Wide-Area Measurement Based Stabilizing Control of Large Power Systems—A Decentralized/Hierarchical Approach

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Abstract—The aim of this paper is to assess the capability of the emerging synchronized phasor measurement technology in improving the overall stability of the Hydro-Québec’s transmission system through supplementary modulation of voltage regulators. Following a thorough singular value and eigenvalue analysis of the system dynamic interactions, five control sites consisting of four generators and one synchronous condenser are chosen to implement new power system stabilizers with a supplementary input from remote phasor measuring units, geographically spread over nine electrically coherent areas. Since the remote feedback loops are built on top of an existing decentralized control system, this design approach results in a decentralized/hierarchical control architecture with significant advantages in terms of reliability and operational flexibility. A systematic control and measurement pairing yielded four dominant natural loops, each associated with a significant open-loop inter-area oscillatory mode at 0.06, 0.4, 0.7 and 0.95 Hz respectively. These PSSs have a speed sensitive local loop operating in the usual way, and a wide-area measurement based global loop which involves a single differential frequency signal between two suitably selected areas. The tuning and coordination technique for these advanced multiple input signals PSSs is described. Their impacts on the system is assessed using both small-signal analysis and nonlinear simulations in a transient stability program. Our study clearly shows by simulation that wide-area stabilizing controllers have a significant potential in improving the dynamic performance of the Hydro-Québec’s existing power system, even when implemented on five control sites only.

Index Terms—Control structure selection, damping controller, dynamic stability, inter-area oscillations, multi-level control, phasor measurement unit (PMU), power system stabilizer (PSS), small-signal stability, wide-area control, wide-area measurement.

I. INTRODUCTION

Several major utilities have recently shown an interest in the synchronous phasor measurement technology [1]. These include Hydro-Québec [2], American Electric Power [3], the New York Power Authority, Électricité de France (EDF) [4] and many utilities of the WSCC [5]–[7] such as BPA and Southern California Edison Co. Accelerated by the fast convergence between high-capacity fiber-optics-based telecommunication network and a more effective management of distributed information systems through LANs and WANs, this trend will soon provide a reliable source of wide-area measurement of the dynamic state of the power system [5]. The availability of this information comes along with the issue of how to effectively put it into use in the various areas of system dynamic performance.

Naturally, when the PMU network is suitably configured [14], use of wide-area measurement in system dynamic performance monitoring is quite obvious [6], [10] but applying it to solve special stability problems is more intricate, although it already has been proposed for out-of step relays [7], [9]. This paper considers an even more challenging problem which consists in improving, on a large scale, the conventional PSS with instantaneous measurements from remote phasor measurement units (PMUs) [11], [15]–[17]. Giving that the best pairing of PMU signals and control sites is not known beforehand [11], this problem is far from trivial. Besides, remote information exchange naturally increases interarea interactions and this may become a serious concern if not managed properly through a naturally decoupling control structure [12] and coordinated tuning of the multiple PSSs involved [13].

Fig. 1 describes the basic architecture used in this work. It consists of a set of \( p \) PSSs together with \( q \) PMUs which are remote to the PSSs. The signals from the PMU are sometimes referred to as “global signals” [16] or “remote feedback control signals” [34], to stress the fact that they convey knowledge related to the overall network dynamics, in sharp contrast with local control signals which often lack good observability of some significant interarea natural modes. This architecture, so-called “decentralized/hierarchical” architecture, is not strictly speaking a centralized control scheme since not every \( (q) \) measurement is fed back to every \( (p) \) controller [28]. It is rooted instead in the multi-level control theory [25]–[29], especially of large-scale systems [30], [31]. In the context of wide-area stabilizing control of bulk power systems, this specific architecture was first discussed in [16], [19], [20] where it was preferred for its higher operational flexibility and reliability, especially when some remote signals are lost. Under such circumstances, the controlled power system is still viable (although with a reduced performance level), owing to the fact that a fully autonomous and decentralized layer without any communication link is always present to maintain a standard performance level. From a grid planner point of view [36], loosing a remote feedback control signal in a decentralized/hierarchical configuration is not very different from a standard \( n - 1 \) condition: the network is still viable, but in some cases we may need a re-dispatch to ensure dynamic security.

