Journal of Marine Science and Technology

Volume 22 | Issue 4 Article 11

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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@ntou.edu.tw

Recommended Citation
Doan, Van-Dien; Tseng, Ta-Hsiu; and Huang, Pei-Hwa (2014) "EFFECTS OF POWER SYSTEM STABILIZER ON INTER-AREA OSCILLATIONS IN VIETNAM POWER SYSTEM," *Journal of Marine Science and Technology*: Vol. 22 : Iss. 4 , Article 11.
DOI: 10.6119/JMST-013-0611-2
Available at: https://jmstt.ntou.edu.tw/journal/vol22/iss4/11

Journal of Marine Science and Technology, Vol. 22, No. 4, pp. 498-505 (2014)
DOI: 10.6119/JMST-013-0611-2

EFFECTS OF POWER SYSTEM STABILIZER ON INTER-AREA OSCILLATIONS IN VIETNAM POWER SYSTEM

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

Key words: power system stability, low frequency oscillation, power system stabilizer, eigenanalysis.

ABSTRACT

The main objective of this paper is to report a preliminary study of the effects of the power system stabilizer on the small-signal stability and the damping of low-frequency oscillations of the Vietnam power system which is under fast development and has a longitudinal grid pattern. Spontaneous low-frequency oscillations are potential to occur in the exchange of regional power flow of a power system with longitudinal network structure under normal operation. The method of eigen-analysis is utilized to perform the study of the inter-area oscillations with an emphasis on the oscillation mode with low frequency and light damping. The eigenvalues, eigenvectors, and participation factors associated with the inter-area oscillation modes are calculated in details and possible locations of power system stabilizer are chosen for study accordingly. The results reveal the effectiveness of the power system stabilizer in damping inter-area oscillatory modes and thus the contribution to the improvement of system stability.

I. INTRODUCTION

Planning and operation of modern power systems have become more complex due to the interconnection of multiple areas for the sake of system reliability and security. Power system stability investigates the system behavior when it is subject to some disturbances, and small signal stability refers to the system dynamics under small perturbations during normal operation with emphasis placed on the analysis of power system spontaneous low-frequency oscillations [1, 15]. Such low-frequency oscillations can be classified into local modes and inter-area modes which refer to the rotor oscillations associated with generators within the same area and those with generators located in some different areas, respectively. 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 within different regions [2, 11].

Spontaneous low-frequency oscillations are potential to occur in the exchange of regional power flow under normal operation, especially in the operation of an interconnected power system with a longitudinal network structure [3, 8, 18]. The main objective of this paper is to study the small-signal stability and damping of low-frequency oscillations under possible installation of power system stabilizer (PSS) for the Vietnam power system [5, 16, 19] which is under fast development and has a longitudinal grid pattern. The method of eigenanalysis is utilized to perform the study of the inter-area oscillations with an emphasis on the lightly damped oscillation mode with relatively low frequency [17, 18, 20, 21]. The eigenvalues, eigenvectors, and participation factors associated with the most critical inter-area oscillation mode is to be calculated and analyzed in details and locations of PSS are selected for study accordingly.

II. THE STUDY SYSTEM

In this paper, the stability analysis is focused on the Vietnam power system which has a longitudinal network structure [5, 16, 19]. According to the geographical characteristics and the power grid structure, the generating units and transmission line system can be classified into three regions, namely the Northern, the Central and the Southern areas.

The Vietnam 500 kV system includes approximately 1500 km of transmission lines that feed the lower voltage system through substations in Hoa Binh, Da Nang, Pleiku and Phu Lam, and has associated Vietnam power system into a unified system with the characteristic of a large system in 1994. The 500 kV system has made significant changes in the structure of Vietnam power system. Besides the advantages of large system such as facilitation of support capacity between areas, improvement in efficiency of economic operation, assurance

Paper submitted 04/01/13; revised 06/06/13; accepted 06/11/13. Author for correspondence: Pei-Hwa Huang (e-mail: b0104@ntou.edu.tw).
Department of Electrical Engineering, National Taiwan Ocean University, Keelung, Taiwan, R.O.C.

