Torsional-mode identification for turbogenerators with application to PSS tuning

A. Heniche, *Member, IEEE*, I. Kamwa, *Fellow, IEEE,* R. Grondin, *Senior, IEEE*

Abstract-- This paper presents the results of a study undertaken to show the effects of filtering torsional modes on the performance of a closed-loop system. The Eigensystem Realization Algorithm (ERA) was used to identify the torsional modes at Hydro-Québec's Gentilly 2 power station. The mode filtering was done by means of two notch filters integrated into the transfer function of a multi-band stabilizer, the MB-PSS. The results obtained show that these torsional modes can in fact be adequately filtered, provided the filters are of the correct dimensions, without necessarily degrading the performance of the closed-loop system.

Keywords: Torsional modes, identification, Eigensystem Realization Algorithm (ERA), notch filter, closed loop.

I. INTRODUCTION

ELECTRICAL utilities find themselves faced with a delicate problem involving torsional oscillations in their turbine generator units. In fact, these modes whose frequency varies between 5 and 50 Hz, can be excited by different types of disturbance. Since the fault type and intensity determine the amplitude of torsional oscillations, under certain circumstances the latter could generate stability problems or even degradation of the material if they are not properly attenuated. The resulting financial losses can be substantial. Another factor is that the machine speed is used by various stabilization devices (PSS, speed regulators) which must have a speed signal that is not corrupted by torsional modes. For all these reasons, effective damping of the torsional oscillations is important for the smooth operation of turbine generator units.

Two approaches are available for solving this oscillation problem. The first is to synthesize new stabilizers so that they are sufficiently robust and capable of damping the torsional modes [1] [2]. The second consists in filtering the torsional modes using correctly dimensioned filters.

In the later case, the filtering can be done with different types of filters such as notch filters or even Kalman filters [3] which, even though they induce delays, especially in the frequency of the torsional oscillations, nevertheless offer an effective means of eliminating torsional modes. Yet one question still needs to be addressed, namely the effect of the filters on the effectiveness of the existing stabilization systems. In other words, as seen in Fig. 1, we need to examine whether the addition of torsion filters in the stabilization loop causes degradation of the performance of the closed-loop system.

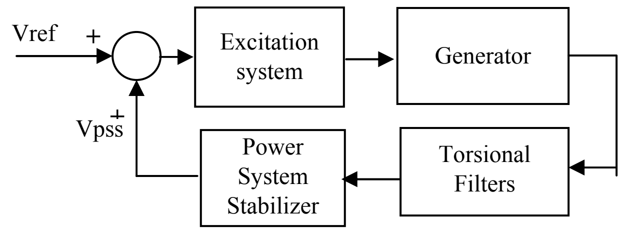

Fig. 1. Closed-loop system

On the other hand, since the effectiveness of the notch filters closely depends on how accurately the torsional modes are known, it is essential to identify these modes properly. The approach adopted in this work is to determine the torsional modes from measured signals. To be more specific, the modes will be identified using the so-called Eigensystem Realization Algorithm (ERA), which was originally introduced in [4]. In the context of electrical power systems, this approach was first applied in [5] then in [6]-[7] in the form of a state representation useful for modal analysis and stabilizer synthesis [8]. Since then it has been used in [9] to identify the torsional modes of turbine generator units yielding results that showed the ERA method to be an effective as well as a robust tool that can be used for identifying such modes.

The aim of this work is to show that a rejection type of notch filter, provided it is properly dimensioned and connected to the system, as shown in Fig. 1, allows torsional modes to be effectively attenuated without necessarily causing degradation in the performance of the closed-loop system.

The paper is organized as follows. Section 2 focuses on modal identification. The following section describes the application while the results are presented in Section 4. The paper is concluded in Section 5.

A. Heniche, is with École de Technologie Supérieure, 1100 rue Notre Dame Ouest, Montréal, Qc, H3C 1K3.
I. Kamwa, R. Grondin, are with Hydro-Québec, IREQ1800 boul. Lionel-Boulet, Varennes, Qc, Canada J3X 1S1
(e-mail: kamwa.innocent@ireq.ca, grondin.robert@ireq.ca)

Presented at the International Conference on Power Systems Transients (IPST'05) in Montreal, Canada on June 19-23, 2005
Paper No. IPST05 - 222

II. MODAL IDENTIFICATION

The usual way to identify the modes of a power system is to take appropriate measurements to record the system behavior when it is affected by a fault. Obviously, the fault applied must excite the modes of interest sufficiently. The measurements then have to be filtered. The signal-processing stage is important, in fact, because it not only allows high frequencies and noise to be eliminated but also enables the frequencies of interest to be extracted. After the data-processing stage is completed, the filtered measurements are used by the modal identification algorithm.

