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Implementation of a discrete fuzzy PID excitation controller for power system damping

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Abstract The power system is nonlinear with frequent changes in operating regions. Analog proportional integral derivative *PID* controllers are widely used in excitation control of power systems. Fuzzy logic control is often viewed as a form of nonlinear *PD*, *PI* or *PID* control. This paper describes the design principle, tracking performance of a fuzzy proportional-integral *PI* plus derivative *D* controller. This controller is developed by first describing discrete time linear *PID* control law and then progressively deriving the steps necessary to incorporate a fuzzy logic control mechanism into the modifications of the *PID* structure. The bilinear transform (Tustin's) is used to discretize the conventional *PID* controller. In this paper some performances criteria were utilized for comparison with other *PID* controllers, such as settling times, overshoots and the amount of positive damping. The proposed scheme is robust to variations in operating conditions to match the fluctuations of load demand in the power system.

1. Introduction

Power system dynamic stability refers to the damping of electromechanical oscillations occurring in the power system. These oscillations are with small magnitude and low frequency, approximately in the range of 0.2–2 Hz. If these oscillations continue for long periods of time, they can constrain power transfer capability, affect system security and damage the operation efficiency of the power system. Conventional *PID* has been widely used in suppressing electromechanical oscillations occur in power systems [1,2]. Since the power system is usually nonlinear, time variant and governed by strong cross-couplings of the input variables, it is necessary to tune conventional *PID* controllers more than one times; otherwise that leads to degrade its performances [3–6].

In recent years, applications of fuzzy *PID* controllers to power systems were reported in a number of publications [7–9]. It solved the same set-point regulation problem addressed by classical *PID* control, except that fuzzy control provides a nonlinear input/output mapping [10,4].

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The common fuzzy *PID* controllers used in power systems applications are the double inputs fuzzy *PID*. The reason to use this type is that the observation of the system's integral error is very difficult task in practice, since more fuzzy control rules are needed. Hence, it is better to design a fuzzy *PID* controller by integrate the output of fuzzy *PD* and then combined with the output of the fuzzy *PD* controller [11,12]. But this type needs to adjust some weights on the *PD* type and the *PI* type fuzzy controller which is considered time consuming [11].

In this paper a fuzzy *PI* and *D* controller is presented. The fuzzy *PI* plus *D* developed here follows the practical approach of the conventional *PI* plus *D* controller design method. The output of the proposed controller is the summation of the outputs of the fuzzy *PI* and fuzzy *D* controllers.

Since the implementation of most modern control systems is in a computer processor, the conventional *PID* control law in this paper is converted into a discrete-frequency domain with the variable z using the bilinear transform to obtain a digital version [13,14].

The proposed controller preserves the basic properties of the general *PID* controller, but it has a simple configuration similar to the fuzzy *PI* and *PD* controllers [15].

The basic characteristics of the proposed design can be concludes:

- The application of the proposed fuzzy *PID* controller is applied and examined to a single machine infinite bus system.
- The conventional *PID* control law is transformed to discrete version using the bilinear discretization formula.
- The final version of the proposed fuzzy *PID* controller is a computationally efficient analytic scheme suitable for implementation in a real-time closed-loop digital control.
- It has the same linear structure as the conventional *PI* plus *D* controller, but it has no constants gains.
- The proportional, integral and derivative gains are nonlinear functions of the input signals.
- The required amount of positive damping is obtained by a proposed digital version controller instead of conventional *PID* controller.
- The membership functions are simple triangular ones with some fuzzy logic if-then-rules similar to classic fuzzy logic controller.
- Fuzzification, control law, which is an explicit conventional formula, so that the fuzzification rules and the defuzzification routine are not, needed at all process control steps.

Finally, various simulations studies are performed in order to demonstrate the robustness of the proposed controller and the effectiveness of its capability to damp out the electromechanically oscillations. Comparison studies have also been extended between the dynamic performance of the proposed discrete fuzzy *PID*, the conventional *PID* controller and the double input fuzzy *PID* controller (will be called in our study fuzzy *PID* controller). The numerical simulations results clearly demonstrate the superiority of the proposed controller in comparison with the conventional *PID* controller and with the fuzzy *PID* controller. Our study considers a single-machine connected to an infinite-bus through a transmission line that to demonstrate the proposed discrete fuzzy *PID* controller technique.

