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Enhancing optimal excitation control by adaptive fuzzy logic rules

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ABSTRACT

Generator excitation system plays an important role in maintaining power system stability. A new fuzzy control strategy is introduced to enhance excitation control by online coordinating Automatic Voltage Regulator (AVR) and Power System Stabilizer (PSS) control tunnels. The method automatically adjusts the weights of the AVR tunnel and PSS tunnel on-line according to different operating conditions by a set of fuzzy logic rules, aiming to improve the overall optimal excitation control performance by the coordination of voltage control and dynamic stability control. The requirements of excitation control in different circumstances are studied, and the fuzzy rules of the coordination are presented. The structure of the presented controller is simple and clear while the conventional design methods in AVR and PSS control tunnels can be kept without change. Numerical simulation results on two cases under different disturbances demonstrate that the proposed controller can get a good performance for a variety of the operating conditions.

Introduction

Power system stability has been proved to be of great importance for power system secure operation and uninterrupted electric power supply [1]. The dramatic blackouts in North America, Europe and India caused by power system instability [2], especially in the past twenty years, have provided compelling evidence of this phenomenon. Historically, transient instability is the dominant stability problem and has drawn considerable attention in both literature and industry. Thanks to the Automatic Voltage Regulator (AVR) controller in generator excitation system, the generator terminal voltage can be maintained by controlling the amount of current supplied to the generator field winding by the exciter [3]. With some up-to-date algorithms, the AVR system can be optimally designed to strengthen the transient stability of power system [4]. Consequently, the transient instability probability has statistically decreased in recent years.

However, the high gain exciters would deteriorate the damping of the system which leads to low-frequency oscillations of the power system [5]. The instability and blackouts resulted from oscillations has enormously increased with the expansion of the interconnection capacity of power system [6]. The potential jeopardy especially lies in the power system which needs a transmission of bulk amount power over long distance through relatively weak tie lines. To end this problem, various controllers have been designed such as Power System Stabilizer (PSS) [3], supplemental damping control of HVDC and FACTS [7–9]. Among these methods, PSS is the most cost-effective one and has been proved to be useful in practical applications [10]. Therefore, a number of generators in power system have been equipped with PSS control loops so as to enhance the damping of the electromechanical oscillations of the generators. Furthermore, a number of algorithms have been proposed aiming to optimize the PSS control effect, the currently available dominant ones are based on the linearized methods, such as pole-assignment and eigenvalue analysis [11]. The inevitable disadvantage of these methods is that the control effect is closely interrelated to the operation state, thus the fixed predefined parameters of the stabilizers may result in poor performance when operating point changes [12]. Addressing this crucial issue, in the last ten years, kinds of modern control techniques have been proposed for PSS self-adaptive tuning in order to provide sufficient damping for the power system under various operating conditions [13–15].

Despite some new approaches have been proposed in literature for generator excitation control, the most commonly used ones in a practical multi-machine power system are still the conventional PI, PID and Lead-lag controllers in which the parameters are tuned by classical, experiential or trial-and-error approaches [16]. The reasons are two-fold: (i) In practical power systems, the controllers with simple structure are particularly desirable since the ever-changing parameters makes it time-costly and infeasible to design the controller with some newly proposed but fairly complicated

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algorithms. (ii) The reliability of the controllers in electric industry is more import compared with some less conservative but more risky ones. Therefore, the traditional AVR and PSS control systems are still widely used although theoretically these methods could not maintain good dynamical performance in a wide range of operating conditions and disturbances.

Conventionally, the AVR and PSS design process are two separate sequential stages. Specifically, the AVR is firstly designed to meet the specified voltage regulation performances; secondly, the PSS is tuned to strengthen the damping and improve the dynamic stability performance. However, it has been long recognized that, essentially, the AVR and PSS have inherent conflicting objectives, which might deteriorate each other in some operating circumstances [16]. More pessimistically, as AVR and PSS are actually executed via a unique control signal, that is field voltage, the successful achievement for simultaneously improving the dynamic stability and voltage regulation might be impossible [17]. The coordination and trade-off between voltage regulation and damping enhancements are feasible solutions to the abovementioned issue. A coordinated design procedure is described in [18], thereby, the design of individual PSSs and AVRs is separated and coordinated to achieve a near-optimal overall power system stability performance. In [19], a new comprehensive criterion for the coordinated AVR–PSS design method is proposed for trading-off between voltage regulation and small signal stability in large-scale power systems.

