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Automatic Voltage Regulator Control System for Synchronous Generator

Isaac A. Ezenugu[1*], Chisom S. Nwokonko[2*]

[1, 2]Department of Electrical and Electronic Engineering, Imo State University, (IMSU) Owerri Nigeria

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***Corresponding author:** Isaac A. Ezenugu and Chisom S. Nwokonko
Department of Electrical and Electronic Engineering, Imo State University, (IMSU) Owerri Nigeria

Abstract

Presented in this paper is Automatic Voltage Regulator (AVR) Control System for Synchronous Generator. A nonlinear model of synchronous generator was developed in Simulink and was later linearized as a single input single output (SISO) transfer function model. A Proportional Integral and Derivative (PID) controller was designed and by using the MATLAB/Simulink PID tuner, the gains of the proportional, integral and derivative parameters were obtained. A Low Pass Filter, F(s) was designed and introduced as part of the input signal to eliminate any noise effect that may be introduced into the AVR control system through the input. Simulations were carried out considering basically three scenarios viz: the AVR control system without the proposed PIDf + F(s) control scheme, the AVR with the proposed technique, and the AVR with the PIDf + F(s) with the introduction of disturbance in form of load variation at 25 seconds. The performance of the proposed scheme was compared with conventional PID control AVR system without F(s). The results of the comparison indicated that the proposed technique provided superior performance in terms of percentage overshoot and settling time. Generally, the PIDf with F(s) control scheme was more stable than the conventional PID controller as indicated by the percentage overshoot, which was 4.58% for PIDf and 4.28% for PIDf + F(s).

Keyword: Automatic Voltage Regulator, Low Pass Filter, PID controller, SISO, Synchronous Generator, overshoot, settling time.

1. INTRODUCTION

An important subject matter in the field of power systems is the excitation control of generators. In order to improve the transient stability and subsequently reduce the oscillation of the voltage on a power system, good excitation control has shown to be exceptionally efficient and supportive. One essential component of power systems that employs excitation control to regulate voltage is the Automatic Voltage Regulator (AVR).

Automatic Voltage Regulator (AVR) adjusts the terminal voltage of excitation system to maintain the output or terminal voltage of generator at a constant value. This way, the generator's field current is varied. Also, the generated electromotive force (EMF) changes by this condition. The power generation of the generator is altered to a new stable point and terminal voltage is kept at the desired value (Özdemir and Çelik, 2017; Ibrahim *et al.*, 2017). However, AVR system without any controller will provide slow responses and may cause instability (Ibrahim *et al.*, 2017)

Several control schemes have been proposed and implemented for AVR system in theory and in practice. Considering these control techniques, Proportional, Integral and Derivative (PID) controller is the most famous and popularly used in industry. The popularity of the PID can be ascribed to its simplicity and ease of implementation.

In a large interconnected power system, manual regulation is much complicated and as such, automatic generation and voltage regulation is necessary. Therefore, to keep the terminal voltage of generator constant, AVRs are employed at every generating station/synchronous generators. Usually, voltage instability is largely caused by load variation, speed, temperature, and power factor. If there is any change in the voltage, the equipment can be damaged.

This paper therefore, presents a PID controller with modification to include a low-pass filter (LPF) system at the input to eliminate low frequency signals that may enter the control loop through the input.

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2. LITERATURE REVIEW

A hybrid meta-heuristic method for optimal tuning of four different types of PID controller for an AVR system was presented by Micev *et al.*, (2020). The approach was based on manta ray foraging model which was combined with simulated annealing algorithm. Graphical-based technique called the stability boundary locus method to determine the stable parameters space of PI controller gains was proposed by Özdemir and Çelik (2017). The stability of closed region was computed on parameters space obtained from roots of characteristic equation of AVR system. The performance of Linear Quadratic Regulator (LQR) controlled AVR system was evaluated on Single Machine Infinite Bus-bar (SMIB) system and compared with conventional AVR system (Ibraheem, 2011). The performance of traditional teaching learning based optimization (TLBO) algorithm assisted one degree of freedom (1DOF) and two degree of freedom (2DOF) controller in an AVR closed loop control system was studied by Rajinikanth and Satapathy (2015). Ibrahim et al. (2017) studied modelling and simulation of AVR system. The objective of the study was to consider a generator AVR system without PID controller and with PID controller. The PID controller was tuned with a view to improving the response of the system and compared the frequency deviation step response and the tuned PID controller block performance using linear block model and control technique implemented in MATLAB/Simulink environment. An AVR control system using double derivative PID controller (PIDD) to provide dead-beat response but generally make the response faster with reduced rise and settling times than conventional PID controller was studied by Eswaramma and Kalyan (2017). Fernaza and Laksono (2014) studied linear quadratic regulator (LQR) control technique and its application to AVR system. The study focused on the use of LQR method to keep the terminal voltage level of a generator steady. Mittal and Rai (2016) carried out performance analysis of conventional controllers for AVR. The primary purpose of study was to evaluate performance of different traditional control schemes in AVR system. Shewtahul *et al.*, (2010) described the optimization of AVR parameters of a multi-machine power system using PSO. The purpose of the study was to apply PSO method aimed at determining the optimal values of the gains and time constants of PID controller of an AVR system installed on generators of a multi-machine power system.

