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Enhancing the Transient Performance of AVR in Synchronous Generator Using PIDD Control System

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Abstract: *Automatic voltage regulator (AVR) is an essential component of power system that used to provide stable and reliable voltage profile from generator to load. Classical AVR may not effectively offer need stability and voltage quality required by a load connected to a generator because of its inability to manage the deviation of the output voltage from the desired voltage. Therefore, controllers are usually integrated with AVR. This is called AVR control system. However, most of the controller have used the popular proportional integral and derivative (PID) controller to enhance the transient performance of AVR and achieve stability and reliability in maintaining a given voltage level from generator to load. However, PID controller is usually propone to high oscillation and as such many modifications have been done in terms of tuning and structural realignment to its algorithm. In this paper, a PIDD controller was developed and used to enhance the transient performance of AVR in synchronous generator. An AVR system was modeled in MATLAB with PID controller and separately with PIDD controller. Simulation results revealed that the PIDD controller outperformed the PID controller by yielding settling time of 9.21 s against 13.8 s and overshoot of 4.85% against 18.3%.*

Keywords—AVR; Control system; PID; PIDD; Transient; Synchronous generator

1. INTRODUCTION

Automatic voltage regulators (AVRs) are vital components commonly used to achieve stability and maintain good voltage level in power systems. Its application can be as an electromechanical device, active or passive electronic components [1]. AVRs may be employed for regulating alternating current (AC) or direct current (DC) voltage [2]. Thus, it is required in practice that AVRs provide steady voltage level for connected loads within specific limits.

Because the voltage level at the output of a generator can be constantly changed by load variation, AVRs are usually used to provide permanent control. This is because for satisfactory mains power supply, keeping a constant voltage at the generator's output terminals is essential [1,3].The need for ensuring stable voltage at the generator's output terminal is because the terminal voltage can be impacted by disturbances like load variation, speed, temperature etc. For this reason, AVR system is utilized to guarantee voltage stability in power generation station. Nevertheless, without any control algorithm, AVR will give slow responses and might cause instability [4].

A system that offers minimum voltage error under unknown load fluctuation is often desired in power operating system. Taking this into consideration, AVR systems are usually design with a controller to enhance their operation by ensuring that the output voltage at the terminal is kept as close as possible to desired level of voltage to achieve minimal or zero deviation. The operation of AVR is such that when the generator's terminal voltage is disturbed because of the application of certain load the excitation field changes which can alter the voltage level at the terminal. Therefore, the controller is forced to act according to this deviation by producing a correctional action that coordinate the generator's exciter system.

The flexibility of AVRs has made it possible to use simple and complex control methods like ON/OFF switch control, proportional integral and derivative (PID) controller, nonlinear controllers, and intelligent based controllers to achieve reliable performance of the entire system for different working conditions of generator and loads. Among these controllers, the PID controller is the most commonly used in many control applications due to the fact that it is easy to design and simple to implement [5].

In this paper, a modified PID controller called proportional integral derivative and derivative (PIDD) control system is used to enhance the transient performance of AVR for voltage stabilization in synchronous generator.

2. LITERATURE REVIEW

In literature different control systems have been used to improve the transient characteristics of AVR in power systems. In [1], PID was used with prefilter to enhance AVR performance for synchronous generator set. Linear quadratic Gaussian tuned controller (LQGTC) was used to provide robust control for different range of AVR operating parameter [6]. Hybrid simulated annealing manta ray foraging optimization (SA-MRFO) algorithm was used to tune PID controller so as to provide optimal control for AVR [7]. Stability analysis of AVR was performed using proportional integral (PI) controller [8]. Discrete linear quadratic regulator (LQR) technique was used to provide optimal control for AVR system in synchronous generator exciter [9]. AVR control has been achieved using teaching learning based optimization (TLBO) tuned PID and two degree of freedom

(2DOF) PID controller [10]. The performance of different conventional control techniques such as PID controller, cascade controller and internal model controller (IMC) were presented and added separately in AVR closed loop system in [11]. Ziegler-Nichol (ZN), particle swarm optimized (PSO), and cuckoo search (CS) algorithms were used to optimize the parameters of PID controller for AVR [12]. In an attempt to address the problem of design efficient PID controller for AVR, symbiotic organism search (SOS) algorithm was used to optimize the parameters of the control variable [13]. PID control was used in AVR to improve voltage stability at Senkang power plant, South Sulawesi, Indonesia [14].

3. MATHEMATICAL EQUATION AND SYSTEM DESIGN

The closed structure of the linearized AVR system of synchronous generator exciter considered in this work is shown in Fig. 1.

