Electric Power Systems Research 134 (2016) 105–113

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Adaptive inter-area oscillation damping controller for multi-machine power systems

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ARTICLE INFO

Article history:
Received 3 November 2015
Received in revised form 8 January 2016
Accepted 9 January 2016
Available online 10 February 2016

Keywords:
Adaptive and innate control
Artificial immune system (AIS)
Damping control
Electric power system
Virtual generator
Wide area control

ABSTRACT

The interconnection of multiple generation units in a power system can lead to inter-area oscillations that generally occur under critical operating conditions. To damp these oscillations, supplementary control can be provided by a wide area control (WAC) system using remote measurements from the power system. Wide area controllers designed with traditional approaches are non-adaptive and thus their control policy may not be optimal to nonlinear operation conditions and disturbances. In this paper, the concept of an artificial immune system (AIS) is applied in the development of an innate and adaptive controller to handle known, unknown and random disturbances in a power system. Furthermore, with synchronous generator coherency grouping, remote virtual generator measurements are used to generate supplementary control signals to a synchronous generator that is identified to have maximum controllability on a power system. Real-time simulation and frequency analysis results show the superior performance of AIS-based controller in damping inter-area oscillations for different power system conditions and disturbances.

1. Introduction

Oscillations are frequently observed in a power system operating under critical conditions as due to lack of sufficient damping torque [1]. Modal analysis using remote measurements reveals the presence of local, intra-area and inter-area modes and their respective damping ratios in an interconnected power system. Conventional power system stabilizers (PSSs) make use of feedback signals that are obtained locally such as speed deviation or active power output of a generator applied to provide supplementary control signal to the automatic voltage regulator (AVR). However, since the local measurements lack observability of inter-area modes, PSSs are only effective for damping local and intra-area modes [2]. In contrast, remote measurements used by wide area control (WAC) enhances control efficacy for the inter-area modes. In [3], inter-area oscillations are damped by static VAR compensator based on optimal measurement signal selection. In [4], WAC is implemented through phase compensation. An earlier study that shows a virtual generator based power system stabilizer (VG-PSS) for damping of inter-area oscillation modes is reported in [5] by the authors. This VG-PSS uses remotely measured virtual generator speeds for supplementary damping control at the generator of maximum controllability. These above-mentioned controllers have fixed parameters. However, it is desired that the parameters self-tune online so that the controllers are adaptive to various changing conditions that affect control effectiveness and system performance. In [6], a conventional multiple-model adaptive control scheme is applied to form a control signal from a bank of controllers; yet the number of operating conditions corresponding to each pre-designed controller is limited. A neural-network based adaptive critic control scheme for WAC is suggested in [7]; however, the update of neural networks parameters is offline, thus the parameters of this controller remain unchanged during the real-time operation of the power system. In [8], artificial immune system (AIS) is introduced for adaptive excitation control of generators in an electric ship to handle high energy demand loads such as pulsed loads.

In this paper, the concept of AIS is applied for the development of wide area signals based adaptive damping controller for inter-area oscillations. The wide area signals are derived from virtual generators formed by coherency grouping. Each coherent group is modeled by a virtual generator. Based on an optimal (innate) controller with best tuned parameters developed in [5], the AIS's adaptive strategy further modifies the control policy

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http://dx.doi.org/10.1016/j.epsr.2016.01.005
0378-7796/

by temporarily adjusting controller parameters for unseen and abnormal disturbances. This is the second aspect of the AIS concept: an adaptive immune controller. Compared to a fixed parameter based damping controller, the AIS-based control is more agile and can stabilize a power system under various operating conditions and disturbances due to its innate and adaptive immune properties. By modeling biological immune systems, AIS adaptively and interactively generates feedback control signals to restore a system to its steady state. During the development of the optimal controller, generators in the power system are assumed to be oscillating in fixed coherent groups. However, it is known that a variation of operating conditions could lead to different coherent groups. For instance, generators near the fault site tend to lose oscillatory coherency [7]. Thus, the performance of the innate controller is degraded. Besides, since the oscillations occur in multiple frequencies during transients, a controller with fixed parameters may not be robust enough to handle all possible power system dynamic behavior for several operating conditions and disturbances. Fortunately, the impact of new and/or changing coherent groups and multiple modes can be minimized by adaptive nature of the AIS. The AIS controller parameters are only temporarily changed in response to perturbations caused by changes in operating conditions and disturbances. Post-disturbances or reaching equilibrium states, the controller parameters are restored to its optimal values for normal operating conditions.