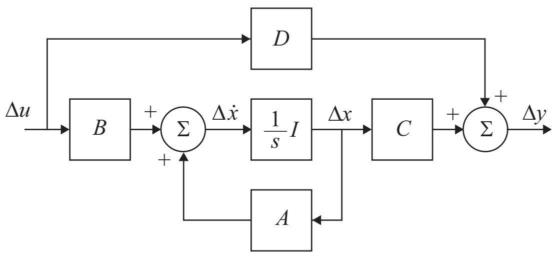

Fig. 1. Diagram of the state space representation.

of reliability for power supply and power quality to consumers, Vietnam power system has been increasing in the complexes in network structure, diversity in power generation technology and scale of power sources, especially the units with larger capacity. Therefore, in view of the unification of extra high voltage lines and the complexity of the network diagram, one important issue is the stability of the operation. In these power systems, failures caused by the instability will stop the power supply or divide the system into separate parts [7]. For this reason, stability problems should be studied meticulously in order to improve the system stability.

III. STUDY METHODS

1. Linear Analysis

Small-signal stability analysis with the method of eigenanalysis has proven as the most effective analysis tool for power system low-frequency oscillations. This method provides not only information related to the mechanism of destabilization but also those areas which have potential instability problems. In this method the system is first linearized about an operating point. Linear approximation of the original system, which is essentially non-linear, can be presented by the following state-space small signal equations [1, 12, 14, 18]:

$$\Delta\dot{x} = A\Delta x + B\Delta u$$
$$\Delta y = C\Delta x + D\Delta u \qquad (1)$$

where

Δx is the n-dimensional vector of state deviations,
Δy is the m-dimensional vector of output deviations,
Δu is the r-dimensional vector of input deviations,
A is the state matrix of size $n \times n$,
B is the input matrix of size $n \times r$,
C is the input matrix of size $m \times n$,
D is the feed forward matrix of size $n \times r$.

The state space representation of (1) can be shown as Fig. 1.

The eigenvalues of the $n \times n$ matrix A are n solutions $\lambda = \lambda_1$, λ_2, …, λ_n of (2)

$$\det(A - \lambda I) = 0 \qquad (2)$$

These eigenvalues may be real or complex numbers. The complex eigenvalues always occur in conjugate pair and are of the form $\lambda = \sigma \pm j\omega$ which denote an oscillation mode. From an oscillation mode the damping ratio and oscillatory frequency for that mode can be determined. The damping ratio of the oscillation is given by,

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

and the damped frequency of oscillation in Hertz is given by

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

The damping ratio determines the rate of decay of oscillation amplitude. If the real part of the eigenvalue is positive then damping ratio will be negative, which means the oscillation will persist with time, whereas the negative real part indicates positive damping which means the oscillation will has the tendency of decaying.

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

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

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

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:

$$P = \left[P_1 \; P_2 \; \dots \; P_n\right] \qquad (7)$$

where $P_i = [p_{1i}, p_{2i}, \dots, p_{ni}]^T = [\varphi_{1i}\psi_{1i}, \varphi_{2i}\psi_{2i}, \dots, \varphi_{ni}\psi_{ni}]^T$, φ_{ki} is the k^{th} entry of the right eigenvector of i^{th} mode and ψ_{ki} is the k^{th} entry of the left eigenvector of i^{th} mode. The element $p_{ki} = \varphi_{ki}\psi_{ki}$ is called the partition facto which is mathematically expressed as the multiplication of left and right eigenvector. It is a measurement of relative participation of the k^{th} state variable in 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 which 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.

