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# Automatic voltage regulator design using a modified adaptive optimal approach

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ABSTRACT

In this paper, an online adaptive optimal controller is firstly designed to optimize the performance of an automatic voltage regulator (AVR). Towards this end, an optimal quadratic tracking problem is defined based on the error between the synchronous generator's terminal voltage and its desired value. Then, this optimal control problem is solved using an adaptive dynamic programming (ADP) method, called the policy iteration technique. Using this technique, the optimal performance is achieved without knowledge of the AVR parameters. To eliminate the steady state error between the AVR output and its desired value, a modification is made in the original policy iteration technique base on the integral action control and another adaptive optimal controller is designed. In addition, an approach is proposed to represent a large-scale power system through several Single-Machine Infinite-Bus (SMIB) systems. The equivalent SMIB system then may be linearized through modal analysis to be employed by the proposed control scheme. Simulation results show that the designed adaptive optimal controllers are so effective and can be used in practical power systems.

## 1. Introduction

Excitation system of generators plays an important role to maintain power systems stability. A well-designed excitation system could improve performance of power grid through enhancing transient stability, supporting the voltage, and damping oscillations. However, fast response Automatic Voltage Regulator (AVR), as the main part of excitation system, acts in contrast to Power System Stabilizer (PSS), as an auxiliary controller. The PSS output signal is applied over the set point of excitation control to modulate the field voltage, in such a way that provides positive damping for angle swings of generator in power systems [1,2].

The so far reported researches in the field of excitation system design could be divided into two categories. The first category relies on the synthesis of AVR–PSS based on a sequential design procedure. In this way, the early stage deals with designing of the AVR to satisfy the specified voltage regulation performance. The later stands to design PSS based on the desired damping characteristic [3]. However, simultaneous enhancement of stability and voltage regulation is a challenging issue as both AVR and PSS utilize a unique control signal, *i.e.* field voltage [4]. To overcome this challenge, in the second category of studies, an integrated design approach for AVR–PSS design has been developed. This type of studies believes that as power systems continuously experience changes in operating conditions, the AVR and PSS should be coordinated in such a way that be robust against perturbations.

Recently, several efforts have been placed to coordinate the various requirements for stabilization and voltage regulation within a single control structure [3–12]. The coordinated control scheme in [3,5,7,8] relies on the model linearization around the operating point. Ref. [3] employs $H_\infty$ static output feedback to formulate the coordination problem as a simple fixed gain vector. Ref. [7] deals with a desensitised controller for coordination of AVR and PSS. Quinot et al. [8] visualizes AVR and PSS coordination through a four-loop desensitised controller in the French power system. It relies on the linear quadratic Gaussian (LQG) which provides a methodology for robust control design. The LQG-based controllers are dynamic control systems with a high-order structure (for large-scale power systems) and hence are not appropriate ones for large-scale power systems. Formulation of coordinated AVR–PSS design as an optimization problem is introduced in [5,13–16]. A damping index, obtained based on the system eigenvalues for the linearized system, may be minimized by means of particle swarm optimization technique. The control strategies based on optimization techniques usually provide a satisfactory performance for the pre-specified operating conditions and therefore, the robustness feature is in concern. Internal Model Control (IMC), which relies on the process

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identification, is employed in [4] to realize a trade-off between AVR and PSS. Complexity of process identification for large-scale power systems limits the application of this methodology. Ref. [9] addresses a Model-Predictive Control (MPC) strategy to realize a coordinated AVR–PSS design. Not only MPC leads to acceptable performance for the process with great time constants, but also power system inherent features, such as time variancy and nonlinearity, may degrade performance of the MPC. Refs. [10,11] employ switching strategy to make a trade-off between voltage regulation and small signal stability. Switching-based schemes guarantee desired performance only for a specific fault on which the optimum switching time is obtained. Weighting the AVR and PSS output signals is introduced in [6,12] to overcome the non-robustness feature of the switching strategy. A coordinated control scheme, called global controller, introduces in [6] to achieve a robust integrated design approach for AVR and PSS. However, performance of the global controller depends on the designing of two positive constants which is not straightforward. Ref. [12] deals with a fuzzy-based coordinated control scheme to enhance power system stability and voltage regulation. Expert knowledge about the process is a key feature in all fuzzy-based control schemes. The global controller is examined on a single machine infinite bus system. A measurement based approach is proposed in [1] to coordinate AVR-PSS based on the generating units voltages and phases. It introduced an approach which leads to acceptable, not optimal, stability performance through several AVR-PSS parameters re-tuning attempts which make the approach far from realistic.

