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Wide-area power system stabilizer design based on Grey Wolf Optimization algorithm considering the time delay

M.R. Shakarami*, I. Faraji Davoudkhani

Department of Engineering, Lorestan University, Lorestan, Iran

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ABSTRACT

This paper proposes a method for designing wide-area power system stabilizer (WAPSS) based on the Grey Wolf Optimization (GWO) algorithm. The stabilizer is used to damp the inter-area oscillations by considering the communication latency which is related to the remote feedback signals. For this reason, a new multi-objective function is proposed for the design of the WAPSS. In this function, in addition to improving the stability of the system by displacing the critical modes, the stabilizer is designed in the minimum-phase with a less control gain. In this method, the maximum delay margin in which the closed-loop power system can remain stable can also be optimally identified.

The proposed approach is tested in a small and a large multi-machine power system. The nonlinear simulation results and eigenvalues analysis have demonstrated that the approach which has been proposed in this article is highly effective in damping the inter-area oscillations as well as compensating for the destructive effects of the communication delay on the remote feedback signals.

1. Introduction

Low frequency oscillations refer to the angle oscillations of the generator rotor after a disturbance. The frequency of these oscillations is usually within the range of 0.2–2 Hz. The oscillations that occur between a single generator or a single power plant and the rest of the power system are called local oscillations which oscillate in a frequency range of 0.8–2 Hz. Inter-area oscillations, ranging 0.2–0.8 Hz, appear from two or more groups of generators in different areas, swinging against each other. Usually, these oscillations occur in the power systems connected via weak power transmission lines. In stressed power systems, damping of inter-area oscillations is generally low [1]. Therefore, power system stabilizers (PSSs) and FACTS devices are used to damp these oscillations [2,3]. In most power systems, local oscillations are often damped well due to installing local power system stabilizers (PSSs) while inter-area oscillations are often weakly damped, because the input control signals used in these PSSs are local signals and do not often have good controllability over some of the critical inter-area modes [4]. When an input signal for damping controllers is a remote signal, the dynamic performance of the system may be improved in comparison with a local signal [5]. Wide-area measurement systems (WAMSs) are widely spread. These systems make use of phasor measurement units (PMUs) enabling the monitoring of dynamic data of the power systems such as the voltage, current, angle, and frequency. Hence, a good opportunity for dynamic control of power system has been created using data obtained from WAMSs [6].

Generally, there are two types of solutions for designing damping controllers which are decentralized approaches and centralized approaches. The main advantage of the former stems from the fact that this method is based on local measurements and therefore does not require additional communications equipment. However, it is clear that decentralized/local control by itself is unable to economically and efficiently meet the damping needs of the future highly stressed networks [7]. On the other hand, a wide area control provides a more efficient solution due to the availability of large amounts of wide area dynamics data and better observation of inter-area modes. Wide area controls include each control that needs a communication interface to collect any entries or send control signals [8]. Although using WAMSs for controllers has great potential to improve the damping of inter-area oscillations, the use of remote signals creates new challenges in designing such controllers. Because the *time delays* caused by communication networks for transmission of remote signals may negatively affect the damping of the inter-area oscillation or even lead to instability of the closed-loop system [9,10]. Time delays caused by the transmission of remote signals are among the key factors

* Correspondence to: Lorestan University, Kamalvand Ave., P.O. Box 68151-44316, Lorestan, Iran. Tel.: +98 663 3120086; fax: +98 663 3120086.
E-mail addresses: Shakarami.mr@lu.ac.ir, m.r.shakarami@gmail.com (M.R. Shakarami).

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affecting the stability of the whole system damping performance [4]. Therefore, considering the time delay is a necessary requirement during the controller design process. In the reported literature, various strategies have been proposed to govern the latency impacts [9–19]. Different methods for the design of the wide-area power system stabilizer are presented in the literature. For the first time, WAPSS was presented in [11] as a two-level controller in a way that a local signal was used for damping local modes, and a wide area feed-forward signal was used for the damping of inter-area modes. In [12–14], the H∞ method was used to design a robust wide-area damper considering the time delay and in [15] a combination of the H2/H∞ method and a TS fuzzy method was used for the selection of different operating conditions for a robust control. The linear matrix inequality (LMI) method was used for the stabilizer design with respect to variable time delay and disturbance in remote communications signal [16]. In [10] and [17], the LMI method was used for finding the maximum time delay margin and the wide-area stabilizer gain and stabilizer parameters were determined classically. Also, optimization techniques were used for coordination between PSS and wide-area dampers where in [18] a sequential quadratic programming (SQC) optimization method was used for minimization of the eigenstructure-based performance index to improve the dynamic stability of a power system. In [19–21], a PSO optimization technique was used for the design of a wide-area damper and its coordination with PSSs without considering the time delay. In [22], PSO was used for the design of a wide area stabilizer considering the constant time delay. In [23], parameters of a wide-area damping controller were calculated by a constrained nonlinear programming algorithm under various operation scenarios. The robust methods mentioned suffer from computational complexity and high computational time. Also, in these methods, a reduced-order model of the system is used instead of the full model and the time delay is not considered in the design of wide-area stabilizers. Another drawback of the methods is related to the use of weak optimization methods.