In more specific terms, the process of identifying torsional modes is done using the schematic in Fig. 2. The instantaneous machine speed ω is obtained with a transducer, which can be mechanical or electrical. Once the filtered speed measurement ω_f is obtained, then the identification process can really begin.

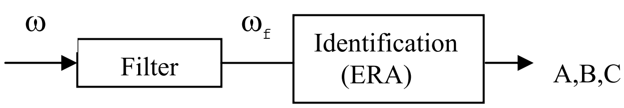

Fig. 2. Torsional-mode computation

The purpose of the identification algorithm ERA is to determine the state representation of the system:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx \end{aligned} \qquad (1)$$

whose impulse response Y is given by the vector y_m = [$y_m(0)$ y_m (T) y_m (2T)…y_m(kT)]. x, y and u are respectively the state, output and control vectors while kT are the sampling instants. y_m is a vector of dimension n representing the filtered speed ω_f of the machine. The λ_i modes found in the measured signals are the modes of the state matrix A.

Fig. 3 describes the identification algorithm ERA, which is based on the construction of two Hankel matrices, H_1 and H_2.

A. Identification parameters

- measured signal y_m
- sampling period T
- dimension n_d of the state representation (A,B,C)
- dimension n_r of the Hankel matrices H_1 and H_2, which in our case are square
- distribution parameters n_i and n_j of the matrices H_1 and H_2, which allow us to change the time span of the window to be used in the identification procedure

B. Construction of the Hankel matrices H_1 and H_2

The h_{ij} elements of the Hankel matrices are measurements that have been organized in terms of the selected identification parameters. For a given set of parameters, construction of the two matrices is almost identical, the only difference being the position of H_2 being offset by one sample compared to H_1. For example, if the first sample used for calculating H_1 is $y_m(0)$, then the first sample used for H_2 will be $y_m(T)$.

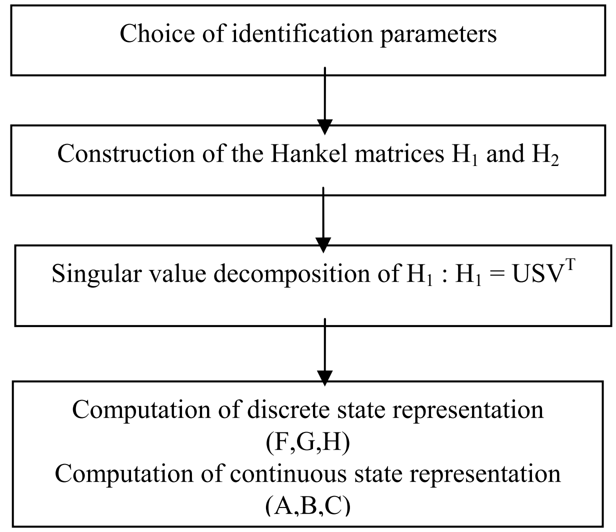

Fig. 3. Description of the Eigensystem Realization Algorithm (ERA)

The notations to be used in the text below are:
$y_m = [y_m(0), y_m(T), \ldots, y_m(nT)] = [y(1), y(2), \ldots, y(n+1)] = \omega_f$
For k =1, 2 and with the notations given, the Hankel matrices H_1 and H_2 are obtained as follows:

$$H_k = \begin{pmatrix} y(k) & y(k+n_i) & \cdots & y(k+(n_r-1)n_i) \\ y(k+n_j) & y(k+n_j+n_i) & \cdots & y(k+n_j+(n_r-1)n_i) \\ \vdots & \vdots & \vdots & \vdots \\ y(k+(n_r-1)n_j) & \cdots & \cdots & y(k+(n_r-1)(n_j+n_i)) \end{pmatrix} \qquad (2)$$

Remarks:
- The H_k matrices depend on the parameters T, n_r, n_i and n_j.
- If $n_i = n_j$ then H_1 and H_2 are symmetrical.
- If $n_i = n_j = 1$, adjacent data are used.
-The parameters n_r, n_i and n_j must be chosen so that $(n_r-1)(n_i+n_j) \le n-1$ where n represents the number of samples.
- For a value of n_r, the parameters n_i and n_j allow the width of the observation window F_o equal to $n_r(n_i+n_j)$ to be increased. So, if n_r=100 and n_i=n_j=1, this means that the identification has been done using the first 200 samples. If, on the other hand, n_r= 100 and $n_i = n_j = 2$, this means that one sample out of two is used by the identification procedure and that the last sample used is the 400th. In both cases, the identification procedure uses 200 samples, the difference being that in the first case it is the first 200 samples, whereas in the second it considers one sample out of two up to the 400th.

