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Effect on Performance of Discrete PID Controller for Digital Excitation Control System due to Variation of Sampling Time

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Abstract: Maintaining terminal voltage of brushless synchronous generator at rated value is accomplished through Automatic Voltage Regulator (AVR). Modern digital AVR are consisting PID controller in forward path ensures fast response in the event of disturbance. Popularity of the digital AVR is based on easy installation, implementation and many advantages that include keeping records of the events in memory that is easily accessible for the analysis whenever needed. Digital keypad is used for setting PID gains to improve performance of the system. Digital PID controller reads the error signal at regular interval unlike analog controller that reads the error signal continuously. Regular interval at which digital processor reads error signal is called sampling time that has substantial effect on the performance of the controller and consequently affects the stability of the power system where synchronous generator using digital excitation system is connected in parallel. This study addresses the issues of variation of sampling time on the performance of digital excitation control system. Analysis is carried out using standard simulation model of excitation control system that is duly validated using industrial controller board by using hardware in the loop experimentation.

Key words: Automatic voltage regulator, digital PID controller, Excitation Control System (ECS), brushless synchronous generator, loop experimentation, variation of sampling

INTRODUCTION

The time constant of the exciter is used to select sampling time of the identified digital excitation control system (Kalman and Bertram, 1959; Astrom and Wittenmark, 1984). There are rules to have sampling time that can keep the performance indices such as rise time 't_r', settling time 't_s' and percentage overshoot '%MP' to a optimum value (Isermann, 1981). These rules estimates the value of sampling time for identified values of PID controller coefficients K_P, K_I and K_D for a excitation control system (Godhwani and Basler, 1996).

Analog controller based synchronous generators excitation control systems allow a lot of setting flexibility to the operator to achieve an optimum generator terminal voltage response and hence these are still a choice of the industry due to greater reliability, faster response, simplicity and robustness (Bonfiglio *et al*., 2012).

However, due to the advancement in 'embedded system technology', the trend of upgrading the analog to a digital excitation control system is in progress that offers a more easy setting flexibility to the operator. A comparison of the popular existing PID controller tuning method as (Kim and Schaefer, 2005) explains the advantage and disadvantage of each method and implements the digital PID controller using the Pole zero cancellation method.

Though this method ensures design of PID controller of digital excitation control system complying industrial standards but custom and competitive design remains a challenge, moreover, sampling time considered is very small. The ECS plays very important role to ensure optimum performance of the generator in terms of maintaining the parameters of the controller at the adequate level, so that, dynamic behavior in generator terminal voltage, reactive power and the power factor can keep the system stable. The industrial standard guidelines to the designer for design of ECS are provided in the documents (IEEE Std 421.5, 2005; IEEE., 1990a, b, 2007).

Design of non-linear controller for the excitation system to ensure adequate dynamic behavior has been noticed (Hassan *et al*., 1994; Gunes and Dogru, 2010). However, industries are using a linear controller for the excitation control system. They prefer control strategies that do not require the complete data of the plant. This is intended to avoid time consuming tests on the generator to evaluate the necessary parameters required to calculate PID controller gains.

Currently, the developers of the control strategy are making use of a complex model of the excitation control system that excludes the use of a standard model.

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The approach to use an intelligent control system provides a method to solve the stability problem of the system but is difficult to establish as a model by traditional equations. For example, the excitation control system is established by a neural network that is rained by the back-stepping algorithm which improves the dynamic response in comparison to the conventional PID controller (Xu *et al*., 2008). Moreover, precise data of the system is required to design a neural network to avoid a dangerous transient response at the initial point.

Loop shaping trade off for fractional order PID controllers have been proposed (Das and Pan, 2014) that uses H_2 and H∞ norms for optimizing the fractional PID parameters. With the help of precise data of the system in all these cases, optimum performance is observed. However, in the absence of precise data, the initial requirements such as initial weight for the neural network, trails in ant colony algorithms (Jiang *et al*., 2007), norms in multi objective optimization, population size in swarm optimization (Yan *et al*., 2012) and rules in fuzzy technique are not precisely set and therefor, the control process fails. In order to calculate the analog controller parameters for excitation systems and to operate it within protection limits, a method is proposed by Saavedra-Montes *et al*. (2012) to make the performance indexes of the designed controller to comply with the Industrial standard but this method is only suitable for analog controllers.