3. Design of AVR Control System

a. Dynamic Model of AVR System

In this paper, the design of a PID controller plus LPF to improve the performance of an AVR aimed at ensuring a steady terminal voltage for a generator regardless of the varying disturbance was carried out. Therefore, this section will focus basically on obtaining the dynamics of the main components of AVR system shown in Figure 1 which determine its voltage control ability. Four components are fundamental in designing an AVR control system. They include: the amplifier, exciter, generator and sensor. Table 1 shows the parameters of the AVR system.

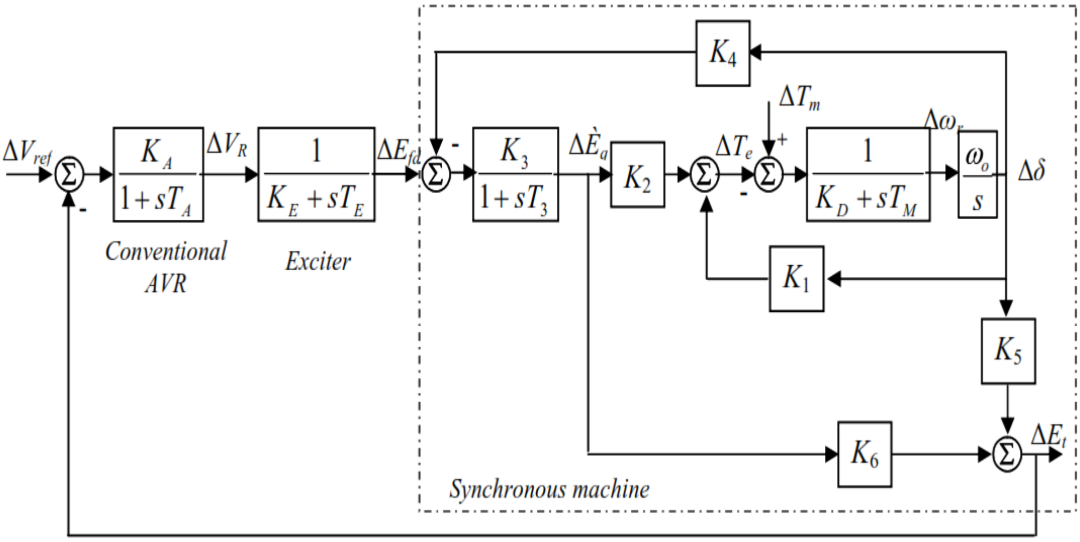

Figure 1: AVR System of Synchronous Generator Exciter (Ibraheem, 2011)

Table 1: Definition of Simulation Parameters (Ibraheem, 2011)

Parameter	Description	Value	Unit
K_d	Damping Factor = torque (pu) / speed (pu)	2	pu
τ_m	Mechanical Starting Time	8	sec
K_a	Conventional AVR Gain	50	-
τ_a	tional AVR time constant	0.02	sec

Parameter	**Description**	**Value**	**Unit**
K_E	Exciter gain	0.17	-
τ_e	Exciter time constant	0.95	sec
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	Sec
ω_O	Frequency of the system	50	Hz

The continuous-time state –space representation of the linearized open-loop system taking the exciter plus synchronous generator can be expressed as given in Ibraheem (2010) by:

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

The values of the parameters of the AVR system are given in Table 1. Substituting the values of the various parameters of the AVR of synchronous generator into Eq. (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 state space representation of the exciter and generator dynamic is further transformed into transfer function model given by:

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

The dynamic model of the amplifier in transfer function form is given by:

$$G_A(s)=\frac{K_a}{1+\tau_a s} \tag{3}$$

Substituting the values of the parameters of the amplifier gives:

$$G_A(s)=\frac{50}{1+0.02s} \tag{4}$$

The dynamic of the feedback sensor is taken as unity in this work. Hence, the closed loop block diagram model of the linearized AVR control loop without PID controller in Simulink is shown in Figure 2.

