Abstract

In recent years, the problem of low-frequency oscillations of multi-machine power system has drawn much attention. The oscillations are primarily due to synchronous generator rotors swinging relative to each other. Supplementary excitation control systems, referred to as power system stabilizers, have been widely used in the electric power industry. This paper presents a hybrid power system stabilizer (HPSS) for the multi-machine power systems. The HPSS is comprised of a conventional power system stabilizer (CPSS) and a fuzzy power system stabilizer (FPSS). The CPSS is investigated to enhance the dynamic performance of the power system based on the conventional le control algorithm. The FPSS is designed to damp the unacceptable oscillations using the fuzzy logic technique. Finally, the efficiency of the proposed HPSS is demonstrated through simulations for a three-machine infinite-busbar power system.

Key Words: Power system stabilizer, fuzzy control, multi-machine power system, oscillations.
I. Introduction

Electric utilities are committed to provide a constant voltage and frequency to their customers. Following disturbances, short circuits and operating point variations, power systems are subject to unacceptable oscillations. To tackle this problem, one is fitting the generators with a feedback controller to inject a supplementary signal at the voltage reference input of the automatic voltage regulator (AVR) to damp the oscillations and improve the stability of power systems [1, 2]. This device is well known as a power system stabilizer. The PSS is now widely used in the electric power industry. With the interconnection of large electric power systems, the low frequency oscillations have become the main problem for power system stability. Recently, the coordination and control of PSS in order to improve the dynamic performance of a multi-machine system has received great attention [3-8]. Among these approaches, the conventional lead compensation type PSS has been the most popular with power utilities because of its fixed gains and operational simplicity [3]. Most of these works were concerned with the tuning of suitable stabilizer parameters to achieve satisfactory damping characteristics of the system. Unfortunately, tuning of the stabilizer parameters is not easy due to the constantly changing nature of the power systems. A series of papers based on pole-placement [5], optimal control [4, 6], linear matrix inequalities [7], and genetic algorithm [8] have been proposed. However, these design methods require complex design procedure and a large amount of computation time.

Most current techniques for designing control systems are based on a good understanding of the plant under consideration and its environment. However, in a number of instances, the plant to be controlled is too complex and the basic physical processes in it are not fully understood. To tackle this problem, fuzzy control using
linguistic information can model the qualitative aspects of human knowledge and reasoning processes without employing precise quantitative analyses [9]. It also possesses several advantages such as robustness, model-free, universal approximation theorem and rule-based algorithm. The fuzzy modeling rules are fuzzy If-Then rules describing the behavior of the system. The fuzzy control rules are fuzzy If-Then rules specifying appropriate control action. There have been many successful applications in using fuzzy control.

This paper presents a hybrid power system stabilizer (HPSS) design for a three-machine infinite-busbar power system. The HPSS is comprised of a conventional power system stabilizer (CPSS) and a fuzzy power system stabilizer (FPSS). The CPSS is investigated to enhance the dynamic performance of the power system and the FPSS is designed to damp the unacceptable oscillations due to synchronous generator rotors swinging relative to each other. Finally, a comparison between a CPSS and the developed HPSS is made. Simulation results demonstrate that the proposed HPSS can improve the performance to reduce the effects of synchronous generator rotors swinging relative to each other.

This study is organized as follows. A three-machine infinite-busbar power system and a CPSS are described in Section 2. Section 3 presents the algorithm of the HPSS. In Section 4, simulations are demonstrated to illustrate the effectiveness of the proposed design method. Finally, a conclusion is drawn in Section 5.

II. Multi-Machine Power Systems and Conventional Power System Stabilizer

For the power system stabilizer design, a linearized model is normally used. Consider an interconnected power system with its linearized equations expressed in the form [1, 3]

\[ \dot{x}_i = A_i x_i + B_i u_i + \sum_{j \neq i} A_{ij} x_j \]

\[ y_i = C_i x_i, \quad i = 1, 2, \ldots, N \]

\[ B_i = \begin{bmatrix} 0 & 0 & \ldots & 0 & b_i \end{bmatrix}^T, \]

\[ C_i = \begin{bmatrix} 0 & 1 & 0 & \ldots & 0 \end{bmatrix} \] (1)

