Electrical Power and Energy Systems 75 (2016) 108–116

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

# An adaptive neuro-control approach for multi-machine power systems

Zhen Ni [a], Yufei Tang [b], Xianchao Sui [c], Haibo He [b,*], Jinyu Wen [d]

[a] Department of Electrical Engineering and Computer Science, South Dakota State University, Brookings, SD 57007, USA
[b] Department of Electrical, Computer and Biomedical Engineering, University of Rhode Island, Kingston, RI 02881, USA
[c] Dalian Power Supply Company, Dalian 116033, China
[d] School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

ARTICLE INFO

*Article history:*
Received 27 April 2014
Received in revised form 13 August 2015
Accepted 21 August 2015
Available online 15 September 2015

*Keywords:*
Multi-machine power system
Transient stability
Excitation control
Goal representation adaptive dynamic programming

ABSTRACT

We investigate an adaptive neuro-control approach, namely goal representation heuristic dynamic programming (GrHDP), and study the nonlinear optimal control on the multi-machine power system. Compared with the conventional control approaches, the proposed controller conducts the adaptive learning control and assumes unknown of the power system mathematic model. Besides, the proposed design can provide an adaptive reward signal that guides the power system dynamic performance over time. In this paper, we integrate the novel neuro-controller into the multi-machine power system and provide adaptive supplementary control signals. For fair comparative studies, we include the control performance with the conventional heuristic dynamic programming (HDP) approach under the same conditions. The damping performances with and without the conventional power system stabilizer (PSS) are also presented for comparison. Simulation results verify that the investigated neuro-controller can achieve improved performance in terms of the transient stability and robustness under different fault conditions.



## Introduction

In current electrical power and energy system, the sophisticated learning and optimization approaches have been studied and investigated among various power grid examples [1–3]. As the power system is usually a large-scale system with grid-connected power plants and various loads, the optimal control strategies for the transient stability have become more and more critical in the field. The objectives for the controller and stabilizer are to achieve satisfied reliable and efficient operation for the power grid. Power system stabilizer (PSS) was adopted in response to the power system oscillations under various faults [4,5]. Conventional PSS was usually designed based on the linearized power system model and conducted the pole-placement technique (i.e., residue-based method) to increase damping for the system oscillations [6–8]. A comprehensive comparison of PSS, static var compensators (SVCs), and shunt static synchronous compensators (STATCOMs) was investigated from both mathematic viewpoint and simulation demonstration in [9].

Current research works and implementations on various PSS design indicate that the PSS is a powerful and promising technique, with which the performance can be guaranteed under certain conditions. However, the PSS based supplementary control is closely related to the characteristics of the power system model. If the mathematic model function is not exactly known or even unknown, it will be very hard or even impossible to obtain the linearized system model and the subsequent PSS design. In this paper, we investigated a novel adaptive neuro-control approach for the multi-machine power system based on [10–12]. From a viewpoint of architectural design, this investigated approach has one additional network, namely goal network, to provide an adaptive reward signal. In addition, the value function is also closely related to this adaptive reward signal. Compared with the conventional neuro-control approaches, this investigated approach can provide improved damping performance (e.g., shorter rising time and less overshoot) for the multi-machine power system under various conditions.

Specifically, we investigate the goal representation heuristic dynamic programming (GrHDP) approach on the multi-machine synchronization control problem. The architecture of this GrHDP is different from the traditional heuristic dynamic programming (HDP) in twofold: one is that there is an additional neural network, namely the goal network, to provide an adaptive reward signal based on the current system state. The other one is that this

* Corresponding author.
*E-mail addresses:* zhen.ni@sdstate.edu (Z. Ni), ytang@ele.uri.edu (Y. Tang), xianchaosui@gmail.com (X. Sui), he@ele.uri.edu (H. He), jinyu.wen@hust.edu.cn (J. Wen).

http://dx.doi.org/10.1016/j.ijepes.2015.08.012
0142-0615/

adaptive reward signal is also set as one of the inputs for the critic network, and thus contributes to the evaluation of the control performance [13,14]. To connect the multi-machine power system, the control action generated by the GrHDP controller is set as the supplementary control signal for the excitation system in each generator. The objective of this design is to improve the damping performance of the system, such that the rotor speed of each generator can be synchronous faster after various faults or disturbances. In this paper, we demonstrate the improved damping performance over the three-machine nine-bus system with three different conditions (i.e., three-phase ground fault, step changes of output active power, and load fluctuations). For fair comparison, we provide the performance with the conventional HDP design under the same settings. The damping performances with and without PSS are also presented for reference.

The rest of the paper is organized as follows: Section ''Related work'' provides a backdrop of the related work. Section ''GrHDP based multi-machine power system simulation platform'' provides the design and the description of the simulation platform. Section ''Design of GrHDP learning controller'' presents the designed new adaptive neuro-control for the multi-machine power system. Then three case studies are provided with four approaches and simulation results are discussed in Section ''Simulation studies''. Finally, the conclusion is presented in Section ''Conclusion''.