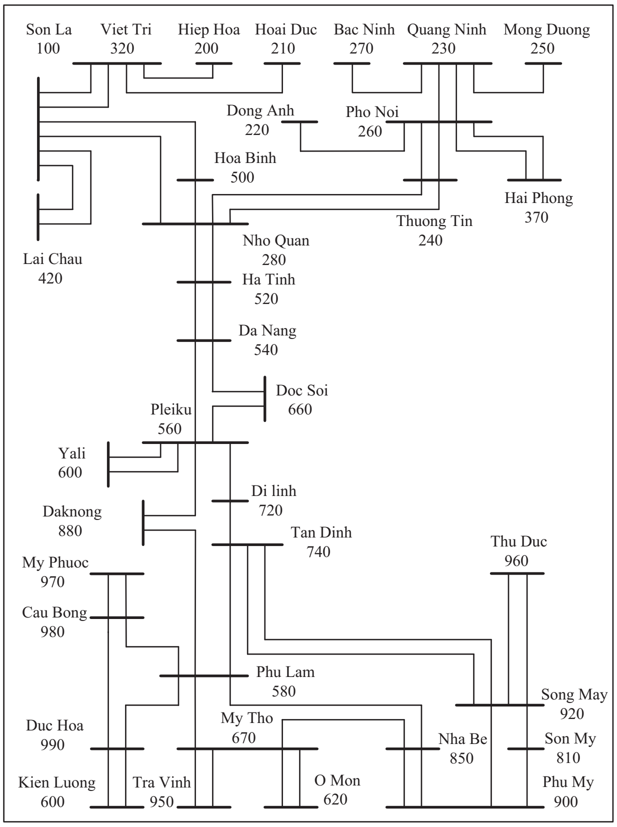

Fig. 2. One-line diagram of Vietnam power system.

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

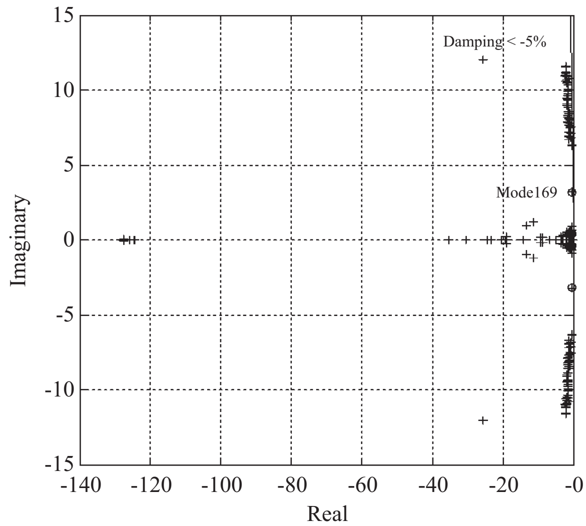

Fig. 3. Eigenvalues (denoted by "+") of the study system.

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

Mode	Eigenvalues	Frequency	Damping ratio
163, 164	$-1.178 \pm j\,6.701$	1.0665	0.1731
165, 166	$-0.471 \pm j\,6.367$	1.0134	0.0737
167, 168	$-0.427 \pm j\,6.286$	1.0004	0.0678
169, 170*	$-0.467 \pm j\,3.233$	0.5146	0.1429
171, 172	$-11.412 \pm j\,1.207$	0.1921	0.9944
173, 174	$-13.425 \pm j\,0.940$	0.1496	0.9975
175, 176	$-0.413 \pm j\,0.906$	0.1442	0.4152
177, 178	$-0.669 \pm j\,0.645$	0.1027	0.7199
179, 180	$-0.553 \pm j\,0.641$	0.1020	0.6530

* Critical inter-area mode

2. Time-Domain Simulation

Time-domain simulations are to be conducted for the identified critical mode by applying the typical and necessary disturbances to the system for making comparison with the results obtained from frequency-domain eigenanalysis.

In this paper, both time domain simulation and 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 method of eigenanalysis for finding the damping, frequency, and mode shape of the critical inter-area mode of oscillation. The installation of PSSs is to be investigated in detail. Time domain simulations will then be conducted to verify the effectiveness of PSSs [9].

IV. INTERAREA OSCILLATION WITHOUT PSS

First, the system eigenvalues are to be calculated from the original normal operating condition, with neither power system stabilizer or damping controller installed nor occurrence of contingency. All generators are modeled in detail of which the governors and exciters are represented by models in accordance with the actual generators of Vietnam power system. Fig. 2 shows the one-line diagram of the study 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 during heavy load operation in the rainy season and power is being transmitted from North to South through two EHV tie-lines. The power transfer is about 1185 MW in total which is summarized in Table 1. The system eigenvalues are then calculated and shown in Fig. 3 from which it is found that the study system is operating at a stable operating point.

