Journal of Marine Science and Technology

Volume 24 | Issue 5 Article 1

EFFECTS OF POWER SYSTEM STABILIZER ON DAMPING OF INTER-AREA OSCILLATION USING REMOTE SIGNAL

Van-Dien Doan
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C

Ta-Hsiu Tseng
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

Pei-Hwa Huang
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C, b0104@mail.ntou.edu.tw

Recommended Citation
Doan, Van-Dien; Tseng, Ta-Hsiu; and Huang, Pei-Hwa (2016) "EFFECTS OF POWER SYSTEM STABILIZER ON DAMPING OF INTER-AREA OSCILLATION USING REMOTE SIGNAL," *Journal of Marine Science and Technology*: Vol. 24: Iss. 5, Article 1.
DOI: 10.6119/JMST-013-0606-4
Available at: https://jmstt.ntou.edu.tw/journal/vol24/iss5/1

Journal of Marine Science and Technology, Vol. 24, No.5, pp. 905-912 (2016)
DOI: 10.6119/JMST-013-0606-4

EFFECTS OF POWER SYSTEM STABILIZER ON DAMPING OF INTER-AREA OSCILLATION USING REMOTE SIGNAL

Van-Dien Doan, Ta-Hsiu Tseng, and Pei-Hwa Huang

Key words: eigenanalysis, power system stabilizer, phasor measurement unit, remote signal.

ABSTRACT

The inter-area oscillations in large interconnected power systems often have features of being low-frequency, lightly damped, and affecting relatively more generating units located in multiple areas. They restrict the allowable power flow on tie-lines and may lead to unexpected contingencies if it is not to be in proper observation. The main objective of this paper is to present a small signal stability analysis applied to Vietnam Power System which is a longitudinal network structure with the consideration of Power System Stabilizers (PSS) in operation to enhance the damping of inter-area oscillation by using local as well as remote feedback signals via phasor measurement unit (PMU). Based on the use of the eigenanalysis and PMU, the study results show that by determination installation location of PSSs and selecting the remote control signal properly, power oscillation on the tie-lines was significantly reduced. Both linear analysis and time-domain simulation are used to investigate the performance of the power system. The results have also illustrated the effectiveness of the PMU application in large power systems.

I. INTRODUCTION

Interconnections of power system have been proving the efficiencies in techniques, economics and environments. They could be compared as a backbone in the power system which supports to transport energy in a cheaper price from the generator center over long distance to the load center as well as to exchange the power between the regions or countries. However, the stability of this power system becomes also more complex, especially the power systems, which must always work under stress conditions in the deregulated competitive environment.

Low frequency electromechanical oscillations are one of the potentially dangerous effects to the working stability of the power system. They are inherent in the weak interconnected power system during contingencies and can be classified into local modes and inter-area modes which refer to the rotor oscillations associated with generators within the same area and with generators located in some different areas, respectively. (Kundur, 1994; Rogers, 2000) Inter-area modes are associated with machines in one part of the system oscillating against those machines in other parts of the system. As compared to the local mode oscillation, the oscillation caused by an inter-area mode often has a lower frequency and less damping, with more generators involved from different regions (Huang and Tseng, 2010).

For many years, PSS has been considered as the best option in terms of cost and damping oscillation performance (Hsu et al., 1987; Chang et al., 1995). PSS has been used to add damping to electromechanical oscillations in order to increase the power transfer or maintain working stable modes in the network. The main purpose of this paper is to demonstrate the design of conventional power system stabilizers for a better damping system characteristic of a longitudinal power system by using instantaneous measurements from remote locations of the power system as its feedback input signals.

SMALL-SIGNAL STABILITY

1. Linear Analysis

Small-signal stability analysis with the method of eigenanalysis has proven to be the most effective analysis tool for power system low-frequency oscillations. This method provides not only information related to destabilizing mechanism but also clearly identify areas which have potential instability problems. In this method the system is linearized about an operating point. Linear approximation of power system, which is essentially non-linear, can be presented by the following state-space equations (Kundur, 1994; Rogers, 2000):

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta y &= C\Delta x \end{aligned} \tag{1}$$

where

Paper submitted 05/14/13; revised 06/03/13; accepted 06/06/13. Author for correspondence: Pei-Hwa Huang (e-mail: b0104@mail.ntou.edu.tw).
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

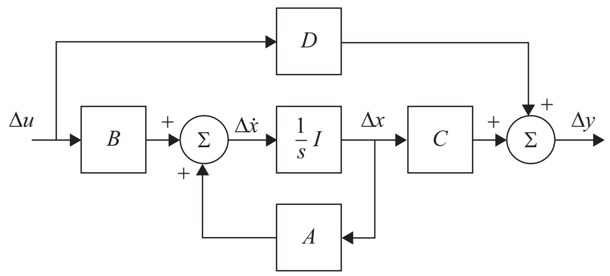

Fig. 1. Diagram of the state space representation.

