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Improvement of low frequency oscillation damping by allocation and design of power system stabilizers in the multi-machine power system

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ABSTRACT

Some of the earliest power system stability problems included spontaneous power system oscillations at low frequencies. These Low-Frequency-Oscillations (LFOs) are related to the small-signal stability of a power system and are harmful to obtain the maximum power transfer. A contemporary solution to this problem is the addition of Power System Stabilizers (PSSs) to the automatic voltage regulators on the generators in the power system. In this paper, allocation of PSSs in an interconnected power system with inter-area modes has been determined by eigenvalue analysis, and PSSs for the allocated generators have been designed by a frequency response method. Furthermore, for designing PSSs by the frequency method, this paper proposed a new linear power system model which can consider both local and inter-area oscillations of the power network. Designed PSSs based on the proposed model improved damping performance of PSSs which have been designed by the Single-Machine-Infinite-Bus (SMIB) model. The stabilization performance of the designed PSSs (by the proposed approach and linear power system model) on the LFO modes have been verified in two multi-machine power system standard models (IEEE 9-bus and 14-bus).

1. Introduction

Two of the most important design criteria for multi-machine power systems are transient stability and damping of electromechanical modes of sustained oscillation [1–6]. Stability of power systems is one of the most important aspects in power electrical system operation. This is because the power system must maintain frequency and voltage levels in the desired level, under any disturbance, such as a sudden increase in the load, loss of one generator or switching out of a transmission line, during a fault [7].

With the increase of the scale and complexity of the interconnected power networks, the problems on the various potential power oscillations, which have the significant impact on the system stability and security operation, have been drawn more and more attention [8–10].

Power system oscillations were first reported in northern American power network in 1964 during a trial interconnection of the Northwest Power Pool and the Southwest Power Pool [11]. Two types of oscillation phenomena can occur on the present power system. One is where the oscillation of one generator at a specific power plant has an influence on the system. This type of oscillation is called local-mode oscillation and its behavior is mainly limited to the local area in the vicinity of the power plant, and it seldom influences the rest of the system. It has been known that the local oscillation is likely to occur when power is transmitted over long-distance transmission lines from a power plant at a remote location. This type of system can be accurately modeled using the Single-Machine-Infinite-Bus (SMIB) system model [12]. The other case has been known as inter-area mode oscillation. This is the case where the low-frequency oscillation is maintained between sets of generators in an interconnected power system. The simplest type of low-frequency oscillation in the inter-area mode is between two interconnected areas. The inter-area mode oscillation has a long history [7]. As a classic oscillation mode, there are relative mature technologies and devices such as kinds of power system stabilizers equipped as a part of the additional excitation system of machine unit to provide the efficient damping ratio to suppress the local oscillation. So far, PSS has been used as an effective and economical facility to tackle the problem [13]. In [14], it has been shown that the appropriate selection of PSS parameters can achieve satisfactory performance during system upsets.

The use of PSS in power system has been both economical and successful in improving the power system stability, and is expected to be installed on many generators connected to the system. However, there are different kinds of power plants connected to the

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Nomenclature

S_n	power rate
V_n	voltage rate
f_n	frequency rate
x_l	leakage reactance
r_a	armature resistance
X_d	d-axis synchronous reactance
X'_d	d-axis transient reactance
X''_d	d-axis sub-transient reactance
T'_{do}	d-axis open circuit transient time constant
T''_{do}	d-axis open circuit sub-transient time constant
X_q	q-axis synchronous reactance
X'_q	q-axis transient reactance
X''_q	q-axis sub-transient reactance
T'_{qo}	q-axis open circuit transient time constant
T''_{qo}	q-axis open circuit sub-transient time constant
M	inertia constant
D	damping coefficient
δ	rotor angle
ω	rotor speed
e_{1q}	q-axis transient voltage
e_{1d}	d-axis transient voltage
e'_{1q1q}	q-axis sub-transient voltage
e'_{2d2d}	d-axis sub-transient voltage
P_m	mechanical power
V_f	field voltage
V_{ref}	reference value of the generator field voltage
U_{PSS}	stabilizing signal
V_b	infinite bus voltage
g	conductance
I_p	active current
P_n	active power
b	susceptance
I_Q	reactive current
Q_n	reactive power

