PSS is insensitive to any **inversion** of the power transfer direction. This is a direct result of the controllability/observability phase profiles in Figs.2 and 3. In effect, an inversion of the power transfer resulting in a simultaneous inversion of the phase of the observability and controllability measures, the product of the two terms (input sign * output sign =+1) is invariant with respect to the power transfer direction.

2) When the SVC is located at the mid-point of the tie-line, the situation is far more complex. The right sign could be a “+”, when the power flows from left to right, or a “-” in the other direction. This paradox, which is valid in local as well as in wide-area control, is yet further proof of the difficulty of adjusting the settings of a SVC located at the mid-point of the interconnection such as to damp the inter-area mode through modulation of its voltage set point.

4.1 Small-signal results

The fuzzy-logic PSS structure was selected because of the simplicity of its three-parameter tuning, in addition to the scaling gain, KFZY. Application of the gains in Table 2, in combination with the basic settings in Fig. 4, leads to the results in Table 3. This table contains (1) the open-loop inter-area mode (i.e. without SVC modulation) and (2) the closed-loop inter-area mode in various operating scenarios: SVC location, level/direction of the power flow and number of tie-lines. The major conclusions from Table 3 are as follows:

1) SVC modulation is more effective at lower inter-area oscillation frequencies, for instance 0.45 Hz versus 0.65 Hz. It is observed that for a high transfer from area 1 (A1) to area 2 (A2), closed-loop damping is five to ten times higher on the single link than on the two-link configurations. This performance gap is observed in all operating scenarios, except when the SVC is located at the tie-line mid-point and the power transfer is zero, which leads to the SVC losing the effective controllability of the inter-area mode.

2) The loop gain equalization process between local and wide-area controllers according to Table 2 appears not to result necessarily in a matched close-loop small-signal performance of the two schemes. In effect, for all scenarios with two tie-lines, wide-area control is 1.5 to 2 times more effective, despite increasing the gain of the local controller so as to make the local control residue as large as the wide-area control residue. This equalization process is only possible, however, when the local control open-loop residue is not zero, i.e. the local control loop is at least controllable, which is no longer true when the power transfer through the tie-line is zero and the SVC is located at the electrical center of the tie-line.

	A1toA2				0				A2toA1			
	1L (310MW)		2L (377MW)		1L		2L		1L (-280MW)		2L (-380MW)	
	f(Hz)	z	f(Hz)	z	f(Hz)	z	f(Hz)	z	f(Hz)	z	f(Hz)	z
OLC	0.4505	-0.0175	0.6428	-0.0271	0.5346	-0.0342	0.6778	-0.0374	0.4819	-0.0343	0.6485	-0.0370
CLC-G	0.5006	0.2784	0.6658	0.0185	0.5407	-0.0429	0.6846	-0.0440	0.5204	0.1808	0.6676	0.0219
CLC-L	0.4755	0.2697	0.6597	0.0141	0.5404	-0.0412	0.6837	-0.0420	0.5250	0.1218	0.6649	0.0024
OLD	0.4367	-0.0196	0.6404	-0.0286	0.5355	-0.0323	0.6781	-0.0358	0.4794	-0.0287	0.6502	-0.0307
CLD-G	0.5423	0.3657	0.6206	0.1184	0.5339	0.2304	0.6363	0.0920	0.5187	0.3138	0.6155	0.1063
CLD-L	0.4518	0.3754	0.6212	0.0592	0.5199	0.1435	0.6501	0.0388	0.4859	0.2166	0.6281	0.0512
OLG	0.4455	-0.0098	0.6426	-0.0225	0.5355	-0.0325	0.6781	-0.0358	0.4735	-0.0371	0.6485	-0.0370
CLG-G	0.5045	0.3663	0.6139	0.0976	0.5257	0.2049	0.6407	0.0710	0.5117	0.3223	0.6157	0.0813
CLG-L	0.4732	0.2710	0.6259	0.0531	0.5241	0.1258	0.6562	0.0294	0.4692	0.2156	0.6282	0.0348

Symbol SX-Y : S=Open-Loop (OL) or Closed-Loop (CL) configuration ; X= SVC site (C=Center, D=Right, G=Left); Y=Global control (G) or Local control (L)

Table 3: Sensitivity of the inter-area mode with respect to the Kundur system configurations, SVC site and PSS structure.

