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Optimal Tuning of the Automatic Voltage Regulator- A General Approach

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SUMMARY

There are several publications in the literature describing the various techniques for the tuning of the automatic voltage regulators (AVRs), [1-12]. The aim of tuning is to determine AVR control parameters to meet performance specifications for the generator in both off-line and on-line operation. The present paper introduces and provides a generalized methodology and analytical basis for optimum tuning of AVR, which provide a set of parameters for the AVR model. Understanding automatic voltage regulators (AVR), its limiters/protection functions and tuning requires familiarity with excitation systems and the role of AVRs in power systems. The present paper discusses the fundamentals of excitation systems and stability of the AVR control system and finally describes the framework for AVR tuning. The developed methodology is then, applied to tune an AVR of a synchronous condenser.

KEYWORDS

Excitation system, automatic voltage regulator, stability of control system, optimal tuning, nonlinear constraints optimization techniques, synchronous condenser.

Excitation System and Control

The main role of an excitation system is to supply direct current to the synchronous machine field winding. In addition, the excitation system performs control and protective functions important to the satisfactory performance of the power system by controlling the field voltage and thereby the field current. The control functions include the control of voltage and reactive power flow, and the enhancement of power system stability. The protective functions ensure that the capability limits of the synchronous machine, excitation system, and other equipment are not exceeded. The role of the excitation system is expanded by using an auxiliary stabilizing input (power system stabilizer, PSS), in addition to the terminal voltage error signal, to mainly damp electromechanical oscillations (see Figure 1).