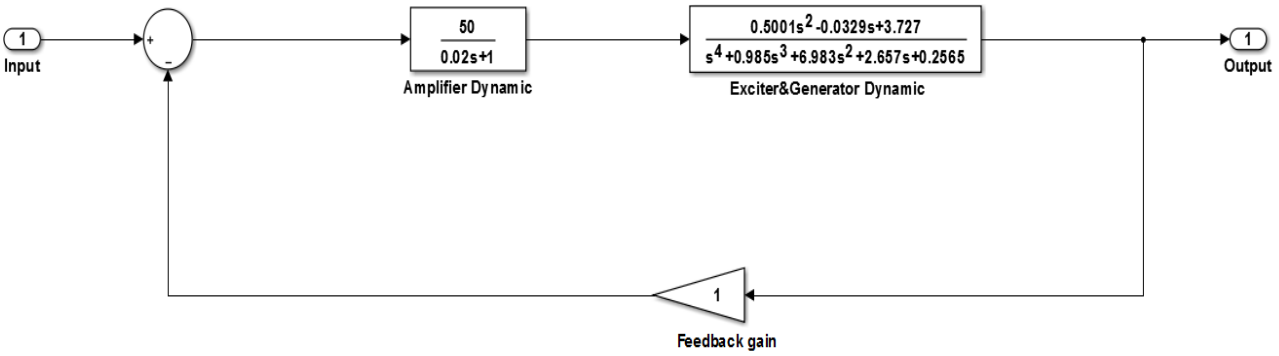

Figure 2: Simulink Model of linearized AVR System

3.3.1. Design of PID Controller

A suitable controller employed in industrial control systems for three-term control-loop feedback mechanism is the Proportional Integral Derivative (PID) controller. The PID controller minimizes system error by adjusting the process through the use of a manipulated variable. It ensures optimum control dynamics including zero steady state error, fast response (short rise time), reduced overshoot, no oscillations and higher stability. The use of PID controller in higher order processes is the main advantage it has over some other linear controllers. Figure 3 shows a block diagram of a PID control model.

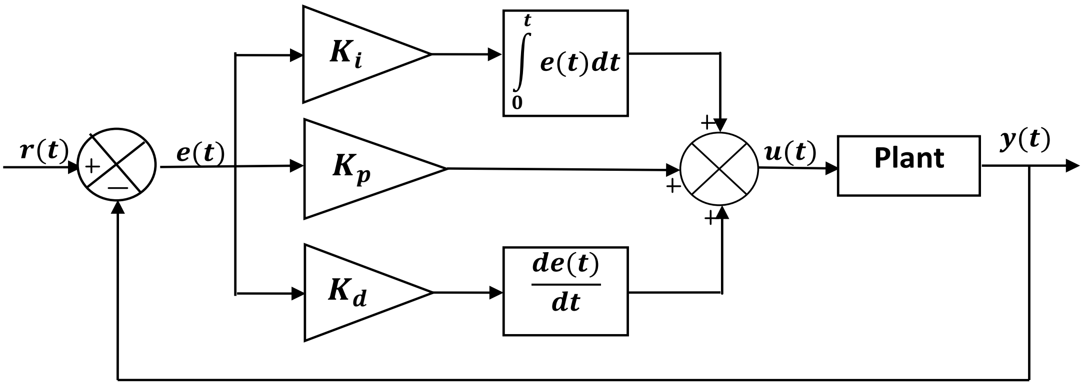

Figure 3: Model of PID Control System

The mathematical representation of PID control algorithm can be obtained by analyzing Figure. 3. The quantities $r(t), e(t), u(t)$ are the reference input (voltage in this case), error (or deviation of the terminal voltage from the reference voltage), and controller output. Also K_p, K_i, K_d are the parameters of the PID controller called the proportional, integral and derivative gains, and $y(t)$ is the output (generator output voltage in this case).

$$e(t) = r(t) - y(t) \tag{5}$$

With the error fed into the PID, proportional, integral and derivative computations are performed on the error and the resulting mathematical expression of the controller output is given by:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{6}$$

Equation (6) is the expression for continuous time ideal PID controller expressed in time domain and can as well be represented as a Laplace transform equation in complex frequency domain assuming zero initial condition as:

$$U(s) = K_p E(s) + K_i \frac{1}{s} E(s) + K_d sE(s) \tag{7}$$

Or in simplified form as:

$$C(s) = K_p + K_i \frac{1}{s} + K_d s \tag{8}$$

Where $C(s) = U(s)/E(s)$ and it is called the PID controller.