By assuming a single data concentrator [5], [6] as in Fig. 1, the architecture for information dispatching to the various control...
sites is simplified, since a single entity is in charge of the filtering and routing of a selected subset of remote phasors to the most effective controllers, thereby solving the "who should know what?" issue [30]. As this global information is required only for some oscillatory modes and under specific network configurations, no more than the few PSS sites with the highest controllability of these modes need be involved in the supplementary global-signal-based actions, which together constitute a second control level in the sense of a multi-level closed-loop control system [31]. The other PSSs should remain fully decentralized since there is little payoff in providing them with remote information ("they need to know nothing more"). By the way, concentrating all remote PMUs signals in a single supervisor (SCADA) is just a way of simplifying the formal analysis of the global control problem. At the implementation level, a completely peer-to-peer distributed architecture can be applied without changing the findings.

II. SYSTEM MODELING

For easy reference, we recall in Fig. 2, a highly simplified one-line diagram of the studied system. The base case corresponds to the planned 1996 Hydro-Québec grid for the summer load (25 000 MW), weakened by the outage of two 735 kV lines in the eastern and western corridors. In addition, as indicated on the figure, the Micoua–Saguenay line will be removed at some point during the study to assess the design robustness (the so-called alternative scenario). The peak winter load is normally 35 000 MW. Other characteristics of the study are the following: 503 buses, 651 lines, 86 machines modeled in detail. Fig. 3 highlights three main geographic areas in the network. They can be further divided into nine smaller areas which are relatively coherent at the electromechanical level.

A. Pulse Response Based Identification of the State-Space Open-Loop Model

In order to excite all system modes, five control inputs were assigned: the first four being excitation system voltage reference inputs of four major generating stations (I1 = LG2 5500 MW, I2 = Churchill Falls 5500 MW, I3 = Manic-5 1500 MW, I4 = Gentilly-2 670 MW) the last one, a synchronous condenser near Montreal (I5 = Duvernay 2 x 250 MVA). Research previously conducted at IREQ allowed a minimum number of PMUs to be optimally placed on the 1996 Hydro-Québec system in order to collectively maximize the amount of dynamic information contained in the wide-area measurement [14]. This made it possible to continuously track the system dynamic state for global control purposes. Since a sequential addition algorithm
Fig. 4. Validation of the State-Space Identification: Speed response of Manic-5 (input #3). The two curves are nearly indistinguishable from each other.

was used, it was necessary to place in the nine areas of Fig. 3, 26 PMUs in addition to the 39 topologically imposed by the need of monitoring all inter-area transfers across the major transmission tie-lines (735 or 315 kV) shown on this figure. For instance, the area #4 (O4) is linked to area #5 (O5) through six 735 kV ac-lines.

For good geographical coverage, PMUs were placed at the four levels of the transmission network: 735, 315, 161 and 120 kV. Still with regard with Fig. 3, the selected outputs of the power system to be controlled are the average frequency at all PMUs in each area. The speed of machines I1 to I5 provide the additional output needed by the local loop of the PSS. In other words, the open-loop system model will have 5 inputs and 14 outputs. Normally, I1 to I3 have conventional acceleration-based PSSs but, before identifying the small-signal model by pulse-testing in a transient-stability program [23], [37], these PSSs were first made inactive to put the system in open-loop. The identification was then performed with and without the
Micoua-Saguenay line (base and alternative scenarios). The resulting state-space MIMO model of the studied system can be explicitly written as:

\[
\begin{align*}
\dot{x}(t) &= Ax + Bu(t) \\
y(t) &= Cx(t)
\end{align*}
\]

(1)

where \(x\) is the \(n \times 1\) (\(n = 36\)) state vector, \(u(t)\) is the \(m \times 1\) (\(m = 5\)) input vector and \(y(t)\) the \(p \times 1\) (\(p = 14\)) measured output vector; \(A(n \times n)\), \(B(n \times m)\) and \(C(p \times n)\) are state, input, output matrices respectively.

Fig. 4 illustrates the goodness of fit of such a model. Despite the instability of the open-loop system, the model matches the speed of the Manic-5 machine (I1) very closely, whatever the location of the exciting pulse input (I1 to I5). Although the example is about the base scenario, similar accuracy was achieved on the alternative scenario as well.

