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Optimal Allocation and Design of PSSs for Damping of Low-Frequency Oscillations in an Interconnected Power System

CHUN LIU
Tokyo Metropolitan University
1-2 Minami Oosawa, Hachioji,
Tokyo, Japan, 192-0397

RYUICHI YOKOYAMA
Tokyo Metropolitan University
1-2 Minami Oosawa, Hachioji,
Tokyo, Japan, 192-0397

MASACHIKA ISHIMARU
TEPCO Systems Corporation
19-15,Shinbashi 6-Cyome
Minato-Ku, Tokyo, Japan

Abstract: - Large extended power systems are often characterized by inter-area oscillations, usually spontaneous, which may be caused by small disturbances such as changes in load that take place continually. Inter-area oscillations have been the subject for studies in fields of operation, control, and devices by many power system utilities in Japan. To analyze and solve the problem of long-term poor-damping oscillation phenomena, a method is presented to find the best allocation and to design PSS for damping long-term poor-damping oscillation. The design method for multi-input PSSs is based on the single-machine-infinite-bus models. The designed PSSs have been verified in a Japanese power system standard model.

Keywords: - Power system stabilizer, Inter-area oscillation, Japanese power system, and Dynamic stability

1 Introduction

In these past several years, the deregulation and restructuring of electric power industries have been promoted in most of countries and then electrical power transactions have rapidly increased. In 1999, Japan also amended the Electricity Utility Act effective March 2000. This permitted participation of PPS (Power Producers and Suppliers) in the market. It deregulated the retail market partially, opening competition up to both domestic and foreign participants. This may result in a future power system which is much more complicated. The combined effect of various factors has made it more difficult to maintain system stability.

As well known, a voltage regulation in the power system could be necessary to improve transient stability and power system oscillation damping properties. So, each machine is generally equipped with an Automatic Voltage Regulator (AVR) and some of the most important ones, with Power System Stabilizers (PSSs). Power System Stabilizers are the first devices employed to add damping to power systems oscillations, acting through the systems excitation and modulating the field voltage Efd. Its washout block inhibits the PSS action when the power system has reached the steady state. When PSSs have been used in power system, it is required to look for an adjustment among them in order to obtain their optimal performance. Such purposes can be understood as a way to get the best efficiency of each PSS to add damping to the responses for the problematic modes, such as the inter-area mode for the diverse operating conditions. The major effort to have success in this intention is to calculate the best parameters of PSS, the time constants and gains, based on a systematic technique [1,2]. Much research has been done on PSS. Some research has focused on developing the PSS using multiple signal inputs such as the generator active power, the generator speed, and reactive power to maintain the linear characteristics toward the phase angle on the heavily-loaded transmission system, and the bus voltage for a long distance line from the generator [3,4]. There are two types of methods for developing PSSs, in which parameter optimization can be used to damp oscillation between interconnected systems. The first is to determine the parameters of PSS taking account of the system operations [5]. The second includes optimization methods using Artificial Neural Networks (ANN) [6] or genetic algorithms (GA) [7].

The use of PSS in power system has been both economical and successful in improving stability, and it is expected to be installed on many generators connected to the system. However, there are different kind of power plants connected to the power system, such as use fossil fuel, hydro and nuclear power plants, and also, the generators have different characteristics. In addition, there are pumped storage power plants in actual use. Whether a PSS is to be installed or not, depends in part of the power generator of type. If low-frequency oscillation is damped by installing an appropriate number of control devices at appropriate locations within the power system, further economic gain can be expected. For this reason, it is very important to have a method for determining the PSSs locations on a realistic power system model. To improve the power system stability of the entire system, a smaller number of PSSs have been designed and installed in a real-size system having inter-area mode oscillations.

The allocation of PSSs have been performed by using a system eigenvalue analysis, so that, the dominant generator with the greatest influence on both the power system stability and the low-frequency oscillation, becomes the candidate for PSS installation. The proposed approach designed a PSS for this dominant generator with the capability of damping the system mode. In the design, the approach used the frequency response method in the Single Machine Infinite Bus (SMIB) system model. In the application of the proposed method, the paper utilized the public domain East10 Model published by the Institute of Electrical Engineering of Japan, which is a standard model for the eastern part of the Japanese interconnection system[8].

2 Power System Model and Eigenvalue Analysis

Analyzing the system stability, the eigenvalues of a power system model can be determined, the characteristics of system dynamics can be outlined through these eigenvalues without a time domain simulations. Therefore, the eigenvalue analysis is effective in evaluating the system's stability for a multi-machine power system [11-12].

