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Coordinated design of PSS and TCSC to mitigate interarea oscillations

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ABSTRACT

Thyristor controlled series compensator (TCSC) as a promising series flexible AC transmission system (FACTS) device is generally used for controlling the real power flow in transmission lines. It can increase the system stability as the complementary functionality by minimizing the power oscillations. The effectiveness of TCSC in its primary and supplementary applications depends on the selection of its optimal location and defining a proper input signal. In this paper, a new method based on the active power sensitivity approach is applied to find the optimal location of TCSC. In addition, Hankel singular values (HSVs) and right half plane-zeros (RHP-zeros) analyses have been proposed to find the most appropriate stabilizing input signal for the supplementary functionality of TCSC to damp out the interarea modes of oscillation. Finally, the optimal design of power oscillation damper (POD) and simultaneous coordinated design of power system stabilizer (PSS) and POD are implemented separately in a large-scale power system. The tuning problem of POD-TCSC parameters as well as the coordinated POD-TCSC & PSS are converted to a multi-objective optimization problem and solved using particle swarm optimization (PSO) algorithm. The performance of the proposed method has been validated through eigenvalue analysis and nonlinear time domain simulation in a 16-machine 68-bus test system. The simulation results show a satisfactory robust performance with an excellent capability in damping of local and interarea power oscillations.

Introduction

Power systems are usually large non-linear systems, which are often subjected to low frequency electromechanical oscillations. One of the most important kinds of these oscillations involving many generators is interarea oscillations (with frequency range of 0.1–1 HZ) [1]. The reliable and secure operation of a power system is highly depending on damping of these oscillations. System operating conditions including the level of generation, the power flow in tie-lines, network topology and system strength greatly affect interarea oscillations damping. The conventional lead-lag compensators have been widely used as the power system stabilizers (PSSs) to damp out low frequency oscillations (LFOs). However, in various cases, because of some limitations in the structure of generators and their exciter system, damping of LFOs using just a single PSS does not lead to a satisfactory response. Beside PSSs, flexible AC transmission system (FACTS) devices are too employed to damp out LFOs and enhance small signal stability. They increase the controllability of power flows and voltages that leads to improvement of stability of existing systems. The FACTS-based power oscillation dampers (PODs) effectively damp out the encountered interarea oscillations [2]. Thyristor controlled series capacitor (TCSC) is a series FACTS device that can be used to control power flows, damp power oscillations and mitigate sub synchronous resonance (SSR). In addition, the TCSC is an economic FACTS device to release active power capacity of transmission lines as its primary application. Furthermore, when a TCSC is installed in the tie-line of a weakly interconnected power system and equipped with a complementary POD, it can damp interarea oscillations as its secondary application. In order to maximize the benefits of TCSC in both defined primary and secondary applications, firstly, its optimal location should be determined. Then, the best input signal for the POD-TCSC has to be selected and finally, the optimal tuning of POD-TCSC parameters or coordinated design of the POD-TCSC with the installed PSSs must be studied accurately.

In literature, the optimal placement of TCSC in power systems has been reported considering different aspects. A method based on the real power performance index and reduction of system

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Var loss to obtain the optimal location of TCSC has been suggested in [3]. In [4], the optimal allocation of TCSC using residue method has been investigated to achieve suitable damping for the most critical oscillation modes. In [5], in the studied test system, the TCSC is installed in one of the tie-lines between two important areas in order to regulate the power flow and increase the dynamic stability limits. In this paper, a new method based on the active power sensitivity approach has been proposed to find the best location of TCSC in a power system. The proposed method considers the improving power transfer criterion and available transfer capability.

To damp out electromechanical oscillations satisfactorily, the best feedback input signal of POD-TCSC should be selected. In [6] the residue (controllability/observability) associated with many input/output combinations is calculated to find the best input signal of controller. A larger residue will result in a larger change in the corresponding mode. Therefore, the input signal, which has the largest residue (for the desired mode) is selected as a proper feedback signal of POD. In [7], a probabilistic method (minimum variance of the modal residue) has been proposed to select the input signal of POD-TCSC. Authors in [8] have proposed the Hankel singular values (HSVs) and right half plane-zeros (RHP-zeros) analyses to choose a suitable feedback signal for the static Var compensator (SVC)-based POD. The RHP-zeros technique investigates various input–output combinations of transfer function zeros in the both pre-fault and post-fault conditions whereas the HSV method uses the concept of joint controllability and observability indices. Although the HSV method cannot connect the controllability and observability of a particular mode [9], but the results obtained using this analysis are reliable. In this paper, using fundamental design limitations, and controllability and observability concepts, the most adequate pair of input–output signals (could be local or global signals) of the controller is identified.

