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A hybrid algorithm to tune power oscillation dampers for FACTS devices in power systems

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ABSTRACT

The interaction between electrical and mechanical torques in the synchronous machines connected to bulk power transmission systems gives rise to electromechanical oscillations which, depending on the operating conditions and type of disturbance, may be poorly damped or even unstable. Recently, a combination of power system stabilizers (PSSs) and power electronic devices known as FACTS (flexible alternating current transmission systems) has been recognized as one of the most effective alternatives to deal with the problem. Tuning such a combination of controllers, however, is a challenging task even for a very skilled engineer, due to the large number of parameters to be adjusted under several operating conditions. This paper proposes a hybrid method, based on a combination of evolutionary computation (performing a global search) and optimization techniques (performing a local search) that is capable of adequately tuning these controllers, in a fast and reliable manner, with minimum intervention from the human designer. The results show that the proposed approach provides fast, reliable and robust tuning of PSSs and FACTS devices for a problem in which both local and inter-area modes are targeted.

1. Introduction

Electric power systems have undergone several transformations in the last years, with a strong focus on more efficient energy consumption (Palensky & Dietrich, 2011; Yang, Barria, & Green, 2011) at the distribution level.

Some transformations have been seen at the generation and transmission level as well, most of them with the objective to boost production efficiency by the introduction of competition. However, from the control viewpoint, most of the typical structures that control the dynamic response of the system to perturbations remain unchanged.

These perturbations may have several different origins (e.g., a sudden load increase or a short circuit in a transmission line) and can induce electromechanical oscillations in the power system, since the angular speed of the generators oscillates due to sudden imbalances in their electrical and mechanical torques (Kundur, 1994). To mitigate the impact of such oscillations, the most common type of controller used is the PSS (power system stabilizer) (Kundur, 1994). In some cases, however, the use of PSSs is not sufficient to guarantee a satisfactory level for a minimum damping, as will be explained later.

Recently, combinations of PSSs and power electronics devices known as FACTS (flexible alternating current transmission systems) have been shown to be an effective alternative to enhance the damping of electromechanical oscillations in power systems (Hingorani & Gyugyi, 2000). Among the most promising FACTS devices to perform oscillation damping control is the thyristor controlled series capacitor (TCSC) (Del Rosso, Canizares, & Dona, 2003), due to its effectiveness for power flow control in series-connected circuit elements such as transmission lines and to its relatively lower cost when compared to other high-end technologies.

In TCSCs (as well as in other types of FACTS devices), the function of oscillation damping control is performed by a supplementary controller know as a power oscillation damper (POD) (Rogers, 2000). The POD acts over the FACTS device much like the PSS acts over the automatic voltage regulator (AVR) in a synchronous machine: it modulates its reference value during the transient period to ensure a well-damped response to a disturbance, with its action vanishing after steady-state conditions are reached again.

These controllers are implemented in digital control panels (during the commissioning stage), and their control actions are usually produced via software using microprocessors in digital control platforms. However, since the sampling frequency (usually more than 1 kHz) is much faster than the frequencies of the oscillations that must be controlled (which lie within the range of 0.1–3.0 Hz), the design of these controllers can be done entirely in the continuous-time domain, with the resulting transfer-functions being discretized for implementation.

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At the middle part of the frequency range mentioned in the previous paragraph (0.7 to 2.0 Hz) lies the type of electromechanical mode in which a single plants oscillates against the remaining of the system (Rogers, 2000). This type of oscillation is known as a local mode, and usually can be dealt with very effectively by PSSs due to their relatively smaller complexity when compared to another type of oscillation: the inter-area mode. Inter-area modes arise in bulk interconnected power systems when a group of generators, in one area of the system, swings against another group, in a different portion of the same system, and are often found within the range of 0.1–0.7 Hz (Rogers, 2000). This type of oscillation is much more complex due to the several factors that play a role in it: the structure of the transmission system, the operating conditions and even the interactions among the several generators involved and their respective controlling devices.

When inter-area oscillations arise, as stated before, one of the most effective alternatives to ensure a well-damped response of the system to a disturbance is the joint use of PSSs for AVRs of the synchronous generators and PODs for the FACTS devices. However, since these controllers have to act simultaneously and in a coordinated manner, the problem of tuning their respective parameters becomes a challenge for even a highly skilled and experienced engineer. The main issue in this case is the fact that the designer has to keep track of multiple parameters at once, and humans have notorious difficulties to deal with these types of multi-dimensional search problems.

Even having to face these difficulties, the industry still relies on human expertise to perform the aforementioned tuning. Classical trial-and-error approaches for controller design are still employed for PSS and POD tuning in utilities and independent system operators (ISOs) all over the world. Among the most used techniques in these trial-and-error processes are the selective modal analysis (Verghese, Perez-Arriaga, & Schweppe, 1982), the residue analysis (Pagola, Perez-Arriaga, & Verghese, 1989) and the induced torque coefficients (Pourbeik, Gibbard, & Vowles, 2002). However, the difficulties in handling a large number of operating conditions and several modes of oscillation while keeping track of multiple controller parameters still place a significant burden on the designer, which usually takes days or weeks to complete its task.