4.2 Impact of time delays on small-signal performances

Since one of the main barriers against wide-area control is telecommunication, we decided to study its impact using small-signal analysis. To this end, a pure delay of variable duration was inserted in series with the wide-area angle shift, in the Simulink model of Fig. 1b. The linearization of the resulting closed-loop system was again performed using the Simulink built-in tools.

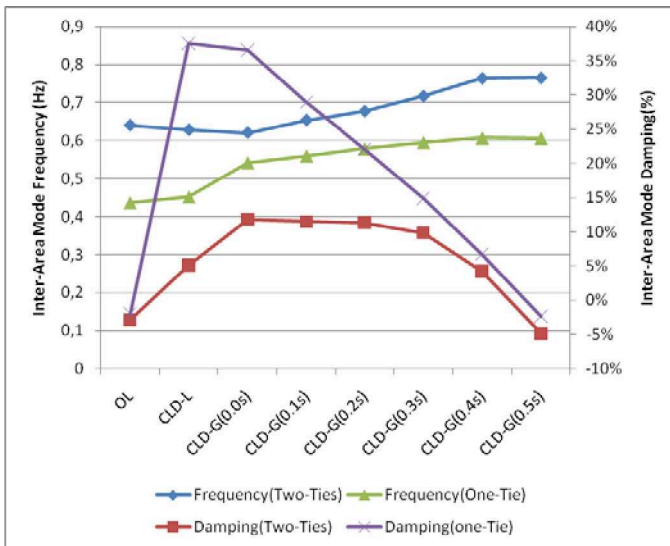


Figure 5: Impact of time delay on the inter-area mode using small-signal analysis of the closed-loop performance. OL=open-loop; CLD-L=local control in closed-loop with SVC at location D (sending end); CLD-G(x)=global control in closed-loop with SVC at location D (sending end) and time-delay= x (in seconds).

The main results are illustrated in Fig.5, where the changes in the inter-area mode frequency and damping are shown for a time delay varying from 0 to 500 ms. The first conclusion is that a delay less than 0.2 s has little impact on the inter-area mode damping, whether the grid has one tie-line (modal frequency of 0.45 Hz) or two (0.65 Hz). However, a delay above 0.3 s results in a significant deterioration of the damping compared to the case without delay. In addition, a delay above 0.4 s destabilizes a local mode (not shown) while introducing new undesirable and poorly damped control modes.

Overall, this study confirms the well known fact that, in wide-area control, a communication delay remains a key concern since large delays tend to reduce the achievable damping while increasing the risk of undesirable interactions with local and control modes. However, it is noted that, in the specific case of the Kundur test system, the delay should be really significant (>0.3 s) to pose a real threat to the small-signal stability of a robust wide-area PSS, which in our case is based on fuzzy-logic concepts.

4.3 Wide-area control performance under severe contingencies

After many trials, only one contingency was selected to illustrate the nonlinear performance of the fuzzy logic-based wide-area PSS. Assuming the two-tie-line configuration, the contingency consisted in applying a three-phase fault, 6 cycles in duration, at the mid-point of one of the tie-lines. The fault is eliminated by opening the two ends of the faulted line, after which the post-contingency network is left with a single tie-line. The post-contingency inter-area mode is then 0.45 Hz.

Figure 6 compares the local and wide-area control schemes when the SVC is located at the mid-point of the un-faulted line. While the wide-area control makes the post-fault system definitely stable, the local controller with equivalently optimized gain leaves the system marginally stable. Next, as shown in Figs 7 and 8, the SVC was moved to the far right of the corridor (receiving end) and the superior performance of the wide-area control scheme was maintained, even when a 200-ms time delay was added in series with the angle shift measurement. However, the wide-area controller was unable to keep the system stable when the time-delay was increased to 0.4 s, thus confirming the small-signal analysis results in Fig.5.

However, the results in Figs. 8 and 7 highlight the difficulty of correctly predicting the time delay impacts under nonlinear conditions. Fig.8 referring to the same contingency as in Fig. 6, it is seen that, up to a 200-ms time delay, the performance of wide-area control is better than or equal to that of local control. But starting at 300 ms, the excess time delay results in sustained and

poorly damped oscillations of small amplitude whose frequency is about 1.43 Hz, which is quite far from the real mode of interest, i.e. the inter-area mode.