Various methods have been suggested in literature to tune the FACTS-based POD parameters [10–14]. Authors in [10] have proposed simulated annealing as a heuristic-based method to tune the PSS and TCSC parameters in a way that the most critical oscillation modes of system are shifted to the stable area in the complex plane. Coordination of SVC and PSS performances using bacterial foraging optimization algorithm (BFOA) is introduced in [11]. The parameters of PSS and SVC-based POD are selected to minimize the integral of time multiple absolute error (ITAE) as an objective function. In [12] a single input single output (SISO) feedback controller has been designed for the TCSC to improve damping of interarea oscillations under the multiple operating points. To ensure the robustness of designed controller, a multi-objective optimization problem in terms of regional pole placement and H_2 performance is considered. The multi-objective criterion is described by a set of bilinear matrix inequalities (BMIs) regarding different system models at multiple operating points. Authors in [13] have proposed a linear quadratic Gaussian (LQG) technique to design a robust TCSC controller to damp out LFOs. In addition, a residue technique is used to find the best location of TCSC. The observability index is implemented to find the proper input signal of TCSC-based POD. The POD design using hybrid fuzzy logic controller associated with conventional proportional integral (PI) controller is presented in [14]. This fuzzy controller changes the proportional gain of PI controller depending on the error and its rate of change. In this paper, the following modifications have been performed:

(i) A new method considering numerical analysis has been proposed to optimally locate the TCSC in a large scale power system.
(ii) The proposed selection criterion analyzes fundamental limitations of the system without designing the controller, the capability of a particular choice of local or global signals to damp out oscillation modes. The study of the controllability and observability characteristics allows determining the input–output pair that will require less control effort to achieve damping of oscillations.
(iii) Optimal tuning of POD-TCSC parameters and coordination of POD-TCSC and PSS is done in order to damp the oscillation modes.

The effectiveness of the proposed coordinated POD-TCSC and PSS is demonstrated through the eigenvalue analysis and time-domain simulation in MATLAB and power system analysis toolbox (PSAT) software.

Power system model

Generally, power systems can be modeled by a set of nonlinear differential algebraic equations (DAE), as follows [15]:

$$\begin{aligned} \dot{x} &= f(x,y,u) \\ 0 &= g(x,y,u) \\ w &= h(x,y,u) \end{aligned} \tag{1}$$

where
- x is the vector of state variables;
- y is the vector of algebraic variables (e.g. bus voltage magnitudes and phase angles);
- u is a set of controllable parameters (e.g. controller reference signals);
- w is a set of output variables (e.g. line current flows);
- f is a set of differential equations that represents a system and a controller;
- g is a set of algebraic equations that represents the transmission network power flows;
- h is a set of equations that represents output variables (e.g. measurements), such as line power flows and rotor angle speeds.

Linearizing the Eq. (1) at an equilibrium point (x_0, y_0, u_0), yields:

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \\ \Delta w \end{bmatrix} = \begin{bmatrix} F_x & F_y & F_u \\ G_x & G_y & G_u \\ H_x & H_y & H_u \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta u \end{bmatrix} \tag{2}$$

where $F_i = \nabla_i^T f,\ G_i = \nabla_i^T g,\ H_i = \nabla_i^T h$, for $i \in \{x, y, u\}$

By eliminating the algebraic equation from system equations, the state matrix A is computed as:

$$A = F_x - F_y G_y^{-1} G_x \tag{3}$$

and the state-space representation of the Eq. (2) is:

$$\begin{aligned} \Delta\dot{x} &= A\Delta x + B\Delta u \\ \Delta w &= C\Delta x + D\Delta u \end{aligned} \tag{4}$$

where the input matrix $B = F_u - F_y G_y^{-1} G_u$; the output matrix $C = H_x - H_y G_y^{-1} G_x$ and $D = H_u - H_y G_y^{-1} G_u$.

Test system

A reduced model of the New England test system (NETS) and the New York power system (NYPS) as a large-scale power system is considered in this paper (NETS–NYPS). The schematic diagram of NETS–NYPS is shown in Fig. 1. This system includes 16 machines and 68 buses. The first eight machines have slow excitation system