The rest of the paper is organized as follows: In Section 2, the inter-area oscillation in an interconnected electrical power system is briefly discussed. Section 3 presents an AIS structure and describes its mechanism for feedback and adaptive control. In Section 4, AIS is applied to an electrical power system to damp the inter-area oscillations. In Section 5 typical results using a real-time digital simulator (RTDS) and frequency response analysis are presented. Finally, conclusions are given in Section 6.

2. Inter-area oscillations in electrical power systems

In an interconnected electrical power system, oscillatory behavior is inherent in the transient response to disturbances and changes in operating conditions such as generation and load variations. The oscillations manifest themselves, primarily, in generator rotor speeds and tie-line power flows, causing loss of generator synchronism, tripping of generators and loads, and furthermore islanding section(s) of power system. Generally, there are multi-modal oscillations that superimpose and interact with each other. Of all the modes, the most severe consequences may arise from inter-area modes caused by multi-areas in a power system swinging against each other, typically in the frequency range of 0.2–0.8 Hz [7].

The inter-area oscillations are caused by many factors that lead to decreased damping torque. The negative damping torque induced by AVRs of generators, the lack of active power transmission capacity linking two power system areas, as well as the nonlinear dynamic interactions between oscillation modes are all possible causes.

Linear differential equations based modeling of power systems can be used to study inter-area oscillations [10]. A linearized model around a nominal operating condition can be expressed using (1). The system matrices in (1) can be identified heuristically with a Stochastic Subspace Identification (SSI) algorithm by injection of Pseudo-Random Binary Signals (PRBSs) at AVRs of each generator and measuring corresponding speed deviation responses [11,12].

$$\begin{aligned} \dot{x} &= \mathrm{Ax} + \mathrm{Bu} \\ y &= \mathrm{Cx} + \mathrm{Du} \end{aligned} \tag{1}$$

Based on this state space representation, modal analysis can be carried out to determine the frequency and damping ratios of oscillations present [13]. Inter-area oscillation impacts large geological areas. The varying generation and load conditions lead to power flow change. For example, scheduled active power transaction in a deregulated market now varies in specific transmission lines. Network topology changes may result by contingencies due to poor damping. Besides, intermittent renewable energy generations bring stochastic change to the system power flow distribution. All these factors add to the difficulty in the development of an optimal damping controller that can be universally applied. It is desired that the controller is adaptive to accommodate the nonlinear, time-varying and stochastic properties of an interconnected power system.

It is observed that electrically adjacent generators tend to oscillate coherently due to the convenience of inter-machine active power transfer. The coherency is reflected by the proximity among speed deviation responses of a generator's cluster. Thus, redundancy can be reduced using a Virtual Generator (VG) as a mathematical equivalent of coherent generators, as expressed in (2), where H signifies the inertia constant of a generator and the subscript j signifies the index of a generator within the group. Detailed implementation of system identification, model analysis and generator coherency were elaborated in [5].

$$\omega_{\mathrm{eq}} = \frac{\left(\sum_{j=1}^{N} H_j \omega_j\right)}{\left(\sum_{j=1}^{N} H_j\right)} \tag{2}$$

Speed deviation from VGs instead of single generators can be used as an input to a damping controller. Unfortunately, generator coherency is subject to changes due to variation of operating conditions as well as contingency types and locations. This may not be best handled by a VG-based damping controller with fixed parameters; instead, an adaptive controller is needed to handle the fast changing dynamics of a power system.

3. Artificial immune system

The defensiveness of a biological immune system relies on the presence of innate and adaptive immunity. As an analogy to a biological immune system that is resistant to antigen incursion, AIS can provide enhanced power system stability by improving controller adaptiveness to disturbances and contingencies. To maximize control effectiveness, an AIS based adaptive controller is introduced in this paper. In the application of AIS, the innate immunity is realized through optimal parameter configuration, and the adaptive immunity is realized through adaptive change of controller parameters, as elaborated in the following subsections.

3.1. Innate immunity

In the biological immune system, innate immunity refers to the ability of living body (such as human) to provide the primary defense reactions against incurring antigens by generating neutrophils (such as blood cells) to identify and destroy the antigens. The antigens are bound and engulfed by macrophages before being further demolished by neutrophils like white blood cells. The control mechanism in innate immunity is the ability to generate a control signal to maintain stability in response to the measured perturbation from equilibrium. This response behavior can be achieved by an optimal action and can be compared to a control system with fixed parameters.

3.2. Adaptive immunity

In the biological immune system, the dendritic cells that bind antigens can be further evolved into antigen presenting cells (APCs),