In this paper, a new fuzzy logic excitation controller (FLEC) is designed to enhance excitation control by online coordination between AVR and PSS control tunnels. Although AVR and PSS are both exerted on the exciter, their primary aims differ from each other during the two different stages after a disturbance. The generator bus voltage will be strongly deviated by a nearby transmission line short circuit fault. Therefore, the AVR needs to respond right away in order to maintain the desired voltage. After a relative long period after the disturbance, the PSS is then primarily needed to damp the ongoing oscillations. Consequently, the proposed method automatically achieves the trade-off between AVR and PSS controllers by dynamically adjusting their participation factors via a supplementary proportional component of which the weights are tuned based on online measurement and a fuzzy logic controller. The advantages therein are that the existing AVR and PSS controllers need no modification. Therefore the upgrading can be accomplished conveniently with an expected improvement of the overall control performance.

The rest of the paper is organized as follows. In Section 'Structural design of new excitation controller', the structure of the conventional AVR and PSS controllers are introduced and then the FLEC is illustrated by a supplementary proportional component in which the proportionality factors can be adaptively tuned based on online measurements. The fuzzy logic rules and the detailed implementation of the fuzzy controller are explicitly illustrated in Section 'Design of fuzzy logic controller'. In Section 'Simulation results', a single machine infinite bus (SMIB) power system and a multi-machine power system both equipped with the FLEC controller are tested, in which the PSS are parameterized by the above-mentioned linear optimal control method and conventional pole assignment method, respectively. Numerical simulation results show the effectiveness and feasibility of the proposed method. Some conclusions are drawn in Section 'Conclusion'.

Structural design of new excitation controller

The structure of the classical excitation controller

Excitation control system usually can be described as Fig. 1, ΔV_t is the deviation between terminal voltage and the reference value.

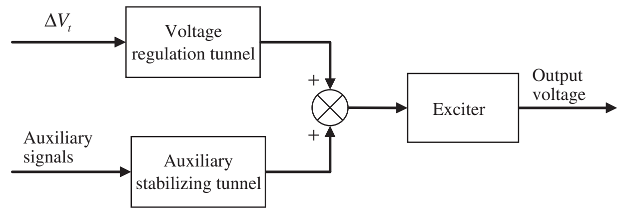

Fig. 1. Excitation system schematic diagram.

The auxiliary signals, normally PSS controller, generally include the deviations of rotor speed, active power and the change rate of speed deviations.

In excitation control system design process, voltage regulation and damping control are the two important goals, which are of great importance for the performance of the controller. The AVR controller, normally tuned by PID method, has excellent performance and high steady state accuracy in voltage regulation [20]. However, it cannot provide sufficient damping torque when the system is subjected to oscillations. Therefore, PSS control tunnel is needed to improve the dynamic stability performance. In design of the conventional PSS, the AVR tunnel is designed as the main tunnel and also taken its negative impacts on dynamic stability into account. This meets the demand of voltage regulation and enhances the dynamic stability in some extent. However, it is hard to choose the optimized control parameters and the controller has bad robustness and low convergence for variation of model parameters. And worse still, it is lack of coordination among different generators. All these defects limit its practical applications [21]. In design of the linear optimal excitation controller (LOEC), AVR tunnel and PSS tunnel are put together with fixed coefficients which are calculated according to a certain steady state. Its performance can satisfy the requirements of dynamic stability in a range of operating conditions, but it cannot meet the requirements of voltage regulation very well.

The proposed new FLEC aims to enhance the excitation controller's performance by coordinating two control tunnels on-line. The AVR tunnel is still based on PID method which uses the generator terminal voltage deviation, ΔV_t, as the feedback signal. The transfer function of the voltage regulation tunnel is

$$G(s) = \frac{y(s)}{\Delta V_t(s)} = K_P + \frac{K_I}{s} + K_D s \quad (1)$$

where K_P is proportional coefficient, K_I is integral coefficient and K_D is differential coefficient, y is the output control signal.

The auxiliary stabilizing tunnel is designed to provide damping torque which can be calculated based on linear optimal control theory or pole assignment methods. A linear optimal control method will be presented in the sequel.

Design of auxiliary stabilizing tunnel

The function of the auxiliary stabilizing tunnel, or PSS tunnel, is dedicated to increase damping torque, and then improve the dynamic stability of the whole system. A linear optimal control method is proposed herein for the auxiliary stabilizing control design in the SMIB system, ΔV_t, $\Delta\omega$ and ΔP_e are input variables, and their corresponding coefficients are determined by linear optimization method. It combines system state variables and non-state variables, according to the principle of minimum variable deviation and the least cost control rules, to determine a control variable vector. The behavior of a power system can be described by a set of nonlinear ordinary differential equations. Through appropriate transformations and simplifications, the