In this paper, a PID having a pre-filter implemented along with the derivative component to solve the problem of noise disturbance that may go into the controller through derivative part called real PID controller which can as well be represented as PIDf is given by:

$$C(s) = K_p + K_i \frac{1}{s} + K_d \left(\frac{sN}{s+N} \right) \tag{9}$$

Equation (9) is the PIDf control algorithm implemented in this study and N is the filter coefficient. The gains of the controller were obtained by employing fast and robust turning of the MATLAB/Simulink PID tuner in continuous time domain. The values of the tuned parameters are given by:

$$K_p = 0.00536;$$

$$K_i = 0.000654;$$

$$K_d = 0.01093;$$

$$N = 39.8$$

Substituting the values of the tuned parameters into Eq. (9) gives:

$$C(s) = 0.00536 + \frac{0.000654}{s} + 0.01093 \left(\frac{39.8s}{s+39.8} \right) \tag{10}$$

Equation (10) is the mathematical expression for the designed PID controller in this paper.

- **Low Pass Filter Design**

A low pass filter (LPF) is designed and its function is to filter out any noise that probably may corrupt the reference input signal before being fed into the comparator is implemented. It is given by:

$$F(s) = \frac{1}{s+1.02} \tag{11}$$

The models of the PID control AVR system and PID + F(s) control AVR system in single input single output (SISO) linearized formed are shown in Figure. 4 and 5.

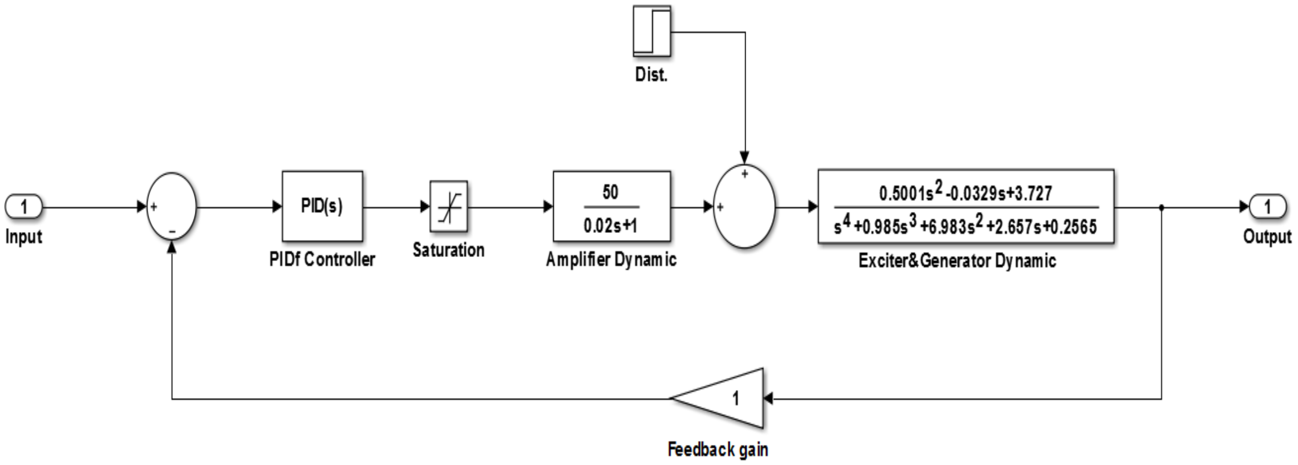

Figure 4: PID Control AVR System

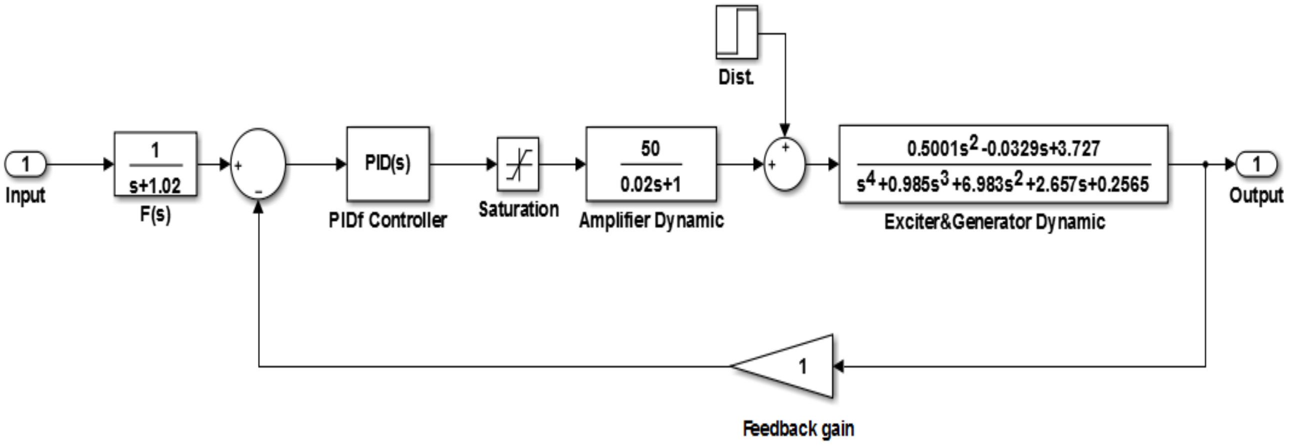

Figure 5: PID + F(s)

A SISO control system has been developed in MATLAB/Simulink to study the performance of AVR system. The overall program used for simulation study is shown in Figure 6.