C. State representation computation

The state, control and output matrices F, G and H respectively of the discrete system are computed using matrices H_1 and H_2. Decomposition of H_1 into singular values yields the diagonal matrix S, which contains the singular values of H_1 arranged in descending order, and the matrices U and V containing the left and right singular vectors respectively. The identification parameter n_d is therefore used to select the n_d highest singular values. Thus we obtain the matrix S_{nd} containing the n_d highest singular values and the matrices of the associated singular vectors U_{nd} and V_{nd} from which the matrices (F,G,H) of the state representation of the discrete system are derived as follows:

$$H_1 = USV^T \qquad (3)$$

$$G = S_{nd}^{1/2} V_{nd}^{T} \qquad H = U_{nd} S_{nd}^{1/2} \qquad F = S_{nd}^{-1/2} U_{nd}^{T} H_2 V_{nd} S_{nd}^{-1/2} \qquad (4)$$

Once the matrices F, G and H have been computed, the continuous system (A,B,C) is obtained using the discrete to continuous transformation.

III. APPLICATION

The identification algorithm described above was applied to identify the state representation (A,B,C) and the torsional modes of the turbo-generator unit at Hydro-Québec's Gentilly 2 nuclear plant. This unit has a rated capacity of 819 MVA.

Field data recorded after a synchronization test were used for identification purposes. More specifically, the machine speed ω was derived from the terminal voltages and currents and then filtered. As shown in Fig. 4, the filter gain is 0 dB up to 40 Hz. Above that frequency, the gain decreases until it reaches -50 dB at 50 Hz.

Fig. 5 represents the filtered speed ω_f, the input signal to identify, which comprises 4762 samples obtained using a 4ms sampling period