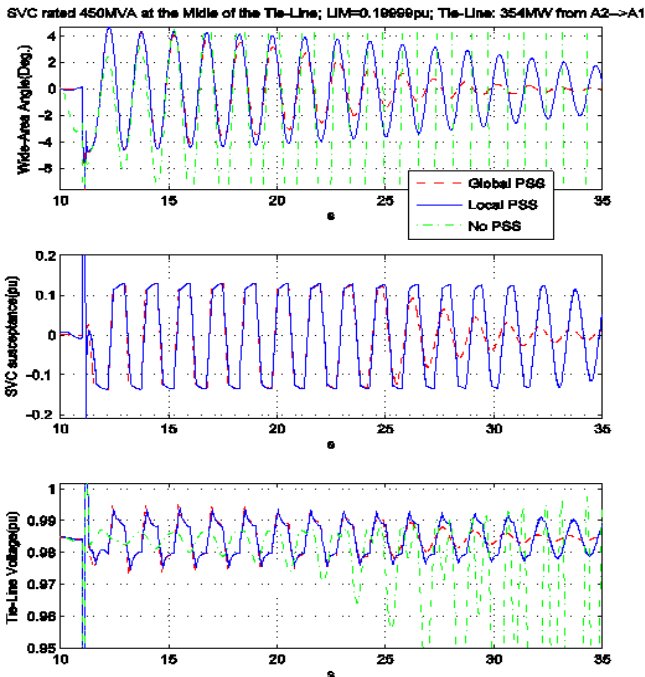


Figure 6: Kundur test system response to a 6-cycle fault eliminated without a line outage-SVC located at the mid-point of the corridor (PSS limiters set at ± 0.2 pu)

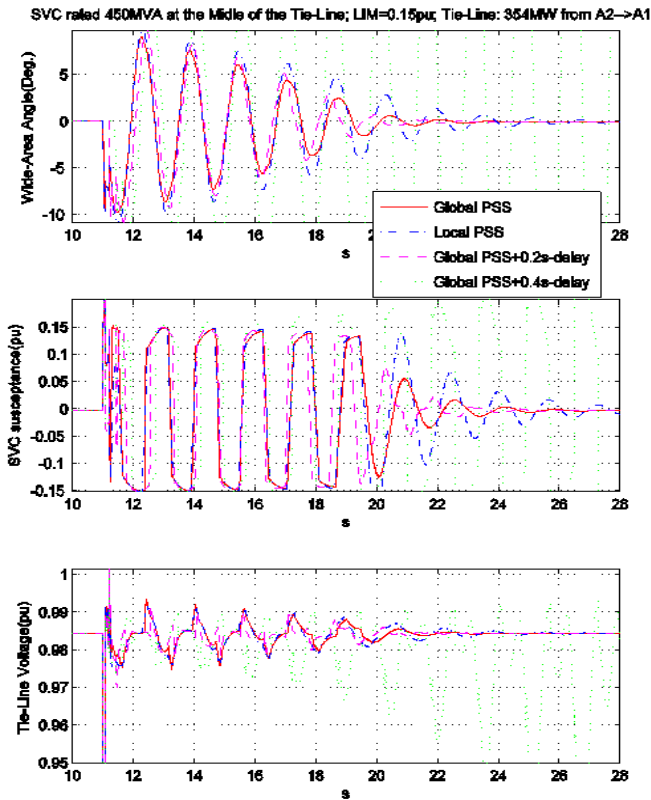


Figure 7: Impact of transmission delays on global fuzzy PSS performance - Kundur test system response to a 6-cycle fault with a line outage SVC located at the far right end of the corridor (PSS limiters set at 0.15 pu)