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 which the low-frequency oscillation mode associated with a complex conjugate pair of eigenvalues $-0.467 \pm j\,3.233$ is a

Table 3. Eigenstructure of Inter-area Oscillation Mode.

Gen. Bus	Right Eigenvector		Participation Factors	MVA	MW	Area
	Mag.	Ang. (°)				
1010	0.92	2.05	0.297	267	160	North
1110	0.93	2.08	0.990	850	206	North
1520	0.92	3.02	0.295	267	220	North
2220	1.00	-3.45	0.459	396	286	North
2530	0.89	-6.28	0.951	833	458	North
2900	0.86	-4.72	0.329	420	344	North
3190	0.62	-9.81	0.446	1100	688	North
3720	0.84	-6.02	0.813	1100	688	North
4220	0.94	2.22	0.182	175	103	North
4610	0.62	179.91	0.469	1100	600	South
4630	0.66	-179.23	0.545	1100	440	South
6120	0.72	-179.71	0.589	1000	277	South
6230	0.63	-178.96	0.452	1000	600	South
6400	0.73	-176.18	0.400	298	100	South
6450	0.71	-175.83	0.303	237	100	South
6470	0.68	-176.06	0.257	292	100	South
6940	0.66	-178.62	0.615	1250	400	South
8140	0.63	-179.01	0.447	1000	600	South
8170	0.68	179.50	0.509	1000	44	South
9520	0.73	178.50	1.000	1666	124	South

mode having a relatively low oscillation frequency (0.5146 Hz). The damping ratio (ζ) of the mode is found as 0.1429 ($\zeta = -\sigma / \sqrt{\sigma^2 + \omega^2}$) 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.

The system behavior depends mainly on the two parameters, namely frequency and damping ratio. Besides that, the successive peak ratio describes also the tendency of decaying for the electromechanical oscillation of the system. It has been calculated as $\psi = \exp(-2\pi\zeta / \sqrt{1-\zeta^2}) = 0.4038$. This means that the amplitude of next successive oscillation is being reduced at a rate of 40.38% with time in comparison with the initial oscillation amplitude.

For more detailed analysis of the interaction between generators of the critical mode, the rotor mode shape as well as the corresponding participation factors are calculated and tabulated as in Table 3. Moreover, the mode shape is depicted as shown in Fig. 4. The remaining oscillation modes of system are stable, revealing local or intra-area behaviors, and hence are not to be discussed here. Meanwhile, the participation factors of modes tabulated in Table 3 are illustrated in Fig. 4.

From Table 3 and Fig. 4, 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, the eigenvector amplitudes of southern generators at the receiving end are lower than those of the generators in the northern group at the sending end, whereas the participation factors of generators between the two areas are not so different in values. Fig. 5 helps to visualize more easily with mode 169 and other modes. It also shows that most of the generators of the system are involved in the oscillation with a relatively high degree of participation. Particularly in the north, the generator of Huoi Quang (1110) hydro power plant and generator of Quang Ninh (2530) and Hai Phong (3720) thermal power plants have participation factors approximately equal to one as compared to the generator of Tra Vinh (9520) thermal power plant which is in the south and has a participation factor of unity magnitude.

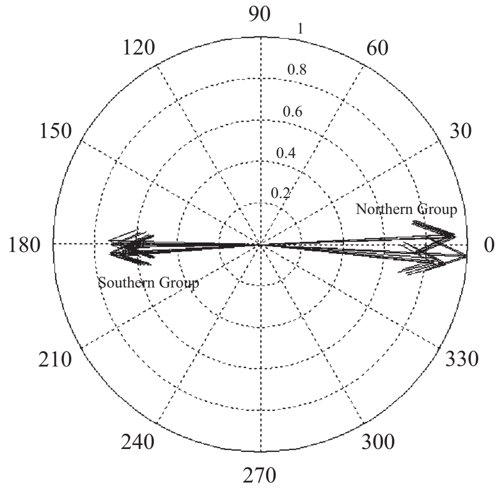

Fig. 4. Mode shape of the critical inter-area mode.