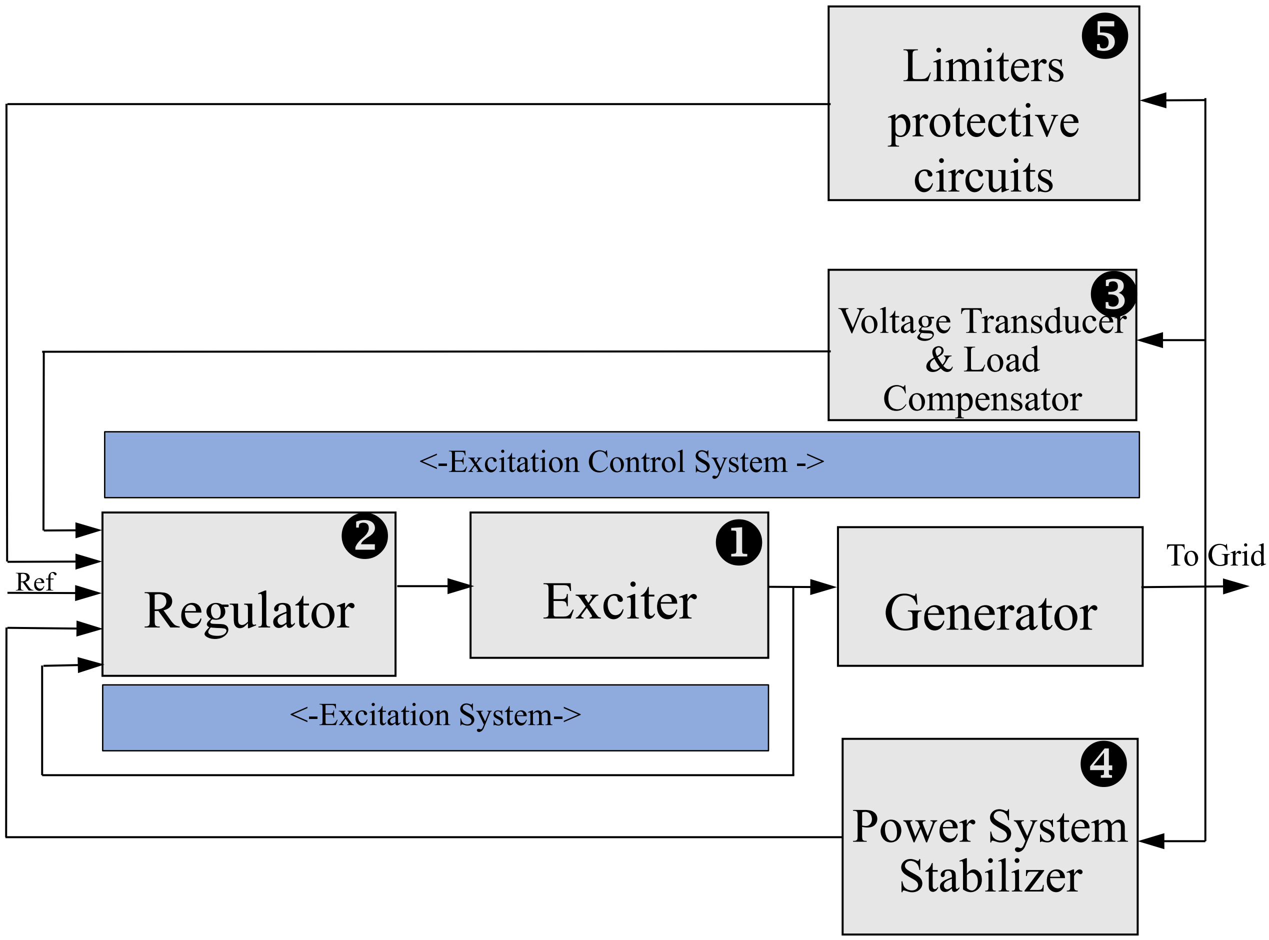

Figure 1: Generator and Excitation System

The IEEE Standard 421.1 [13] defines the excitation control system (ECS) as the feedback control system that includes the synchronous machine and its excitation system. The excitation control system as well as the excitation system (ES) are shown in Figure 1. The main power source is the exciter, however, the 'regulating, control, and protective elements' are referred to as the 'synchronous machine regulator'. Synchronous machine regulator is referred to as the 'automatic voltage regulator' or AVR. A component of the AVR is the compensating control provided to ensure that the excitation control system satisfies certain steady-state and dynamic performance criteria for the unit off and on-line. The main objective in 'AVR tuning' is to determine the parameters of the appropriate compensator which satisfy the design criteria. The block diagram of the excitation control system, which forms the basis for the analysis is shown in Figure 2 (a simplified static exciter is shown). When the generator is on-line the transfer function $G_{gen}(s)$ includes the dynamics associated with the external power system. When the unit is off-line it is assumed to be under closed loop voltage control and operating at rated voltage at synchronous speed. It should be noted that the dynamic behaviour of the excitation system and generator differ significantly when off- or on-line under closed-loop voltage control.

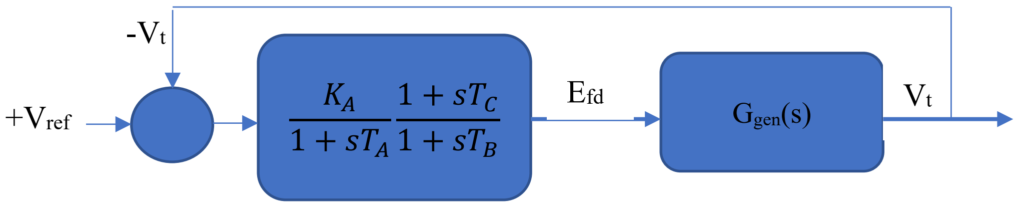

Figure 2: Simple Excitation System

Opened-loop frequency response characteristics are useful in determining gain and phase margins, both of which are measures of relative stability. Relative stability of a closed-loop control system can be determined from the properties of the Bode plot of the opened-loop transfer function. However, this method can be used only if the opened-loop transfer function has no poles and zeroes in the right half S-plane (minimum phase characteristics).