B. Controllability/Observability Analysis of the State-Space Model

Once the model is identified, the comparative strength of a signal or the performance of a controller with respect to a given mode can be evaluated using geometric measures introduced by Hamdan [21]. For completeness, we will briefly recall these definitions here. If we assume that this system has distinct eigenvalues, an eigenanalysis of the matrix \(A\) produces the eigenvalues \(\lambda_k = \alpha_k \pm j \omega_k\), \(k = 1, \cdots, n\) and the corresponding matrices of right and left eigenvectors respectively:

\[
E = [e_1 \ e_2 \ \cdots \ e_n] \quad \text{and} \quad F = [f_1 \ f_2 \ \cdots \ f_n].
\]

(2)

The eigenvectors \(e_k\) and \(f_k\) corresponding to \(\lambda_k\) are orthogonal and normalized, so we have:

\[
EF^H = FE^H = I_n
\]

with \(G^H\) the complex conjugate transpose of \(G\), and \(I_n\) the identity matrix of size \(n\). Giving these assumptions, the geometric measures of controllability \(m_{ci}\) and observability \(m_{oj}\) associated with the mode \(\lambda_k\) are:

\[
\begin{align*}
m_{ci}(k) &= \cos(\theta(f_k, \ b_i)) = \frac{\|f_k \cdot b_i\|}{\|f_k\| \|b_i\|} \\
m_{oj}(k) &= \cos(\theta(e_k, \ c_j)) = \frac{\|e_k \cdot c_j\|}{\|e_k\| \|c_j\|}
\end{align*}
\]

(3)

with \(b_i\) the \(i\)th column of \(B\) (corresponding to the \(i\)th input) and \(c_j\) the \(j\)th row of \(C\) (corresponding to the \(j\)th output). Likewise, \(\|z\|\) and \(\|z\|\) are the modulus and Euclidean norm of \(z\) respectively. \(\theta(f_k, \ b_i)\) is the geometrical angle between the input vector \(i\) and the \(k\)th left eigenvector, while \(\theta(e_k, \ c_j)\) is the geometrical angle between the output vector \(j\) and the \(k\)th right eigenvector. These equations show that the controllability measure is related to the angle between the left eigenvectors and the columns of the input matrix \(B\) and that the observability measure is related to the angle between the right eigenvectors and the rows of the output matrix \(C\). If \(m_{ci}(k) = 0\), then the mode \(\lambda_k\) is uncontrollable from input \(i\). If \(m_{oj}(k) = 0\), then the mode \(\lambda_k\) is unobservable from the output \(j\).

It should be recalled that residue matrices were also used in the past to assess the modal controllability/observability and then properly pair input and output signals for a number of damping controllers [15], [16], [34]. These alternative indices can in general be expressed in a normalized form as follows, for the \(k\)th natural mode:

\[
\begin{align*}
m_{ci}(\lambda_k) &= \frac{\|R_{ik}(\cdot, i)\|}{\|R_{ik}\|} \\
m_{oj}(\lambda_k) &= \frac{\|R_{ik}(j, \cdot)\|}{\|R_{ik}\|}
\end{align*}
\]

(4)

with \(m_{ci}(\lambda_k)\) (\(i = 1, 2, \cdots, m\)), the “relative” controllability measure, and \(m_{oj}(\lambda_k)\) (\(j = 1, 2, \cdots, p\)), the “relative” observability measure. In addition, \(R_{ik}\) is the matrix of residues associated to the \(k\)th natural mode:

\[
R_{ik} = C e_k f_i^T B.
\]

(5)

In practice, when signals of a widely differing physical significance, such as power flow in a tie-line (MW), bus frequency (Hz), shaft speed (rad/s), angle shift (deg.), etc. are involved in the output matrix \(C\) simultaneously, the residue approach suffer a scaling problem. The validity of the relative measure can be ensured only when all outputs are of the same type. By contrast, being based on directional properties of the underlying column vectors in the system matrices, the geometrical measures remain effective classifiers, even for inputs and outputs of widely differing types [33]. In addition, they are naturally dimensionless, being derived from cosine functions. Nevertheless, the two approaches will yield quite similar conclusions when assessing controllability/observability of a system with inputs and outputs of the same type. This is the case for instance, for the 5-input–14-output model identified in the previous section, since all its outputs are synchronous speed or bus frequency deviations expressed in per unit.

Application of geometrical measures more specifically to the dominant inter-area modes of the studied power system yields the figures in Table I. However, it is easier to interpret these data using the bar charts in Fig. 5. The main conclusions from these
data is that after the outage of the Micoua–Saguenay line (see Fig. 2), the frequency of the oscillations between the northern regions 1 and 3 of the Hydro-Québec system drops from 0.73 to 0.67 Hz, with half the damping. Sample frequency responses with and without the Micoua–Saguenay line (base and alternative scenarios) shown in Fig. 6 clearly confirm that they differ
sufficiently to raise concern about the robustness of any model-based control system design. Hopefully, the modal shape (controllability angle [15]) did not change as much as the resonant frequency. Churchill Falls plant (I2) still shows the highest controllability although the best observability is provided by the area 5 or 6 depending on whether the line is in service or not (Fig. 5: top vs. bottom). These two areas are very close to each other however.