Equation (1) gives the energy balance between a mechanical input and an electrical output of this i-th generator:

$$M_i \frac{d^2}{dt^2}\delta_i = Pm_i - Pe_i - D_i\omega_i \qquad (1)$$

This active power output of the i-th generator in Eq. (1) is calculated as inEq. (2):

$$Pe_i = \sum_{j=1}^{n} E_i E_j Y_{ij} \cos\left(\theta_{ij} - \delta_i + \delta_j\right) \qquad (2)$$

Also, a damping constant of each generator is expressed as in Eq. (3):

$$D_i = e_i^2 \omega_{0i} \left\{ \frac{\left(X'_{di} - X''_{di}\right) T''_{doi}}{X'_{di} - X_{ei}} \sin^2 \delta_{0i} + \frac{\left(X'_{qi} - X''_{qi}\right) T''_{qoi}}{X'_{qi} - X_{ei}} \cos^2 \delta_{0i} \right\} \qquad (3)$$

For this purpose of the stability analysis, the damping constants are very important coefficients, since they affect the real part of system's eigenvalues. In a conventional approach on power system stability for multi-machine power system, network reduction has been performed for analysis and control purposes. The technique used here is able to deal with transmission lines, transformers, loads, and other equipments in the power system by using the per unit (p.u.) method. The system eigenvalues have been evaluated by considering the power system components and structures what is equivalent to say, that the eigenvalues reflect electrical distances between generators. Therefore, the power system stability has been evaluated in the multi-machine power system by considering the network configurations. The condition of that all eigenvalues are in the negative real half of the complex plane, has been well known for a stable system. Also, an eigenvalue existing nearby the imaginary axis, influences the system stability severely. Moreover, the imaginary parts of system eigenvalues dominate the system oscillation frequency in the time domain.

The power system dynamics can be analyzed by the system eigenvalues. The dominant root, which is the nearest located of the imaginary axis, can be identified. The power system stability can be achieved by applying an appropriate controller to allocate the dominant poles on the stable region of the complex plane. This paper proposes an approach to determine which generator should be equipped with a controller. First, the eigenvector ϕ_j and the eigenvalue λ_j of the system matrix A(nxn) are caculated by Eq. (4).

$$\Phi = \left[\phi_1 \mid \phi_2 \mid \cdots \mid \phi_n\right] \qquad (4)$$

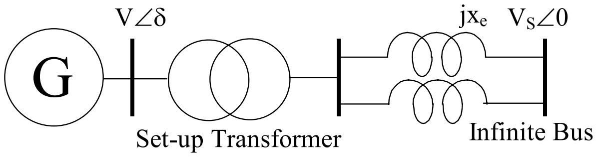


Fig. 1. Single-Machine-Infinite-Bus (SMIB) System Model.

3 Design of PSS based on the Frequency Response Method

A PSS for the local mode improvement is designed for Single Machine Infinite Bus system model shown in Fig. 1. The SMIB system model is considered to be in an infinite bus, this ignores power system networks. Therefore, the model does not take account of the electrical distances, for example: structures of transmission lines components and structures and other equipments. However, this model is suitable for the designing of PSS parameters, because the generator model has already been exhaustive studied.

Equation express the generators' dynamics for small-signal stability analysis in SMIB system after linearization, assuming constant the flux linkages of the field winding.

$$\frac{M}{\omega_0}s^2\Delta\delta+\frac{D}{\omega_0}s\Delta\delta+K\Delta\delta=0 \qquad (5)$$

If the damping constant D is a positive number (D>0), and the synchronizing coefficient K is also positive (K>0), the solution of the in Eq.(6) is not a positive real number, this system's dynamics are stable.

$$s=\frac{-D\pm j\sqrt{4K\omega_0 M-D^2}}{2M} \qquad (6)$$

Figure 2 shows a block diagram with a damping constant and synchronizing coefficient of a generator and an AVR with a PSS. $\Delta\delta$ is the synchronous torque of the generator electrical oscillation and $\Delta\omega$ is 90 phase lag of $\Delta\delta$ signal, and is a function of the damping torque. Therefore, each torque of the generator is respectively expressed and analyzed in the design and evaluation of PSS parameters. The constants K' and D' in the figure respectively mean the changes in synchronous torque and damping torque, due to the allocation of both an AVR and a PSS on the power system. The synchronous torque and damping torque of the combined generator and the excitation controller are defined as the synchronizing torque coefficient K_s and the damping torque coefficient K_d.