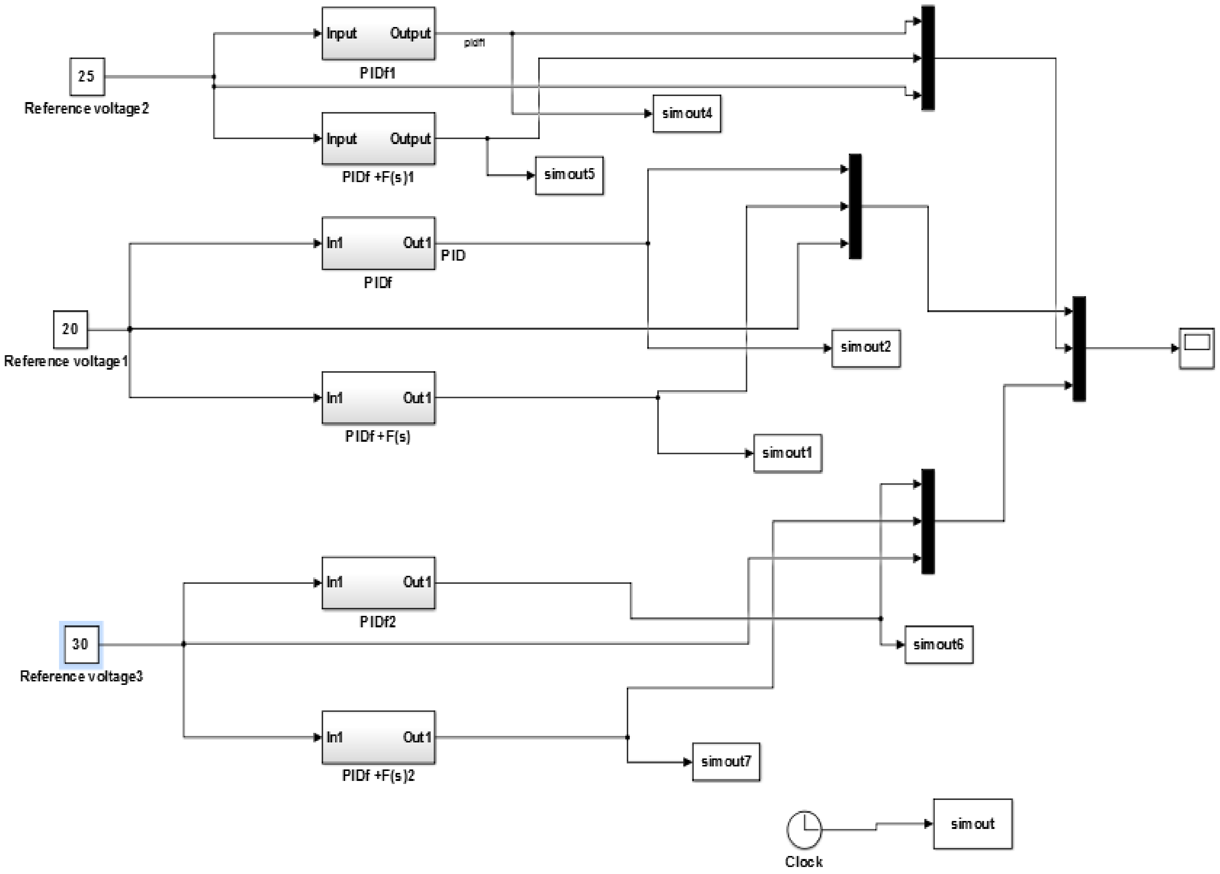

Figure 6: Simulation Program

4. RESULTS, ANALYSIS AND DISCUSSION

4.1 Results and Analysis

The performance responses of the various control models used to study the characteristics of AVR system for different control loop scenarios are shown in Figure 7 to 10. The performance analyses of the plots are shown in Tables 2 to 4.

