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Calculation of excitation system controllers to fulfill IEEE standard performance indexes

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ABSTRACT

A method to calculate the controller parameters for excitation systems is proposed in this paper. The controllers are designed to accomplish the performance indexes recommended in the IEEE std. 421.2, which characterize the conditions for the excitation control system to achieve a desired performance. To simplify the design process for the power plant engineers, the controller parameters are calculated using expressions derived from a two-loop standard excitation system model in terms of performance indexes: phase margin, damping ratio, overshoot, and settling time. In addition, the proposed method guarantees the excitation control system stability, which together with the fulfillment of the performance indexes, ensures the safe operation of the generation unit. Finally, the controller design procedure is validated by means of simulation and experimental results.

1. Introduction

The excitation systems play an important role in the power system stability. An adequate dynamic behavior in generator terminal voltage, reactive power, and power factor is largely due to the use of adequate control strategies in the excitation systems [1,2]. Complex control strategies have been proposed in excitation systems to guarantee an adequate dynamic behavior [3,4], however in the industry and facilities, simple techniques are preferred to avoid the requirement of specialized knowledge to the power plant engineer.

In this way, advanced control theory requires a complex model of the excitation system leaving out standard or recommended excitation system models [5]. Another tendency in advance control of excitation systems is the use of computational intelligence [1,2,6–9]. Such a theory provides an approach to solve the stability problems in systems that are difficult to model by means of traditional equations. For example, [6] presents a neuro-controller trained by a back-propagation algorithm, which improves the dynamic response in comparison with classical PI or PID controllers; but specialized knowledge of the power plant is required to define the initial neural-net parameters to avoid dangerous transient responses at the startup. Other authors present the combination of intelligence computational algorithms and classical PID or fractional order PID controllers. Such works present methodologies to adjust the PI or PID parameters by means of intelligent algorithms [1,2,7–10]. In those cases, a good performance in the regulating voltage is showed, but specialized knowledge is required: initial weight for the neural network [2,7], trails in ant colony algorithms [9], fitness function in genetic algorithms [11], population size in swarm optimization [10], and rules in fuzzy technique [1,2,8].

Currently the PI and PID controllers are widely used in excitation systems [1,2,7–12] since the design of such controllers is simple and well known [11]. The challenge in the PI and PID design consists in providing satisfactory dynamic performance and system stability using standard models.

The excitation system models and the dynamic performance requirements are standardized by IEEE [5,13]. Additionally, the last updating of the IEEE Recommended Practice for Excitation System Models for Power System Stability Studies [5] includes PI and PID controllers which are commonly used in modern excitation systems. The adoption of standard models and performance indexes is useful for stability analysis, since they are commonly used by power plant and planning engineers, and also they are available in analysis software packages.

In this paper a method to calculate the controller parameters for excitation systems is proposed. The controllers are designed to

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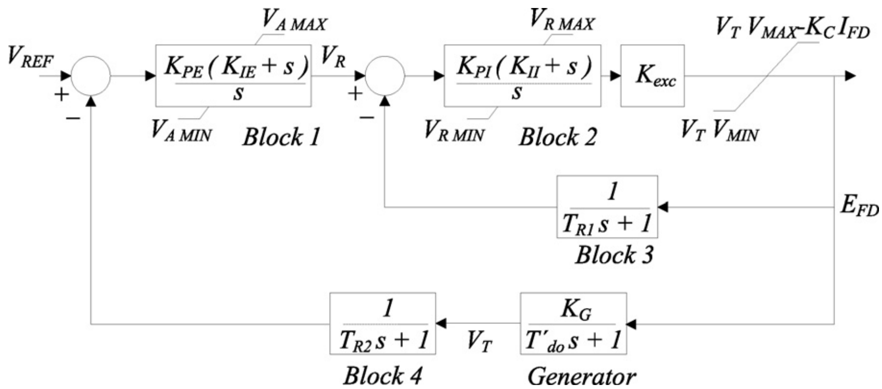

Fig. 1. Excitation control system model.

accomplish the performance indexes recommended in the IEEE std. 421.2-1990, and to operate within protection limits. To simplify the design process to the power plant engineers, the controller parameters are calculated using expressions derived from the standard excitation system model and the recommended performance indexes. In addition, the excitation control system stability is demonstrated and verified. Additionally, a flow diagram is presented to follow the design in both control loops. Finally, the procedure is applied to an experimental setup obtaining satisfactory results.

The rest of the paper is organized as follows: In Section 2, the excitation system model is given. Then, Section 3 presents the design of the generator field voltage controller and, the design of the generator terminal voltage controller is given in Section 4. Section 5 shows an application example and finally the conclusions are given in Section 6.