Generally effectiveness of the designed control schemes in the aforementioned approaches depends on the accuracy of system model. The proposed control scheme in this paper extends the previous work [1] by formulating of the AVR-PSS coordination design though an optimal quadratic tracking problem which in turn eliminates the error between the generator's terminal voltage and the desired value. As the parameters of the AVR are not exactly known to the controller, traditional optimal control methods, such as LQ tracker [17], do not work appropriately. Therefore, the proposed control scheme in this paper utilizes a policy iteration technique, as a class of adaptive/approximate dynamic programming (ADP) algorithms, to overcome this crudity. The policy iteration method leads to online solutions of the optimal control problems without complete knowledge of the system dynamics. In other words, the utilized policy iteration technique has the ability to converge to the optimal performance without knowledge of the AVR dynamics. The obtained adaptive optimal controller leads to a closed-loop system with some steady state error between the generator's terminal voltage and its desired value. To eliminate this error, a modification is made in the original policy iteration technique base on the integral action control. It is proved that the observed steady state error is completely eliminated. Moreover, a new approach is proposed to represent an interconnected power system through several single-machine-infinite-bus (SMIB) systems. In this way, the proposed model-free control scheme could be applied to large-scale systems without any concerns. In closing, the main contributions of the paper can be listed as follows.

- A recently developed technique is systematically used to design adaptive optimal controllers for the AVR. Since the method leads to optimal performance without knowledge of the system parameters, it can be concluded that applying the technique to optimize the performance of the AVR is so important.
- Since the utilized adaptive optimal technique leads to a closed-loop system with steady-state error between the system output and its desired value, a modification is made in the technique to eliminate this error. This claim and the necessary conditions for using the modified adaptive optimal controller are proved through a new theorem.
- The modified adaptive optimal technique is applied to the AVR and its performance is compared with well-known controllers.
- An approach is proposed to represent a large-scale power grid through several SMIB systems. This justifies applicability of the proposed control scheme for real power system applications.

The rest of this paper is organized as follows. In Section 2, the AVR model and associated state space description are presented. Section 3 discusses the utilized policy iteration technique and its modified version for solving the optimal tracking problem. In Section 4, simulation and results are explained in detail, and finally Section 5 concludes the paper.

## 2. Mathematical model of the AVR

### 2.1. Hypothesis

I. As the feedback control techniques are used for the AVR-PSS design, there are some sensors in the AVR. However, the time constant of utilized sensors are usually smaller than the other components' dynamics and hence, it can be assumed that the sensors are ideal (see Fig. 2).
II. The nonlinearity of the AVR is negligible and linear transfer functions are sufficient for modelling each components of the AVR [18] (see Remark 5 for further details).

### 2.2. AVR model

By defining the state vector $x(t) = [V_t(t) \quad V_f(t) \quad V_r(t)]^T$, a linear state space representation of the AVR is explained as follows:

$$\dot{x}(t) = \begin{bmatrix} -\frac{1}{\tau_a} & \frac{K_g}{\tau_g} & 0 \\ 0 & -\frac{1}{\tau_e} & \frac{K_e}{\tau_e} \\ 0 & 0 & -\frac{1}{\tau_a} \end{bmatrix} x(t) + \begin{bmatrix} 0 \\ 0 \\ \frac{K_a}{\tau_a} \end{bmatrix} u(t),$$
$$y(t) = V_t(t) = [1 \quad 0 \quad 0]x(t), \tag{1}$$

where $V_t(t)$ is the terminal voltage, $V_f(t)$ the is field voltage, $V_r(t)$ the is reference voltage, and $u(t)$ is the control input. Here, it should be noted that all the components of the AVR are modelled through first order transfer functions on which includes a gain and a time constant. Table 1 represents the ranges of these parameters which are taken from [19].

### 2.3. SMIB systems representation

In previous work by the authors, the concept of Center-of-Gravity (COG) was introduced to study long-term power-frequency transients following large perturbations [2]. Its use in the case of power system transient stability is now reviewed in the light of an equivalencing approach to deal with excitation system behavior. To represent the original power grid by several SMIB systems, assume that an interconnected power system is divided into $n$ coherent areas $\{i = 1, \ldots, n\}$, where a local Center of Inertia (COI) is associated with each area. Based on COG concept, the physical system would be represented by an equivalent system in which each area is characterized by area COI and interacts with COG by means of fictitious reactance. This means that a system consisting of $n$ areas may be represented through $n$ SMIB

**Table 1**
Parameters of the AVR.

| Component | Transfer Function | Parameter |
|---|---|---|
| Amplifier | $\frac{K_a}{1+\tau_a s}$ | $10 \leqslant K_a \leqslant 40$<br>$0.02 \leqslant \tau_a \leqslant 1$ |
| Exciter | $\frac{K_e}{1+\tau_e s}$ | $1 \leqslant K_e \leqslant 10$<br>$0.4 \leqslant \tau_e \leqslant 1$ |
| Generator | $\frac{K_g}{1+\tau_g s}$ | $0.7 \leqslant K_g \leqslant 1$<br>$1 \leqslant \tau_g \leqslant 2$ |