The academy has attempted to deal with this problem in a variety of ways. Approaches relying on H mixed-sensitivity theory (Chaudhuri & Pal, 2004), regional pole placement using linear matrix inequalities (de Oliveira, Kuiava, Ramos, & Bretas, 2009; Ramos, Castoldi, Rodrigues, Borges, & Bretas, 2009) and genetic algorithms (Do Bomfim, Taranto, & Falcao, 2000) are examples of the many approaches that have been proposed, but none of them has already reached the status of the technique of choice for PSS and POD tuning by the industry worldwide, at least to the knowledge of the authors.

The cited tuning algorithms use search approaches based on either local optimization methods or global optimization methods to pursue their objective. The local optimization methods have the speed as their main advantage, but they can present convergence issues or get stuck in a local minimum point (Luenberger, 2003). On the other hand, global optimization methods tend to be slow due to their many strategies to avoid getting stuck into local minimum points (Luenberger, 2003).

Based on this observation, this work proposes a controller tuning method that uses a hybrid structure mixing the two previously mentioned approaches, i.e., a global search method combined with a local search method. The method works by initially setting up a minimum damping ratio to be achieved for all oscillation modes in all operating conditions of interest. This minimum damping ratio is defined as the goal of the search procedure, and is a user-defined input value. In the sequence, a global search is performed by an evolutionary algorithm (EA), which starts with an initial set of candidate tunings for the controller parameters and works on this set in order to maximize the resulting minimum damping ratio, until it becomes larger than the defined goal.

Due to the previously mentioned reasons, a pure global optimization approach could be too slow and, therefore, in our procedure the EA is stopped if a threshold (which is smaller than the design goal, yet close to it) is reached on the minimum damping provided by a particular set of tunings provided by the EA. This is an indication that the EA has approached a promising convergence basin, and that the design goal can be reached within this basin by a local search approach.

At this point the algorithm switches to a gradient descent method, using the tuning that provided the best result from the previous EA and working on it until the design goal is reached. If it is not reached, this is an indication that the local minimum associated with the present convergence basin is smaller than the design goal, and the process has to be restarted with a different set of initial tunings. However, from the experience gained with the application of this proposed hybrid approach, the need for restarting can be seen as a rare event, with the hybrid algorithm providing a satisfactory result in the vast majority of the tests that were carried out.

The paper is structured as follows: Section 2 depicts the formulation of tuning problem in terms of the controller parameters and Section 3 presents our proposal for a hybrid algorithm that tunes these controller parameters; the results of the application of the proposed algorithm to the New England/New York benchmark model are presented in Section 4, and Section 5 finishes the paper with some concluding remarks.

2. Formulation of the tuning problem

The problem of parameter tuning of controllers is typical in large-scale industrial systems (Wu, Buttazzo, Bini, & Cervin, 2010). In the power system industry, the modeling process for designing PSSs and PODs is usually based on a set of nonlinear differential-algebraic equations in the form

$$\dot{\tilde{x}} = f(\tilde{x}, \tilde{u}, z, \lambda) \tag{1}$$

$$0 = h(\tilde{x}, \tilde{u}, z, \lambda) \tag{2}$$

$$\tilde{y} = g(\tilde{x}, \tilde{u}, z, \lambda) \tag{3}$$

where $\tilde{x} \in \Re^n$ is the system state, $\tilde{u} \in \Re^p$ is the control input, $\tilde{y} \in \Re^q$ is the measured output (which can be used for feedback), $z \in \Re^m$ is a vector of algebraic variables representing the transmission network coupling among the states of different generators, and $\lambda \in \Re^l$ is a vector of parameters, representing the load levels and other quantities defining the system operating condition.

The algebraic constraints (2) can be eliminated from (1) to (3) using a linearization of this set of equations, followed by the substitution of the linearized algebraic constraints resulting from (2) into the linearized equations resulting from (1) and (3). The set of equations resulting from this process has the form

$$\dot{x}_j = A_j x_j + B_j u_j \tag{4}$$

$$y_j = C_j x_j + D_j u_j \tag{5}$$

where $x_j \in \Re^n$ represents a deviation from an equilibrium value of $\tilde{x}_j$ with respect to (1)–(3), obtained for a particular value of the parameter vector λ. Similarly, $u_j \in \Re^p$ and $y_j \in \Re^q$ represent deviations from $\tilde{u}_j$ and $\tilde{y}_j$, respectively. In the industry, it is a typical practice to select a number of operating conditions, defining different equilibria for $\tilde{x}_j$, in such a way that these conditions are