III. TWO-LEVEL CONTROLLER STRUCTURE SELECTION

The controllability/observability measures computed separately for each mode in the previous section have shown to be successful in site and measurement screening for routine applications [13], [15], [21], [33] but have a drawback in that they are valid only at the system natural system frequencies. They cannot rigorously be used in assessing controllability/observability at forced sinusoidal excitation frequencies which are normally located on the imaginary axis. As consequence, they are unable to reveal in theory controller interactions at nonnatural oscillatory modes, which makes them useless in robust control where the whole frequency range is to be considered during the analysis or design. To remove this limitation, an approach studied in [22] has been reviewed and successfully adapted to power system applications. Consider the following transfer matrix:

\[ Y(s) = \Phi(s)U(s) \]  

where \( Y \) is the \( p \times 1 \)-output vector, \( U \) is the \( m \times 1 \)-input vector and \( \Phi \) is the \( p \times m \)-transfer matrix.

The Singular Value Decomposition (SVD) of the latter is [32]:

\[ \Phi(s) = Z(s)\Lambda(s)V^T(s) \]  

where

\[ \Lambda(s) = \begin{bmatrix} \Delta_{rr}(s) & 0_{r(m-r)}(s) \\ 0_{(m-r)r}(s) & 0_{(m-r)(m-r)}(s) \end{bmatrix} \]

\[ r = \text{rank}(\Phi(s)) \leq \min(p, m). \]  

\( \Delta_{rr}(s) \) is a \( r \times r \) diagonal matrix whose entries are the singular and distinct values of \( \Phi(s) \), \( \delta_1(s) \), \( \delta_2(s) \), \ldots, \( \delta_r(s) \) defined as the square root of the eigenvalues of the matrix \( \Phi^T(s)\Phi(s) \) or \( \Phi(s)\Phi^T(s) \). Let \( Z(s) \) be the \( m \times m \) matrix consisting of the eigenvectors of \( \Phi(s)\Phi^T(s) \) and \( V(s) \) the \( p \times p \) matrix consisting of the eigenvectors of \( \Phi^T(s)\Phi(s) \):

\[ Z = \begin{bmatrix} z_1 & z_2 & \cdots & z_r & \cdots & z_p \end{bmatrix} \]

and

\[ V = \begin{bmatrix} v_1 & v_2 & \cdots & v_r & \cdots & v_m \end{bmatrix}. \]
The entries of the transfer matrix is then \( \Phi(s) = \sum_{i=1}^{r} \delta_i(s)z_i(s)r_i^T(s) \), leading to the following output vector component:

\[
y_{kl}(s) = \sum_{i=1}^{r} \delta_i(s)[z_{ki}(s)v_{il}(s)]||v_i(s)||$

\[
(k = 1, 2, \ldots, r, l = 1, 2, \ldots, m)
\] (9)

where the scalars \( z_{ki}(s) \) and \( v_{il}(s) \) designate respectively the \( k \)th and \( l \)th components of the vectors \( z_i(s) \) and \( v_i(s) \) \((i = 1, \ldots, r)\). This expression shows that when the product \( z_{ki}(s)v_{il}(s) \) vanishes, the singular value \( \delta_i(s) \) has no influence on the response \( y_{kl}(s) \). By contrast, when it takes a unit value, the input–output pair \((k, l)\) is the only one to be influenced by \( \delta_i(s) \), which implies the following definition: the interaction between the input \( l \) and output \( k \) for the singular value \( \delta_i(s) \), is the scalar \( I_{kl}(s) = ||z_{ki}(s)v_{il}(s)|| \).

Therefore, the global interaction, incorporating contributions from all singular values is:

\[
\exists_{kl}(s) = \sqrt{\frac{1}{E} \sum_{i=1}^{r} \delta_i^2(s)||I_{kl}(s)||^2} \quad E = \sum_{i=1}^{r} \delta_i^2(s). \quad (10)
\]

This index, always between 0 and 1, holds at all frequencies, without the need of any hypothesis about the number of inputs/outputs (square/rectangular) or the eigenstructure of the original system \((A, B, C)\) (distinct eigenvalues or not).

