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Analysis and Simulation of the AVR System and Parameters Variation Effects

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Abstract- **The primary role of an automatic voltage regulator (AVR) is to regulate the reactive power and voltage magnitude. The system modeled consists of the amplifier, exciter, sensor and stabilizer or proportional-integral-derivative (PID) controller. The state-space technique is used to model the system. Their characteristics and behavior are also briefly discussed. Results of the simulation studies on the AVR system using Matlab are presented. By examining the parameters of the stabilizer and controller, the generator terminal voltage variations are predicted.**

I. INTRODUCTION

The reactive power is one of important factors for exploitation and designing in the power system. The balance of reactive power in the system implies constant output voltage. The most common strategies for the reactive power and voltage control can be classified as injection of reactive power by shunt compensator, displacement of reactive power in the system by tap changing transformers and reducing inductive reactance of the lines by series capacitor. The AVR systems are used extensively in exciter control system. The primary means of generator reactive power control is the generator excitation control by AVR. The role of an AVR is holding the generator terminal voltage constant under normal operating conditions at various load levels [1]. The AVR loop of the excitation control system employs terminal voltage error for adjusting the field voltage to control the terminal voltage [2]. The basic components of an exciter control system comprises four main components namely amplifier, sensor, exciter and generator. Control principles for the AVR system have been described in a few publications [2-5]. A design method for determining the optimal proportional-integral-derivative (PID) controller parameters of AVR system using the particle swarm optimization algorithm is presented in [6]. In the present paper dynamic behavior and transient stability of AVR system with parameters variation are proposed. Also application of PID controller and stabilizer in the AVR system are discussed.

II. SYSTEM EQUATION

In the controller design for AVR systems, analytical model is important tools for the prediction of dynamic performance and stability limits with different control laws and system parameters. The block diagram of an AVR system compensated with a three-mode controller and a rate feedback is shown in Fig. 1,

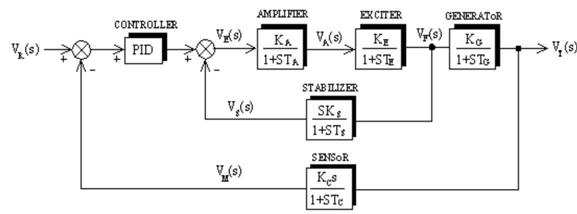


Fig. 1. Block diagram of the AVR system

where V_R, V_E, V_A, V_S, V_M, V_F and V_T denote the reference signal, voltage error signal, amplifier output voltage, feedback signal, sensor output voltage, field voltage and generator terminal voltage respectively. Also, (K_G, T_G), (K_A, T_A), (K_E, T_E), (K_S, T_S) and (K_C, T_C) are gain and time constant of generator, amplifier, exciter, stabilizing and sensor, respectively. This is one of the important types of exciter control systems. This block diagram include multi linear block which shows the relationship between each input and output represent as transfer function. The transfer function relating the input and output variables of the amplifier, sensor, exciter, generator and stabilizer and ignores the nonlinearities due to exciter saturation and limits exciter output as shown in Fig. 1. Synchronous generator plays a very important role in the stability of the power systems. The generator block showing the effects of changes the field voltage on the generator terminal voltage, can be developed from synchronous machine equations [7, 8]. A PID controller with following transfer function can be added in the forward path of the AVR system as shown in Fig. 1:

$$G_T(s) = K_P + K_D s + \frac{K_I}{s} \tag{1}$$

where K_P, K_I and K_D are proportional, integration and derivative constant, respectively. The closed-loop transfer function from the terminal voltage to the reference signal is given by:

$$T(s) = \frac{V_T(s)}{V_R(s)} = \frac{G_A(s)G_E(s)G_G(s)G_T(s)}{1 + G_A(s)G_E(s)[G_S(s) + G_G(s)G_C(s)G_T(s)]} \tag{2}$$

The amplified error signal controls the exciter filed and increases the exciter terminal voltage. If V_R is raised (or dropped), V_E goes up (or down), V_R increases (or decreases), V_F increases and V_T tends to increase. If V_T changes because of load, a correcting action is achieved [9]. The differential equations are expressed in the following matrix form $\dot{X} = AX + BU$ and $Y = CX$, where A is the system matrix, B is the control matrix, X is the state variables vector, U is the input vector and C is the output matrix. The limits of the variation of system parameters values are given in Table I.