where \( x_i \) is the state vector of the \( i \)th machine; \( u_i \) is the scalar supplementary excitation control signal of the \( i \)th machine; \( y_i \) is the scalar output of the \( i \)th machine; \( A_i, B_i \) and \( C_i \) are the system matrices of the \( i \)th machine; \( A_{ij} \) is the
coupled matrix from the $j$th machine to the $i$th machine, and $N$ is the total number of machines. A three-machine infinite-busbar power system has been considered in [3]. This power system consists of one thermal and two hydroplants which are mutually coupled and radially connected to an infinite-busbar as shown in Fig. 1. The original generator model must be generalized to take the interactions among the various machines into account. The result is a block diagram of the linearized multimachine system with the interaction constants $K_{ij} \sim K_{6ij}$, $i \neq j$ as shown in Fig. 2 [4]. For excitation control design, each machine can be modeled as a fourth order system with changes in the load angle ($\Delta \delta$); the rotor speed ($\Delta \omega$); the internal voltage of the generator ($\Delta E'$); and the field voltage ($\Delta E_{fd}$). The system matrices and the machines data and terminal conditions of the power system are given in Table 1 [3]. The input to this system is the change in the AVR voltage reference and its output is the change in the rotor speed. Following disturbances, short circuits and operating point variations, power systems are subject to unacceptable oscillations. The regulation objective is to design a power system stabilizer to suppress the oscillations and to damp them quickly. The well-known CPSS of each local stabilizer is chosen as a lead-type compensation form as [3]

$$K_i \left[ \frac{1+sT_{ii}}{1+sT_{2i}} \right]^2$$  (2)

where $K_i$, $T_{ii}$ and $T_{2i}$ are constants.

III. Design of Hybrid Power System Stabilizer

The CPSS in Section 2 has been widely used in the electric power industry, and many studies have shown that a well-tuned power system stabilizer can improve power system dynamic stability effectively [3]. The CPSS is quite popular for power systems due to its simplicity, however, the performance of these CPSS is degraded with the changes in the operation conditions, and the low frequency oscillation can not be damped quickly in multi-machine power systems.

In this study, to damp the low-frequency oscillations in the multi-machine power systems, a hybrid power system stabilizer (HPSS) is developed as shown in Fig. 3. The HPSS is comprised of a CPSS and a FPSS. The control law of the HPSS is taken of the following form:

$$u = u_{cs} + u_{fs}$$  (3)
where $u_{ci}$ is the CPSS and $u_{fi}$ is the FPSS. The CPSS is investigated to enhance the dynamic performance of the power system and the FPSS is designed to damp the oscillations relative to each synchronous machine. The fuzzy rules of the FPSS are in the following form:

Rule $i$: If $\Delta \omega$ is $F_{\Delta \omega}^i$ and $\Delta \dot{\omega}$ is $F_{\Delta \dot{\omega}}^i$, Then $u_{fi}$ is $\alpha_i$ (4)

where $\Delta \omega$ and $\Delta \dot{\omega}$ are the input variables of the fuzzy rule; $u_{fi}$ is the output variable of the fuzzy rule, and $F_{\Delta \omega}^i$, $F_{\Delta \dot{\omega}}^i$ and $\alpha_i$ are the linguistic terms characterized by their corresponding fuzzy membership functions $\mu_{F_{\Delta \omega}^i}$, $\mu_{F_{\Delta \dot{\omega}}^i}$, and $\mu_{\alpha_i}$, respectively. In this study, the membership functions $\mu_{F_{\Delta \omega}^i}$ and $\mu_{F_{\Delta \dot{\omega}}^i}$ are the triangular-typed functions, and the membership function $\mu_{\alpha_i}$ is a singleton function. The defuzzification of the fuzzy stabilizer output is accomplished by the method of center-of-gravity [9]

$$u_{fi} = \sum_{i=1}^{m} v_i \times \alpha_i / \sum_{i=1}^{m} v_i$$ (5)

where $v_i$ is the firing weight of the $i$th rule and $m$ is the number of fuzzy rules.