PID controllers for the modern excitation control system are used in the forward path. For example, the digital excitation control system as by Kim *et al*. (2010) uses the conventional method for PID gain calculation. Such a design results in optimum performance even in the absence of precise data of the system. However, in this method saturation data of the generator is used for calculating PID gains and the sampling time of the processor needed for implementing the digital PID controller is very small thus increasing labor and the cost of hardware. The unwanted effect caused due to sampling of error signal on the performance of the PID controller is by Laskawski and Wcislik (2016).

This study presents the impact of changes in sampling time on the performance of discrete PID controller to be used in the digital excitation control system of a synchronous generator.

The method selected for tuning analog PID controller is the well established PID tuning method in the industry 'Cancelling zeros by poles'. The experimental results with digital excitation control system demonstrate the effect of change in sampling time on the performance of a digital PID controller. Simulation model used for the analysis is the IEEE standard model type AC 5A.

The proposed model is then built on hardware 'Dspace 1104' an industrial controller board connected in the loop to validate the results of simulation depicting digital excitation control system of a brushless synchronous generator.

MATERIALS AND METHODS

Standard excitation control system model: A standard excitation control system model for brushless excitation systems with a rotating rectifier type AC 5A is used for the study and is shown in Fig. 1.

The voltage regulator of this system is supplied from a source like a permanent magnet generator that benefits the regulator by not affecting its source voltage in case of disturbance. The saturated data of loaded generator is used in this ac model unlike other available ac models that improves authenticity of output results. Therefore, simplified version of this model is widely used in the industry as the detailed data of the system is not required for the simulation (IEEE., 1990a, b).

The model shown in Fig. 1 is modified to incorporate the PID controller and is shown in Fig. 2. A closed loop excitation control system model as in Fig. 3 is used to calculate. Proportional gain K_P integral gain K_I and derivative gain K_D.