TABLE I: Typical values for parameters

Parameter	Typical value	Nominal value
T_G	1 – 2	1.5 s
K_G	0.7 – 1	0.8
K_A	10 – 400	10
T_A	0.02 - 0.1	0.05 s
K_E	10 – 400	10
T_E	0.5 – 1	0.5 s
K_S	0.02 – 0.1	0.1
T_S	0.35 - 2.2	0.4 s
T_C	0.01 – 0.06	0.05 s

A AVR system with stabilizer

One of the prime reasons for the utilization of a stabilizer in AVR system is to increase the relative stability. By choosing $Y=[v_T]$, $U=[v_R]$ and $X=[v_T\ v_F\ v_A\ V_S\ v_M]^T$, matrices A, B, C and D for AVR system with stabilizer will be given as follows:

$$A=\begin{bmatrix} -\frac{1}{T_G} & \frac{K_G}{T_G} & 0 & 0 & 0 \\ 0 & -\frac{1}{T_E} & \frac{K_E}{T_E} & 0 & 0 \\ 0 & 0 & -\frac{1}{T_A} & -\frac{K_A}{T_A} & -\frac{K_A}{T_A} \\ 0 & -\frac{K_S}{T_S T_E} & \frac{K_S K_E}{T_E T_S} & -\frac{1}{T_S} & 0 \\ \frac{K_C}{T_C} & 0 & 0 & 0 & -\frac{1}{T_C} \end{bmatrix} \tag{3}$$

$$B=[0\quad 0\quad K_A/T_A\quad 0\quad 0]^T \tag{4}$$

$$C=[1\quad 0\quad 0\quad 0\quad 0]^T \tag{5}$$

The characteristic equation is as follows:

$$\Delta_S(s)=s^5+c_4 s^4+c_3 s^3+c_2 s^2+c_1 s+c_0 \tag{6}$$

where:

$$c_4=\frac{1}{T_A}+\frac{1}{T_S}+\frac{1}{T_E}+\frac{1}{T_G}+\frac{1}{T_C} \tag{7}$$

$$c_3=(\frac{1}{T_G}+\frac{1}{T_C})(\frac{1}{T_E}+\frac{1}{T_S}+\frac{1}{T_A})+\frac{1}{T_G T_C}+\frac{1}{T_S T_A}+\frac{1}{T_E T_S}+\frac{1}{T_A T_E}+\frac{K_S K_E K_A}{T_A T_E T_S} \tag{8}$$

$$c_2=(\frac{1}{T_G}+\frac{1}{T_C})(\frac{1}{T_A T_S}+\frac{1}{T_E T_A}+\frac{1}{T_S T_E})+\frac{1}{T_G T_C}(\frac{1}{T_A}+\frac{1}{T_S})+\frac{K_S K_A K_E}{T_A T_E T_S}(\frac{1}{T_E}+\frac{1}{T_G})+\frac{1}{T_A T_E T_S} \tag{9}$$

$$c_1=\frac{1}{T_A T_S T_E}(\frac{1}{T_G}+\frac{1}{T_C})+\frac{K_C K_G K_E K_A}{T_G T_A T_C T_E}+\frac{1}{T_G T_C}(\frac{1}{T_A T_S}+\frac{1}{T_E T_A}+\frac{1}{T_S T_E})+\frac{K_S K_E K_A}{T_G T_S T_A T_C T_E} \tag{10}$$

$$c_0=\frac{1+K_C K_G K_E K_A}{T_G T_A T_C T_E T_S} \tag{11}$$

The closed-loop transfer function for AVR system with stabilizer is given by:

$$T(s)=\frac{1}{\Delta_S(s)}\frac{K_A K_E K_G}{T_G T_E T_A}[s^2+(\frac{1}{T_S}+\frac{1}{T_C})s+\frac{1}{T_S T_C}] \tag{12}$$

B AVR system with PID controller

The signal flow graph of the AVR system with a PID controller is shown in Fig. 2. It is a fifth-order system and by choosing five state variables (x_1, x_2, x_3, x_4, x_5), matrices A, B,