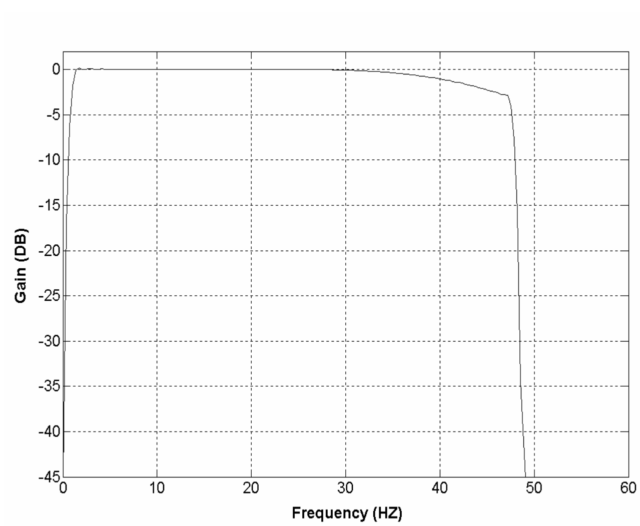

Fig. 4. Speed filter gain

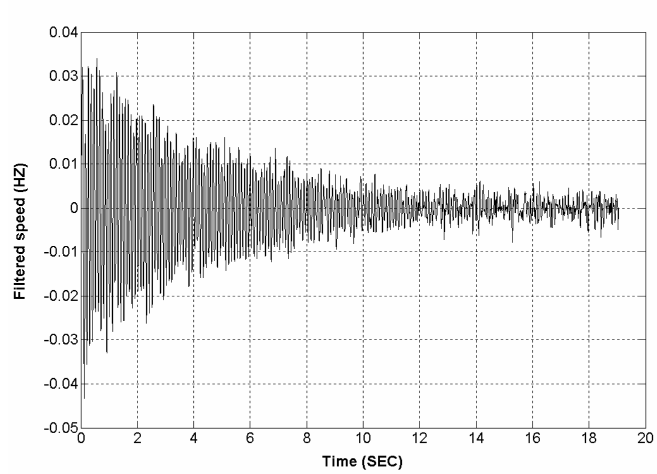

Fig. 5. Filtered speed ω_f

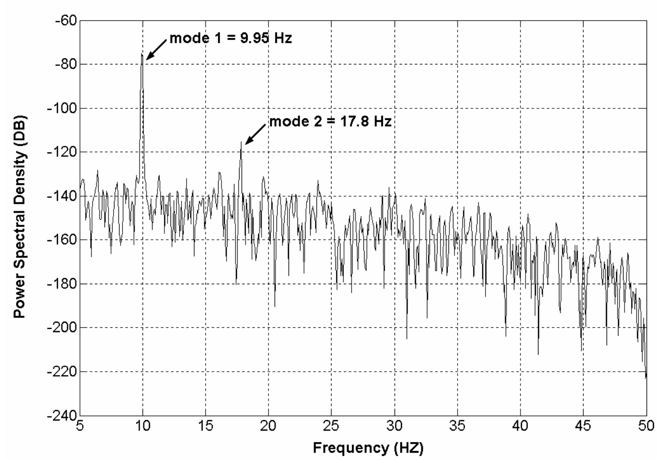

Fig. 6. Power spectral density of filtered speed ω_f

Fig. 6 shows the spectral density of ω_f. Two torsional modes can be seen in the shape of two peaks at 9.95Hz and 17.8Hz respectively.

The identification parameters used to obtain these torsional modes are given in the following table:

TABLE I:
IDENTIFICATION PARAMETERS

T(ms)	nd	nr	ni	nj
4	10	460	2	2

With these parameters, among the 4762 samples available, the last one to be used for computing the Hankel matrices is the 1838th which, considering the 4ms sampling period, corresponds to a recording time of 7.3480 s.

Once the torsional modes have been identified, two PSSs were used to show the effect of the rejection filters on the closed-loop system performance, as illustrated in Fig. 1. These PSSs are the MB-PSS (IEEE PSS4B) [10] developed jointly by Hydro-Québec and ABB and the standard Delta P_e stabilizer (IEEE PSS1A). The latter PSS is currently installed at Gentilly.

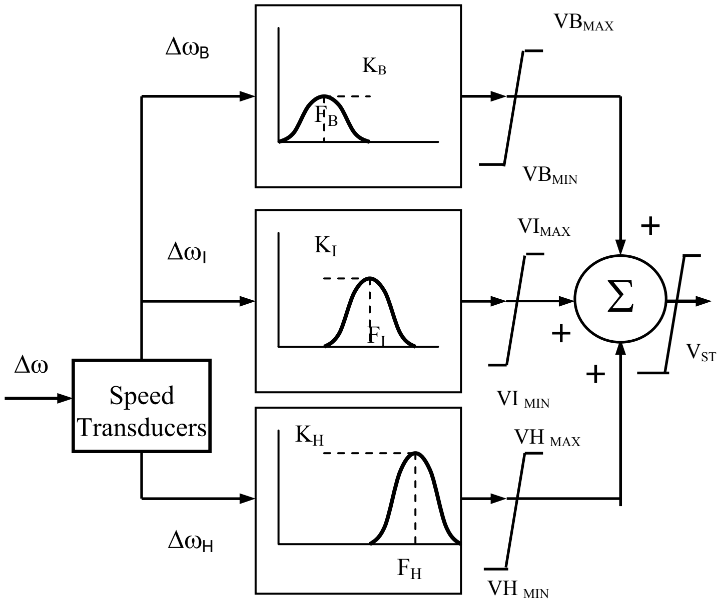

Fig. 7 . MB-PSS Stabilizer : PSS4B
(L=Low, I=Intermediate, H=High)

The main parameters for the MB-PSS setting are as follows:

Band gains:	K_L =	3
	K_I =	5.5
	K_H =	53
Central band frequencies:	F_L =	0.1076 Hz,
	F_I =	1.1958 Hz
	F_H =	12 Hz.