The peak value (Mp) of the terminal voltage to voltage error in the closed-loop frequency response is also a measure of relative stability. A high value of Mp (greater than 1.6 dB) is indicative of an oscillatory system exhibiting large overshoot in its transient response. Generally, Mp less than 1.6 dB and greater than 1.1 dB is considered good. Figure 3 shows the closed loop response for different AVR parameters. 3dB bandwidth (ω_B, shown in Figure 3 for Ka=600, TB1=10 and TC1=2.5) is an important closed-loop frequency response performance index because it is indicative of the rise time T_r. It measures, in part, the ability of the system to reproduce input signals. In feedback control systems having a step response exhibiting less than 10% overshoot, rise time T_r in seconds is related to bandwidth ω_B in hertz approximately by: $T_r * \omega_B = 0.3 - 0.45$.

Table 1: AVR tuning design criteria

Gain margin	≥ 6 dB
Phase margin	≥ 40°
Overshoot	0-15%
Peak value, M_p	1.1-1.6 dB
Damping ratio	≥ 0.6
$T_r * \omega_B$	0.3 (negligible overshoot) - 0.45(10% overshoot)

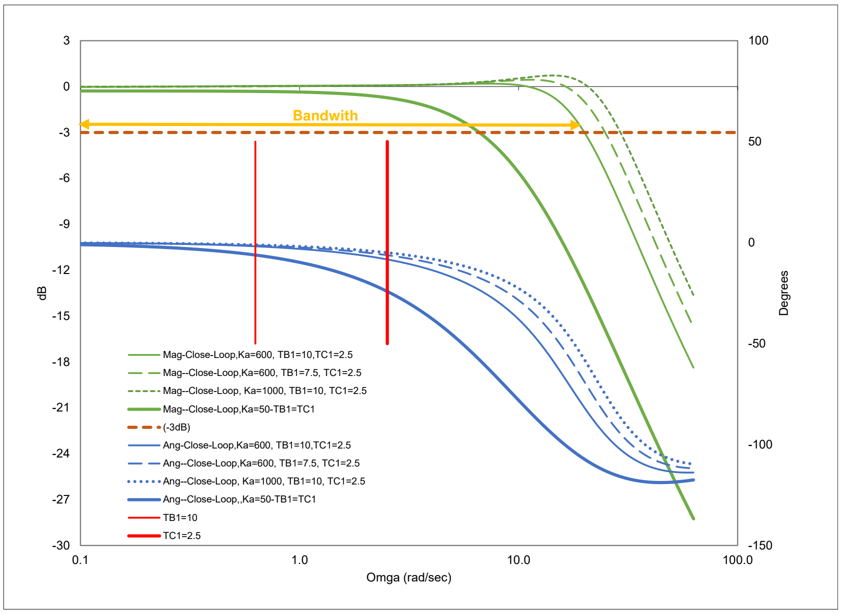

Figure 3: Close-Loop frequency response for different AVR parameters

Fast excitation response is beneficial for transient stability because generator terminal voltages see less voltage depression for less time during and after network faults. Such speed of excitation response can, however, cause problems for damping. We will use Figure 4 to analyze the stability behavior of the machine. This analysis is based on the following observations made from the block diagram.