Δx is the n-dimensional vector of states

Δy is the m-dimensional vector of output

Δu is the r-dimensional vector of input

A is the state matrix of dimension $n \times n$

B is the input matrix of dimension $n \times r$

C is the output matrix of dimension $m \times n$

$\Delta x = x - x_o$, $\Delta y = y - y_o$, $\Delta u = u - u_o$.

The state space representation of systems is shown in Fig. 1. Eigenvalues of $\boldsymbol{A}$ matrix, λ_i , are calculated by solving

$$\det(A - \lambda_i I) = 0 \quad (2)$$

The eigenvalues of the $n \times n$ matrix A are the n solutions $\lambda = \lambda_1, \lambda_2, \ldots, \lambda_n$. These eigenvalues may be real or complex and the complex eigenvalues always occur in conjugate pairs and are of the form $\lambda = \sigma \pm j\omega$.

From the eigenvalues the damping ratio and oscillatory frequency for that mode can be determined. The damping ratio of the oscillation is given by

$$\zeta = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}} \quad (3)$$

and the damped frequency of oscillation in Hertz is given by

$$f = \frac{\omega}{2\pi} \quad (4)$$

The damping ratio determines the rate of decay of the amplitude of the oscillation. If the real part of eigenvalue is positive, then damping ratio will be negative, which means the oscillation increases, whereas the negative real part indicates positive damping which means the oscillation will fall into decay.

For each eigenvalue λ_i of the $n \times n$ matrix A, there are right and left of eigenvectors which satisfy (5) and (6), respectively.

$$A\varphi_i = \lambda_i \varphi_i \quad (5)$$

$$\psi_i A = \lambda_i \psi_i \quad (6)$$

where

λ_i is the i^{th} eigenvalue

φ_i is the right eigenvector (n-column) associated with λ_i

ψ_i is the left eigenvector (n-row) associated with λ_i

The participation factor matrix can be calculated by combining the left and right eigenvectors:

$$P = \left[P_1 \; P_2 \; \ldots \; P_n \right] \quad (7)$$

where

$$P_i = [\, p_{1i}, \, p_{2i}, \ldots, \, p_{ni} \,]^T = [\varphi_{1i}\psi_{1i}, \, \varphi_{2i}\psi_{2i}, \ldots, \, \varphi_{ni}\psi_{ni}\,]^T$$

The element $p_{ki} = \varphi_{ki}\psi_{ki}$ is called the partition factor. It is a measurement of relative participation of the k^{th} state variable in the i^{th} mode and is mathematically expressed as the multiplication of left and right eigenvector. Note that φ_i is the k^{th} entry of the right eigenvector of the i^{th} mode and ψ_{ki} is the k^{th} entry of the left eigenvector of the i^{th} mode.

The rotor angle modes can be identified from left and right eigenvectors in conjunction with the participation factors, and can be termed as Mode shape. If a mode is found in places where the generators can be grouped according to the similarity of their rotor angle characteristics in different areas, then that mode can be identified as an inter-area oscillation mode.

2. Time-Domain Simulation

Conduct time-domain simulations for the identified critical mode by the applying typical and necessary disturbances to the system for making comparison with the results obtained from frequency-domain eigenanalysis (Hsu and Hsu, 1986; Huang and Hsu, 1990; Lee and Wu, 1995). Both the time domain simulation and the frequency domain analysis, i.e., the method of eigenanalysis, are used in the task of system analysis. The small signal stability of the system under study is investigated by the method of eigenanalysis for finding the damping, frequency, and mode shape of the critical inter-area mode of oscillation. The power system stabilizer is to be investigated in detail. Time domain simulations will then be conducted to verify the effectiveness of installing PSSs (Huang and Tseng, 2010).

III. MULTI-INPUT POWER SYSTEM STABILIZER

1. Phasor Measurement Unit

Phasor Measurement Unit has developed in recent years to

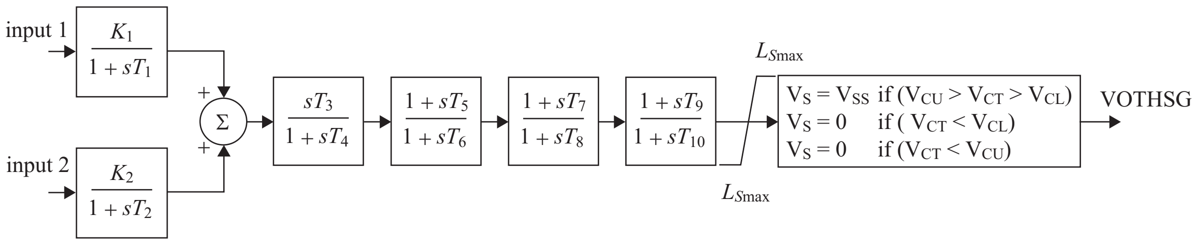

Fig. 2. Dual-input power system stabilizer type IEE2ST.