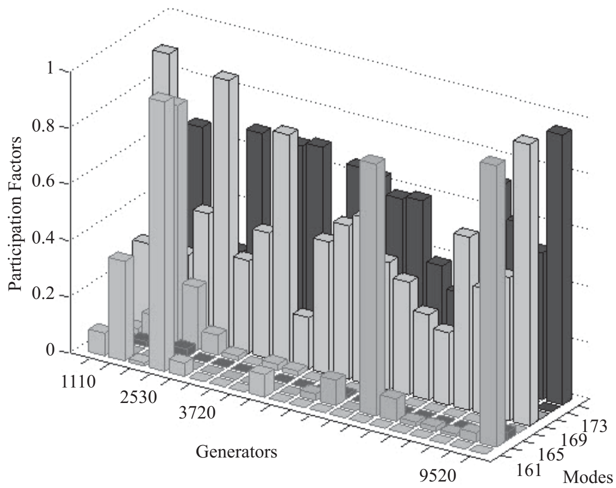

Fig. 5. Participation factors of generators speed.

In order to evaluate the effects of low frequency oscillation on the power system, time domain simulations have been conducted to verify the results from the linear analysis. A fault

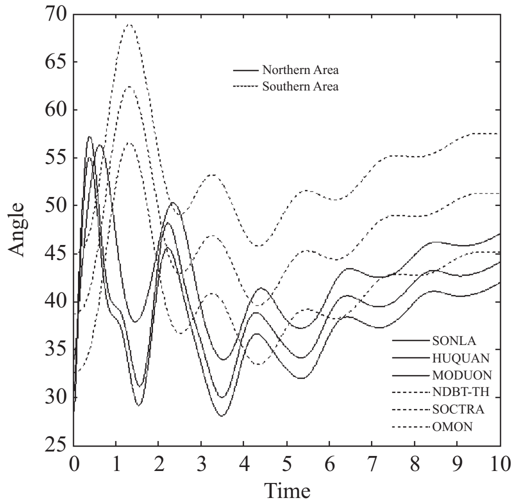

Fig. 6. Rotor angle oscillations under short-circuit at Hoa Binh.

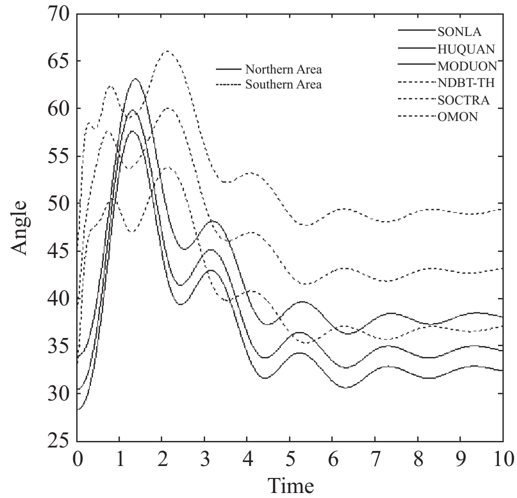

Fig. 8. Rotor angle oscillations under short-circuit at Phu Lam.

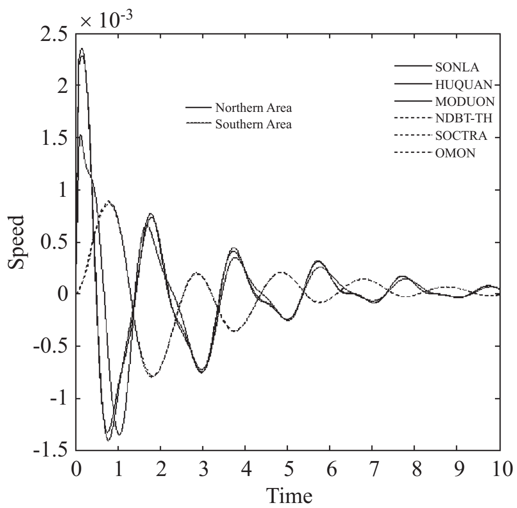

Fig. 7. Generator speed without PSS.