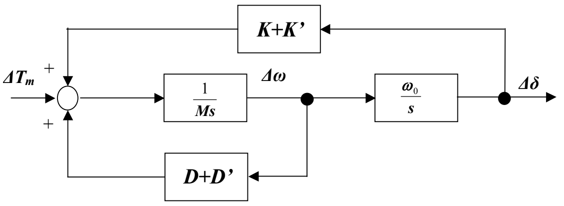


Fig. 2. Linearized Model of SMIB System.

4 Allocation of Power System Stabilizers in EAST10 Model

The optimal allocation and design of PSSs using the proposed approach have been appliedto a Japanese power system standard model, named 'East10 Model', released by the Institute of Electrical Engineering of Japan, as shown in Fig. 3.The EAST10 model consists of 47 buses and 100 branches including 22 transformers and 78 transmission lines. The power flow condition is assumed to be at peak demand of 80GW in the daytime. Ratings of generators operated in the power system are listed in Table 1. The system load characteristic is assumed to be constant current and constant impedance for active and reactive power, respectively.

The power system model is expressed by Eqs. (1) to (3). The eigenvalues of the controlled system are derived from these expressions and also the SMIB system. The obtained eigenvalues are shown in Fig. 4. First, the authors performed eigenvalue analysis to study the dominant modes in the power system. Dynamic stability of power system is most influenced by eigenvalues of weak damping, and inter-area power oscillations. Fig.4 shows two dominant eigenvalues and eigenvectors given by the analysis. The mode of the most weakest damping mode (eigenvalue : -0.08818+j4.66873) and lowest frequency mode (eigenvalue : -0.27368 +j2.65531)is chosen as a target install PSS. The results show that a Generator G_6 and G_{10} dominate the power system stability.

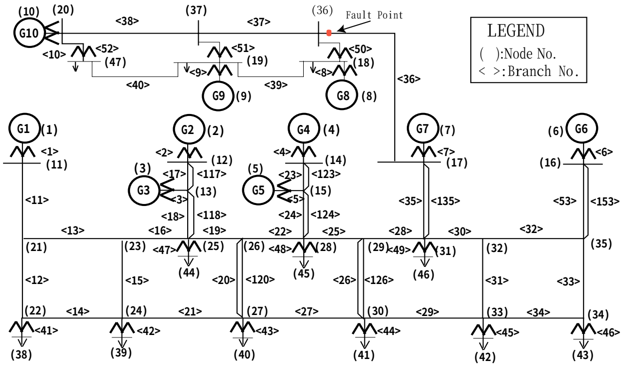
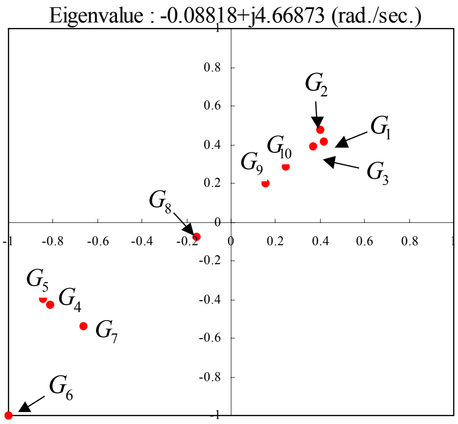


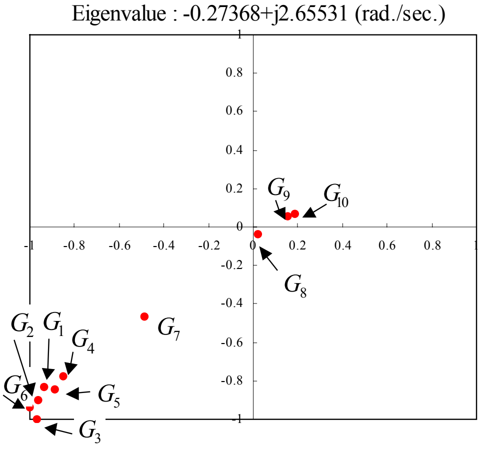
Fig. 3. IEEJ EAST10 Power System Standard Model.