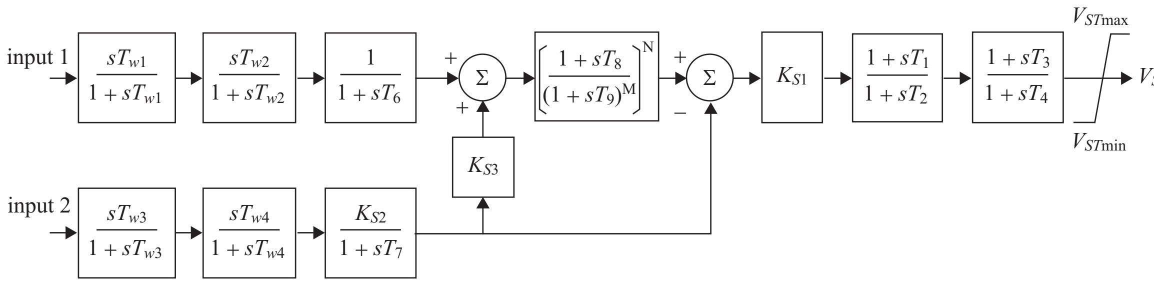

Fig. 3. Dual-input power system stabilizer type PSS2A.

become a powerful tool to observe, protect and control large power system under abnormal operations. PMU allows a global view of the power system by providing synchronous phasor information from different locations of the power system such as voltage, current, angle, frequency in real time and control signals at high speed via modem telecommunication to the controllers. PMU is used widely and has been proving effective more and more in advanced power system monitoring, protection and control applications (Aboul-Ela et al., 1996; Phadke, 2002; Kakimoto et al., 2006).

2. Multi-input Power System Stabilizer

Most of the conventional power system stabilizers are designed with single-loop structures and utilizes local input signals such as accelerating power or frequency deviation, rotor speed deviation as feedback signals (Michigami, 1995; Korba and Uhlen, 2010). Under global observability of power system it seems to be limited since inter-area oscillation is a global dynamic phenomenon as well as all oscillation modes, which cannot be exactly identified by only local measurements. With the synchronized phasor measurement technology, it may allow observation in one place to be under control in other ones (Klein et al., 1991; Kamwa et al., 2001; Liu, 2002; Kitauchi et al., 2002). The combining one or more remote signals with local signals to design of PSS may be a better choice for enhancement damping of inter-area oscillations. Fig. 2 and Fig. 3 depict the functional block diagrams of the multi-input power system stabilizer studied in this paper, which is to be designed by local and remote measurements as its input signals for providing a supplementary signal for the excitation system (Huang and Tseng, 2010).

IV. CHARACTERISTICS OF THE STUDY SYSTEM

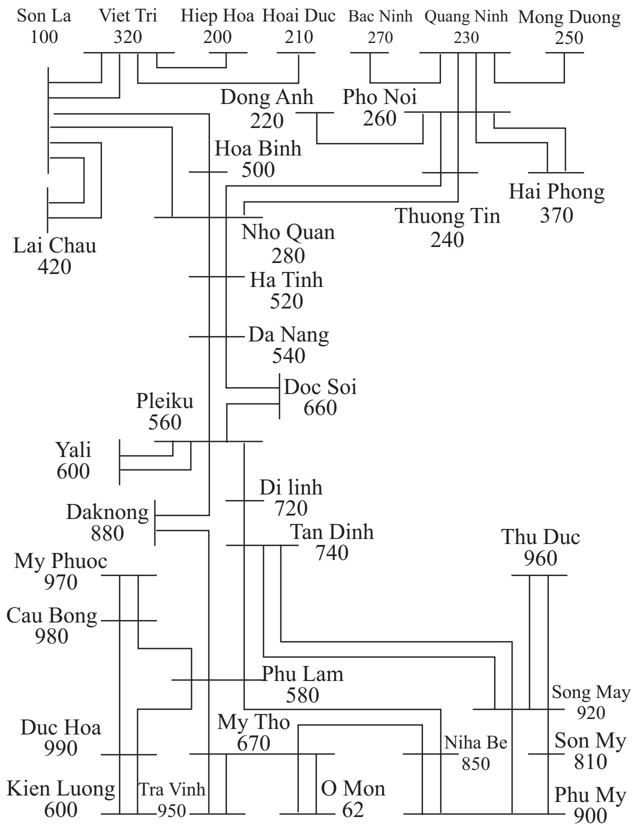

Fig. 4. One-line diagram of Vietnam Power System.

In this paper, the stability analysis is focused on the Vietnam Power System which has a longitudinal network structure with the trunk 500kV transmission system as shown in Fig. 4 (Tran-Quoc et al., 2003; Hoang et al., 2011).

Table 1. Power transfer through tie-lines.

From	To	MW
Pleiku 524.24 kV	Daknong 506.44 kV	575.6
	Dilinh 510.66 kV	609.4

Table 2. Oscillation modes with frequencies 0.1-1.1 Hz.