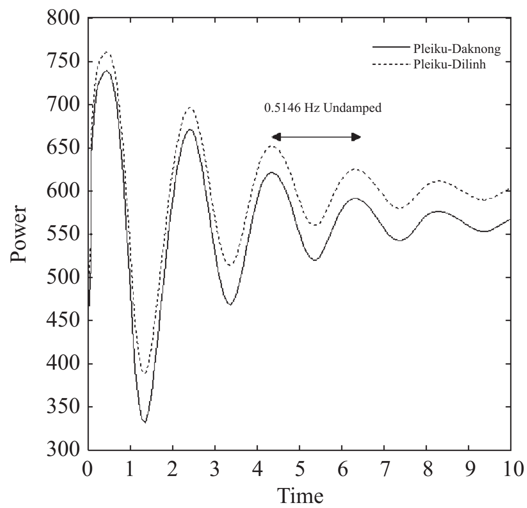

Fig. 9. Responses of active power on tie-line without PSS.

is applied to disturb the system on bus 500 of Hoa Binh hydro power plant with eight generating units (1520 and others) in the northern area and then cleared after 80 ms (4 cycles). It is also noted that, with 1920 MW in total, Hoa Binh hydro power plant is one of those power plants that have the largest capacity in the northern area. Prior to the disturbance, the generation power capacity of plants reaches 1581.5 MW. During the disturbance, the power is reduced to 512.9 MW. Fig. 6 shows the swings of rotor angles and Fig. 7 describes the speed of generators. As compared to those observations in linear analysis, we found that in time domain analysis the system is also stable after a few cycles of oscillation and oscillations in rotor angles are similar. In other word, generators in the northern area oscillate out of phase with generators in the southern area and these phenomena are highly consistent with those results obtained from the linear analysis.

To further clarify the above points, the second disturbance is applied on 580 Phu Lam bus at receiving end in the south. Fig. 8 depicts the response of the power system and Fig. 9 demonstrates the responses of active power on the tie-lines.

It can be easily observed from Fig. 9 that the active power of the tie-lines and the system damping is not sufficient since the oscillation persists up to 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 system with a longitudinal structure is likely to excite an electromechanical mode with poor damping.

V. INTER-AREA OSCILLATION WITH PSS

One of the most effective methods for damping the inter-area oscillations is to use the PSS [4, 6, 22]. In modern

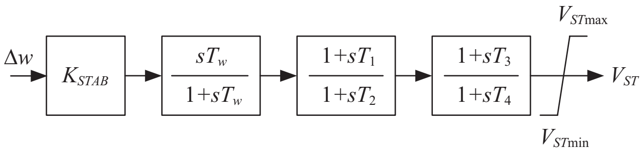

Fig. 10. Block diagram of PSS.

Table 4. Effect of PSS locations on the damping ratio.

Location(s)	Eigenvalue	Frequency	D. Ratio
(No PSS)	$-0.467 \pm j\,3.233$	0.5146	0.1429
1110	$-0.275 \pm j\,2.934$	0.4670	0.0936
9520	$-0.393 \pm j\,3.270$	0.5205	0.1193
1110, 9520	$-1.282 \pm j\,4.337$	0.6903	0.2836
1110, 2530, 9520	$-1.479 \pm j\,4.542$	0.7229	0.3097

power systems the PSS has been used widely to add damping to electromechanical oscillations in order to increase the power transfer in the network. The function of a PSS is to provide an additional input signal to the automatic regulator of the excitation system. When properly designed and tuned, a PSS can provide additional damping for the generator and has been widely adopted as a measure for improving power system stability. The conventional PSS was designed with the decentralized structure, using some local measurement, such as accelerating power, rotor speed deviation, or frequency deviation [10, 12, 13, 18].

The general structure of PSS consists of a washout block, a dynamic compensator block, a torsional filter and a limiter as shown in Fig. 10 [1, 12, 18]. The input signal of PSS used in this study system is rotor speed deviation. The washout is mainly provided to exclude steady-state bias and to avoid the controller response to the dc offsets in the signal.