Another notion closely related to this interaction concept is that of natural system loop. In effect, the orthonormality of the input and output space vectors, \([v_1(s) \quad v_2(s) \quad \ldots \quad v_r(s)]\) and \([z_1(s) \quad z_2(s) \quad \ldots \quad z_r(s)]\) imposes the constraint that if an input/output pair \((k, l)\) exists such that the interaction index is unitary (hence maximal), it is because all the remaining pairs \((k', l)\) in the system have zero interaction:

\[
\exists(K, L)[\exists_{KL}(s)] = 1 \Rightarrow \exists_{kl}(s) = 0, \quad \forall (k \neq K, l \neq L).
\] (11)

The existence of a natural loop that is valid at all frequencies of interest means that it is possible to fully control the system using single Single-Input Single-Output (SISO) controller based on that loop. On the other hand, the nonexistence of a dominant loop generally points out that either a multivariable controller is required or at least, the SISO controllers should be designed taking into account their mutual interactions, i.e., their tuning should be carefully coordinated.

Fig. 7 shows the system interaction gains for four main natural loops in the frequency range of interest. The control inputs and phasor measurement units (PMU) referred to in these figures are geographically located in Fig. 3. Selecting a natural controlling loop for damping a relevant mode is a more challenging task than simply choosing an input–output pair which maximizes the residue or modal sensitivity at the given mode. While the latter objective can easily be achieved from the conventional plots in Fig. 5, the former needs the more advanced concept of “dominant” or “natural” loop just introduced in this section. In fact, to be qualified as “natural loop,” not only should a control-measurement pair maximize the transfer gain at the mode of interest, it should also minimize the gain at any other frequency or modes that may influence the system behavior. This latter feature makes it possible to design sequentially, by simple superposition, as many single channel controllers as there are natural loops in the system, with inherently low interactions between the different loops, allowing them in particular, to be closed individually without mutually destabilizing each other.

In this context, one may conclude the following from Fig. 7:

1) 0.4 Hz: the best SISO controller should act on Duvernay synchronous condenser (I5) using area frequency #9.

2) 0.7 Hz: the best SISO controller should act on Churchill Falls (I2) generator using area frequency #6 (or #4). Another good solution (not shown on Fig. 7) is to act on LG2 (using area frequency #7 or #8)

3) 0.95 Hz: the best SISO controller should act on Churchill Falls generator (I2) using Montreal area frequency (area #2). However, a good alternative solution is to use speed-based local PSSs acting on I2 and I3. 0.06 Hz: the best SISO controller should act on Duvernay synchronous condenser (I5). However, it is already known that this common low frequency is well observed everywhere in the grid.

Even tough these selected loops are largely dominant, the resulting SISO controllers will show some level of interaction at various frequencies (see the sidelobes in Fig. 7). It is also possible to achieve control and measurement pairing by a careful screening of Fig. 5 (cf. Section II), but the “dominant loop” approach offers a faster and more definite quantitative solution. However, it is worth mentioning that the “coupling function” recently proposed in [24] targets a similar objective.

IV. OPTIMIZATION BASED PSS DESIGN

The interaction analysis performed in the previous section naturally yields the control system structure in Fig. 8. This produces five control sites each equipped with two loops: a local loop, based on the machine speed signal, which simply means a conventional \( \omega \)-PSS; and a global loop, based on a differential frequency between two remote areas. The total PSS signal applied to the machine voltage reference is the sum of these two basic components. In order to avoid the curse of dimensionality inherent to the coordination of multiple PSSs in a large power system, the tuning is performed according to the following sequential procedure:

1) Tune the local channel first.

2) Then tune the global loops to provide additional performance: the “value of inter-area information” is the transmission capacity or reliability gained between the system operated with the local loop alone and with both types of loop in effect. This value should be high enough to justify the telecommunication and engineering costs of information exchange between remote areas.

3) Finally (optional stage), coordinate the two types of loop to improve their synergistic effects and further increase the benefits yielded by the global-control strategy.