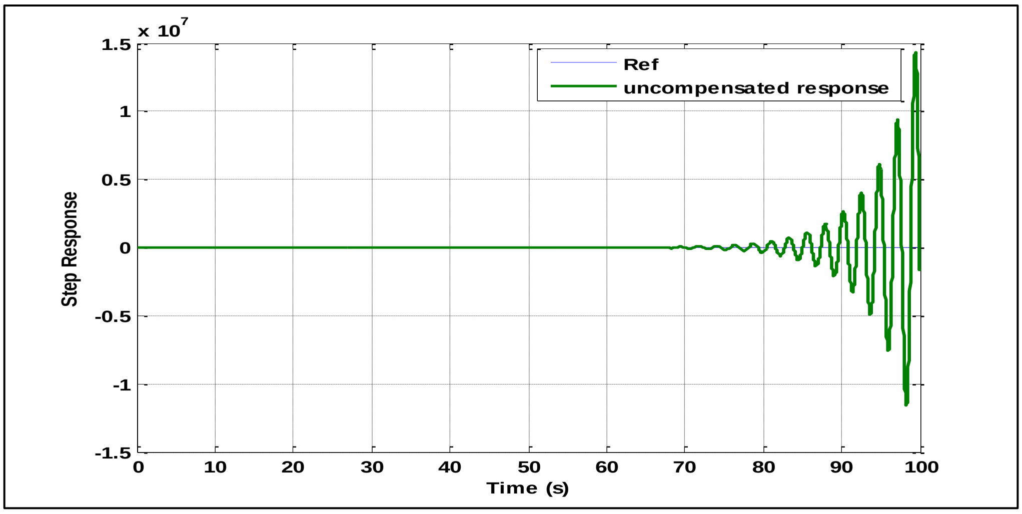

Figure 7: Step Response Plots of Generator Output Voltage to Unit Input

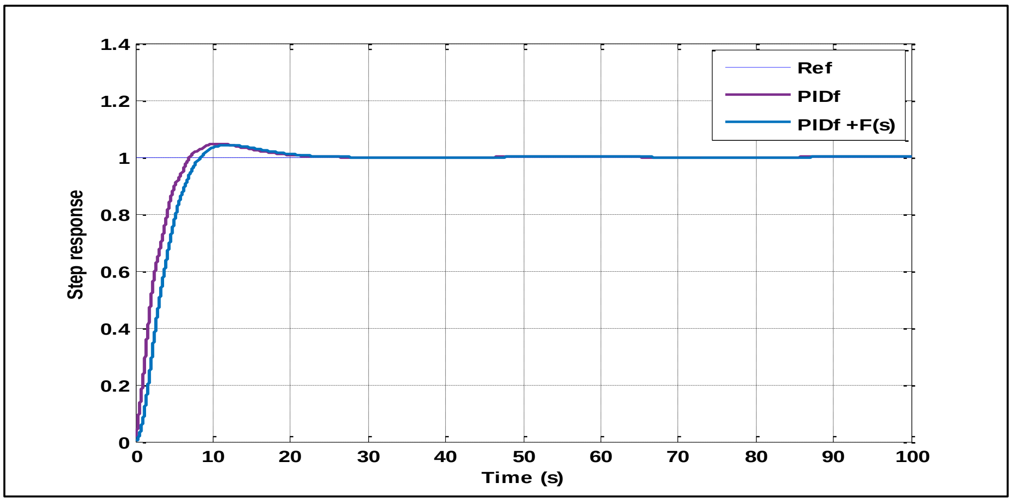

Figure 8: Step Response Plots of PIDf and PIDf+F(s) to Unit Input

Table 2: Analysis of PID and PID with LPF Generator Output Voltage to Unit Step Input

AVR system	Rise time	Peak time	Overshoot	Settling time	Final value
Uncompensated	13.55 s	99.42 s	605.72%	99.99 s	-1.638×10^{6}
PIDf	4.65 s	10.02 s	4.58%	16.54s	1.0
PIDf + F(s)	5.30 s	12.32 s	4.28%	17.61 s	1.0