From the viewpoint of inter-area oscillations, this washout time constant is chosen as 10 seconds. The dynamic compensator is made up of two lead-lag stages to provide necessary phase lead characteristics of the input signal in the range of frequency considered. Finally, the limiter is used to prevent the PSS from acting to counter the automatic voltage regulator.

The important issue here is the locations to install PSS(s). According to participation factors in Table 3, the generators have the largest participation in oscillation in both south and north areas will be considered. First, the generators of Tra Vinh (9520) and Huoi Quang (1110) are investigated based on the amplitude of participation factor for installing PSSs with parameters $T_1 = T_3 = 1.1542$, $T_2 = T_4 = 0.0828$, $K_{STAB} = 30$. Various combinations of PSS installation are considered and the results with eigenanalysis are summarized in Table 4.

From Table 4, it is observed that after PSSs are installed in both areas, the damping ratio of the system has been significantly increased, as compared with the condition with only single PSS installed in each area. Fig. 11 shows the variation of generator speeds with PSSs installed in both areas and

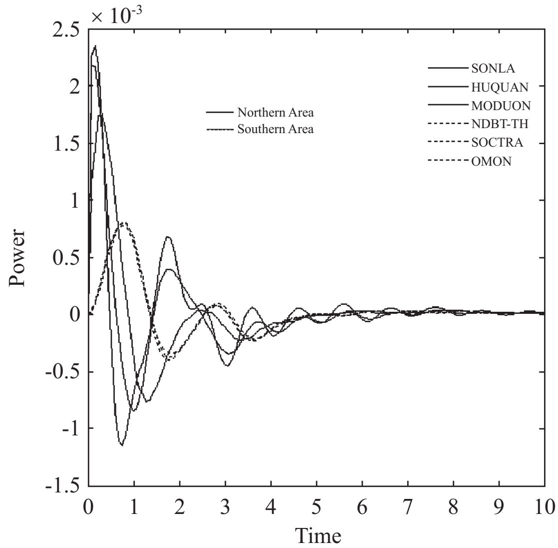

Fig. 11. Change of Generator speed with PSS installed in both areas.

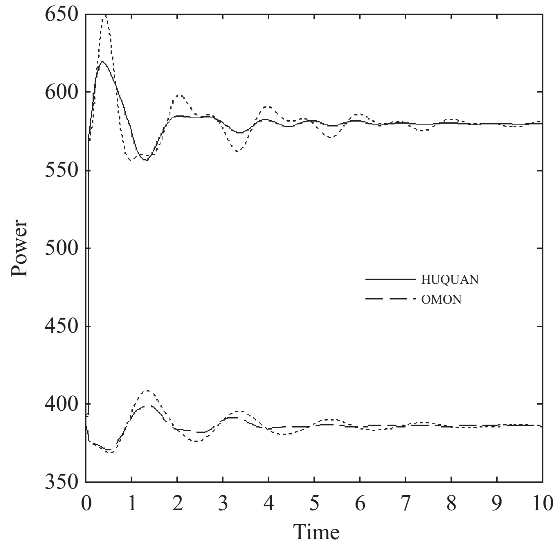

Fig. 12. Responses of active power on Huoi Quang and Omon power plant.

Fig. 12 shows the responses of electric power of Huoi Quang (1110) and Omon (6940) generators.

Fig. 13 and Fig. 14 shows the responses of active power on tie-line when PSSs are installed on Huoi Quang and Tra Vinh (9520), respectively. The responses of active power on tie-line when PSSs are installed in both areas are shown in Fig. 15 and Fig. 16. Comparing these results from Table 4 with the results obtained from time domain simulation it is found that the time domain responses are very consistent with those results in the frequency domain. It is demonstrated that in this case of a longitudinal power system, the effectiveness of PSSs to improve the damping of inter-area oscillation is significant.