Mode	Eigenvalues	Frequency	Damping ratio
163-164	$-1.178 \pm j6.367$	1.0665	0.1731
165-166	$-0.471 \pm j6.367$	1.0134	0.0737
167-168	$-0.427 \pm j6.286$	1.0004	0.0678
169-170*	$-0.467 \pm j3.233$	0.5146	0.1429
171-172	$-11.412 \pm j1.207$	0.1921	0.9944
173-174	$-13.425 \pm j0.940$	0.1496	0.9975
175-176	$-0.413 \pm j0.906$	0.1442	0.4152
177-178	$-0.669 \pm j0.645$	0.1027	0.7199
179-180	$-0.553 \pm j0.641$	0.1020	0.6530

* Critical inter-area mode

According to the geography characteristics and the power grid structure, the generating units and transimisstion line system can be classified into three regions, that is, the Northern, the Central and the Southern areas (Ngo and Nguyen, 2011).

The system eigenvalues are to be calculated from the normal operating condition, with neither power system stabilizer or damping controller installed nor the occurrence of the contingency. All generators are modeled in detail of which the governors and exciters are represented by models in accordance with the actual generators in Vietnam Power System. With the status quo that hydro power plants of large capacity are located mainly in the North and thermal power plants of large capacity are situated mainly in the South, the system is to be investigated with the scenario in the rainy season and power is being transmitted from North to South through two EHV tie-lines. The power transfer is about 1185MW in total which is summarized in Table 1.

The eigenvalues and damping ratios of those oscillation modes with frequencies in the range of 0.1-1.1 Hz are listed in Table 2 and they are electromechanical modes. Among them, the low-frequency oscillation mode associated with a complex conjugate pair of eigenvalues $-0.467 \pm j3.233$ is a mode having a relatively low oscillation frequency (0.5146 Hz).

The damping ratio (ζ) of the mode is specified by $\zeta = -\sigma / \sqrt{\sigma^2 + \omega^2} = 0.4129$ that determines the rate of decay of the oscillation amplitude where σ and ω denote the real part and imaginary part of the eigenvalue, respectively.

It is a poorly damped oscillation mode. This mode is thus designated as the critical oscillation mode. For more detailed analysis of the interaction between generators of this mode, the mode shape is depicted as shown in Fig. 5. The remaining oscillation modes of system are stable, revealing local or intra-area behaviors, and hence are not to be discussed here. From

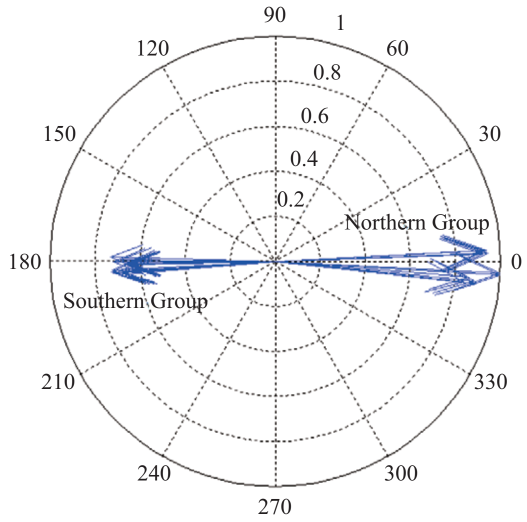

Fig. 5. Mode shape of the critical inter-area mode.

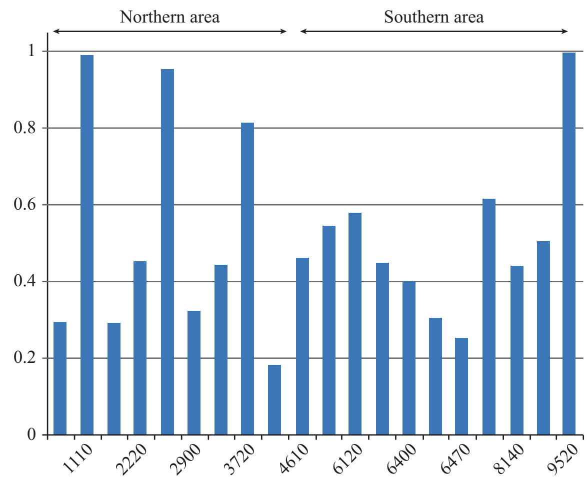

Fig. 6. Participation rate of generators speed.

Fig. 5, it is found that this critical mode demonstrates an inter-area mode shape with northern generators as a group oscillating against the group of southern generators.

Furthermore, southern generators at the receiving end swing with lower amplitude than the northern group at the sending end, whereas the participation factors of generators between the two areas are equal in value. Fig. 6 helps to visualize more easily about the critical oscillation mode (mode 169).

In order to evaluate the effects of low frequency oscillation in the power system, time domain simulations have been conducted to verify the results of the linear analysis. A fault is applied to disturb the system on Bus 500 of Hoa Binh hydro power plant with eight generating units in the northern area and then cleared after 80 ms (4 cycles). Fig. 7 describes the active power oscillation on generators. Fig. 8 describes the voltage oscillations at 500 kV buses on tie-lines, those typical voltage signals will be considered to be a remote control signal for PSSs. Fig. 9 shows the responses of active power on tie-lines.