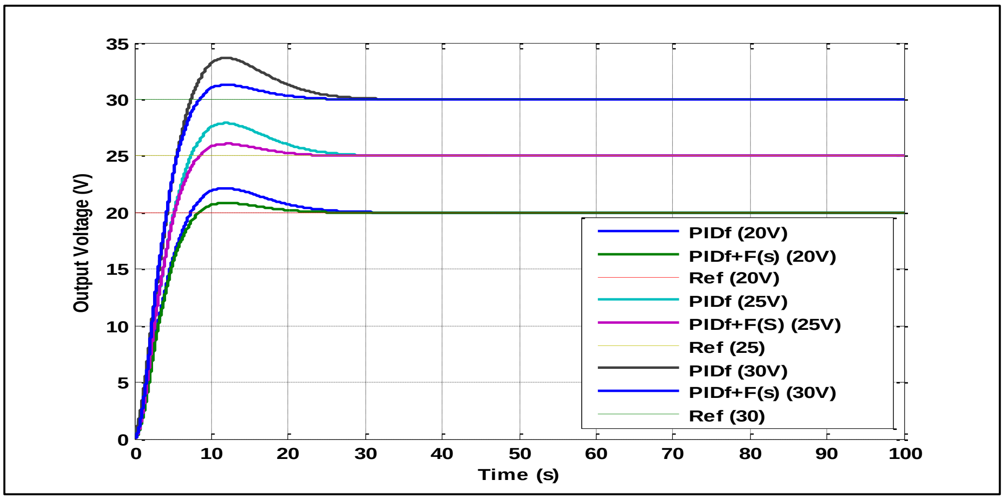

Figure 9: Step Response Plots for 20 V, 25 V and 30 V

Table 3: Time Domain Performance Analysis for Various Desired Generator Voltage

AVR System	Rise Time	Peak Time	Overshoot	Settling Time	Final Value
PIDf (for 20 V)	5.24 s	12.00	10.84%	22.69 s	20 V
PIDf + F(s) (for 20 V)	5.24 s	12.32	4.28 %	17.61 s	20 V
PIDf (for 25 V)	5.24 s	12.02 s	11.64%	23.09 s	25 V
PIDf + F(s) (for 25 V)	5.30 s	12.32 s	4.28%	17.61 s	25 V
PIDf (for 30 V)	5.23 s	12.04 s	12.23%	23.37 s	30 V
PIDf + F(s) (for 30 V)	5.30 s	12.32 s	4.28%	17.61 s	30 V

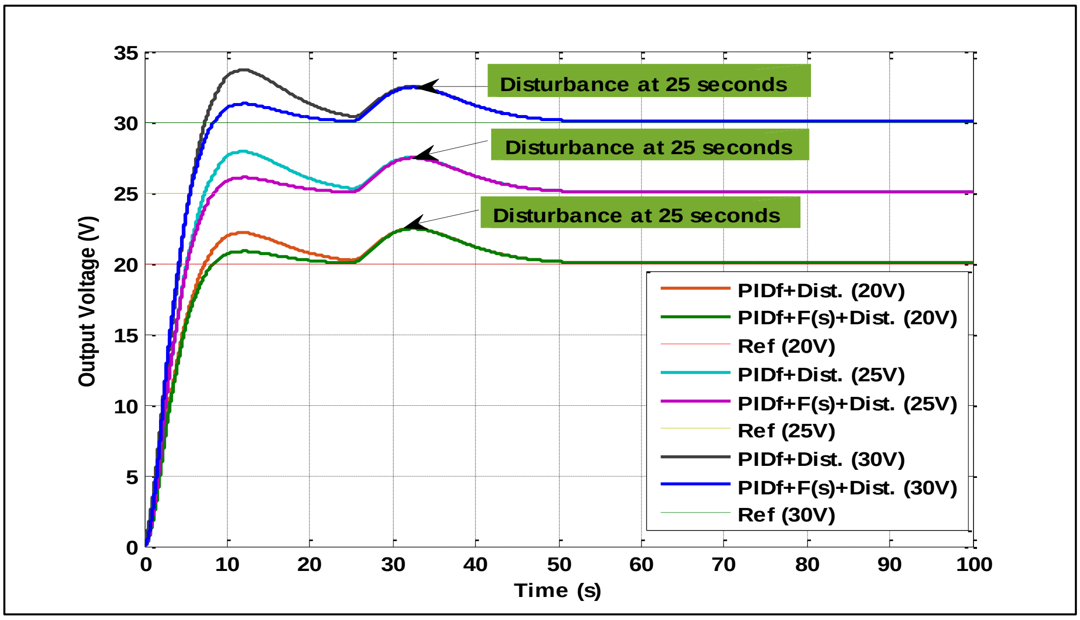

Figure 10: Step Response Plots for 20 V, 25 V and 30V Plus Disturbance

Table 4: Time Domain Performance Analysis for Various Desired Generator Voltage Plus Disturbance at 20 Seconds

AVR System (plus disturbance at 25 s)	Rise Time	Peak Time	Overshoot	Settling Time	Final Value
PIDf (for 20 V)	5.24 s	32.52 s	12.28%	45.36 s	20 V
PIDf + F(s) (for 20 V)	5.30 s	32.60 s	12.40	45.37 s	20 V
PIDf (for 25 V)	5.24 s	12.02 s	11.64%	39.38 s	25 V
PIDf + F(s) (for 25 V)	5.30 s	12.32 s	4.28%	39.35 s	25 V
PIDf (for 30 V)	5.23 s	12.04 s	12.23%	38.56 s	30 V
PIDf + F(s) (for 30 V)	5.30 s	12.32 s	4.28%	38.49s	30 V