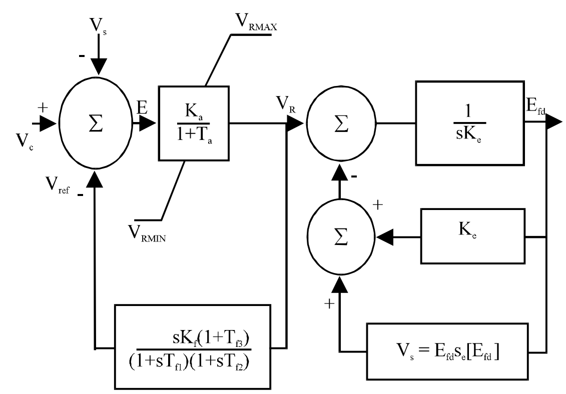

Fig. 1: Industrial model type AC 5A

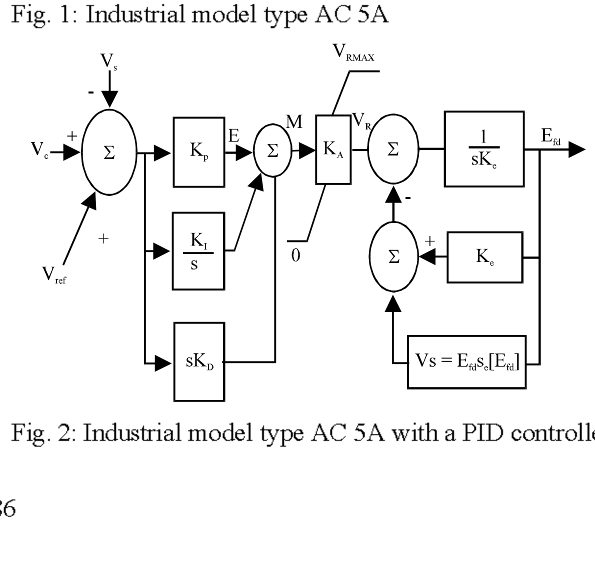

Fig. 2: Industrial model type AC 5A with a PID controller

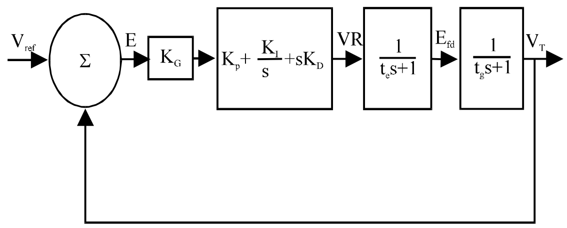

Fig. 3: Closed Loop model of ECS

In the closed loop model, the output is a generators terminal voltage, the generator and exciter blocks are reduced to the first order model. 'KG' is the forward gain of the generator and 't_g' and 't_e' are the generator and exciter time constants. The controller used for controlling the terminal voltage of the generator is a PID controller (Jiang *et al*., 2007; IEEE Std 421.5, 2005; IEEE., 1990a, b, 2007).

The open loop transfer function of the generator, exciter and the PID controller are $G_g(s)$, $G_e(s)$ and $G_c(s)$ and their relation is given in Eq. 1-3. The closed loop transfer function 'TEC(s)' of the reduced model shown in Fig. 3 is given in Eq. 4:

$$G_g(s) = \frac{K_G}{t_g s + 1} \quad (1)$$

$$G_e(s) = \frac{1}{t_e s + 1} \quad (2)$$

$$G_c(s) = K_P + \frac{K_I}{s} + sK_D \quad (3)$$

$$T_{EC}(s) = \frac{G_c(s).\, G_g(s).G_e(s)}{1+G_c(s).\, G_g(s).G_e(s)} \quad (4)$$

The PID controller $G_c(s)$ needs to be tuned with the proper values of gains, i.e., K_P, K_I and K_D in such a way that the controller complies with the industrial standard performance indexes.

To ensure the design of the PID controller for the excitation control system to work in the bounded region for maintaining dynamic stability by using a closed loop model of ECS, step and bode response of the industrial standard closed loop model of a typical excitation control system is compared and given in Fig. 4 and 5 for using as a reference to scale of the design in terms of peak overshoot and phase margin. It can be noted that a closed loop model of ECS gives an increased phase margin as compared to the industrial standard model.

Pole zero cancellation method: The method selected for the analog PID controller design is "cancelling zeros by

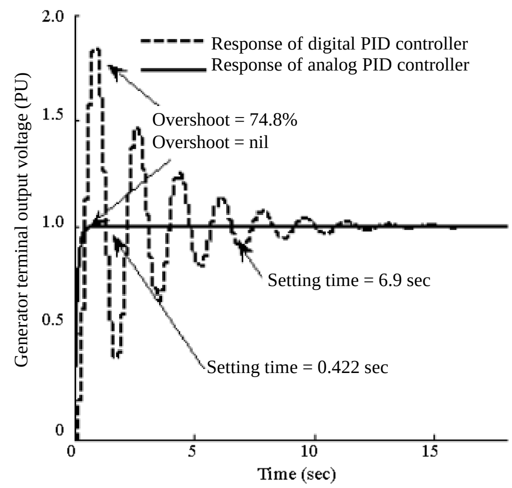

Fig. 4: Step response comparison of a typical analog and digital ECS. Discrete PID controller tuned by an analog gain

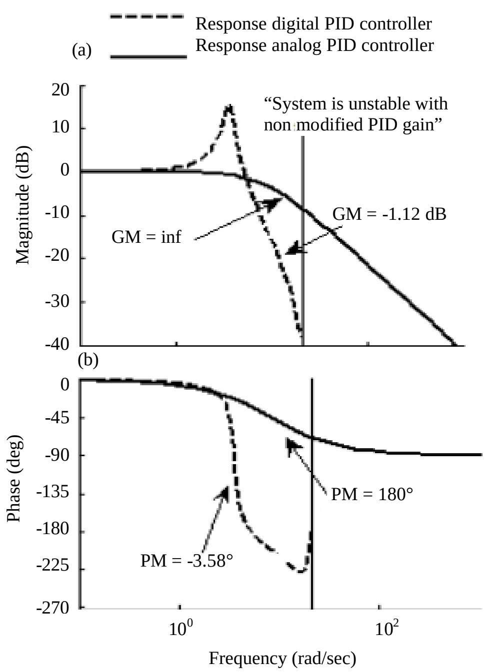

Fig. 5a, b: Bode response comparison of a typical analog and digital ECS. Discrete PID controller tuned by an analog gain