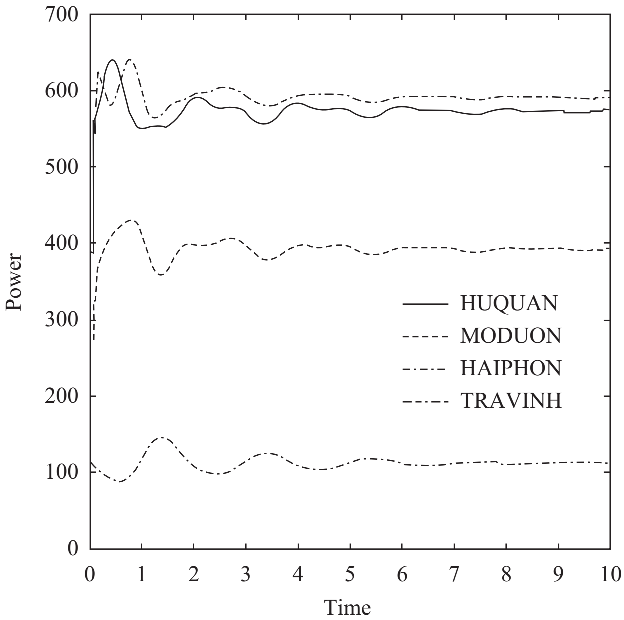

Fig. 7. Active power oscillations of generators without PSSs.

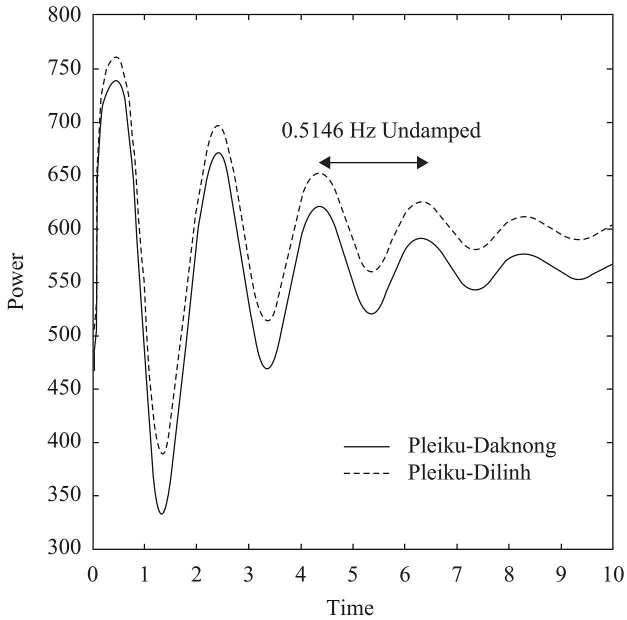

Fig. 9. Responses of active power on tie-line without PSSs.

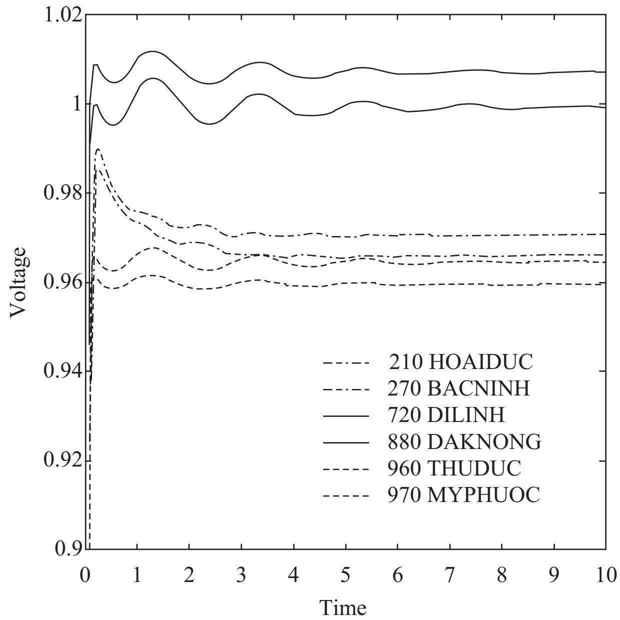

Fig. 8. Voltage oscillation at 500 kV buses without PSSs.

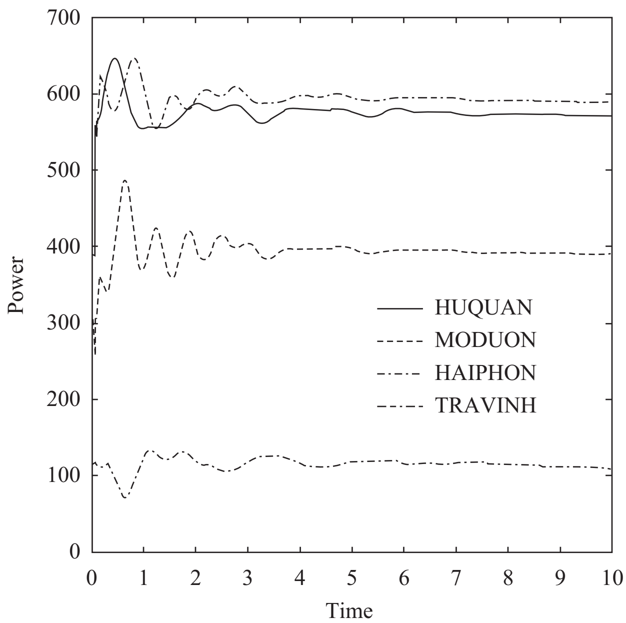

Fig. 10. Active power oscillations of generators with PSSs installed both areas with remote signals from Bus 270.