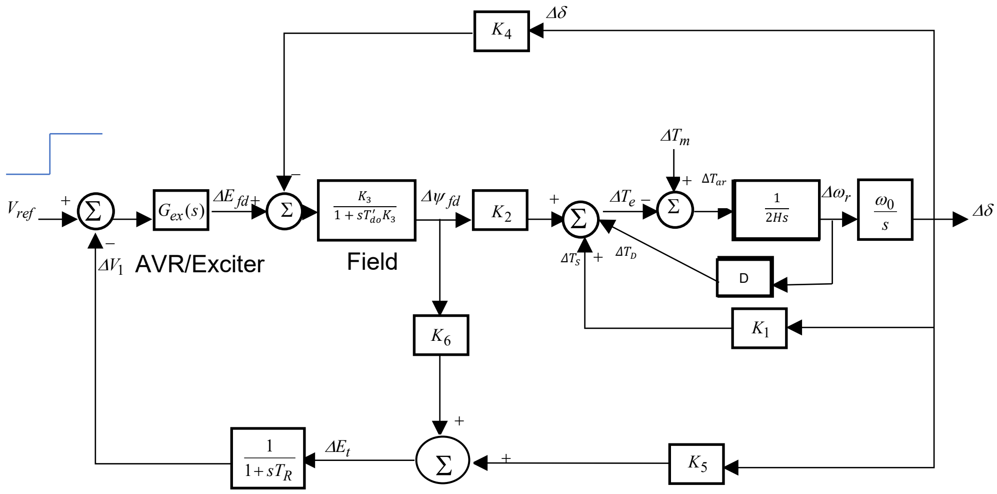

Figure 4: Linearized generator and excitation system control block

- ΔTd, the damping torque, is in phase with speed deviation Δω.
- ΔTs, synchronizing torque, is in phase with angle deviation Δδ. We call this synchronizing torque because the higher it is, the more “stable” the machine will be with respect to loss of synchronism.

Large K_1 means low loading, as indicated by the fact that K_1 is the slope of the tangent to the power-angle curve at the operating point (this applies exactly to the application in this paper since the AVR is to be tuned for a synchronous condenser).

Generalized Approach to AVR Tuning

The power system consideration requires excitation system to effectively control system voltage and enhance power system stability. To fulfil the above roles satisfactorily, the excitation system must satisfy the following requirements:

- meet specified response (design) criteria such rise time (T_r), settling time (T_s), overshoot (O_S), etc.
- provide limiting and protection to prevent damage to itself, the generator, and other equipment
- meet specified requirements for operating flexibility
- meet the desired reliability and availability

The understanding of the control system behaviour allows for translating the control objectives and constraints into a mathematical model which can be solved by suitable optimization technique. The present paper utilizes a non-linear optimization technique available in common Python libraries. The Integral Square Error (ISE) method is used to formulate the objective function:

$$\underset{x}{\text{Minimize}}\ \text{error} = \int_{t_i}^{t_f} f(x,t)^2 dt \qquad \textit{Suject to}:$$

$$g(x,t) \le 0$$

$$x_{min} \le x \le x_{max}$$

The error is the difference between applied step and the AVR response (see Figure 5). Overshoot is used as a performance criterion in this paper, for instance, no overshoot or overshoot less than a certain percentage. Another important parameter is the settling time, which is defined as a time needed to achieve a new steady state with a specified accuracy. The settling time can also be used in controller tuning procedures. Hence, depending on the controller parameters, a new steady state can be achieved either quickly with overshoots (damped oscillations), which is actively expensive and increases wear on control equipment, or without over- shoot (non-oscillatory response) for longer settling times. The critical case is a borderline case between the oscillatory and non-oscillatory responses.