power system, such as fossil fuel, hydro and nuclear power plants in which generators have different characteristics. In addition, there are pumped storage power plants in actual application. Whether a PSS is to be installed or not depends, in part, on the type of power generation. If low-frequency oscillation is damped by installing an appropriate number of control devices at appropriate locations within the power system, even further economic benefits can be expected. For this reason, it is very important to have a method for determining the locations of PSSs in a realistic power system model. To improve the power system stability of the entire system, a smaller number of PSSs has been designed and installed in a real-size system having inter-area mode oscillations [15].

In this paper, allocation of PSSs has been performed by using an eigenvalue analysis on the system, 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 utilized a PSS for this dominant generator with the capability for damping the system mode. Moreover, in this paper, a new model based on linear model of the dominant generator has been proposed for designing PSS in which both local and inter-area mode oscillations of the power system have been considered. This means that after finding the dominant generator in the power system for supplying the PSS via eigenvalues analysis, the PSS has been designed based on the proposed linear model of the dominant generator regarding the oscillation modes of power system (local and inter-area modes). The proposed linear model is called Developed-Single-Machine-Infinite-Bus (DSMIB) system. As a result, this paper has been shown that damping performance of the designed PSS based on the proposed approach and proposed power system model has been improved in comparison with the designed PSS based on the SMIB model. In the application of the proposed method, the paper utilized the standard IEEE 9 bus system [16] for investigating the proposed approach in details and IEEE 14 bus system for validating the proposed approachy [17].

2. Eigenvalue analysis of multi-machine power system

In an analysis of the system stability, eigenvalues of a power system model have been derived and evaluated. Through analyzing eigenvalues, characteristics of system dynamic states are understood without a time domain simulation. Hence, the eigenvalues analysis is efficient in appraising the system stability for a multi-machine power system model [18,19]. The system eigenvalues have been evaluated with respect to the components of the power grid; that is to say, the eigenvalues with regard to electrical distances between generators. Therefore, the power system stability has been evaluated in the multi-machine power system with respect to the network formations. A situation, in which all eigenvalues are in the negative real half of the complex plane, has been specified for a stable system. In addition, an eigenvalue existing in the vicinity of the imaginary axis, impact the system stability significantly. Furthermore, the imaginary parts of system eigenvalues dominate the system oscillation frequency in the time domain.

2.1. Small signal modeling

The act of a normal power system can be described by a set of first order nonlinear ordinary differential equations and a group of nonlinear algebraic equations. It can be written in the following form by using vector-matrix notation:

$$\dot{x} = f(x,u), \quad y = g(x,u) \tag{1}$$

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{bmatrix}, \quad g = \begin{bmatrix} g_1 \\ g_2 \\ \vdots \\ g_m \end{bmatrix} \tag{2}$$

where x is the vector of state variables, such as rotor angle and speed of generators. The column vector y is the vector of outputs, and g is a vector of nonlinear functions relating state and input variables to output variables. Although power system is nonlinear, it can be linearized by small signal stability at a certain operating point. Suppose that x_0 and u_0 are the equilibrium points of this power system, then based on direct feedback, it can be expressed as the following standard form [20]:

$$\Delta\dot{x} = A\Delta x + B\Delta u, \quad \Delta y = C\Delta x + D\Delta u \tag{3}$$

where Δx, Δy, Δu, A, B, C and D are the state vector of dimension n, the output vector of dimension m, the input vector of dimension r, the state or plant matrix of size $n \times n$, the control or input matrix of size $n \times r$, the output matrix of size $m \times n$, and the (feed forward)