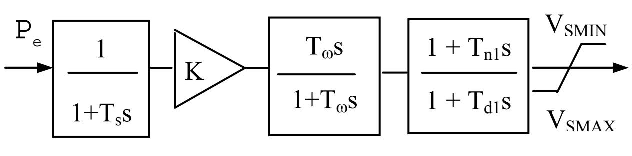

Fig. 8. Delta Pe Stabilizer : PSS1A

The parameters of the active-power PSS are:

T_s=	0.195	T_w=	1.4
T_{n1}=	0.15	T_{d1}=	0.39
Vsmin=	-0.1	V_{smax}=	0.1
K=	0.7143		

The frequency responses of these PSSs are given in Fig. 13. For the purpose of comparison, the Delta Pe stabilizer response was multiplied by the factor 2H*jω. This is the way to compare two speed stabilizers.

IV. RESULTS

A. Identification

By applying the ERA algorithm to identify the torsional modes characterizing the Gentilly plant, we were able to identify the following modes:

TABLE II:
TORSIONAL MODES IDENTIFIED

Mode number	Frequency (Hz)	Damping
1	9.951	0.0030
2	17.80	0.0021

It is clear from Table 2 that the algorithm offers a highly accurate identification of these torsion modes. In fact their frequency is identical to that observed in the spectral density.

Fig. 9 shows the Bode locus of the system (A,B,C). Not only do the results produce peaks at frequencies corresponding to the torsional modes but the system also presents a local mode with a frequency of 1.43 Hz. Prony analysis shows that the damping coefficients zeta of the torsional modes are smaller than the one associated with the local mode.

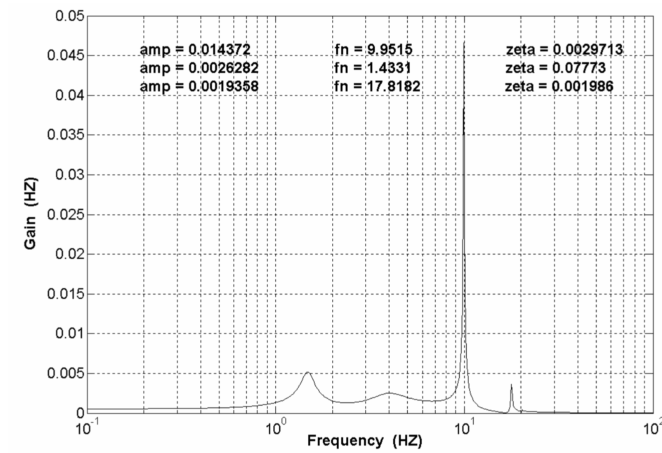

Fig. 9. Bode diagram of identified system

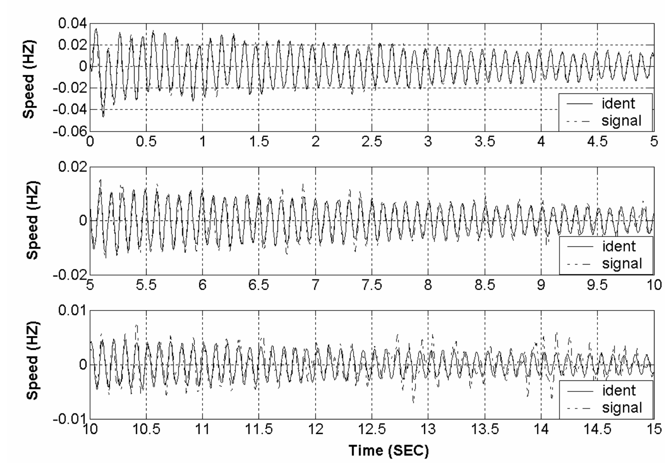

Fig. 10. Comparison between measured and identified speed

Fig. 10 compares the measured signal (signal) with the identified signal (ident). Good agreement can be seen between the two, at least in the first ten seconds. The differences observed after that are due to our previous choice of identification parameters that were making use of the first 7.3480 s of the recorded signal. This result is significant because it shows that the ERA algorithm is still effective outside the selected observation window.

B. Influence of notch filters on the PSS performances

The notch filter used to reject the torsional modes is represented by the following transfer function:

$$\frac{s^2+(2\pi f_1)^2}{s^2+2\pi b_1 s+(2\Pi f_1)^2}\bullet\frac{s^2+(2\pi f_2)^2}{s^2+2\pi b_2 s+(2\pi f_2)^2} \tag{5}$$

$f_1 = 9.95\text{Hz}$, $b_1 = 6$ Hz , $f_2 = 17.8\text{Hz}$, $b_2 = 12$ Hz.

Fig. 11 presents the Bode locus of the notch filter used to eliminate the torsional modes. It can be seen that the filter is very effective in cutting the 9.95Hz and 17.8Hz mode frequencies and good attenuation is achieved. However, the filter introduces a phase shift around these frequencies, causing a delay in the time domain.