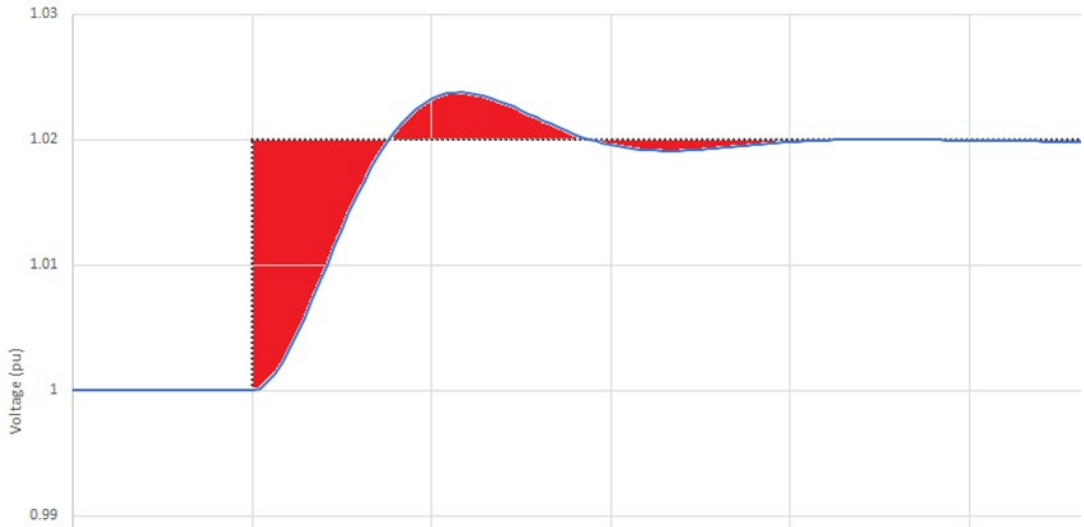

Figure 5 : Error between applied step and generator terminal voltage

We have also formulated the optimization as a Pareto optimization (multi-objectives, [17]) in the following linearized form:

$$\underset{x}{\text{Minimize}}\ a_1 \int_{t_i}^{t_f} f(x,t)^2 dt + a_2 * T_r + a_3 * T_s + a_4 * O_s$$

Our experience, so far, shows weighting factor for different objectives $a = [1.0\ 6.0\ 1.0\ 1.0]$ to be satisfactory.

Application of the Proposed Methodology

The framework for the proposed AVR tuning, which is coded in Python, is shown in Figure 6. Initialization consists of registering and loading different application DLLs including a time domain simulation, Python library, etc. Next all the necessary data files required for the time simulation are assembled. The optimization routine used in this study is based on the BFGS technique (Broyden–Fletcher–Goldfarb–Shanno). The optimization will repeatedly call two user-defined functions to evaluate the objective function and constraints respectively. The objective and constraints functions in turn, in a coordinated fashion, will execute the time domain simulation for the newly defined optimization variables (X_{i+1}). Once optimal feasible solution is found, then, on-line step response of the tuned AVR as well fault performance is assessed. The present tuning technique was used to tune AVR of a synchronous condenser. The synchronous condenser is equipped with a static excitation system and the AVR of the unit was recently upgraded with a new controller, IEEE model ESST1A [18]. The main parameters selected for tuning are the gain (KA), T_B and T_C. The ratio between lead and lag is called transient gain reduction (TGR=T_C/T_B) which is employed to reduce gain (at higher frequency) without any reasonable reduction in the DC gain. The time constants T_B and T_C are also a design issue such that $T_B > T_C$. If the open loop gain is around 20 dB (without the TGR block) at 10 rad/s, then T_B and T_C are chosen in such a way that at higher frequencies the gain is reduced by 20 dB, which is by placing the zero and pole one decade apart. Furthermore, the net phase due should be approximately zero near the cross-over frequency. It is clear from theoretical considerations that a TGR acts as a damper without affecting the steady-state error.

Figure 7 shows step response of the closed loop of the exciter for a few intermediate results. The effect of increasing gain and using TGR to prevent over-shoot can be seen clearly.

Conclusion

In this paper, we have presented a general approach for tuning automatic voltage regulator of an excitation system. The methodology is not limited to AVR tuning and can be extended to any control system (e.g., wind/solar farm plant controller) in power system if performance criteria (optimization objective) can be evaluated using any commercial or publicly available time domain software.