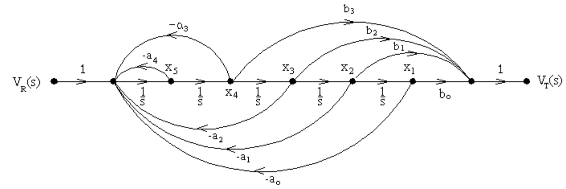


Fig. 2. The signal flow graph of the AVR system

C and D for AVR system with PID controller will be given as follows:

$$A=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ -a_o & -a_1 & -a_2 & -a_3 & -a_4 \end{bmatrix} \tag{13}$$

$$B=[0\quad 0\quad 0\quad 0\quad 1]^T \tag{14}$$

$$C=[b_o\quad b_1\quad b_2\quad b_3\quad 0]^T \tag{15}$$

$$a_4=\frac{1}{T_G}+\frac{1}{T_C}+\frac{1}{T_A}+\frac{1}{T_E} \tag{16}$$

$$a_3=\frac{1}{T_G T_C}+\frac{1}{T_A T_E}+\frac{1}{T_E T_C}+\frac{1}{T_G T_E}+\frac{1}{T_A T_C}+\frac{1}{T_G T_A} \tag{17}$$

$$a_2=\frac{T_A+T_E+T_G+T_C+K_D K_A K_E K_G K_C}{T_A T_E T_G T_C} \tag{18}$$

$$a_1=\frac{K_P K_A K_E K_G K_C+1}{T_A T_E T_G T_C} \tag{19}$$

$$a_o=\frac{K_I K_A K_E K_G K_C}{T_A T_E T_G T_C} \tag{20}$$

$$b_3=\frac{K_A K_E K_G K_D}{T_A T_E T_G} \tag{21}$$

$$b_2=\frac{K_A K_E K_G(K_P T_C+K_D)}{T_A T_E T_G T_C} \tag{22}$$

$$b_1=\frac{K_A K_E K_G(K_I T_C+K_P)}{T_A T_E T_G T_C} \tag{23}$$

$$b_o=\frac{K_I K_A K_E K_C}{T_A T_E T_G T_C} \tag{24}$$

when a PID controller is used for the AVR system, the closed-loop transfer function from $V_T(s)$ to $V_R(s)$ is given by:

$$T(s)=\frac{1}{\Delta_T(s)}\frac{K_A K_E K_G}{T_A T_C T_E T_G}[K_D T_C s^3+(K_D+K_P T_C)s^3+(K_I T_C+K_P)s+K_I] \tag{25}$$

where $\Delta_T(s)$ is the closed loop characteristic polynomial and given by:

$$\Delta_T(s)=s^5+a_4 s^4+a_3 s^3+a_2 s^2+a_1 s+a_0 \tag{26}$$

III. EIGENVALUES ANALYSIS

The transient response and closed-loop feedback control system can be described in terms of the location of the poles of the transfer function. In the simplified AVR system without stabilizer and PID controller, the steady-state response is:

$$v_T(\infty)=\frac{K_A K_E K_G}{1+K_C K_A K_E K_G} \tag{27}$$

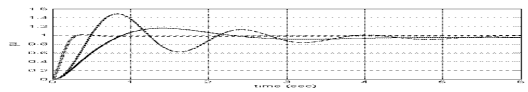


Fig. 3. Terminal voltage step response of an AVR system with PID (dot), stabilizer (solid) and without compensation (dash)

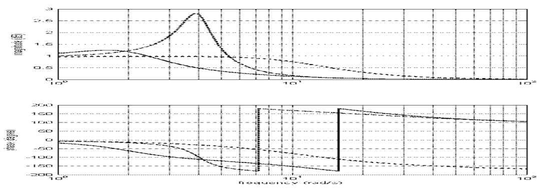


Fig. 4. Frequency response of terminal voltage an AVR system with PID (dot), stabilizer (solid) and without compensation (dash)

In order to obtain a small reduction of the steady-state error, K_A, K_E, K_G and K_C must be increased. However, a quite large gain results in an unstable control system. It is not possible to have a small steady-state error and a satisfactory transient response at the same time. For a simplified AVR system, the response is highly oscillatory, with a very large overshoot and a long settling time. The transient performance can be adjusted to satisfy the system specifications by adjusting the system constants. The transient response of the system is required to have an overshoot less than or equal to 10%. The original terminal voltage step responses of the AVR system and frequency response with and without compensation are compared in Figs. 3 and 4, respectively. The rise time is 0.30, 0.56, 0.20 s and the peak time is 0.83, 1.42, 0.40 s and the percent overshoot is 57.9, 23.1 and 1.8 for without compensation, with stabilizer and PID controller, respectively. The roots of characteristic equation and time domain performance for three different values of K_A, where the stabilizer loop and PID controller are given, have been summarized in Tables II and III. Figs. 5-6 show the response of an AVR system with stabilizer loop and PID controller in terms of change of K_A, where K_A=5 (dot), K_A=20 (solid) and K_A=40 (dash). The time constant of generator is large and able to make instability in the system. Fig. 7 shows the response of an AVR system with stabilizer loop, PID controller and without compensation in terms of change of T_G, where T_G=1 (dot), T_G=1.5 (solid) and T_G=2 (dash). Table IV lists some dominant eigenvalues when AVR system has been compensated. An increase of the generator time constant increases the both rise and peak time. Conversely, increasing the amplifier gain decreases the both the rise and peak time.