poles" academically, this method is impractical but in the rotary excitation system, the poles corresponding to the generator and the exciter are lying far away from each other (i.e., exciter poles lying 6-10 times away from the generator pole) on the pole zero map as in (Bonfiglio *et al*., 2012). When the loop gain increases, the pole moves towards the corresponding zeros. Since, the poles of the exciter and the generator are well separated, the resulting system through the cancellation of zeros by the poles is not affecting the original systems required dynamics. This makes the selected method suitable for the rotary excitation system applicatio (Jiang *et al*., 2007; Das and Pan, 1991).

The open-loop system transfer function of the reduced model shown in Fig. 3 with typical assumption '$K_g = 1$' is by Godhwani and Basler (1996):

$$G_c(s)G(s) = \frac{K_D\left(s^2+\frac{K_P}{K_D}s+\frac{K_I}{K_D}\right)}{t_g t_e s\left(s+\frac{1}{t_g}\right)\left(s+\frac{1}{t_e}\right)} \tag{5}$$

The numerator and the denominator of the transfer function (Eq. 5) have two zeros and three poles and the cancellation of two zeros with two farthest poles of Eq. 5 is achieved by ensuring Eq. 6:

$$\frac{\left(s^2+\frac{K_P}{K_D}s+\frac{K_I}{K_D}\right)}{\left(s+\frac{1}{t_g}\right)\left(s+\frac{1}{t_e}\right)} = 1 \tag{6}$$

Equating the numerator and denominator of Eq. 6 results in Eq. 7:

$$s^2+\frac{K_P}{K_D}s+\frac{K_I}{K_D} = \left(s+\frac{1}{t_g}\right)\left(s+\frac{1}{t_e}\right) \tag{7}$$

Expansion and arrangement makes RHS polynomial of Eq. 7 as in Eq. 8:

$$s^2+\frac{K_P}{K_D}s+\frac{K_I}{K_D} = s^2+\left(\frac{t_g+t_e}{t_g t_e}\right)s+\frac{1}{t_g t_e} \tag{8}$$

Equating LHS and RHS of Eq. 8 gives expression for K_P in Eq. 9 and K_I in Eq. 10:

$$K_P = K_D\left(\frac{t_g+t_e}{t_g t_e}\right) \tag{9}$$

$$K_I = \frac{K_D}{t_g t_e} \tag{10}$$

Submitting K_P and K_I in Eq. 5 results in Eq. 11:

$$G_c(s).G(s) = \frac{K_D}{t_g t_e s} \tag{11}$$

The closed loop transfer function of the system in Fig. 3 using Eq. 11 is in Eq. 12:

$$\frac{G_c(s)G(s)}{1+G_c(s)G(s)} = \frac{K_D/t_g t_e s}{1+K_D/t_g t_e s} \tag{12}$$

The time response of the system in Eq. 12 to a unit step input is given in Eq. 13:

$$G_g(s) = \frac{K_G}{t_g s+1} \tag{13}$$

If 't_r' is the required rise time for the design it is defined as the time required for the response to rise from 10-90% of its final value, the resulting expression for K_D is given in Eq. 14:

$$K_D = \frac{t_g t_e}{t_r K_G}.\ln 9 \tag{14}$$

Derivative gain K_D in Eq. 14 depends on the plant parameters t_g, t_e and the desired rise time 't_r'. An observation shows that the controller design is aiming for a faster response with the proposed method makes settling time (t_s), percentage peak overshoot (%MP), Gain Margin (GM) and Phase Margin (PM) comply with the industrial standard.