**IV. Simulation Results**

The stabilization of the three-machine power systems previous studied in Ref. 6 is considered to illustrate the effectiveness of the developed techniques. The system response to a step disturbance input at the AVR voltage reference is simulated with and without stabilizer at operating condition. The simulation responses to a 5% step disturbance input at AVR voltage reference are simulated shown in Fig. 4. From Fig. 4, the natural system response (without any stabilizer) is unstable. This will lead to unsafe operation of the system for occurring to the danger to the operators. To tackle this problem, the CPSS is used in the electric power industry. The parameters for CPSS are selected as follows: [3]

$$K_1 = 24.48, \quad T_{11} = 0.226, \quad T_{21} = 0.055,$$
$$K_2 = 9.53, \quad T_{12} = 0.418, \quad T_{22} = 0.055,$$
$$K_3 = 20.05, \quad T_{13} = 0.169, \quad T_{23} = 0.055.$$ (6)

These parameters of CPSS are found by the eigenvalues design method to achieve good transient response. However, to achieve better transient response and oscillation regulation, these parameters must be re-constructed by time-consuming trial-and-error procedure. The simulation responses to a 5% step disturbance input at
AVR voltage reference are simulated shown in Fig. 5. From Fig. 5, the simulation results show that the low-frequency oscillations appear.

To tackle this problem, the HPSS is designed to damp the oscillations relative to each synchronous machine. For the FPSS, the fuzzy rules are given in Table 2. The fuzzy rules can be constructed by the sense that $\Delta \dot{\omega}$ and $\Delta \dot{\phi}$ will approach to zero with short time and without large overshoot. The fuzzy labels used are negative big (NB), negative medium (NM), negative small (NS), zero (ZO), positive small (PS), positive medium (PM) and positive big (PB). The simulation responses to a 5% step disturbance input at AVR voltage reference are simulated shown in Fig. 6. Simulation result shows that a stabilizer can considerably improve the regulation performance of a step disturbance.

V. Conclusion

A hybrid power system stabilizer (HPSS) for multi-machine power systems is proposed in this paper. The hybrid power system stabilizer is comprised of a conventional power system stabilizer (CPSS) and a fuzzy power system stabilizer (FPSS). The simulation results show that the proposed HPSS is more effective in improving the performance of the system than the CPSS. The low frequency oscillations are damped out quicker than that using the CPSS. Thus, the HPSS is effective for multi-machine power systems.

Acknowledgement

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References


Table 1. The three-machine power system data.

<table>
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<tr>
<th>machine</th>
<th>(x_d)</th>
<th>(x_q)</th>
<th>(x'_d)</th>
<th>(T'_d)</th>
<th>(H)</th>
<th>(K_A)</th>
<th>(T_A)</th>
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<td>G1</td>
<td>1.68</td>
<td>1.66</td>
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<td>0.33</td>
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<tr>
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<td>0.20</td>
<td>7.76</td>
<td>4.63</td>
<td>50</td>
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Table 2. Fuzzy rules \(\alpha_i\) for FPSS.

<table>
<thead>
<tr>
<th>(\Delta \omega, \Delta \omega^*)</th>
<th>NB</th>
<th>NM</th>
<th>NS</th>
<th>ZO</th>
<th>PS</th>
<th>PM</th>
<th>PB</th>
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<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
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<tr>
<td>PM</td>
<td>-0.002</td>
<td>0.000</td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>PS</td>
<td>-0.003</td>
<td>0.002</td>
<td>0.000</td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>ZO</td>
<td>-0.005</td>
<td>0.003</td>
<td>-0.002</td>
<td>0.000</td>
<td>0.002</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>NS</td>
<td>-0.005</td>
<td>0.005</td>
<td>-0.003</td>
<td>-0.002</td>
<td>0.000</td>
<td>0.002</td>
<td>0.003</td>
</tr>
<tr>
<td>NM</td>
<td>-0.005</td>
<td>0.005</td>
<td>-0.005</td>
<td>-0.003</td>
<td>-0.002</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td>NB</td>
<td>-0.005</td>
<td>0.005</td>
<td>-0.005</td>
<td>-0.005</td>
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Fig. 1. Three-machine infinite-busbar power system.

Fig. 2. Block diagram for a three-machine power system.

Fig. 3. Scheme of the HPSS for a power system.
Fig. 4. The system responses without controlled.

Fig. 5. The system responses using CPSS.

Fig. 6. The system responses using HPSS.