From Fig. 9, it can be easily observed that the active power of the tie-lines swing is very strong and the system damping is not sufficient since the oscillation persists as long as 10 seconds. The main reason in this case could be that, under the scenario considered, a large flow of power (1185 MW) through tie-lines in such a system with a longitudinal structure is likely to excite an electromechanical mode with poor damping.

V. INTER-AREA OSCILLATION WITH DUAL-INPUT PSS

The nature of PSSs is to provide immediately damping torque to balance the mechanical power input and the electrical power output and to maintain system stability when a serious fault occurs suddenly in a power system. The advantages of dual-input PSS is that the control signals can be obtained at any point of the power system, creating a closed-loop control. In this paper, the local input signals for PSSs are speed signals, and meanwhile the remote signals are voltage signals which will be obtained through PMU. Based on participation factors

Table 3. Parameters of PSSs.

Parameter	PSS	
	IEE2ST	PSS2A
K_1	45	45
K_2	45	0.5
K_3	-	0.5
T_1	0.02	0.120
T_2	0.02	0.018
T_3	4	0.120
T_4	4	0.018
T_5	0.016	-
T_6	0.180	0
T_7	0.150	0
T_8	0.140	0.5
T_9	0.05	0.1
T_{10}	0.04	-
T_{w1}	-	2
T_{w2}	-	2
T_{w3}	-	2
T_{w4}	-	0

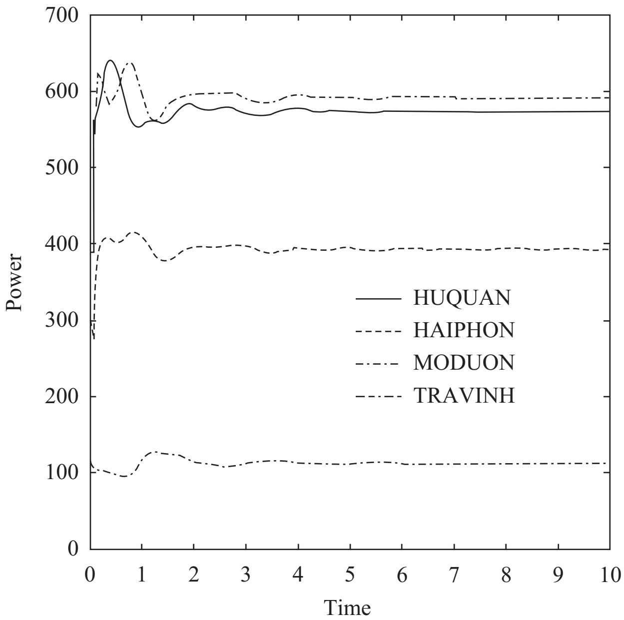

Fig. 11. Active power oscillations of generators with PSSs installed both areas with remote signals from Bus 880.

in Fig. 6, the generators have the largest participation factors in oscillation in both south and north areas will be considered to install PSSs to provide an effective degree of damping. The generator Huoi Quang (1110) is equipped with a power stabilizer of type IEE2ST. The generator of Tra Vinh (9520) and Mong Duong (2530) are equipped with a type PSS2A power system stabilizer. The parameters of PSSs are listed in Table 3.

The local signals of PSSs are speed signals on the shafts of the generators. The remote input signals of PSSs are to be

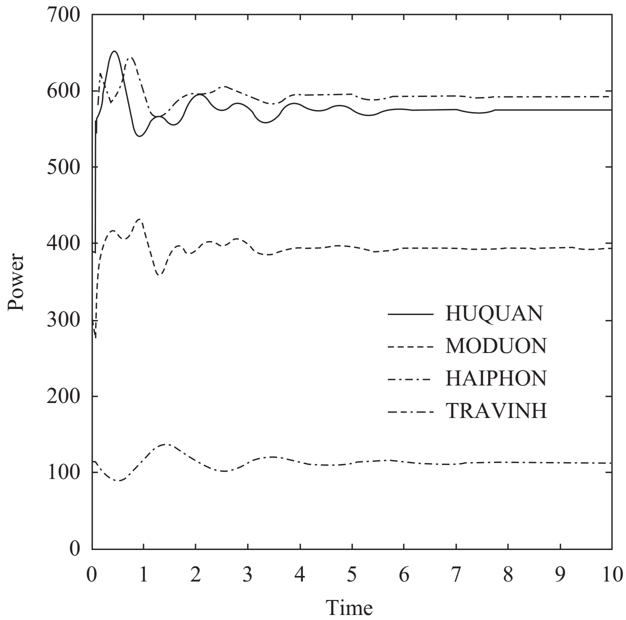

Fig. 12. Active power oscillations of generators with PSSs installed both areas with remote signals from Bus 990.

collected from different buses along the power system. In order to verify the effects of the dual-input power system stabilizer on the damping ratio of the critical oscillation mode, the time domain simulation for each power system stabilizer with different combinations of input signals are conducted by applying a fault similar to the case without PSSs which are presented in the previous section. First, the remote signals are obtained from 500 kV buses in north and south areas, respectively. Fig. 10 shows the responses of active power oscillations of generators when PSSs are installed in both areas with remote signals from Bus 270 (Bac Ninh) in the northern area.