Fig. 9 illustrates the Matlab/Simulink model of a multi-loop PSS with one speed-sensitive local and two PMU-based remote
feedback loop or global signals [16], [20]. For simplicity, only one global input will be fully implemented in the sequel. Each branch or stage of the PSS is a differential filter defined as:

\[
F(s) = \frac{1 + sT_{AX}^X}{1 + sT_{AX}^A} \frac{1 + sT_{AX}^X}{1 + sT_{AX}^B} \frac{1 + sT_{AX}^X}{1 + sT_{AX}^B}
\]

\[
(X = A, B).
\]

where \( F_X \) is a rational fraction such as:

\[
F_X(s) = \frac{1 + sT_{Ax}^X}{1 + sT_{Ax}^A} \frac{1 + sT_{Ax}^X}{1 + sT_{Ax}^B} \frac{1 + sT_{Ax}^X}{1 + sT_{Ax}^B}
\]

\[
(X = A, B).
\]
Fig. 8. Information flow within the selected control structure. Control input: LG2(I1), CHU(I2), MANIC(I3), GENT(I4), DUV(I5); \( \omega_m \) is the machine speed deviation. Remote signal: PMU #2 - PMU \#y = pilot frequency of area \#x - pilot frequency of area \#x.

Fig. 9. Sample SIMULINK model of the PSS with two global loops.

Tuning the PSS consists in assigning adequate values to the various time constants and gains in each differential filter, based on a genetic optimization or a constrained nonlinear optimization procedure [23], [37]. This problem can be formally posed as follows:

\[
\min_{p \in \mathbb{T}^p} J(p) \quad \text{s.t.} \quad \max \{\Re(\lambda_k)\} < 0, \quad k = 1, 2, \ldots, n
\]

where \( p \) is the PSS parameter vector and \( J \) is a user specified cost function characterizing the overall damping performance of the closed-loop system. To simplify the optimization process, only the mandatory stability constraints are included while robustness as well as other qualitative constraints in [23], [37], are discarded. The cost function \( J \) used in this work is the modal performance index [23], [37], which aims at assessing the energy contained under the envelopes of the closed-loop, damped-sinusoidal signal responses following an impulse excitation. A large performance index therefore means a poorly damped closed-loop system while minimization of this cost function by adjusting the compensator parameters yields an well damped system. To compute \( J \), a modal decomposition of the closed-loop system:

\[
\begin{align*}
\dot{x}_c(t) &= A_c x_c(t) + B_c \theta(t) \\
y_c(t) &= C_c x_c(t)
\end{align*}
\]

can first be assumed in the form:

\[
\begin{align*}
\dot{z}(t) &= \Lambda z(t) + G \theta(t) \\
y(t) &= F z(t)
\end{align*}
\]

\( \Lambda = \text{diag}(\lambda_1, \lambda_2, \ldots, \lambda_n) \) contains the eigenvalues of \( A_c \), assumed distinct, while \( T \) is a corresponding eigenvector matrix. In addition, let define the following matrices:

\[
F = CT = [f_1^T, f_2^T, \ldots, f_p^T]^T, \quad G = TB^{-1} = [g_1, g_2, \ldots, g_m]^T.
\]

From equation (16) and assuming initial zero conditions, a unit impulse in the \( j \)th input yields the following state vector and \( j \)th output responses:

\[
\begin{align*}
\zeta_i(t) &= e^{\lambda t} \zeta_{i,j}^j(t) \\
y_{ij}(t) &= \sum_{k=1}^{m} R_{jki} e^{\lambda t} = \sum_{k=1}^{m} \tilde{y}_{jki}(t)
\end{align*}
\]

where \( R_{jki} = I_{jk} k_{ij} \) is the residue of the \( k \)th mode in the transfer function of \( i \) to \( j \) while the scalar \( y_{ij}(t) \) is the \( j \)th output response to the \( i \)th unit impulse excitation. The envelope of the \( k \)th mode contributing to the output signal \( y_{ij}(t) \) can be defined by:

\[
a_{ij} \tilde{y}_{jki} = R_{jki} \exp(\varepsilon_i^2 \lambda t)
\]

where \( ak = 1 \) if \( \lambda_k \) is real, \( ak = 2 \) if \( \lambda_k \) is complex, and \( \varepsilon_k = \sigma_k/\sqrt{\omega_k^2 + \sigma_k^2} \) denotes the damping factor of \( \lambda_k \). The performance index is basically the integral of the surface under the modal response envelope through a time horizon \( \tau \) and is summed over all natural modes \( \lambda_k \) and all system inputs and outputs \( y_{ij}(t) \):

\[
J_{\text{rew}} = \sum_{k=1}^{n} \sqrt{J_k}
\]

with

\[
J_k = \int_0^\tau \left( \sum_{j=1}^{p} \sum_{i=1}^{m} a_{ij} \tilde{y}_{jki} R_{jki} \right) dt = a_k \Psi(\sigma_k, \omega_k) \sum_{j=1}^{p} \sum_{i=1}^{m} R_{jki}^2
\]

and

\[
\Psi(\sigma_k, \omega_k) = \frac{\sigma_k^2 + \omega_k^2}{2\sigma_k^2} \left( \exp \left( \frac{2\sigma_k^2}{\sigma_k^2 + \omega_k^2} \right) - 1 \right).
\]