Impact of sampling rate on digital ECS: In digital ECS model, the generator, exciter machine is of continuous nature and AVR is of discrete nature consist discrete PID controller as its component. The digital PID controller is implemented on a computer chip by the discretisation of an integral and derivative block and the computer chip reads the continuous error signal at regular time intervals that is referred to as sampling time.

The analog PID controller in Fig. 3 can be discretised by the use of Forward Euler, Backward Euler method but as reportrd in Eq. 20 Forward Euler method of integration is very sensitive and makes system unstable, therefore, trapezoidal integration method is used for accumulation of error signal. This method replacing an integral term '$1/_s$' with 'T.(1+z-1)/2.(1-z-1)' and a first difference method replaces derivative term 's' with (1-z-1)/T where, T is the sampling time (Fig. 6).

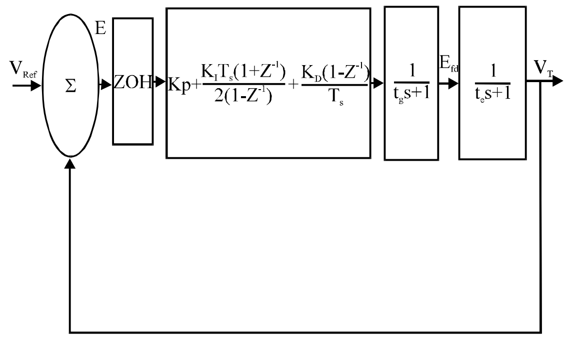

Fig. 6: Block digarm of digital ECS

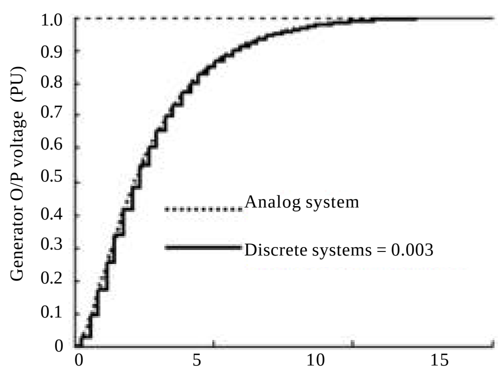

Fig. 7: Comparison of 10% step increment response of a typical analog and discrete open loop ECS with sampling time t_s = 0.003 sec

In the proposed tuning method of the discrete PID controller, the analog gains calculated earlier in section are used with an assumption that "Behavior of the discrete PID controller is similar to continuous when the sampling time is very small" as described in Fig. 7, a comparison of 10% step increment response of a typical analog and discrete open loop ECS shows that when sampling is chosen very small, i.e., 't_s = 0.003 sec' response of analog and discrete PID controller is almost same.

However, if the gains calculated by the earlier selected analog method are directly used to implement the discrete PID controller then the system becomes unstable as described by the step and bode response of a typical excitation control system in Fig. 8 and 9.

It is noted that for different values of sampling time, performance of ECS changes. Table 1. presents the performance of the discrete PID controller used in ECS for different values of sampling time when a typical value of forward loop gain is K_G = 1, from this table it is noted that the best performance is achived when 'T_s' = 0.15 sec.

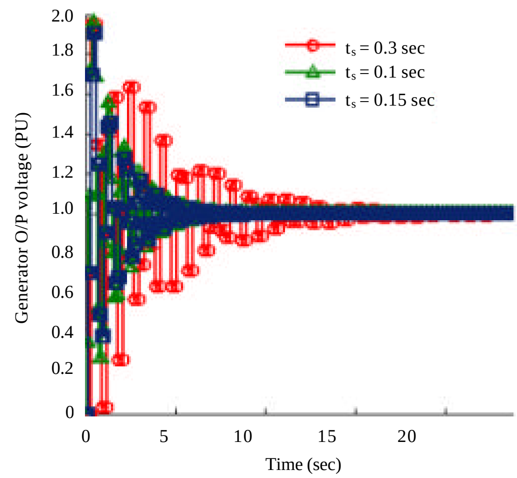

Fig. 8: Comparison of 10% step increment response of a typical discrete closed loop ECS with different sampling time