In this paper, a new objective function is proposed for the design of the stabilizer. In the function, the magnitude of stabilizer, displacement of critical modes and finding the maximum delay margin are used in a multi-objective form. Also, for designing the stabilizer in the minimum phase, inequality constraints are calculated and applied to stabilizer parameters. In order to solve the function, a new meta-heuristic method, namely, the GWO algorithm has been used.

2. System modeling

2.1. Multi-machine power system modeling

Model of a multi-machine power system is described by a set of nonlinear differential algebraic equations. These equations have been derived from the models of generators, loads, and other control systems that are connected to each other through algebraic equations of the network. In this paper, synchronous generators are considered as a two axis model in the following way [24]:

$$\dot{\delta}_i = \omega_i - \omega_s \tag{1}$$

$$\dot{\omega}_i = \frac{\omega_s}{2H_i}(T_{mi} - P_{ei} - D_i(\omega_i - \omega_s)) \tag{2}$$

$$\dot{E}'_{qi} = \frac{1}{\tau'_{d0_i}}(E_{fdi} - E'_{qi} + (X_{di} - X'_{di})I_{di}) \tag{3}$$

$$\dot{E}'_{di} = \frac{1}{\tau'_{q0_i}}(-E'_{di} + (X_{qi} - X'_{qi})I_{qi}) \tag{4}$$

$$P_{ei} = (I_{di}E'_{di} + I_{qi}E'_{qi}) + (X'_{qi} - X'_{di})I_{di}I_{qi} \tag{5}$$

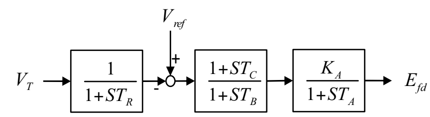

Fig. 1. Block diagram of the exciter.

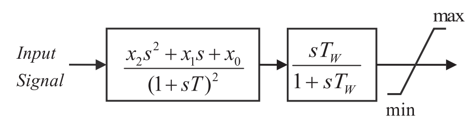

Fig. 2. Block diagram of the stabilizer.

2.2. Excitation modeling

The standard IEEE type-AC4A excitation system, as shown in Fig. 1, is used in this paper [25].

2.3. Wide-area power system stabilizer

In this paper, the wide-area power system stabilizer is considered with a lead-lag structure whose poles and zeroes can be set to be optimal. The schematic of the WAPSS is shown in Fig. 2 in which $x_2, x_1, x_0 > 0$ are stabilizer parameters that should be set, T is an adjustable time constant and, T_W is washout time constant [26].

2.4. Latency computation and time delay

Generally, there are two different types of communication links, wired and wireless. Satellites or microwave links are examples of wireless links, and fiber optic or telephone lines are examples of wired links. Among wireless links, microwave is known as the best option for its reliability, easy implementation, high speed data transmission, and also noise immunity. Delays associated with the specified links act as a fundamental indicator the amount of time-lag happening before the action is commenced. Detailed information about the communication links and their associated time delays is presented in [27,28] and a brief description is presented in Table 1.

The phasor data concentrator (PDC), or super PDC, is used to transmit the remote signals from the PMUs to the control center. The global positioning system (GPS) renders an exact timing pulse. By exploiting the GPS signal, the WAMS precise time synchronization is accomplished. The main task for PDC is to synchronize the measurements of entire PMUs and to send the data every 20 ms to the control center. In the case where congestion occurs in one or more communication lines, the PDC pauses until the data of all PMUs are completed. Hence, the total delay in delivering the WAMS data for control center applications is the latency of the most congested line plus the time needed for synchronization. Once the PDC gathers the data from all channels, it starts sending the data to the control center at a much faster rate (1 kHz max) until it clears the backlog. Most likely, the damping controller is not located at the control center; thus, a fraction of data is sent toward the controller location. The total latency of received data is calculated by subtracting the local time at the control center or the damping

Table 1
Communication links and their associated time delays.

Communication link	Associated delay (ms)
Fiber-optic cables	100–150
Digital microwave links	100–150
Power line carrier (PLC)	150–350
Telephone lines	200–350
Satellite link	500–700