Table 1. Rating of generators in EAST10 model

Generator	Rated MVA	Rated MW	Types
G1	8,240	7,000	fossil-fired
G2	12,940	11,000	nuclear
G3	7,060	6,000	hydraulic
G4	12,940	11,000	fossil-fired
G5	7,060	6,000	hydraulic
G6	12,940	11,000	fossil-fired
G7	12,940	11,000	nuclear
G8	8,240	7,000	fossil-fired
G9	8,240	7,000	fossil-fired
G10	5,880	5,000	fossil-fired



(a) A mode of the most weakest damping



(b) A mode of lowest frequency

Fig. 4. Power System Eigenvalues in EAST10 Model.

5 Design of PSS in the East10-Machine Model

For East10 model, the dominant generators that had the frequency oscillation damped most effectively and the generator which should be equipped with a PSS to improve the stability of the entire system have been identified. In this section, PSSs for these two generators are designed. The proposed approach for allocation and design of PSSs has been applied to the East10 Model. In the power system model, the low-frequency oscillation between 2 and 4 [sec.] per cycle has been observed by opening a single-line for 0.07 seconds nearby node No.36.

5.1 Design of PSS parameters for the Low-Frequency Dominant Generator

This section presents a PSS design the low-frequency dominant generator G10, assuming node No.20 to be the infinite bus. A block diagram of designed P Type PSS is shown in Fig. 5 and effects of the PSS on the system are shown in Fig. 6. The designed PSS has not had any influence on the synchronous torque coefficient (Ks), but for low frequency oscillation, the damping torque coefficient (Kd) has an increase up to 35 [p.u.]. Therefore, the PSS has an effective damping torque over the selected generator power oscillation.

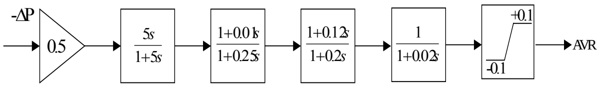


Fig.5. Δ P-type PSS Block Diagram for Low-Freq. Dominant Generator.

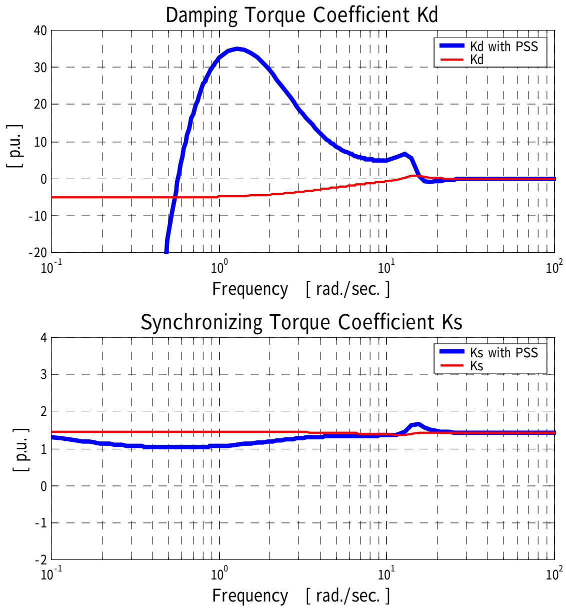


Fig. 6. K_d and K_S in Generator No. 10. with PSS.

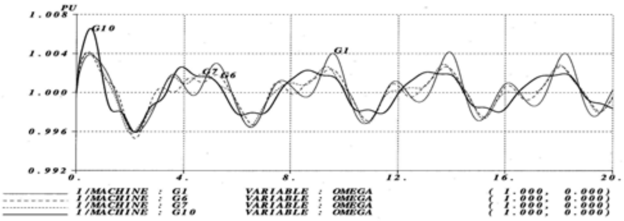


Fig. 7. Power System Oscillations without PSS.

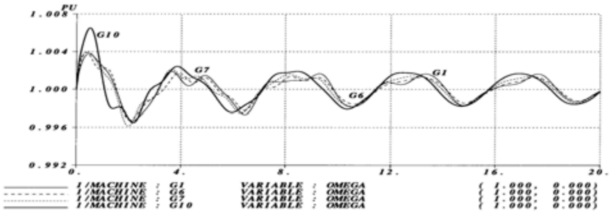


Fig. 8. P. S. Oscillations with Δ P-type PSS.

Comparing these results, the low-frequency oscillation of about 2.5 [sec.] per cycle of the generator speed G10 in Fig. 7 is damped by installing the designed PSS for it in the Fig.8, the low-frequency oscillations are removed from all the outputs in Fig. 7. These results indicate that the proposed approach can damp the low-frequency oscillation of the generator equipped with the excitation controller, which model has the dominant eigenvalue. Therefore, the approach proposed the low-frequency oscillation damping in a multi-machine power system, by designing and allocating a PSS suitably.