Outside the frequency domain of these torsional modes, the degree of attenuation is negligible but there is a small phase lag in the useful frequency range of the PSS. Nonetheless, as shown in Fig. 12, the synthesized notch filter proves highly effective for removing torsional modes.

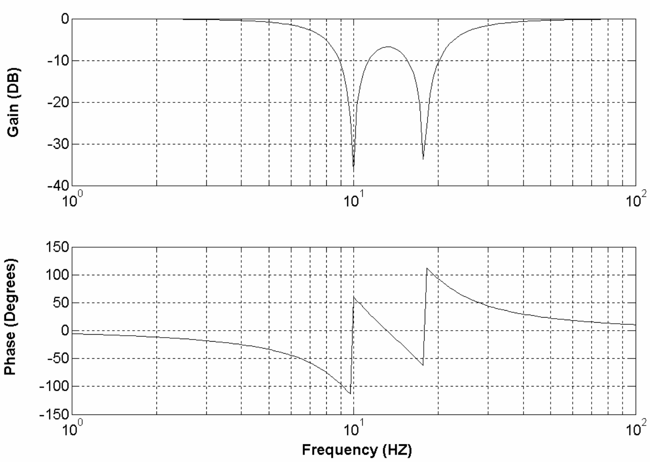

Fig. 11. Bode diagram of notch filter

The simulations in Fig. 14 (a-b) show that the results obtained after applying a 1% amplitude 0.5 s width pulse on the voltage reference input of the Gentilly 2 excitation system. The performance of the closed-loop system is shown for the Delta Pe stabilizer and for the MB-PSS with or without a notch filter. The Bode locus of these two stabilizers is given in Fig. 13. The MB-PSS equipped with the notch filter obviously sees a faster phase decrease at higher frequencies.

Time domain responses of Fig. 14 (a-b) first show that the system without a stabilizer will oscillate. In this case, the oscillation frequency will be 1.30 Hz. On the other hand, it can be seen that the addition of the notch filter does not have any significant effect on the closed-loop performance. In fact the results clearly show that the performance of the MB-PSS with or without the filter is essentially the same.

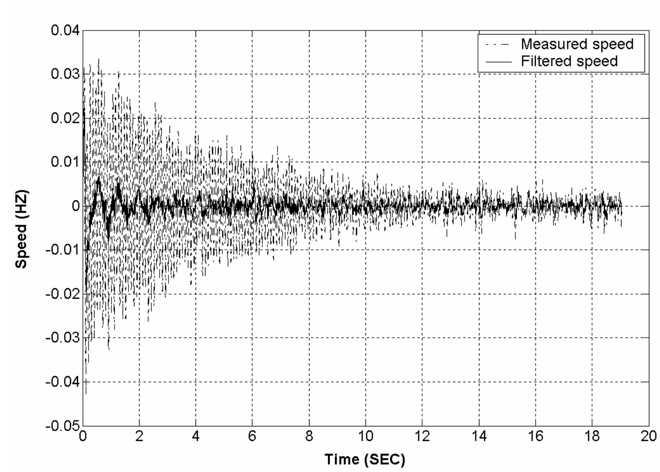

Fig. 12. Torsional-mode filtering

The results also reveal that the presence of the three stabilizers allows the oscillations to be damped. Nevertheless, the damping is noticeably better with the MB-PSS compared to the PSS installed at Gentilly. This demonstrates that a notch filter that creates a minimum delay in the useful band allows better performances than a low-pass filter with a high time constant (T=195 ms). It should be noted that this low-pass filter, as seen in Fig. 8, is currently used on the watt transducer of the Gentilly PSS for rejecting torsional modes.