Using this modal performance in the optimization, the sequential tuning procedure specifically applied in this 5-input–14-output case is summarized as follows:

1) Obtain the 5 × 14-MIMO model of the system without any of the PSS to be tuned (Section II)
2) Obtain the initial PSS parameters at LG2 and Churchill plants (the biggest plants)
3) Install the default Churchill PSS in the 5–open-loop model. Derive from the resulting MIMO model, a reduced
3 inputs and one-output model to be used to tune the next (LG2) PSS.
4) Optimize the LG2 PSS and install it into the $5 \times 14$-open-loop model. Derive from the resulting MIMO model, a reduced $3 \times 1$-MIMO model that will be used to tune the next (Churchill) PSS.
5) Optimize the Churchill PSS and install it into the $5 \times 14$-MIMO model already containing the LG2 PSS. Derive
6) Optimize the Manic-5 PSS and install it into the $5 \times 14$-MIMO model already containing the LG2 and Churchill PSSs. Derive from the resulting model a reduced 3-inputs and one-output MIMO model that will be used to tune the next (Gentilly-2) PSS.

7) Optimize the Gentilly-2 PSS and install it in the $5 \times 14$-MIMO model already containing the LG2, Churchill and Manic-5 PSSs. Derive from the resulting model, a

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**Fig. 11.** Frequency responses of the optimal global PSSs. Control input #1, 2, 3, 4, 5 = LG2, CHU, MANIC, GENT, DUV.
reduced 3-inputs and one-output MIMO model that will be used to tune the Duvernay PSS.

8) Optimize the Duvernay PSS and install it into the $5 \times 14$-MIMO model already containing the LG2, Churchill, Manic-5 and Gentilly-2 PSSs. At this stage, the $5 \times 14$-MIMO model contains no remaining open-loop since optimal PSSs have been installed at all five machines under consideration.

Figs. 10 and 11 illustrate the frequency responses of the PSS yielded by the above procedure. Notice that, being within the same coherent area (cf. Fig. 8), Churchill (Input #2) and Manic (Input #3) have the same global PSS (Fig. 11), although their local PSSs are different (Fig. 10). While the local loops simply introduced some amount of phase lead from 0.01 Hz up to 1.5 Hz, the global loop behavior is more difficult to interpret using the standard framework. It is apparent that the latter
profiles of frequency responses could hardly been reached without the help of a computer-aided optimization tool.

V. FULL SCALE ASSESSMENT OF THE DESIGN USING SMALL-SIGNAL ANALYSIS AND NON-LINEAR MULATIONS

The effectiveness of the resulting decentralized/hierarchical control system was first assessed using the small-signal 5 x 14-MIMO model, and the results are provided in Figs. 12 and 13. Table II summarizes the improvement achieved on the damping of each major inter-area mode. The main conclusions are as follows:

1) The common low frequency mode is already well damped by the decentralized controller with a 0.5-damping ratio.
2) Global control has a significant damping effect on the 0.4-Hz-mode. By contrast, it is not required for the 0.95-Hz-mode.
3) The 0.7-Hz mode is significantly improved by global control, even if it can be equally enhanced locally by using decentralized PSSs. Table II also confirms the control robustness with respect to this important mode, since even basing the design on the nominal configuration yields a global control system which remains 30%
TABLE II

<table>
<thead>
<tr>
<th>Micoua-Saguenay line in service</th>
<th>$f_n$(Hz)</th>
<th>$z$(damping ratio)</th>
<th>Open loop</th>
<th>Decentralized</th>
<th>Decentralized/Hierarchical</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.064</td>
<td>0.50</td>
<td>&gt;0.6</td>
<td>&gt;0.6</td>
<td>&gt;0.6</td>
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<tr>
<td></td>
<td>0.44</td>
<td>0.04</td>
<td>0.055</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.74</td>
<td>-0.022</td>
<td>0.21</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.96</td>
<td>-0.014</td>
<td>0.46</td>
<td>0.49</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Micoua-Saguenay line out of service</th>
<th>$f_n$(Hz)</th>
<th>$z$(damping ratio)</th>
<th>Open loop</th>
<th>Decentralized</th>
<th>Decentralized/Hierarchical</th>
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<tr>
<td></td>
<td>0.063</td>
<td>0.48</td>
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<td>0.040</td>
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<td>0.22</td>
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<tr>
<td></td>
<td>0.95</td>
<td>-0.016</td>
<td>0.47</td>
<td>0.43</td>
<td></td>
</tr>
</tbody>
</table>

more effective than a fully decentralized scheme with the Micoua–Saguenay line out.