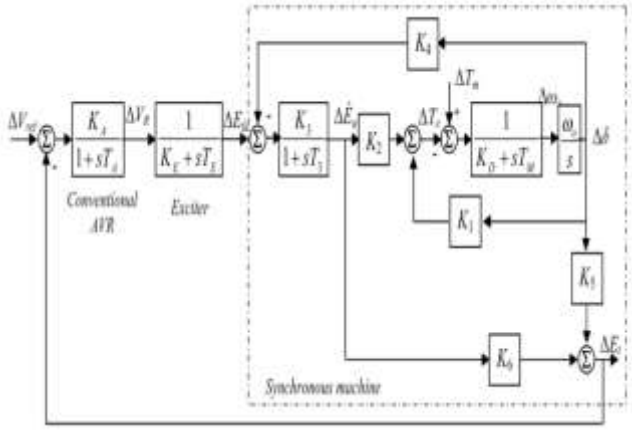

Fig. 1. *Linearized AVR system of synchronous generator exciter (Ibraheem, 2011)*

The AVR system shown in Fig. 1 consists of an amplifier circuit (conventional AVR), exciter, and synchronous generator. The objective is to design a PIDD controller to enhancing it performance at different voltage levels. The simplified circuit diagram with the PIDD controller is shown in Fig. 2. The parameters of the AVR system are given in Table 1.

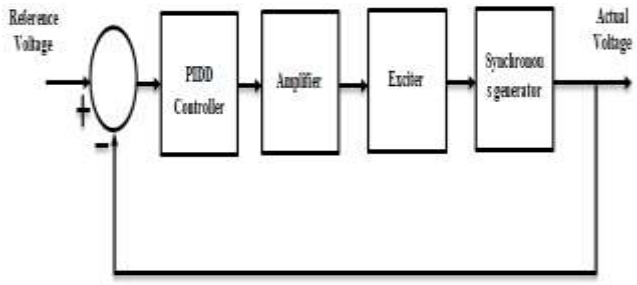

Fig. 2. *Simplified closed loop block diagram of AVR system*

Table 1: Parameters of AVR system [9]

Parameter	***Definition***	***value***
K_d	Damping factor = torque (pu) / speed (pu)	2 pu
τ_m	Mechanical starting time	8 s
K_a	Conventional AVR gain	50
τ_a	Conventional AVR time constant	0.02 s
K_E	Exciter gain	0.17
τ_e	Exciter time constant	0.95 s
K_1	Synchronous Machine factor	1.0753
K_2	-	1.2581
K_3	-	0.3071
K_4	-	1.7124
K_5	-	-0.0476
K_6	-	0.4972
τ_3	Time constant of the field circuit	1.8 s
ω_O	Frequency of the system	50 Hz

3.1 Mathematical of AVR System

For the AVR system shown in Fig. 1, its state-space representation for exciter and generator is given by Ibraheem [9]:

$$\left.\begin{aligned} A &= \begin{bmatrix} -\frac{K_e}{\tau_e} & 0 & 0 & 0 \\ \frac{K_3}{\tau_3} & -\frac{1}{\tau_3} & 0 & -\frac{K_3K_4}{\tau_3} \\ 0 & -\frac{K_2}{\tau_m} & -\frac{K_d}{\tau_m} & -\frac{K_1}{\tau_m} \\ 0 & 0 & \omega_o & 0 \end{bmatrix} \quad B = \begin{bmatrix} \frac{1}{\tau_e} \\ 0 \\ 0 \\ 0 \end{bmatrix} \\ C &= \begin{bmatrix} 0 & K_6 & 0 & K_5 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \end{aligned}\right\} \quad (1)$$

Equation (1) conforms to the general description of linear state space model [15-17]:

$$\begin{aligned} \dot{x} &= Ax + Bu \\ y &= Cx + Du \end{aligned} \quad (2)$$

where A is the matrix of the system, B is the control matrix, C is the system output matrix, and D is the direct transition matrix. Substituting the values of the AVR system in Table 1 gives:

$$A = \begin{bmatrix} -0.179 & 0 & 0 & 0 \\ 0.171 & -0.556 & 0 & -0.292 \\ 0 & -0.157 & -0.25 & -0.134 \\ 0 & 0 & 50 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 5.882 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 0 & 0.4972 & 0 & -0.0476 \\ 0 & 0 & 1 & 0 \end{bmatrix} \quad D = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

The exciter and generator state space model is transformed into transfer function using the MATLAB script: [num,den]= ss2tf(A,B,C,D) and G = tf(num,den). This gives:

$$G(s) = \frac{0.05001s^2 - 0.0329s + 3.727}{s^4 + 0.985s^3 + 6.983s^2 + 2.657s + 0.2565} \quad (3)$$

For the AVR amplifier, the transfer function is given by:

$$G_a(s) = \frac{K_a}{1 + \tau_a s} \quad (4)$$

The substitution of the parameters as in Table 1, gives:

$$G_a(s) = \frac{50}{1 + 0.02s} \quad (5)$$

The feedback sensor gain is assumed unity in this paper.