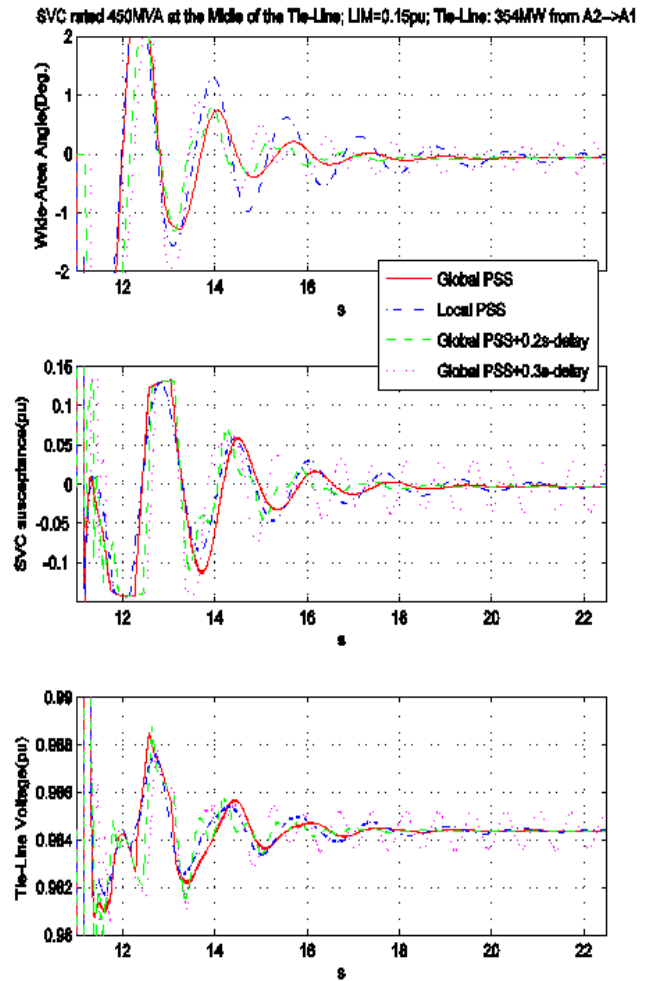


Figure 8: Impact of transmission delays on global fuzzy PSS performance - Kundur test system response to a 6-cycle fault without a line outage when the SVC is at the far right end of the corridor (PSS limiters set at 0.15 pu)

5 MAIN CONSIDERATIONS FOR WIDE-AREA CONTROL OF THE TEST SYSTEM

1. On a radial network, the SVC-based controllability of the inter-area mode is maximized at the sending and receiving ends of the corridor. This controllability is much less marked at the corridor center where it drops to zero at zero power transfer.
2. The global/local control is insensitive to the direction of power flow when the SVC is located at the sending or receiving end, since a PSS with fixed settings can stabilize the system effectively at all power transfer levels from zero to maximum, in both directions, without any need for on-line setting or reconfiguration.
3. Supplementary modulation systems appear to be more effective when the oscillation frequency of the inter-area mode is low (e.g. 0.45 Hz as opposed to 0.65 Hz). The same phenomenon was observed on the Anderson and Farmer nine-bus system [4], where the frequency of the inter-area mode was 0.25 Hz.

4. The inter-area mode observability is twice as high for wide-area control compared to a local signal, and this remains true whatever the SVC location along the corridor, which dictates the chosen local signal. Therefore, the loop gain of the local PSS should be multiplied by two to match the wide-area PSS performance for damping the inter-area mode. Detailed computations on all system configurations show that, despite applying this ‘gain equalization’ process, on two tie-line configurations (with an oscillation frequency of 0.65 Hz) the local PSS obtained resulted in lower damping, compared to the corresponding wide-area controller.
5. Nonlinear simulations broadly confirmed the small-signal observations, the gap between local and wide-area controllers being most obvious when the SVC is sited at the tie-line mid-point. In this case, the wide-area control performs three to five times better than a similarly tuned local control. The signal observability advantage characterizing the wide-area angle-shift results here in such an improvement to the damping performance that the local PSS cannot match it by merely increasing its gain (since the control signal effort is bounded in both cases by the same limit).
6. Assessing the time delay impacts on the closed-loop performance of wide-area control demonstrates that, on the Kundur test system, no loss of performance is noticed when the delay is less than 100 ms. However, delays greater than 100 ms could easily destabilize the inter-area mode targeted by the wide-area control or any local mode excited by the SVC switching.