This paper is organized as follows. In Section 2 a nonlinear model for the power system is considered. In Section 3 design of the discrete fuzzy *PI* and fuzzy *D* controllers are derived. In Section 4 the combination of the two controllers are considered. Results of testing the discrete fuzzy *PID* controller on the single-machine infinite-bus system is considered in Section 5. The conclusions are given in section 6.

2. Nonlinear single machine infinite bus power system model

The power system considered in this paper is a single-machine infinite-bus system. This system is used to evaluate the proposed fuzzy *PID* controller. It consists of a synchronous generator, a turbine, a governor, an excitation system and a transmission line connected to infinite-bus as shown in Fig. 1. The model of power system considered is built using a C^{++} software program. In Fig. 1, P_{ref} is the mechanical power reference, P_g is the feedback through the governor, T_M is the turbine output torque, V_∞ is the infinite bus voltage, V_{ref} is the terminal voltage reference, V_t is terminal voltage, E_{fd} is the exciter output voltage, and U is the supplementary output signal which depends mainly on the location of the switch S. The four blocks *DFPID*, *FPID*, *PID* and no control (open loop) stand for discrete fuzzy *PID* controller, fuzzy *PID* controller, conventional *PID* controller, and the case of no control, respectively. The synchronous generator is described by a seven order d–q axis set of equations with the machine currents; speed and rotor angle as state variables. The turbine is used to drive the generator, and the governor is used to control the speed of the turbine and the real power. The differential equations describing the different subsystems of the power system are given below [16,17]:

Machine winding is represented by fifth order as follows:

$$\dot{X}_w = X_1^{-1}(\omega_b V_1 - (\omega_b R_1 + G_1)X_w) \tag{1}$$

where X_W is a state vector represents the state variables of the machine windings, while X_1, R_1, V_1 and G_1 are parameter matrices given in Appendix A.

The IEEE Type ST1 excitation system is considered in this study. It can be represented as follows:

$$\dot{E}_{fd} = -\frac{1}{T_e}E_{fd} + \frac{K_e}{T_e}(V_{ref} - V_T) \tag{2}$$

The output must be limited to prevent the controller to counter action of automatic voltage regulator AVR.

The set of the differential equations describing the steam–turbine–governor system is given as follows:

$$\begin{aligned}
\dot{Y}_{HP} &= \frac{1}{T_{CH}}(P_0 - Y_{HP})\\
\dot{Y}_{RH} &= \frac{1}{T_{RH}}(Y_{HP} - Y_{RH})\\
\dot{Y}_{IP} &= \frac{1}{T_{IP}}(G_{VI}Y_{RH} - Y_{IP})\\
\dot{Y}_{LP} &= \frac{1}{T_{CO}}(Y_{IP} - Y_{LP})\\
\dot{G}_{VM} &= \frac{1}{T_{GVM}}(U_{GM} - G_{VM})\\
\dot{G}_{VI} &= \frac{1}{T_{GVI}}(U_{GI} - G_{VI})
\end{aligned} \tag{3}$$

where *HP*, *IP* and *LP* stand for high, intermediate and low pressures in per unit respectively, and *VM* is the control valve.