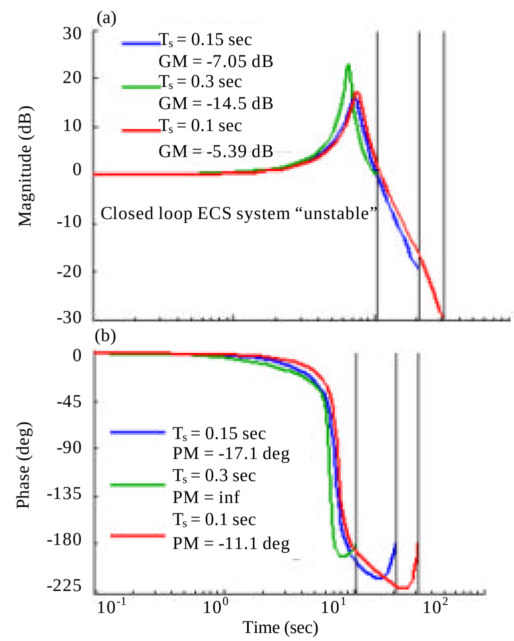

Fig. 9a, b: Comparison of Bode response of a typical discrete closed loop ECS with different sampling time 'T_s'

Table 1: Time response of the discrete PID in ECS with the sampling time is varying

Sampling time (sec) 'T_s'	Peak overshoot (%)	Settling time (sec)'t_s'	Rise time (sec) 't_r'
0.003	System unstable		
0.1	95.9	6.7	0.1
0.15	90.6	6.15	0.15
0.2	98.7	7.8	0
0.3	95.4	16.2	0
0.4	183	24	
00.5	System unstable		
0.8	System unstable		

which means sampling time is twice shorter than lowest exciter time constant 't_e' = 0.3 sec but overshoot is very high and the system becomes unstable due to negative gain and Phase margin.

RESULTS AND DISCUSSION

Application example and results: The rotary excitation system of 500 kVA, 440 V and a 50 Hz brushless synchronous generator whose manufacturer's data in Table 2 is used to demonstrate the methods described in study 3.

The excitation system for this generator is analog type and provided with AVR that has Proportional 'P' controller in forward path. This generator's output terminal voltage (PU) response for 10% step increment and 10% step decrement of reference voltage is given in Fig. 10 that confirms terminal voltage is not reaching steady state therefore makes power system unstable. The solution for this problem is use of PI controller or PID controller.

The disadvantage of the PI controller is an integral gain that decreases system dynamics and increases phase delay thus decreases system stability. The proposed controller for this system is the PID controller whose derivative element compensates systems deceleration caused by an integral element.

The data sheet provided by the manufacturer does not contain the value of the exiter time constant, therefore for the design of the controller,the exciter time constant is approximated as one sixth of the generator time constant t_e = 0.3 sec as proposed by Jiang *et al*. (2007).

Analog PID controller gains as described in section 3 are used and gains K_P = 52, K_I = 21 and K_D = 14 is calculated using Eq. 9, 10 and 14, respectively.

The analog ECS response for the calculated PID gain is shown in Fig. 11. It is observed that system gives fast response with rise time <1 sec and almost no overshoots that ensures stable operation of the generator.

When these gains are used to design a discrete PID controller of digital ECS as in Fig. 6 with sampling time t_s = 0.15 sec calculated, so that, t_s twice shorter than the lowest exciter time constant t_e. The response of the generator terminal voltage is oscillatory and has 5% overshoot as shown in Fig. 12.

The step increment response of the designed controller at t = 30 sec for the digital excitation control system after adjusting the value of forward gain K_G to 0.37 is shown in Fig. 13 that shows oscillatory output voltage response with 10% overshoot.