6 APPLICATION OF FUZZY LOGIC-BASED WIDE-AREA CONTROL TO HYDRO-QUÉBEC POWER GRID

6.1 Large-signal study with PSS at four locations

The behaviour of local and wide-area fuzzy logic-based PSSs was tested on the Hydro-Québec network (Fig. 9) using the transient stability program ST600 [1,2]. The fuzzy PSS has the structure shown in Fig.4, with the following baseline settings adopted in local control mode at all sites:

$$T_{pmu} = 0.3s; T_w = 0.3s; K_D = 1; \quad (2)$$

$$K_p = 7.5; K_I = 0.07; KFZY = 20$$

To maximize the impact of each concept, the four best locations for local and wide-area control were selected independently based on the joint observability/controlability measure between the measurement and control input sites [14]. This systematic analysis resulted in the following choices (cf. Fig. 9 for their geographical positioning on the network map):

- Local control: SVC at Nemiskau, Albanel and Laurentides; synchronous condenser at Manic.
- Wide-area control: SVC at Nemiskau, Albanel and Lavérendrye; synchronous condenser at Manic.

Table 4 summarizes the local and wide-area PSS input signals at each selected location, in addition to the modifications needed on the PSS gain (KFZY) and its sign to achieve the correct performance. The settings of the wide-area PSS at all sites are the same shown in eq.2 except that the gain KFZY is divided by the so-called technical gain in Table 4, the ratio of the observability measure of the wide-area angle (which is the angle-shift between Churchill Falls and La Forge 1 power plants) to the local angle-shift (which is the angle difference between the busses in columns 1 and 2).

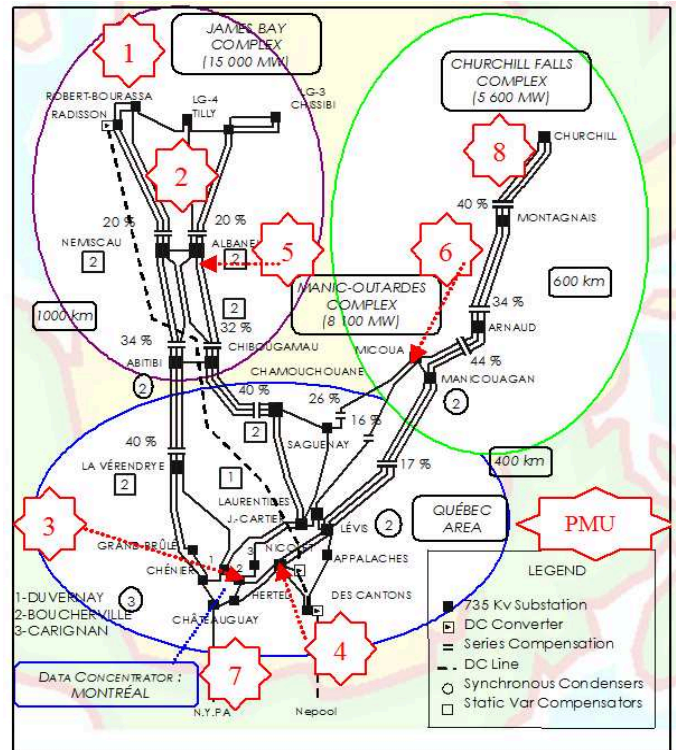


Figure 9: Hydro-Québec network

SITE	Bus for local angle shift	Local PSS sign	Wide-Area PSS sign	Technical gain [4]
SVC-LVD	ABI	-1 (North)	+1 (CHU-LA1)	20
SC-MAN	LEV	+1 (South)	-1 (CHU-LA1)	4.54
SVC-NEM	RAD	-1 (North)	+1 (CHU-LA1)	10.75
SVC-ALB	NEM	-1 (North)	+1 (CHU-LA1)	13.33
SVC-LTD	MIC	-1 (North)	-1 (CHU-LA1)	4.56

Table 4: Sites selected for local and a wide-area control. The sign of the reference gain (cf.eq.2) should be changed according to column 3 or 4 for local and wide-area PSS respectively. The wide-area PSS gain is obtained by dividing the local PSS gain by the technical gain in column 5.

Three contingencies were selected to illustrate the discrepancy between local and wide-area control schemes. The corresponding results are shown in Figs. 10-12. In the first case, only wide-area control was able

to maintain the system stability, which became unstable with and without a purely local control scheme. The next contingency resulted in both local and wide-area controllers being able to retain system stability, showing a big improvement in dynamic responses with respect to the base case (which is stable). Finally, the third contingency results in an unstable system without supplementary modulation of shunt compensators. However, the two control schemes were able to restore the stability with similar effectiveness, to judge from the angle shift and load voltage dynamic responses.