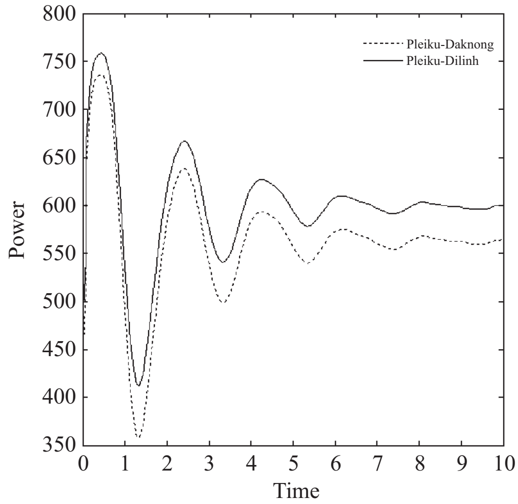

Fig. 13. Responses of active power on tie-line with PSS installed in the northern area (1110).

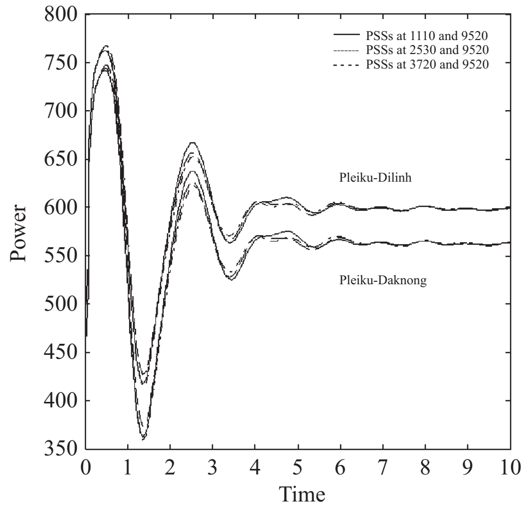

Fig. 15. Responses of active power on tie-line with PSS installed in both south and north areas.

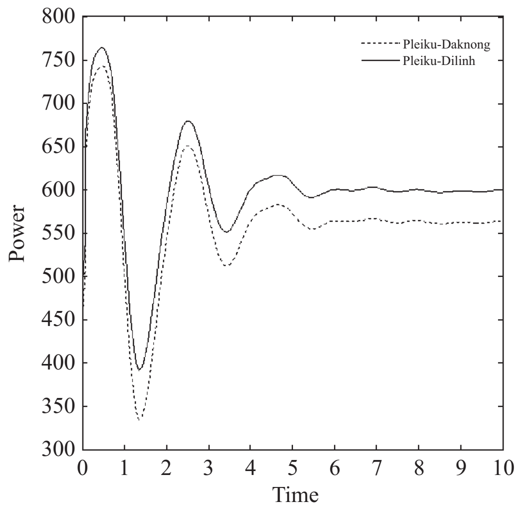

Fig. 14. Responses of active power on tie-line with PSS installed in the southern area (9520).

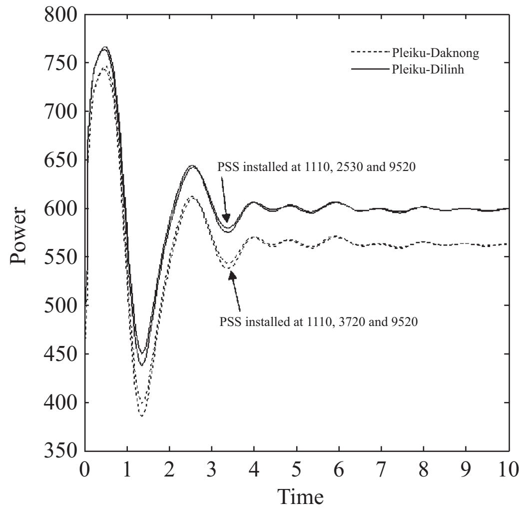

Fig. 16. Active power oscillations on inter-area transmission lines with PSS installed both areas.

VI. CONCLUSION

This paper focuses on the small-signal stability analysis of a longitudinal power system by using the method of eigenanalysis with emphasis on the critical inter-area mode of oscillation. The PSS is employed as a measure of improving the system stability. Locations of PSSs are specified according to the participation factors of generators in the inter-area oscillation mode. The results show that, by adding an appropriate number of stabilizers at both ends of the system, the power flows on the tie-lines, which play an important role in a unified multi-area system, can be transferred to remain in a stable state. The study results illustrate the effectiveness of PSS not only in damping inter-area mode but also contributing to the stability improvement of the study system.

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