Table 2: Parameter of brushless synchronous generator

Generator time constant 't_g'	2.2 (sec)
Moment of Inertia	8.0068 (k.m^2)
Damping factor	65
No of poles	2
R	0.0049 (Ω)
L	0.1273x10^{-3} (H)

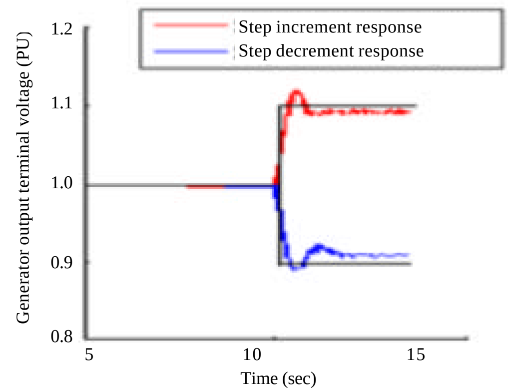

Fig. 10: 10% step increment and decrement response of generator terminal voltage wfen AVR consists of only the proportional controller

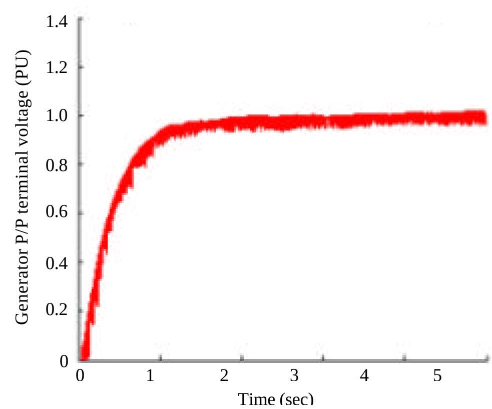

Fig. 11: Generator O/P terminal voltage response without step disturbance

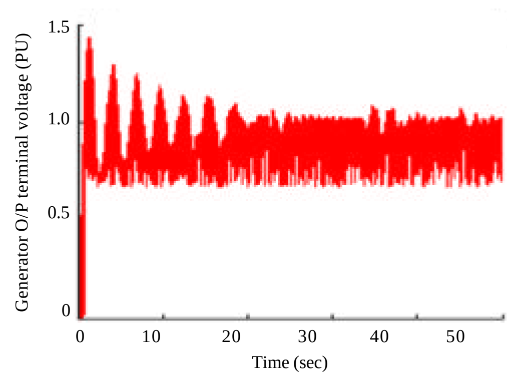

Fig. 12: Step response of generator O/P terminal voltage without step disturbance

The step decrement response of the same system is shown in Fig. 14 that shows 10% overshoot and undershoot.

Though the design of PID controller with adjustment of forward gain gives acceptable range of overshoot, rise time and settling time but oscillatory response with discrete PID controller can make the system unstable.

The design is tested on the simulation model of the standard IEEE excitation system 421.5 type AC-5A is given in Fig. 2 by considering anti integral wind up reset for integral action scheme is in Fig. 15. Discrete PID controller is then implemented in hardware d-space 1104 controller board to validate the results.

The DS 1104 controller board is the real-time hardware based on Power PC technology and it's set of I/O interfaces make the controller board to be used for developing controllers for various systems with a Real-Time Interface (RTI).

The real-time model is compiled, downloaded and started automatically in the MATLAB platform. The scheme for the HITL experiment to test the designed digital PID controller of the excitation control system is shown in Fig. 15 and the experimental setup for the HITL experiment to test the designed digital PID controller of the excitation control system is given in Fig. 16.

The discretised PID controller is built in a D-space 1104 controller board using a real time interface of the MATLAB Simulink and the continuous model of the plant, i.e., the exciter and the generator are built in the PC. Thus, the scheme takes a shape of Hardware in the Loop (HITL) and following the IEEE standard model given in Fig. 2. Function models on the DS1104 controller board can be easily configured and run by inserting the blocks into a simulink block diagram and generating the model code via. a simulink coder.

