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Optimal coordinated design of UPFC and PSS for improving power system performance by using multi-objective water cycle algorithm

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ABSTRACT

This paper presents an optimal design for simultaneously locating unified power flow controller (UPFC) and power system stabilizer (PSS). The parameters of their controllers are also tuned coordinately to enhance the power system stability. A mixed integer nonlinear problem is obtained for the design procedure due to the characteristics of selected objective functions. A new population-based meta-heuristic algorithm, called water cycle algorithm (WCA) is used to solve this problem. The best Pareto optimal set is also attained by defining this problem as a multi-objective function. The simulations results on IEEE 39-bus power system confirm the efficiency and the superior performance of the proposed method when compared with other algorithms.

Introduction

Dynamic stability concerns small amplitude oscillations which can be initiated by sudden changes in the load or the network. In a large interconnected power system these oscillations occur at low frequency in the range of 0.2–2.5 Hz [1] and can be particularly troublesome to damp out. This may impose severe limitations on the power transfer capability of the system. Power system stabilizers (PSSs) are widely used as supplementary controllers to improve this situation by increasing system damping [1,2]. In this regard, determining the locations of PSSs in order to have the best performance is important [3].

Flexible AC transmission system (FACTS) devices are commonly employed to increase the ability of the power flow control in power systems [4]. Among these devices Unified power flow controller (UPFC) is able to control voltage, impedance and phase angle in the transmission line [5] at the same time. It has been also proved that UPFC has a remarkable effect for the enhancement of the power system damping, especially for inter-area oscillations by employing a stabilizing signal in its control system [6].

The first and most important step of using the UPFC in a power system is the selection of its location and this has been the subject of many researches in this field [7–10]. A coordinated aggregated-based particle swarm optimization algorithm is used in [7] to obtain the optimal location and size of UPFC in a market-based power system by minimizing a multi-objective function of cost and power flow. Another multi-objective optimal location of UPFC is done in [8] for satisfying the power loss and loadability constraints in power system by using the Pareto optimal solution. Determining the optimal location and size of UPFC is represented in [9] to enhance the dynamic stability by using a hybrid technique including an Artificial Bees Colony (ABC) algorithm and gravitational search algorithm (GSA). In [10] a hybrid chemical reaction technique is applied to obtain the optimal parameter setting and the location of UPFC by minimizing the cost of UPFC installation, loss of transmission and voltage deviation.

As mentioned above, in addition to the primary objective of using UPFC which includes the power flow control, it can be also used to enhance the power system damping with PSS [11]. However, the simultaneous usage of both these devices without the predetermined coordination may have negative effect [11]. Therefore, many studies have been recently developed to coordinate the design of both PSS and UPFC controllers by using different techniques [11–13]. Coordinated design of UPFC and PSS was developed in [11] to obtain their control parameters by using MPSO algorithm. In [12] the optimal location and control parameters of both PSS and UPFC are obtained by using genetic algorithm. The optimization problem is defined as one objective function to optimize the damping ratio of the electromechanical modes. A decentralized modal control method according to pole placement planning is used in [13] for coordinated design of PSS and FACTS

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controllers to find their control parameters for enhancing the stability of New England 39-bus power system.

In all papers published so far, as of our best knowledge, the locations of UPFC and PSS with their controller parameters are not simultaneously considered by using the multi-objective optimization design. In doing so, this paper uses a multi-objective function which includes minimizing both the power losses in transmission lines and the voltage deviations of buses, and also considering the dynamic criteria to obtain the best Pareto optimal set. Then, a population-based meta-heuristic algorithm, called water cycle algorithm (WCA) based on fuzzy decision making method is employed for solving the multi-objective problem (MOP). The idea of the proposed algorithm is based on one of the phenomenon of the real world, called water cycle process [14]. The robustness, high efficiency, and high accuracy to find the Pareto optimal solution and the exploratory capability of this algorithm make it be a suitable method for solving the MOP given in this paper [15]. In addition to obtaining the locations and controller parameters of both PSS and UPFC, the best input signal for power oscillation damping (POD) controller of UPFC is also determined in order to achieve the best dynamic performance of the power system. The 39-bus New England power system is employed as a test system and the comparative simulation results show the superior performance of the proposed method.

The paper is organised as follows: Section 'Modeling' deals with the modeling of synchronous generator, PSS and UPFC and its POD controller. In Section 'Problem formulation', the problem of the optimal location with the control parameters of UPFC and PSS is formulated. Also, the multi-objective function which is a compromise between the selected conflicting objectives and their related constrains is described in Section 'Problem formulation'. The formulation of WCA is provided in Section 'Water cycle algorithm'. Solving the proposed multi-objective problem by using WCA is described in Section 'Water cycle algorithm'. Simulation results are given in Section 'Simulation results' following with S ection 'Conclusions' in which the conclusion is given.