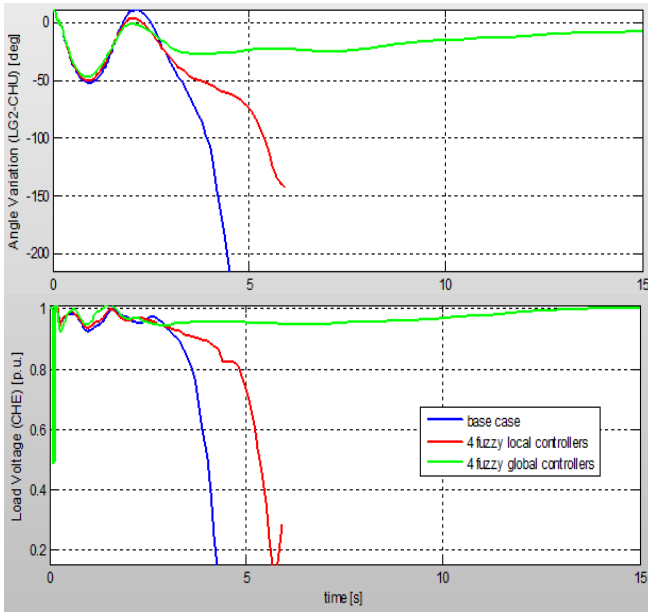


Figure 10: Typical performances of fuzzy PSS on the Hydro-Québec system (2003 peak load) - Three-phase fault at Micoua substation eliminated by Micoua-Saguenay line outage. Top: angle shift (LG2-Churchill); bottom: bus voltage at Chénier substation.

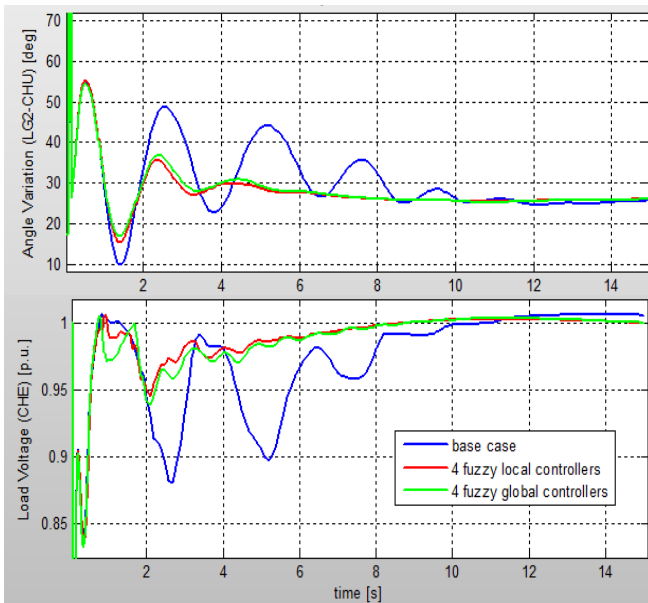


Figure 11: Typical performance of fuzzy PSS on the Hydro-Québec system (2003 peak load) - Three-phase fault at LG2 substation eliminated by LG2-NEM line outage south of the station. Top: angle shift (LG2-Churchill); bottom: bus voltage at Chénier substation.