3.2 PID/PIDD Control System

For simplicity, the structure of PID model is shown in Fig. 3. It uses three complex computation schemes: proportional, integral, and derivative, to achieve the control objective. The error due to the deviation of the current output voltage from the reference voltage is used by these three computational elements of the PID controller to produce a command signal. The resulting signal is used to drive the amplifier, which in turns conditions the exciter and the generator via a simultaneously coordinated operation to execute a correctional action [18] to keep the output voltage to desired stable value.

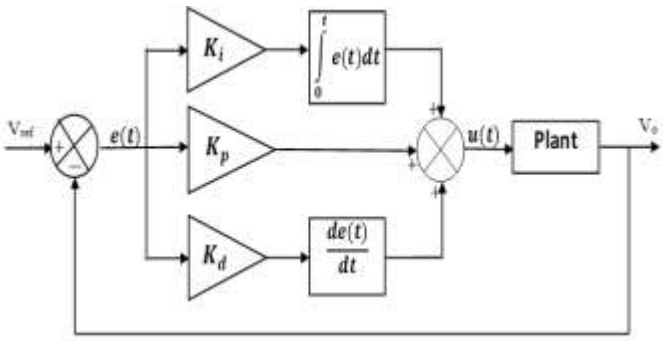

Fig. 3. *Structure of PID model*

From Fig. 3, the mathematical model of the PID controller can be established. The error due to deviation of the measured voltage level of the output from the reference voltage is given by:

$$e(t) = V_{ref} - V_o \quad (6)$$

where e(t) is the error in time domain, V_{ref} and V_o are the reference and output voltage level of the AVR system respectively. Utilizing this error, the output of the PID u(t) in both continuous time form and s-domain (Laplace transform) is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \quad (7)$$

$$U(s) = K_p E(s) + K_i \frac{1}{s} E(s) + K_d s E(s) \quad (8)$$

where E(s) is the error in s-domain. K_p, K_i, K_d are the proportion, integral and derivative gains. The resulting algorithm of the PID is given by:

$$C(s) = K_p + K_i \frac{1}{s} + K_d s \quad (9)$$

where C(s) is the PID controller.

The PID model in Equation (9) is a classical model and very popular in control system. However, several modifications of PID controller have been made in recent time. One of such modification is the PIDD, whose algorithm is defined in [19]:

$$C(s) = K_p + K_i \frac{1}{s} + K_{d1} s + K_{d2} s^2 \quad (10)$$

The values of the designed PID parameters are $K_p = 0.015$, $K_i = 0.00068$, and $K_d = 0.01$. For the PIDD, $K_p = 0.015$, $K_i = 0.00068$, $K_{d1} = 0.01$, and $K_{d2} = 0.01$.

4. RESULTS

The results obtained from the simulations conducted in MATLAB/Simulink environment are presented in this section. The section consists of two subsections. In the first section, the results from the performance analyses of system with neither the PID nor PIDD and with the PID/PIDD for unit step input are presented. The second subsection is the discussion of the performance of the system with respect to the obtained results from the simulation for each control condition.

4.1 System Response

Figure 4 shows the response plot of the output voltage of the AVR without the designed controllers. The output of PID controlled AVR system is shown in Fig. 5. The plot for the output voltage of the AVR system with PIDD is presented in Fig. 6. Comparison plot of PID and PIDD is shown in Fig. 7. The numerical values of the results obtained in terms of transient response characteristics of each control scenario considered is shown in Table 2.

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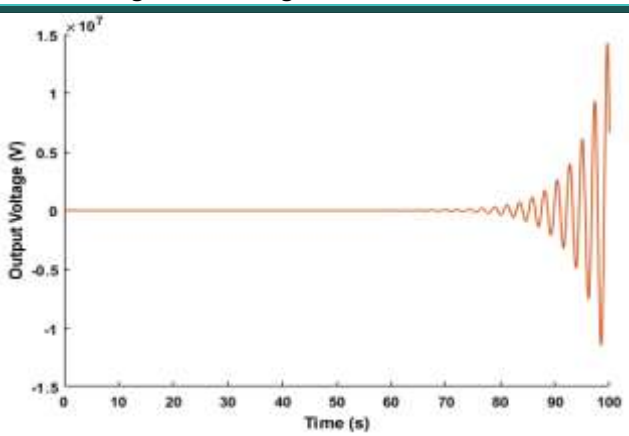