DISCUSSION

Figure 7 is the time domain transient characteristics of unit step response plots of the AVR system without a PID controller (uncompensated) and the performance analysis is shown in Table 2. It can be seen in Table 2 that the rise time t_r is 13.5521 seconds, the peak time t_p is 99.420 seconds, the overshoot is 605.7186%, the settling time t_s is 99.9927 seconds, and final value of -1.638×10^6. These characteristics indicate that the performance of the uncompensated AVR system is unsatisfactory. It is obvious that the generator has cycling output voltage and this indicates instability considering the high overshoot. Also, with unit step input applied, the output does not meet the desired or reference input. Considering the settling time, it takes very long time for the generator response to settle.

Considering the unsatisfactory characteristics performance of the uncompensated AVR system, a PIDf controller was included into the AVR control loop and simulation was carried out for unit step input. Subsequent simulation was conducted by adding a low pass filter circuit, F(s) at the input. Figure 8 shows the unit step response plot of the simulation results for both cases involving only PIDf and PIDf + F(s). The performance analysis of each result is shown in Table 2. The introduction of PIDf controller yielded a rise time of 4.6453 seconds, peak time of 10.0161 seconds, overshoot of 4.5788%, settling time of 16.5366 seconds, and final value of 1. In terms of these time domain parameters, it means that the PIDf controlled AVR system provided faster response to step input signal (in terms of rise time and peak time), better stability with reduced peaking and no cycling (in terms of overshoot), reaches or tracks the desired voltage level faster (settling time and final value). The addition of F(s) at the input further reduced the overshoot to 4.2765%.

Additional simulations were conducted to ascertain the effectiveness of the designed PIDf controller and PIDf + F(s) scheme by setting the desired voltage at 20 V, 25 V, and 30 V respectively and resulting simulation plots are shown in Fig. 9 and the performance analysis is presented in Table 3.

Table 3 is the time domain performance characteristics analysis of the AVR system when PIDf and PIDf + F(s) schemes were introduced into the control loop. It can be seen that the PID and PIDf + F(s) techniques provided comparable rise time on average of 5 seconds, peak time on average of 12 seconds for all voltage levels simulated. However, in terms of peak percentage overshoot, the PIDf + F(s) compensated AVR system outperforms the PIDf controlled AVR system. For the voltage levels: at desired voltage of 20 V, peak percentage overshoot for PIDf was 10.482% while PIDf + F(s) yielded 4.28%; for 25 V, PIDf and PIDf + F(s) provided 11.64% and 4.28% respectively; for 30 V, the peak percentage overshoot was 12.23 % and 4.28% for PIDf and PIDf + F(s) compensated system respectively. An important observation was the fact that various desired voltage levels, PIDf + F(s) maintained robust and constant peak percentage overshoot of 4.28%. In terms of settling, the PIDf + F(s) also maintained the same value (17.61 s) for all simulated desired voltage level.

Finally, simulations were conducted by adding a disturbance into the AVR closed loop control system at 25 seconds to determine the effectiveness and robustness of the proposed PIDf and PIDf +F(s) control techniques in handling disturbances assuming due to load variation. The response plots in terms of the actual generator output voltage with their corresponding performance analysis table when a disturbance is introduced into the loop are shown in Figure 10 and Tables 4.

The analysis of the plots in Fig. 10 for the simulation of PIDf and PIDf + F(s) compensated AVR system at desired voltage of 20 V, 25 V, and 30 V respectively subject to unit step disturbance representing load variation is presented in Table 4. It can be seen that the only parameter affected by the introduction of disturbance in to the system in form of load variation is the settling time. Though for desired voltage of 20 V, the peak time increased. The superiority of the PIDf + F(s) control AVR system over the PIDf control AVR system can be seen from the perspective of overshoot and settling time. Hence, with the PIDf +F(s), the system will be more stable and robust.

5. CONCLUSION

This paper has studied the use of Proportional Integral and Derivative (PID) controller with low pass filter F(s) to improve the performance of Automatic Voltage Regulator (AVR). The dynamic model of an AVR system of a synchronous generator was developed and implemented in MATLAB/Simulink environment. The characteristics performance of the system in time domain was examined via simulations. The effect of adding the proposed PIDf + F(s) control scheme was demonstrated by conducting simulations considering a step input voltage, different desired voltages and response to disturbance. Simulation results showed that the addition of PIDf + F(s) provided robust and stable output voltage.

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