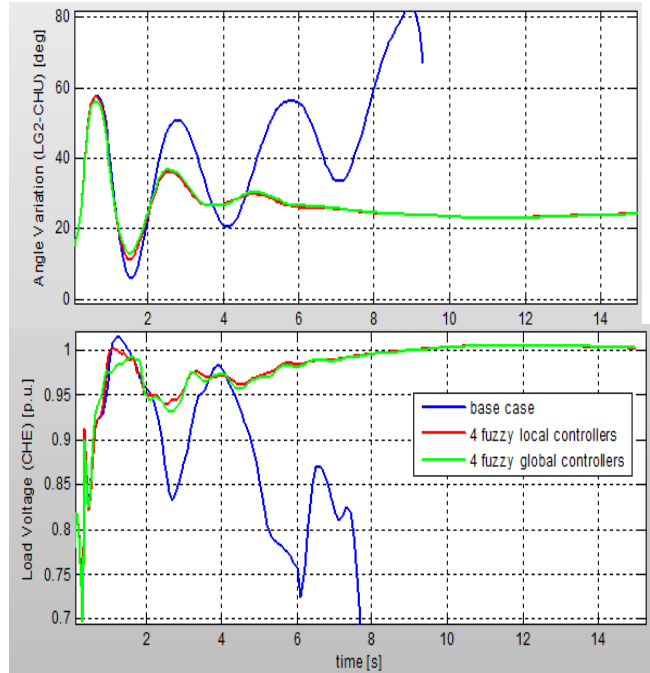


Figure 12: Typical performance of fuzzy PSS on the Hydro-Québec system (2003 peak load) - Single-phase fault at LG2 substation eliminated by LG2-NEM line outage south of the station. Top: angle shift (LG2-Churchill); bottom: bus voltage at Chénier substation.

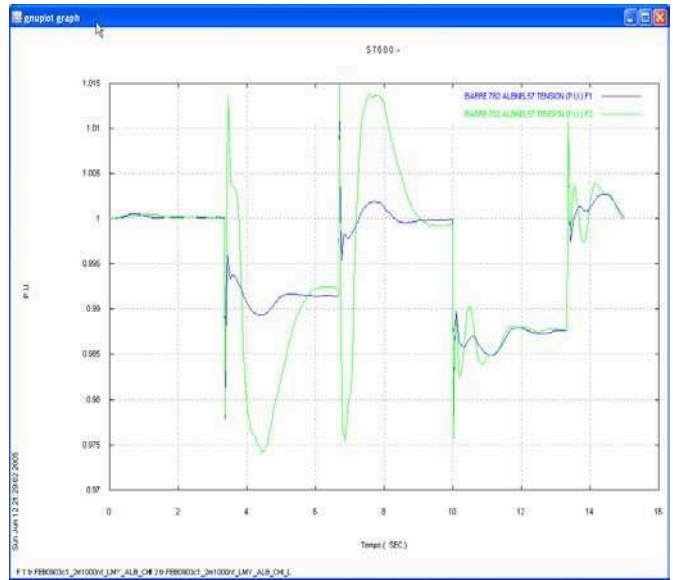


Figure 13: Typical performances of fuzzy PSS on the Hydro-Québec system (2003 peak load) - Line switching (OUT/IN) and Albelnet SVC.

A last contingency consisting of single-line switching near the control site of Albelnet (SVC) was performed in order to assess the security of the local and wide-area control schemes under routine network operations. The results presented in Fig. 13 show the voltage at the SVC bus where the line disturbance (with no fault) occurred. It is obvious that the wide-area PSS voltage response is smoother thanks to its lower pass-through gain. In fact, even though the performances of the two PSS look very similar in Fig. 11-12, Table 4 shows that the wide-area

PSS has a gain 13 times lower than the local PSS gain. The higher gain of the latter explains its higher sensitivity to routine network manoeuvres.

6.2 Statistical analysis of a large number of contingencies

A total of 780 contingencies with 60 load flows and 13 faults were simulated for the statistical analysis of the wide-area and local control schemes studied in the previous sections. The load flows were derived from the same nominal 2003 peak load configuration by means of a step-by-step stressing of the system to determine its stability limits. It should be recalled that SVC NEM, SVC ALB, SVC LTD and SC MAN were equipped with local control while in the wide-area control scenario, SVC LTD, was replaced by SVC LVD.