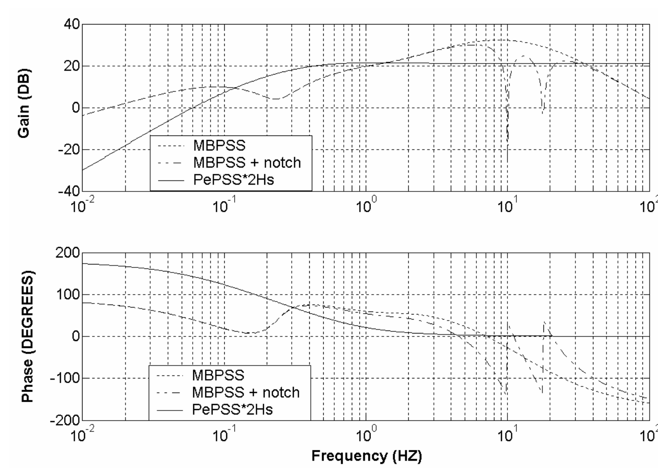

Fig. 13. Frequency response of PSS

Fig. 15 compares the responses of the MB-PSS with and without a notch filter to a sine wave of 1.30 Hz, the frequency of the oscillations observed in the open-loop system. In the time domain, the notch filter can be seen to create a 0.0158s delay.

In the frequency domain, Fig. 13 shows a phase difference of 7.5° between the MB-PSSs with or without a notch filter. This phase shift corresponds to the observation made in the time domain.

Lastly, it is interesting to stress that the performance of the closed-loop system, as shown in Fig. 14 (a-b), is by and large not affected

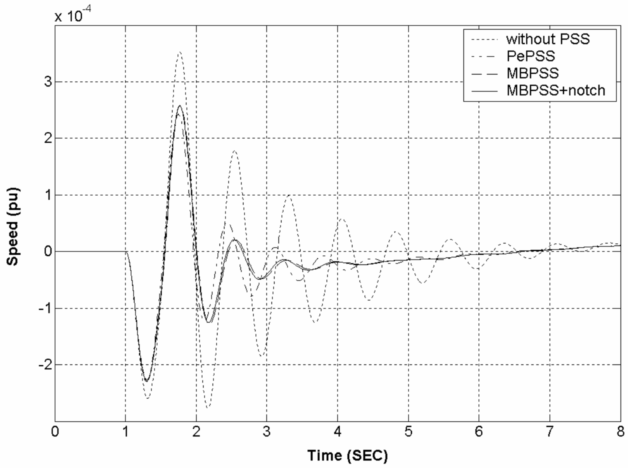

Fig. 14a. Speed of Gentilly 2

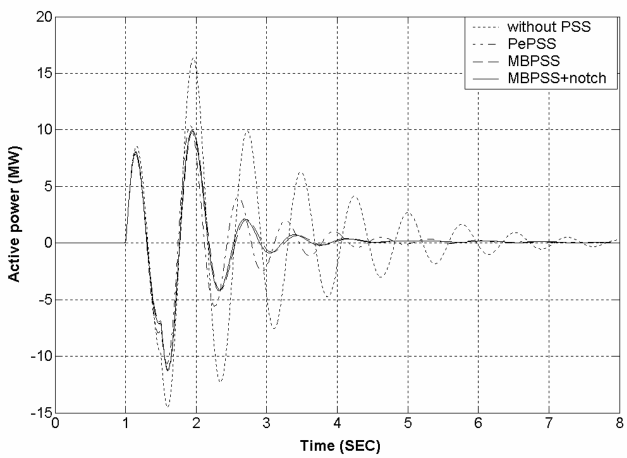

Fig. 14b. Active Power of Gentilly 2

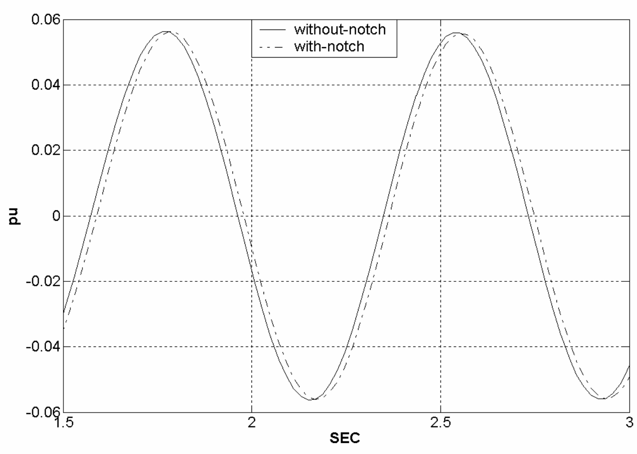

Fig. 15. MB-PSS responses with and without notch filter

V. CONCLUSIONS

The ERA algorithm was used to identify the torsional modes affecting the performance of Hydro-Québec's Gentilly 2 generating station. Field data were recorded for the study. A notch filter was synthesized for the purpose of rejecting the torsional modes identified. The results show that the ERA method is highly appropriate for identification purposes.