Fig. 4. *Step response of AVR model without designed controller*

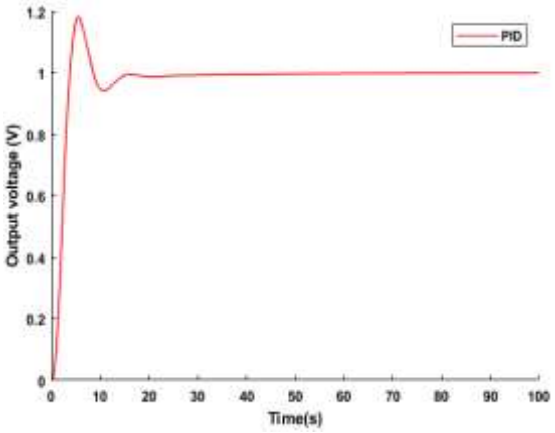

Fig. 5. *Step response of AVR model with designed PID controller*

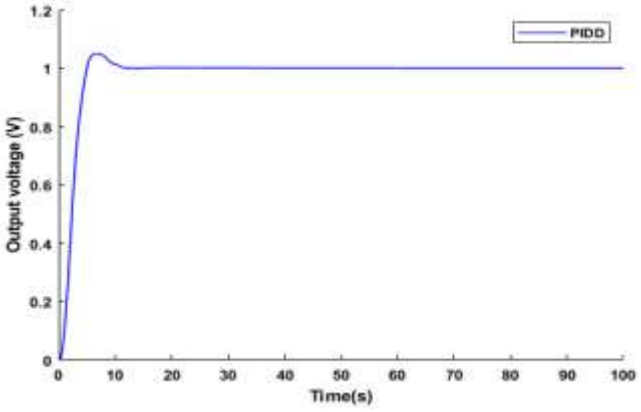

Fig. 6. *Step response of AVR model with designed PIDD controller*

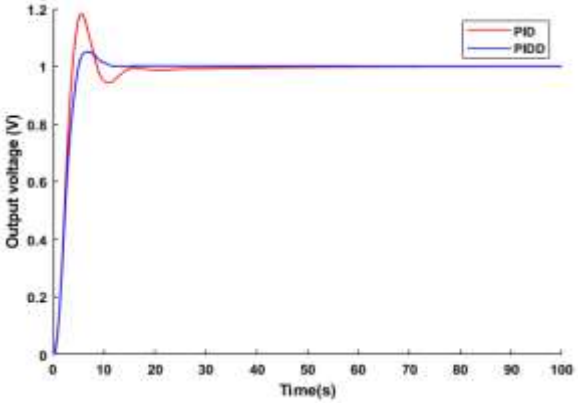

Fig. 7. *Step response of AVR model with designed PIDD controller*

Table 2: Numerical analysis of different control condition

Parameter	Control System		
	Classical AVR (no controller)	***PID***	***PIDD***
Rise time (s)	11. 6	2.36	3.15
Transient time (s)	100	13. 8	9.21
Settling time (s)	100	13.8	9.21
Overshoot (%)	116.4	18.3	4.85
Peak time (s)	99.6	5.55	7.03

4.2 Discussion

As shown in subsection 4.1, the analysis of the AVR control system via simulation in MATLAB showed that for each various conditions, the output voltage yielded different response performances. For the classical AVR system shown in Fig. 4, the desired voltage level (step input voltage of 1 V) was not achieved. Also, the AVR at this condition, the performance of the system was not satisfactory considering its transient characteristics parameters. Thus, as shown in Table 2, the classical AVR produced rise time of 11.6 s, settling time of 100 s, overshoot of 116.4 %, and peak time of 99.6 s.

With the introduction of PID controller, the performance of classical AVR was largely improved. As shown in Fig. 5 and Table 2, the PID control system maintained the desired level of voltage for unit step input. It also yielded rise time of 2.36 s, settling time of 13.8 s, overshoot of 18.3 %, and peak time of 5.55 s. Then with the PIDD controller added, the desired voltage level was achieved and the system response was further enhanced except the rise time. The use of PIDD yielded an output voltage whose transient characteristics are

rise time of 3.15 s, settling time of 9.21 s, overshoot of 4.85%, and peak time of 7.03 s respectively.

The comparison of the designed controllers indicated that the PIDD outperformed the PID except for the rise time. However, the high overshoot and settling time associated with the PID makes it inappropriate for use in place of PIDD.

5. CONCLUSION

The performance of AVR in synchronous generator has been enhanced using PIDD control system. First, PID controller was introduced to address the poor performance of classical AVR system. The result of the simulation analysis revealed that the PID improved the performance of the AVR to a significant extent but the settling time and the overshoot were still inadequate to offer efficient transient response performance though the desired voltage was achieved. To address these limitations in the PID controlled AVR, PIDD was introduced. The result of the PIDD controlled AVR proved its significance in providing enhanced transient response performance.

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