Similar to those in Fig. 11 and Fig. 12 are the responses of active power oscillations of generators when remote signals are obtained from Bus 880 (Daknong) and Bus 990 (Duc Hoa), respectively.

In another case, Fig. 13 describes the responses of active power oscillations of generators when PSSs are installed in both areas, but the remote signals from generator buses in the southern area are used for control of PSSs in the northern area and vice versa. The various results with eigenanalysis are summarized in Table 4.

From Table 4, it is observed that the combination of the locals and remote signals which are obtained from Bus 880 will provide the best performance of damping in the system. After PSSs are installed, the characteristics of inter-area oscillation changed significantly. In particular, the damping ratio increased from 0.1429 to 0.2657 and the oscillation frequency decreased from 0.5146 to 0.1442.

In addition, in the time domain simulation, the responses in Fig. 14, for which the PSSs are installed in both areas with the remote signal from Bus 880 yield also the most damping in

Table 4. Eigenvalues and damping ratio at different remote buses.

Location of PSS and local signal	Remote Bus	Eigenvalue	D. Ratio
9250-1110, 2530	210	$-0.301 \pm j3.213$	0.093
9250-1110, 2530	880	$-0.249 \pm j0.906$	0.265
9250-1110, 2530	990	$-0.294 \pm j3.281$	0.089
9250-1110, 2530	2230	$-0.272 \pm j3.225$	0.084
9250-1110, 2530	6110	$-0.260 \pm j3.274$	0.079
9250-1110, 2530	210 - 990	$-0.232 \pm j3.332$	0.069
9250-1110, 2530	2230 - 6110	$-0.278 \pm j3.220$	0.086

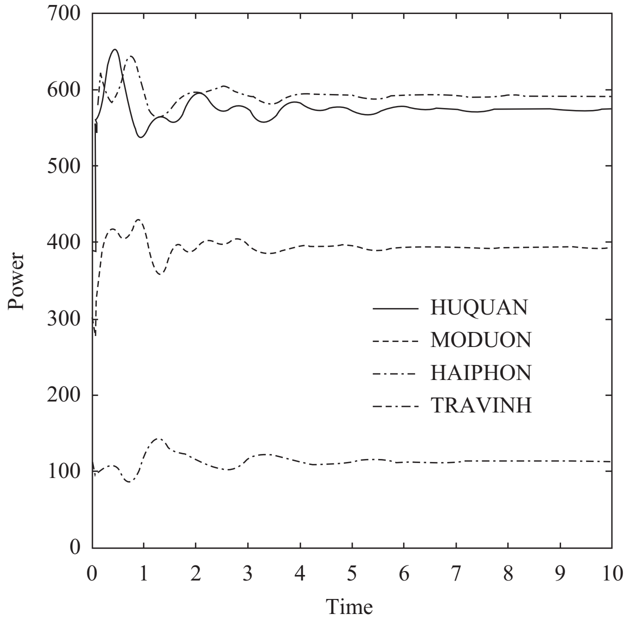

Fig. 13. Active power oscillations of generators with PSS installed both areas with remote signals from Buses 2230-6110.

the system. This is consistent with the eigenvalues shown in Table 4. And we can make an observation that the PSSs employs remote bus voltage as one of the input signals will also improve the system damping.

VI. CONCLUSIONS

This paper has focused on inter-area oscillation damping improvement using PSS with remote feedback input signals in a longitudinal power system. It is based on the method of eigenanalysis to specify the installation place of PSS; by the use of local as well as remote signals which are obtained via the phasor measurement unit for dual-input PSS, the inter-area oscillation is well damped. Both eigen-structure analysis and time domain simulation are conducted to verify the effectiveness of proposed dual-input PSS in improving the stability of the power system. The results are instrumental in increasing