Meanwhile, the simulation results revealed that it is indeed possible to effectively damp the system and eliminate the torsional modes with appropriate setting of PSS and notch filters. The results confirm that the insertion of notch filters does not necessarily lead to degradation of the performance of the closed-loop system.

VI. REFERENCES

[1] G.N. Pillai, A. Ghosh, A. Joshi, "Robust Control of SSSC to Improve Torsional Damping," in *Proc 2001 IEEE Power Engineering Society Winter Meeting*, vol. 3, pp.1115-1120.

[2] R. Asgharian, "A Robust H-infinite Power System Stabilizer with no Adverse Effect on Shaft Torsional Modes," *IEEE Trans. on Energy Conversion*, vol. 9, no.3, pp. 475-481, September 1994.

[3] M.P Houry, H. Bourles, "Rotation Speed Measurement for Turbine Governor: Torsion Filtering by Using Kalman Filter," *IEEE Trans. on Power Delivery*, vol. 11, no. 1, pp. 110-115, Jan 1996.

[4] J. Juang, R.S Pappa, "An Eigensystem Realization Algorithm for Modal Parameter Identification and System Reduction," *Journal of Guidance and Control*, vol. 8, no. , pp. 620-627, 1985.

[5] I. Kamwa, R.Grondin, J. Dickinson, S. Fortin, "A Minimal Realization Approach to Reduced-Order Modeling and Modal Analysis for Power System Response Signals*", IEEE Trans. on Power Systems*, vol. 8, no. 3, pp. 1020-1029, Aug 1993.

[6] I. Kamwa, G.Trudel, L. Gérin-Lajoie, "Low-order Black-box Models for Control System Design in Large Power Systems*", IEEE Trans. on Power Systems*, vol. 11, no. 1, pp. 303-311, Feb 1996.

[7] J.J. Sanchez-Gasca, J.H. Chow, "Computation Of Power Systems Low-order Models From Time Domain Simulations Using a Hankel Matrix,*" IEEE Trans. on Power Systems*, vol. 12, no. 4, pp. 1461-1467, Nov 1997.

[8] I. Kamwa, L. Gérin Lajoie, "State-Space System Identification- Toward MIMO Models for Modal Analysis and Optimization of Bulk Power Systems,*" IEEE Trans. on Power Systems*, vol. 15, no. 1, pp. 326-335, Feb 2000.

[9] J.J Sanchez-Gasca, "Computation of Turbine Generator subsynchronous Torsional Modes From Measured Data Using the Eigensystem Realization Algorithm," in *Proc 2001 IEEE Power Engineering Society Winter Meeting*, vol. 3, pp.1272-1276.

[10] R.Grondin, I. Kamwa, G.Trudel, J. Taborda, R. Lenstroem, L. Gérin-Lajoie, J.P. Gingras, M. Raine, H. Baumberger, "The Multi-Band PSS, a Flexible Technology Designed to Meet Opening Markets,*"CIGRE 39-201,* 2000.

VII. BIOGRAPHIES

Annissa Heniche (M'03) has a degree in Electrical Engineering from "École Nationale des Ingénieurs et des Techniciens Algérie" (1985) and a master and a Ph.D in automatic control from " Paris 11 University " respectively in (1992) and (1995). She is currently a researcher in the field of power system analysis, and control.

Innocent Kamwa (S'83, M'88, SM'98, FM'04) has been with the Hydro-Québec research institute, IREQ, since 1988. At present, he is a Senior Researcher in the Power System Analysis, Operation and Control Department. He is also an associate professor of Electrical Engineering at Laval University in Québec, Canada. Kamwa received his B.Eng. and Ph.D. Degrees in Electrical Engineering from Laval University in 1984 and 1988 respectively. A member of the IEEE Power Engineering and Control System societies, Kamwa is a registered professional engineer.

Robert Grondin (S'77, M'80, SM'99) received his B.Sc.A. in Electrical Engineering from University of Sherbrooke, Canada in 1976 and his M.Sc. from INRS Énergie, Varennes, Canada in 1979. He then joined Hydro-Québec research institute, IREQ. Currently a Senior Research Engineer in the Power System Analysis, Operation and Control Department, he is leading research activities in the field of power system dynamics and defense plans. Member of IEEE Power Engineering society and of CIGRÉ, he is also a registered professional engineer in province of Québec, Canada