IV. CHANGE OF PID CONTROLLER PARAMETRAS

The analog PID controller is generally used for the AVR of the synchronous generator to improve the dynamic response as well as to reduce or eliminate the steady-state error. The derivative controller adds a finite zero to the open-loop plant transfer function and improves the transient response. The integral controller adds a pole at origin and increases the system type by one and reduces the steady-state error due to a step function to zero [1, 5]. In the AVR system with PID controller, the steady-state response is as follows:

TABLE II. Characteristic equation roots of AVR system for different values of K_A

	K_A=5	K_A=20	K_A=40
with stabilizer	−19.9	−19.8	−18.9
	$-4.2 \pm j3.0$	$-4.2 \pm j4.3$	$-4.3 \pm j5.1$
	$-0.9 \pm j1.5$	$-1.0 \pm j1.8$	$-1.4 \pm j2.0$
with PID controller	−36.5	−41.3	−45.1
	−20.0	−2.4	−2.3
	−0.2	−0.2	−0.2
	$-2.1 \pm j0.8$	$-8.5 \pm j7.5$	$-6.6 \pm j13.9$

TABLE III. Time domain performance of AVR system for different values of K_A

		K_A=5	K_A=20	K_A=40
with stabilizer	Rise time	0.781	0.572	0.395
	Peak time	1.915	1.501	1.090
	Overshoot	20.2%	26.6%	23.0%
with PID controller	Rise time	2.2	0.20	1.84
	Peak time	20	0.40	0.22
	Overshoot	-0.36	1.84	23.34

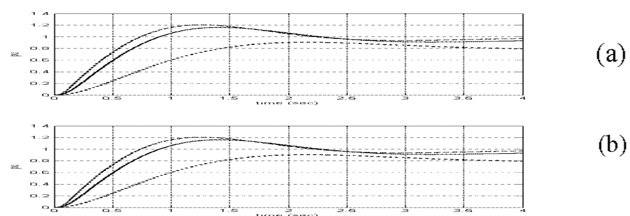
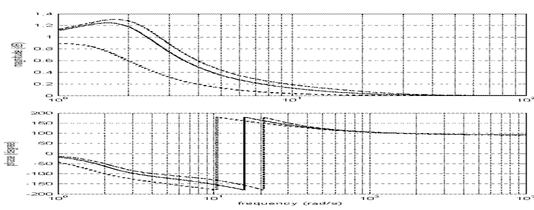
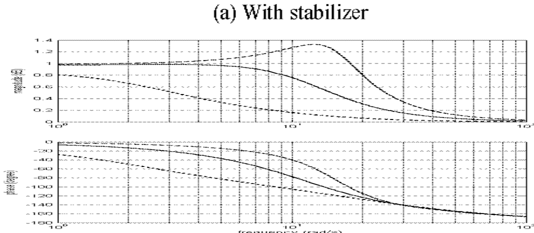


Fig. 5. Terminal voltage step response for AVR system for different values of K_A (a) With stabilizer (b) With PID controller



(a) With stabilizer



(b) With PID controller

Fig. 6. Frequency response of terminal voltage of an AVR system versus K_A change

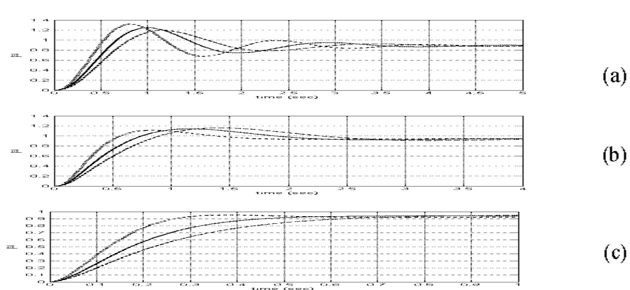


Fig. 7. Terminal voltage step response versus T_G change: (a) without compensation (b) with stabilizer (c) with PID controller