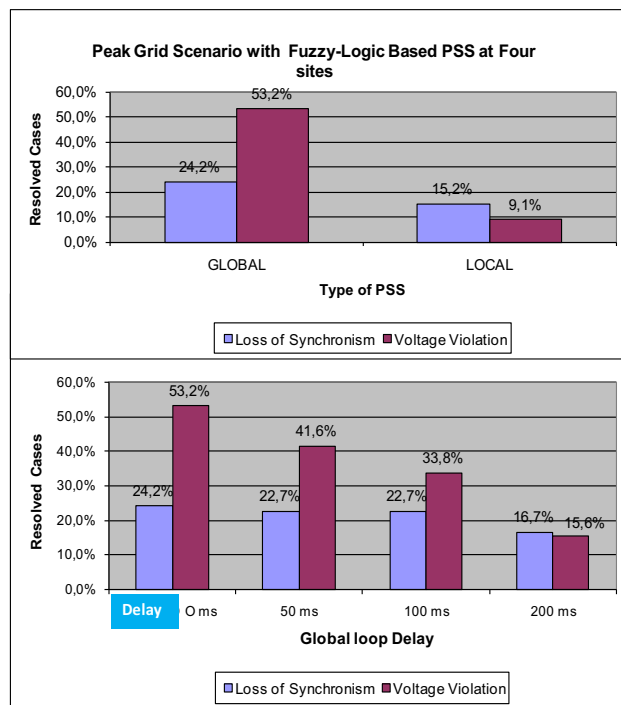


Figure 14: Statistical performance of the fuzzy PSS on the Hydro-Québec system (2003 peak load) - % decrease in the number of cases violating the criterion with respect to the base case. Top: local vs global control; bottom: global control with a variable delay

The behavior of the stabilizers was compared using two indicators. The first is the number of voltage and/or frequency criteria-violation cases, and the second is the number of loss-of-synchronism cases observed with the simulation time-frame of 15 s. In Fig. 14, for each stabilizer, the bars represent the value of the four indicators (in %) with respect to the reference case. It thus appears that the wide-area PSSs with no telecommunication delay are significantly more efficient than the local PSSs. To be more precise, compared to a local PSS, global stabilizers allow an increase in the number of secure cases by a larger reduction in the number of volt-

age and frequency criteria violations and loss-of-synchronism cases.

The bottom plot in Fig. 14 shows the statistical results obtained when a variable delay from 50 to 200 ms is added in the global control loop. The results associated with the wide-area stabilizer are quite robust with respect to a less than 100 ms delay. However, its capability to improve voltage and frequency profiles is significantly impaired by delays even as small as 50 ms. Interestingly, we need to increase the delay up to 200 ms in order to cause sufficient deterioration of the wide-area control to make it equivalent statistically to the reference local control scheme, which is already well tuned, as shown in the previous section.

6.3 Discussion

In the statistical study, the time delay was varied from 50 to 200 ms. Even if the technology today makes delays of around 50 ms realistic, we chose to consider longer delays for two reasons. The first was to evaluate the robustness of the closed loop with respect to the delay and neglected dynamics, while the second relates directly to the implementation solution cost. In fact, looking to the future, Hydro-Québec has already begun working on a pilot project to test wide-area control on its power system [16] and, the longer the delay, the lower the cost of telecommunication lines ownership.

7 CONCLUSION

In the present paper, a previously developed methodology to compare wide-area and local signal-based control of shunt FACTS devices for improved damping of inter-area modes [4] is applied to a simple test system [8,9]. Many intricacies of wide-area control, which are difficult if not impossible to study on a large interconnected system, were properly identified and studied analytically because of the structural simplicity of the four-machine two-area test system. It was therefore possible to show that, in this case, wide-area measurement-based control is about twice as efficient as local control, whatever the network configuration and FACTS location, although the wide-area control benefit was maximized when the SVC was sited at the grid's electrical center.

Novel fuzzy logic-based PSSs for SVCs help demonstrate the superior effectiveness of wide-area control on both small-signal perturbations and large fault-induced contingencies. Furthermore, the fuzzy PSS was experimented on the Hydro-Québec network in both wide-area and local control schemes applied to carefully selected dynamic shunt compensators. According to statistics derived from 780 simulations, the global fuzzy PSS achieved a 53% reduction in the number of cases violating a voltage criterion, while the local fuzzy PSS reduced this number by only 9%. Regarding the loss of synchronism events, the improvement was 24% for global PSSs versus 16% for local PSSs. Finally, the delay had more impact on the Hydro-Québec grid than on the Kundur test system, since on the former, a 200-

ms delay cancelled all the benefits of the global control with respect to local control. Clearly, great care should be invested in minimizing delays or, alternatively, advanced delay compensation methods should be included in wide-area PSS design [10].

Broadly speaking, wide-area control without a time-delay seems advantageous on the Hydro-Québec grid because it can restore the stability or security of three to five times more unstable/unsecure cases than the equivalently tuned local control with equalized pass-through gain. However, since the paper confirms that local control can be quite effective even at moderate gains, we would rather suggest always starting with local loops and then adding wide-area control loops, as needed, following a two-level, decentralized/hierarchical architecture [2,16]. This scheme will therefore exploit the substantial damping resulting from the larger observability of wide-area signals while keeping the local loop as backup.

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