## Related work

In recent years, researchers have been working towards the self-tuning adaptive control schemes to enhance power system dynamics and stability. For instance, the coordinated tuning of PSS was proposed and demonstrated promising performance with flexible ac transmission systems (FACTS) in [15]. The decentralized nonlinear optimal excitation control was provided with improved performance on three-machine six-bus system over both the conventional PSS and automatic voltage regulator (AVR) [16]. In addition, the novel parameter tuning and implementation steps for PSS based excitation control were investigated in [17,18]. Many others also proposed the optimal damping performance with their controllers through the fuzzy logic control [19,20], particle swarm optimization (PSO) [21,22], model predicted control [16,23], evolutionary programming (EP) [24] and so on [25–27]. The excitation control based on various PSS designs has been demonstrated with powerful capability in the power system, including excitation control for multi-machine power systems [28,16], the wide-area damping controller (WADC) with FACTS devices [29–31], and energy storage device (ESD) based damping control [32,33].

Computational intelligence (CI) has been introduced into power system stability control areas, and has also shown promising performances on various applications based on adaptive dynamic programming (ADP) [1] [34–38]. In ADP based controller design, the exact mathematic model function is not a prerequisite. The controller observes the input vector from the power system, and provides the supplementary control signal for the exciter. A reward signal will be provided based on the current system performance and a value function will be used to critique the performance of this control action. There are usually two neural networks in the ADP design: an action network is used to provide the control action while a critic network is used to evaluate the performance of this control action with a value function. In many cases, a model network is also adopted to identify the system dynamics. In literature, the researchers have implemented the dual heuristic dynamic programming (DHP) approach into the multi-machine turbogenerator control, and compared the performance with the conventional AVR and PSS [39]. The model network was built to represent the dynamics of the turbogenerator based on the input and output data, and the action/critic networks were trained offline to achieve shorter rise time and faster convergence to synchronous speed than that of the conventional governor and PSS. In [40], the authors investigated the coordinated reactive power control of a large wind farm and a STATCOM. The similar power system modeling and offline training for the action and critic networks were conducted. In [41], the authors proposed the model-free heuristic dynamic programming and demonstrated the promising results on general nonlinear systems. Then, in [42], the authors demonstrated this online model-free HDP for the damping control on a four-machine two-area example, and further in China Southern Power Grid. This model-free adaptive control scheme was also investigated for the reactive power control on the grid connected wind-farm [43]. The further comparison between the PSS and the HDP controller on the doubly-fed induction generator (DFIG) was also provided in [44]. The intelligent local area signals damping control in power system oscillations was investigated in comparison with existing intelligent controllers [45]. Many others also studied the ADP based adaptive control approach on smart grid frontier applications, including grid-connected converter [46], static compensator in multi-machine power system [47], wide area optimal control [48], and many others [49–51][52]. Among these research work, the reward signal is usually defined as the fixed (and derivable) formulas, such as the weighted linear quadric forms [39–42]. We realize that the fixed or pre-defined reward function may not be a optimal choice when the system is under different operation conditions. In addition, the parameters in the reward function are significantly relying on the engineering knowledge for such system, which may not be a good thing if the system is unstructured or with uncertainties [53–55].

Therefore, it is desirable to investigate the general purpose reward function for multi-machine power system adaptive control based on ADP, specifically GrHDP technique. To this end, the past experience for engineering hand-craft reward design is not a prerequisite anymore, and the proposed one in this paper will help to overcome the uncertainties of dynamics in power system over time.

## GrHDP based multi-machine power system simulation platform

The multi-machine power system modeling and the simulation platform is introduced and discussed in this section. The schematic diagram of the GrHDP controller and the three-machine nine-bus system is presented in Fig. 1. The loads $A, B$, and $C$ are provided and the admittance matrices between each line and bus are included in Table 4. The three generators $G1, G2$ and $G3$ are connected through $230kv$ transmission lines and their parameters are provided in Table 3. As one can see from the figure, the GrHDP controller observes the measurement of rotor speed from each generator, and then provide supplementary control action signals $u_1, u_2$, and $u_3$ for the multi-machine accordingly. These control signals will be applied on each generator respectively, to adjust its rotor speed. It is possible that the generator, load and transmission lines are subjected to noise and disturbance, therefore a closed-loop control system is made through this process.

Fig. 2 shows the control schematic diagram for a single generator. The rotor speed is transmitted from local synchronous generator and the grid (i.e., the other two synchronous generators). The rotor speed difference is then calculated and set as the input for GrHDP controller or the PSS. In the simulation studies, we also include the delayed signals of rotor speed difference for better

[1] Both HDP and DHP designs mentioned are the different type of implementations in the ADP design family. Specifically, HDP design is used as a benchmark in this paper.