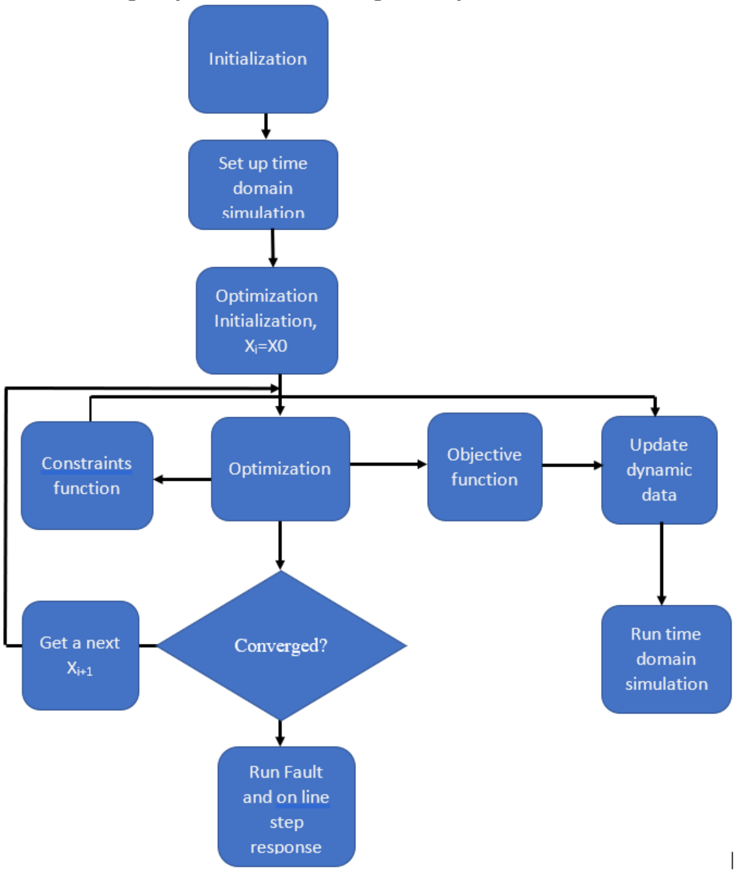

Figure 6: AVR Tuning Process flow

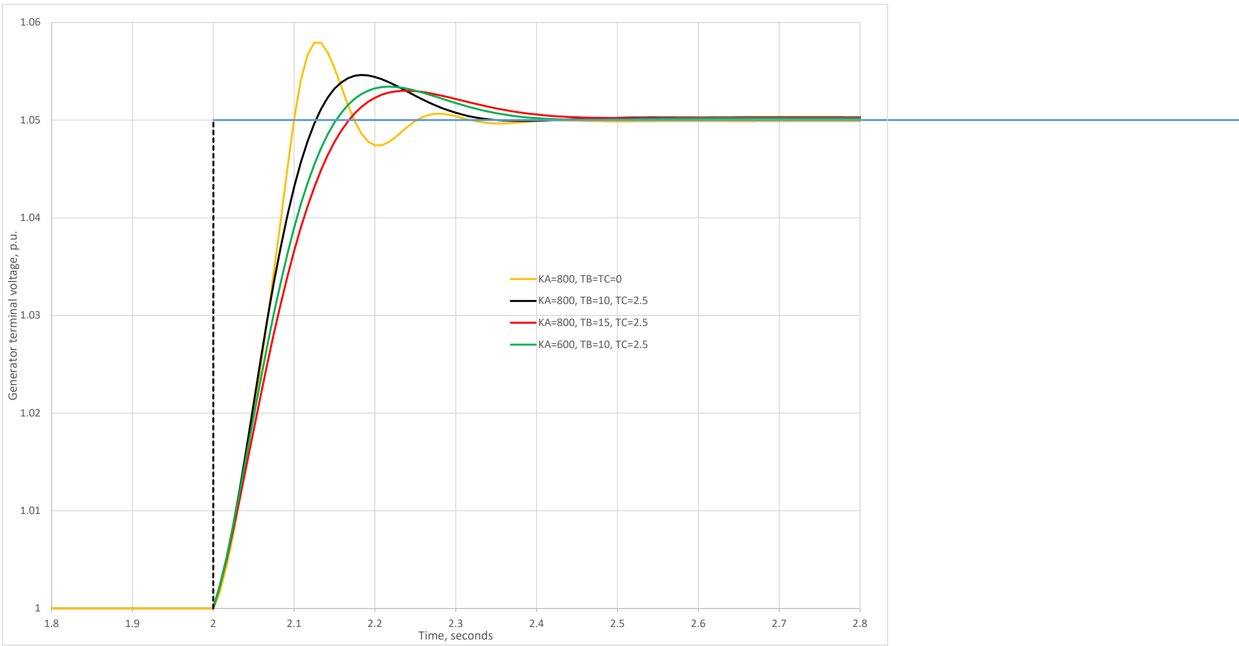

Figure 7: Generator voltage step response for several AVR settings

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