Modeling

The state space form of the n-generator power system with a UPFC can be written as:

$$\dot{x} = f(x, u), \quad x = [x_1, x_2] \tag{1}$$

where x is a vector of state variables with UPFC. Also, x_1, x_2 refer to the state variables of generators and UPFC respectively.

Synchronous generator

Each generator can be represented by the following five-order dynamic equations [16]:

$$\dot{\delta}_i = \omega_o \omega_i \tag{2}$$

$$\dot{\omega}_i = -\frac{1}{2H_i}[P_{mi} - P_{ei} - D_i\omega_i] \tag{3}$$

$$\dot{e}'_{di} = \frac{1}{T'_{qoi}}[-e'_{di} - (x_{qi} - x'_{di})I_{qi}] \tag{4}$$

$$\dot{e}'_{qi} = \frac{1}{T'_{doi}}[E_{fdi} - e'_{qi} + (x_{di} - x'_{di})I_{di}] \tag{5}$$

$$\dot{E}_{fd_i} = -\frac{1}{T_{Ai}}(E_{fdi} - E_{fdi0}) - \frac{K_{Ai}}{T_{Ai}}(V_{ti} - V_{ti0}) \tag{6}$$

where $\delta_i, \omega_i, \omega_o, H_i, P_{mi}, P_{ei}\ D_i, e'_{di}, e'_{qi}, E_{fdi}, T'_{doi}, K_{Ai}, T_{Ai}, V_{ti}$ refer to rotor angle, rotor speed, rotor synchronous speed, damping coefficient, moment of inertia, internal voltage of components for d- and q-axis, field voltage, transient time constant, gain and time constant of field voltage, terminal voltage of i-th synchronous generator respectively. Therefore, x_1 in Eq. (1) will be defined as $[\delta_i, \omega_i, e'_{di}, e'_{qi}, E_{fdi}]$.

Power system stabilizer

The block diagram of PSS is shown in Fig. 1 [16]. It contains a gain K_{PSS}, a wash-out block with time constant T_W, two lead-lag blocks with time constants of T_1, T_2, T_3 and T_4 and a limiter. The PSS input signal is $\Delta\omega$ and its output signal is injected to the excitation system of the generator.

Unified power flow controller

The equivalent circuit of UPFC is shown in Fig. 2 [17]. This circuit contains series and shunt parts represented by a series voltage source ($\bar{v}_s$) and one shunt current source ($\bar{i}_{SH}$) respectively.

The aggregated form of the third order dynamic model of UPFC controller with POD controller is depicted in Fig. 3. In this block diagram, the parameters v_p, v_q and i_q are state variables of series and shunt parts of UPFC respectively [18]. The parameters K_r, T_r are the gain and time constant of the controller respectively. The u_{POD} is an additional output stabilizing signal of POD controller injected into UPFC control system for enhancing the damping of inter-area modes. Similar to PSS block diagram, it contains a gain K_{POD}, a wash-out block with time constant of T_W, two lead-lag blocks with time constants of T_1, T_2, T_3 and T_4 and a limiter. It should be noted that the input signal of POD controller is selected as the deviation of active power (ΔP) of any transmission line so that the best dynamic performance is achieved [18]. In this regard, the wide area measurement system (WAMS) can be easily used to transfer (ΔP) to the POD controller of UPFC. Finally, by setting the parameters of PSS and UPFC controller coordinately, the desirable damping is obtained. In the next sections, the proposed meta-heuristic algorithm, WCA, is applied to find the optimal parameters of controllers.

Problem formulation

In this section, the multi-objective function which is a compromise between the selected conflicting objectives and their related constrains are described.

Decision variables

The decision variables are determined for achieving the best optimal solution. Therefore, the design procedure can be formulated as a constrained optimization problem of minimizing a multi-objective function which is subject to $K_{i\min} \leqslant K_i \leqslant K_{i\max}$, $T_{i\min} \leqslant T_i \leqslant T_{i\max}$ and $L_{i\min} \leqslant L_i \leqslant L_{i\max}$. The K_i, T_i and L are decision

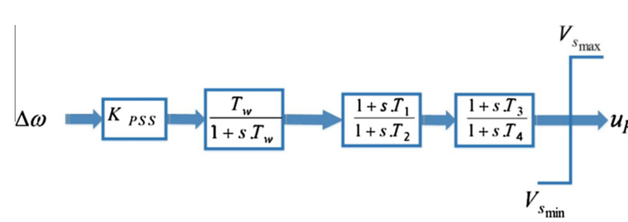

Fig. 1. Block diagram of PSS [16].