As usual for this type of study, nonlinear simulations in a transient stability program were also used to confirm the initial results of small-signal analysis. The same two system configurations were used to this end, in conjunction with 6 different contingencies of various severity levels. However, only two of them will be presented in this paper:

1) Eastern contingency: fault at Micoua resulting in a single line outage (stable or unstable depending on the fault duration).

2) Western contingency: fault at Chibougamau followed by rejection of 1480-MW generation at LG2 powerhouse and a two-line outage in the western corridor (stable or unstable depending on the fault duration).

Fig. 14 illustrates the system performance for a stable eastern contingency. The zoom of the response tails clearly confirms the improved damping achieved by global control. For the western contingency on Fig. 15, it is observed that the global control is the only scheme able to keep the system stable. Therefore, information exchange really has some “system stability” value which can (and should) be quantified by the system planner using criteria similar to those in [36]. It is believed that in some cases, the reward provided could pay for the implementation costs and cover the additional risks inherent in long-distance telemetry. Interestingly, this is done with a modest control effort as illustrated in Fig. 16: the benefit of global control is thus achieved using a small fraction of the total PSS signal only.

Finally, Fig. 17 illustrates another benefit of global control, this time on bus voltage profiles during an unstable western
Fig. 16. Unstable western contingency: decomposition of PSS signal for the decentralized/hierarchical control scheme.

Fig. 17. Unstable eastern contingency: Remote bus voltages.
contingency. It is quite obvious that additional modulation of PSS signal using remote pilot frequency measurement can significantly enhance voltage support at weak busses even if they are located very far from the PSSs.

VI. DISCUSSION OF SOME LIMITATIONS OF THE STUDY

In practice, taking advantage of the overall effectiveness provided by global control, especially in term of a strikingly low-effort control, turns to be complicated by two important factors not consider in the present analysis: Communication time lag and remote control signal loss [20], [34], [35].

Although processing and communication delay can be very important with today PMUs interconnected using fiber-optic or satellite based technology (reportedly in the range 100–400 ms), it is essentially when its value is a randomly variable with a large standard deviation that the time delay becomes a significant limitation in the design and operation. For fixed time-delay communication links, it is often possible to design a control system taking time delay effects into account [35], for instance by introducing a suitable amount of additional phase lead into the PSS transfer function. A simple heuristic approach [20] for this end could be to design the global PSS using remote phase angle signals and then implement the same controller using the corresponding remote frequency signals instead: this is a cheap and easy way to introduce a 90º phase lead into the PSS transfer function. Nevertheless, since it may be impractical to compensate very large time delays (i.e., more than 500 ms), it was shown in [20] that, although less effective and more difficult to design, bang-bang nonlinear control is the best way of dealing with this type of situation owing to its higher robustness with respect to large telecommunication delays (up to one second in [20]).

On the other hand, remote control signal loss is less critical with the proposed decentralized/hierarchical control structure than with its fully centralized alternative, since in the former, a decentralized layer is still present under these exceptional circumstances, thus serving as a fully working backup control system. In any event, protection engineers are familiar with reliable line protection using fast telemetry and remote switching. By using redundancy in designing critical components and implementing rigorous maintenance policies, it is possible from our view point to implement, even with today technology, reliable communication links providing a very low outage rate during long periods of time.

VII. CONCLUSION

This paper demonstrates by simulation of an actual 1996 Hydro-Quebec grid that a global control scheme tailored around the so-called hierarchical/decentralized architecture is very effective in stabilizing a large power system under various operating conditions. The main premise is the availability of a PMU based wide-area measurement network, built on the top of a powerful LAN/WAN which can guarantee the real-time delivery of synchronous phasors and control signals at a high speed (say at a 30 Hz sampling rate). This case study revealed that significant benefits ranging from improved damping of key inter-area modes, enhanced voltage profiles at remote weak busses, as well as an overall better system robustness under a wider range of operating conditions can combine to offset the significant costs associated with a commitment for a brand new technology.

REFERENCES


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