2. Excitation control system model

The excitation control system model adopted in this study was selected from the IEEE Recommended Practice for Excitation System Models for Power System Stability Studies [5], and it is depicted in Fig. 1. The exciter was extracted from the model ST1A and the controller from the model ST4B. In the model, the synchronous generator in offline operation is represented by a first order system [13], and blocks 1 and 2 are PI regulators. The first one represents the terminal voltage regulator and the second one represents the field voltage regulator. Each regulator also includes a non-windup integral function. The methodology proposed in this paper is intended to calculate the proportional and integral gains of the internal and external controllers, K_{PI}, K_{II}, K_{PE}, and K_{IE}, to fulfill desired performance indexes. Blocks 3 and 4 represent the field and terminal voltage signal filters, respectively. K_{exc} is the gain of the exciter, which represents the gain of the bridge rectifier and its linearization. The positive and negative limits of the field voltage are modeled. The generator is represented by a first order system, which includes a gain K_G and the direct-axis open-circuit time constant T'_{do} [13].

3. Generator field voltage controller

From the block diagram of Fig. 1, an internal controller for the excitation system is needed. The excitation system actuator is modeled by means of the bridge rectifier gain K_{exc}. Moreover, the field voltage signal filter also includes the fast dynamics of the bridge rectifier (10 ms), since its time constant is calculated from the step response of the field voltage to a perturbation in the bridge rectifier input signal. The dynamics of the bridge rectifier and field voltage signal filter $G_{IS}(s)$ is represented by block 3, given in (1), and the commonly adopted PI controller $G_{IC}(s)$ is represented by block 2 given in (1), which is also recommended by the IEEE standard 421.5 [5].

$$G_{IS}(s)=\frac{1}{T_{R1}\cdot s+1},\quad G_{IC}(s)=\frac{K_{PI}(K_{II}+s)}{s} \tag{1}$$

From Fig. 1, the exciter closed loop transfer function is given by:

$$T_I(s)=\frac{K_{PI}\cdot K_{exc}[T_{R1}\cdot s^2+(K_{II}\cdot T_{R1}+1)s+K_{II}]}{T_{R1}\cdot s^2+(K_{PI}\cdot K_{exc}+1)s+K_{PI}\cdot K_{II}\cdot K_{exc}} \tag{2}$$

In (2) it is noted that a positive K_{II} parameter is required to avoid a non-minimum phase behavior that leads to undesired performance or complex control requirements [14]. In addition, since the time constant T_{R1} and gain K_{exc} are always positive, and $K_{II}>0$ is adopted for minimum phase behavior, K_{PI} must be positive to avoid closed loop instability in agreement with the Routh–Hurwitz stability criterion [15].

3.1. Controller parameter design based on phase margin requirements

To provide more detailed information about the system behavior, a relative stability analysis based on gain and phase margins is provided. The gain margin GM_i is measured at the frequency w_{ig} where $\angle GH_i(s)|_{s=j\cdot w_{ig}}=-\pi$ rad [15], $GH_i(s)=G_{IC}(s)\cdot G_{IS}(s)\cdot K_{exc}$ is the loop transfer function:

$$GH_i(s)=\frac{K_{PI}\cdot K_{exc}(K_{II}+s)}{s(T_{R1}\cdot s+1)} \tag{3}$$

Frequency w_{ig} is derived from (4), where applying the arctan() function, there is not a real and positive w_{ig} (5), therefore the PI controller provides an infinite gain margin GM_i to the internal closed loop system.

$$\angle GH_i(s)|_{s=j\cdot w_{ig}}=\arctan\left(\frac{w_{ig}}{K_{II}}\right)-\arctan\left(\frac{w_{ig}}{-w_{ig}{}^2\cdot T_{R1}}\right)=-\pi \tag{4}$$

$$w_{ig}{}^2=-\frac{K_{PI}}{T_{R1}}<0,\quad \forall K_{PI}>0 \tag{5}$$

Taking into account that the loop transfer function $GH_i(s)$ exhibits a real zero $Z_I=-K_{II}$, a real pole $P_{I1}=-1/T_{R1}$, and an integrator $P_{I2}=0$, the phase of $GH_i(s)$ is constrained to $-\pi$ rad $\leq\angle GH_i(s)\leq 0$ rad. Such limits are defined by the contribution of $-\pi/2$ rad provided by the integrator to the loop phase, and the minimum and maximum phase contributions of the real zero [0, $\pi/2$] rad, and real pole [$-\pi/2$, 0] rad. From the phase margin definition (6) [15], where w_{ip} is the frequency where the loop gain $|GH_i(s)|_{s=j\cdot w_{ip}}|=1$, and taking into account the loop phase constraints [$-\pi$, 0] rad, the phase margin PM_i of the exciter closed