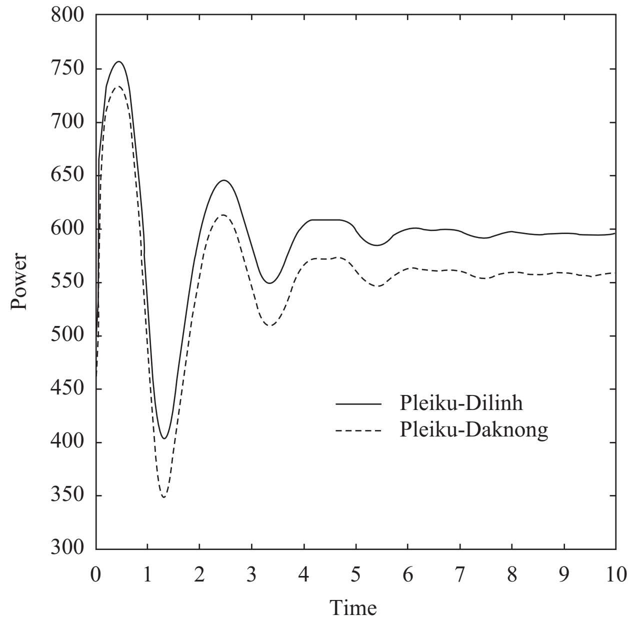

Fig. 14. Active power oscillations on inter-area transmission lines with PSS installed both areas with remote signals from Bus 880.

the understanding of Vietnam Power System characteristics and besides that they have also illustrated the effectiveness of the phasor measurement unit technology in large power systems. Especially in the current context of globalization, when the interconnection and electrical trading between countries is promoted to enhance energy security, the use of the remote feedback control signal is one of the really effective solutions that not only improve the stability of power system, but may also give optimal power flow control between countries or regions.

REFERENCES

Aboul-Ela, M. E., A. A. Fouad, J. D. McCalley and A. A. Sallam (1996). Damping controller design for power system oscillations using global signals. IEEE Transactions on Power Systems 11, 767-773.

Chang, C. L., C. S. Liu and C. K. Ko (1995). Experience with power system stabilizers in a longitudinal power system. IEEE Transactions on Power Systems 10, 539-545.

Hoang, T. D., A. T. Nguyen and T. T. Nguyen (2011). Vietnam power system overview and challenges. Proceeding of 2011 EPU-CRIS International Conference on Science and Technology, 1-5.

Hsu, Y. Y., S. W. Shyue and C. C. Su (1987). Low frequency oscillations in longitudinal power systems: experience with dynamic stability of Taiwan power systems. IEEE Transactions on Power Systems 2, 92-98.

Hsu, Y. Y. and C. Y. Hsu (1986). Design of a proportional-integral power system Stabilizer. IEEE Transactions on Power Systems 1, 46-53.

Huang, P. H. and Y. Y. Hsu (1990). Eigenstructure assignment in a longitudinal power system via excitation control. IEEE Transactions Power Systems 5, 96-102.

Huang, P. H. and T. H. Tseng (2010). Voltage feedback controller for power system damping improvement. Journal of Computational Information Systems 6, 4683- 4690.

Kamwa, I., R. Grondin and Y. Hebert (2001). Wide-area measurement based stabilizing control of large power system - a decentralized/hierarchical approach. IEEE Transactions on Power Systems 16, 136-153.

Kakimoto, N., M. Sugumi, T. Makino and K. Tomiyama (2006). Monitoring of Interarea oscillation mode by synchronized phasor measurement. IEEE Transactions on Power Systems 21, 260-268.

Kitauchi, Y., H. Taniguchi, T. Shirasaki, Y. Ichikawa, M. Asano and M. Banjo (2002). Setting scheme and experimental verification of multi-input PSS parameters for damping low frequency power swing in multi-machine power system. Transactions of IEE Japan 122-B, 137-144.

Klein, M., G. J. Rogers and P. Kundur (1991). A fundamental study of inter-area oscillations in power systems. IEEE Transactions on Power Systems 6, 914-921.

Korba, P. and K. Uhlen (2010). Wide-area monitoring of electromechanical oscillations in the Nordic power system: practical experience. IET Generation, Transmission & Distribution 4, 1116-1126.

Kundur, P. (1994). Power System Stability and Control. McGraw-Hill, New York.

Lee, Y. C. and C. J. Wu (1995). Damping of power system oscillations with output feedback and strip eigenvalue assignment. IEEE Transactions on Power Systems 10, 1620-1626.

Liu, C. W. (2002). Phasor measurement applications in Taiwan. Proceeding of IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific 1, 490-493.

Michigami, T. (1995). The development of a new two-input PSS to control low-frequency oscillation in interconnecting power systems and the study of a low-frequency oscillation model. Transactions of IEE Japan 115-B, 42-61.

Ngo, S. H. and T. H. Nguyen (2011). Operational problems and challenges in power system of Vietnam. Proceeding of 2011 EPU-CRIS International Conference on Science and Technology, 1-5.

Phadke, A. G. (2002). Synchronized phasor measurements-a historical overview. Proceeding of IEEE/PES Transmission and Distribution Conference and Exhibition 2002: Asia Pacific 1, 476-479.

Rogers, G. (2000). Power System Oscillation. Kluwer Academic, Norway, MA.

Tran-Quoc, T., T. Tran-Anh, S. Lam Du, T. Tran-Anh, B. Nguyen, A. Nguyen-Hong, R. Feuillet and C. Praing (2003). Stability study for the Vietnam power system. Proceeding of 2003 IEEE PES Transmission and Distribution Conference and Exposition 2, 729-735.