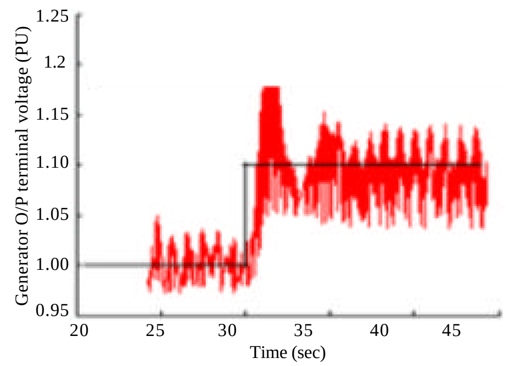

Fig. 13: Step response of generator O/P terminal voltage with 10% step increment at t = 30 sec

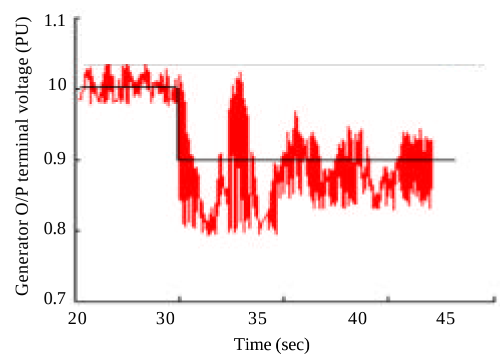

Fig. 14: Step response of generator O/P terminal voltage with 10 % step decrement at t = 30 sec

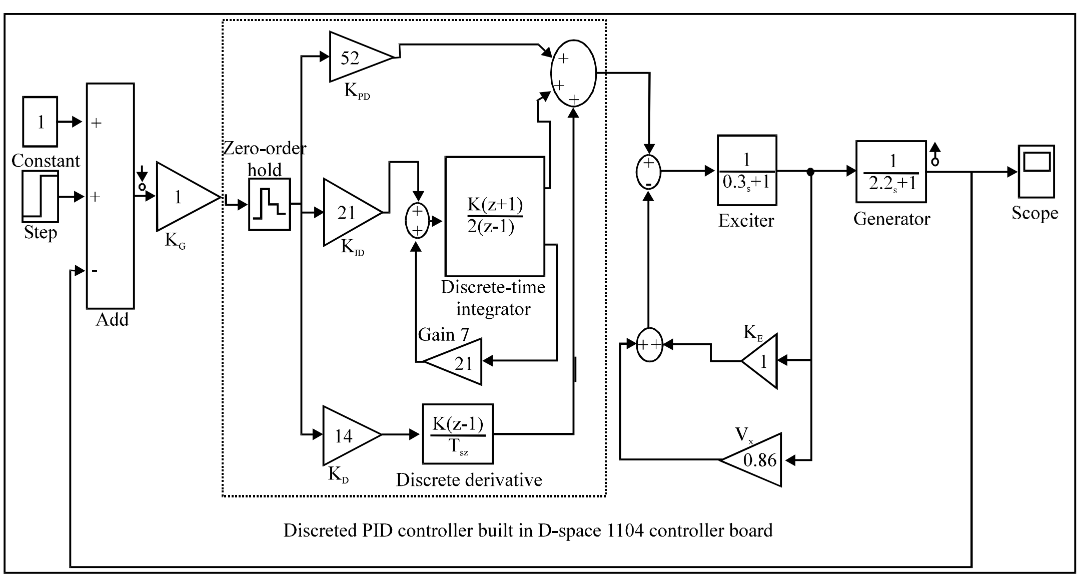

Fig. 15: Scheme for the HITL experiment to test designed digital PID controller of excitation control system

Fig. 16: Experimental setup with DS 1104 in the loop to test the designed digital excitation control system

CONCLUSION

The analog PID controller is designed by cancelling zeros by the poles method and ensures the desired rise time and almost a negligible overshoot in the output terminal voltage of a synchronous generator. The use of a calculated analog PID gains when used for the design of discrete PID controller the system becomes unstable. An investigation shows that the variation of sampling time affects the performance of the PID controller and consequently the performance of ECS. However, the design can be brought to acceptable range by precise adjustment of the forward gain but terminal voltage response remains oscillatory increases risk of systems stability. This research can be extended for finding precise method to calculate gains that will make custom design of discrete PID controller for digital excitation control system.

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