However, the power system stability of local mode has not been improved (Fig.8). These results indicate the need to equip the generator G6 with another PSS.

5.2 Design of Two-input PSS Parameters for the Stability Dominant Generator

A Two-input PSS for the generetor G6 is also designed utilizing SMIB system. A block diagram of a designed PSS for G6 is shown in Fig. 9, and the effects of introducing the PSS in the power system are shown in Fig. 10.

The maximum damping torque coefficient to regulate the EAST10 model is shows about 3 [p.u.] shown in Fig.10. Higher damping torque coefficient can make the system unstable. Therefore, the design of PSS parameters must be turned to improve the dynamics of the entire power system.

The designed PSS for the generator G6 has been verified for the EAST10 model. The low-frequency oscillation PSS has been installed for the generator G10. The damping torque coefficients shown in Fig. 10 are smaller than the one in the low-frequency oscillation PSS shown in Fig.6. However, the designed PSS succeeded in enhancing the power system stability. The results indicate that the design of PSS needs to consider the system configurations, i.e., the electrical distance between generators.

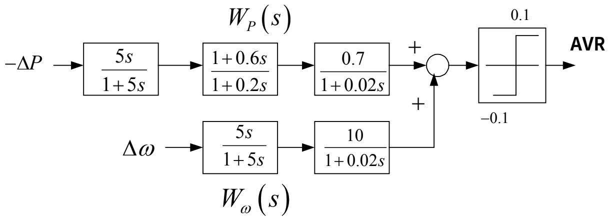


Fig. 9. P and ω-type PSS Block Diagram for Stability Dominant Generator.

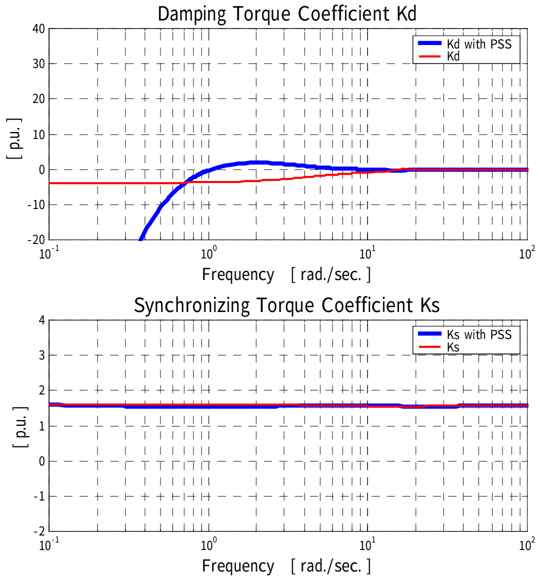


Fig. 10. K_d & K_S in G6 with P and ω-type PSS.

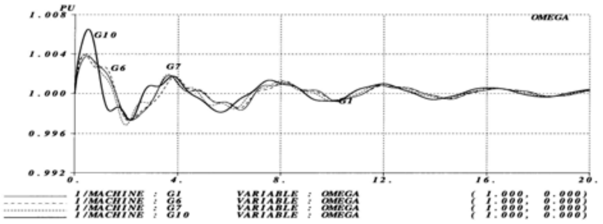


Fig. 11. P. S. Oscillations with P and ω-type PSS

The designed PSS for the generator G_6 has been verified for the EAST10 model. The low-frequency oscillation PSS has been installed for the generator G_{10}. The results indicate that the design of PSS needs to consider the system configurations, i.e., the electrical distance between generators.

6 Conclusions

In this paper, the allocation and design method of PSSs have been proposed to suppress the low-frequency oscillation of a power system. The proposed method was applied to the EAST 10 Model, which models the power system of the eastern area of Japan.

The proposed approach created an aggregated model of the multi-machine power system and performed the eigenvalue analysis. Among the eigenvalues, two dominant modes, i.e., low-frequency dominant mode and stability dominant mode have been identified and optimally allocated. These modes are intrinsic to the damping torque of each generator and the transmission system components and structure, i.e., the electrical distance between generators. The proposed approach has well succeeded in determining the dominant generator with the ability to influence these modes by evaluating the participation rates to the low-frequency dominant mode and the stability dominant mode.

This paper has examined a system by designing and configuring a PSS at a particular time of the day using the EAST10 Model. Since the power system changes over time, in the future we will need to examine a robust design and allocation of PSS that ensures stability at various times.

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