Table IV: Some dominant eigenvalue

T_G	Eigenvalue	Damping ratio	Frequency
1.0	-30.3±j3.8 -0.4±j5.5	0.992 0.073	30.54 5.51
1.5	-29.9±j2.1 -0.6±j4.5	0.998 0.132	29.97 4.54
2.0	-0.7±j4.0 -30.5 -29.0	0.172 - -	4.06 - -

$$v_T(\infty) = \frac{1}{K_C} \tag{28}$$

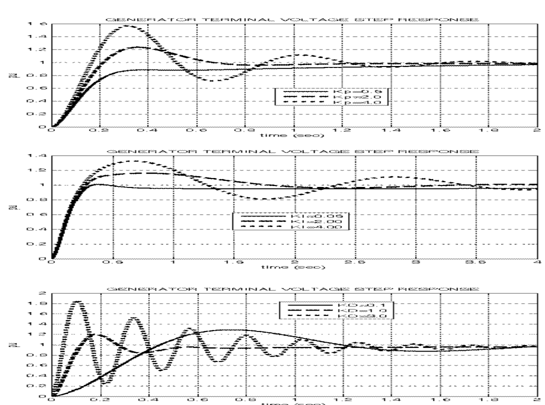
Fig. 8 shows the response of the AVR system with PID controller versus PID parameters change. Increase of K_P and K_D decreases both rise and peak time. Increasing K_I decreases the rise time and increases the overshoot percent. In fact changing one of these variables can change the effect of the other two; therefore K_P, K_I and K_D depend on each other.

V. THE CHANGE OF THE STABLIZER PARAMETRAS

The control loop with a rate feedback, have three time constants T_E, T_A and T_G. Ability to increase the relative stability by introducing a controller, which adds a zero to the AVR open-loop transfer function, is an important advantage of rate feedback control system. The stabilizer loop acts similar to derivative feedback which accelerates circuit response and stability system. In the AVR system with stabilizer, the steady-state response is as follows:

$$v_T(\infty) = \frac{K_A K_E K_G}{1 + K_A K_E K_C K_G} \tag{29}$$

The roots of characteristic equation AVR system with stabilizer loop for three different values of the stabilizing loop gain (K_S) and time constant (T_S) are given in Table V. Figs. 9 and 10 show the simulation results for changing K_S and T_S. From the results, it is realized that K_S and T_S variation affects the peak of the curve, settling time and overshoot, but has no effect on the final values of terminal voltage in a stable system. A higher value of K_S and lower value of T_S lead to small overshoot and short settling time. Increase of the stabilizer time constant decreases both rise and peak time. Conversely, increasing the stabilizer loop gain increases both rise and peak time and decreases the overshoot percent.



(a)

(b)

(c)

Fig. 8. Terminal voltage step response for AVR system in terms of PID parameters for (a) K_P change (b) K_I change (c) K_D change

Table V: Characteristic equation roots of a AVR system for different values of T_S and K_S

T_S=0.35	T_S=1.40	T_S=2.20
−32.5 −14.7 ± j9.7 −0.95 ± j1.8	−31.7 −25.4 −0.7 −1.9 ± j3.7	−31.4 −26.6 −0.5 −1.4 ± j3.9
K_S=0.02	**K_S=0.06**	**K_S=0.10**
−31.6 −25.6 −3.4 −1.4 ± j3.3	−32.2 −1.2 ± j2.0 −15.1 −13.6	−32.5 −14.5 ± j10.6 −0.9 ± j1.6

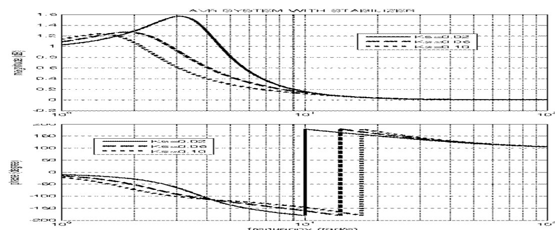


Fig. 9. Terminal voltage frequency response for K_S change

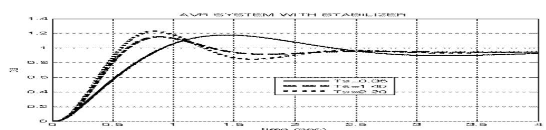


Fig. 10. Terminal voltage step response for T_S change

VI. CONCLUSION

In this paper, application of PID controller and stabilizer in exciter control system with variation in its time constant and gain was examined. By using PID controller and stabilizer, not only the system will have an appropriate steady-state error but also provides good dynamic response with a less over shoot for the voltage terminal. Finally, the AVR system was simulated and effects of some parameters were investigated.

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