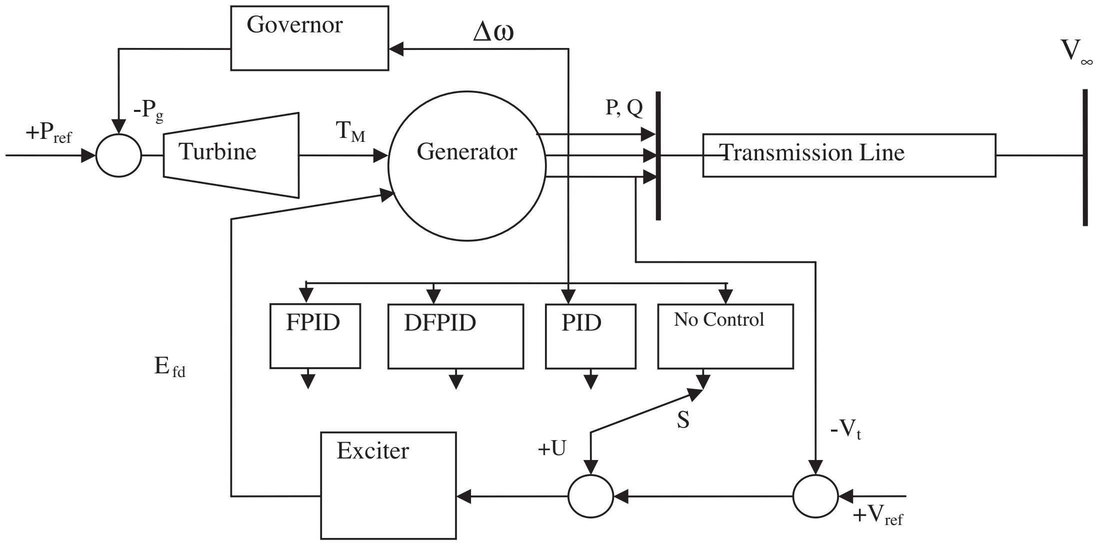

Figure 1 Nonlinear single machine infinite bus power system.

The mechanical shaft is represented by a second order swing equation given by

$$\dot{\omega} = \frac{\omega_b}{2H}(P_m - P_e - k_d\omega) \quad (4)$$

$$\dot{\delta} = \omega - \omega_b \quad (5)$$

where P_m, P_e and k_d are the accelerating power, the electrical power of the synchronous generator and the damping, respectively.

Eqs. (1)-(5) can be organized in the following form:

$$\dot{\underline{X}} = f(\underline{X}, \underline{u}, t) \quad (6)$$

where $\underline{X}$ is a vector of the state variables, $\underline{u}$ is an input vector representing the output of the exciter E_{fd}, and f is a set of nonlinear functions describing the differential equations of the complete power system under study.

3. Design of the fuzzy *PI* and *D* controllers

The general structure of the proposed discrete fuzzy *PID* controller is shown in Fig. 2. It consists of two nonlinear fuzzy channels; one for the *PI* controller and the other for the *D* controller. Both the *PI* and *D* controllers have two discrete inputs as shown in Fig. 2.

3.1. Derivation of the discrete fuzzy PI controller

The output of the analog *PI* controller in the frequency S-domain is:

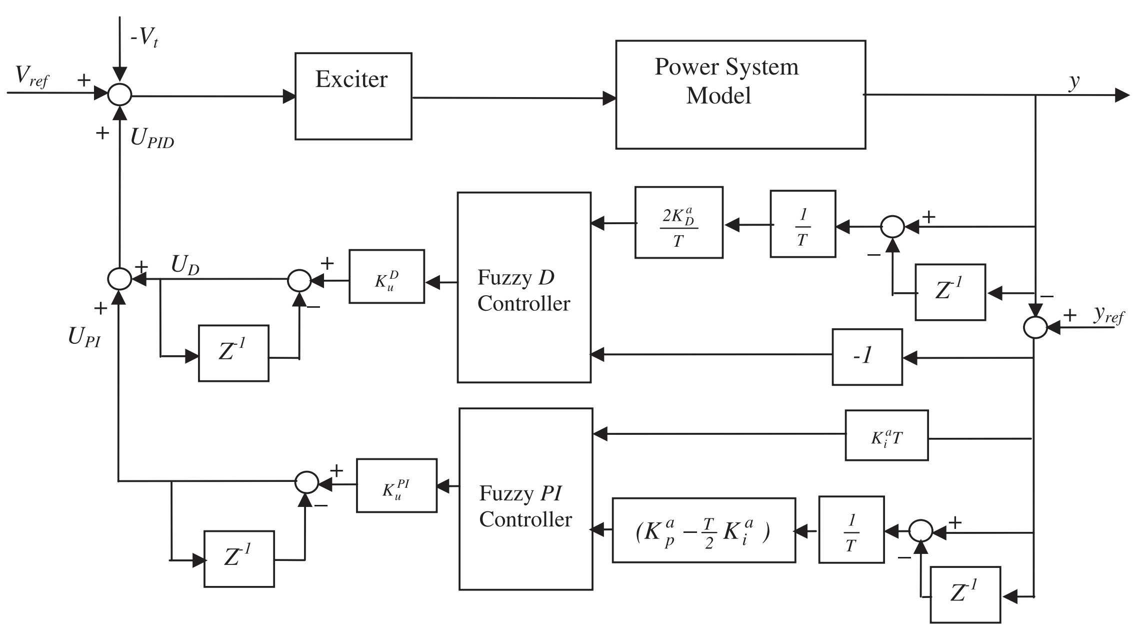

Figure 2 Structure of discrete fuzzy *PID* controller.

$$U_{PI}(s) = \left(K_p^a + \frac{K_I^a}{s}\right)E(s) \tag{7}$$

where K_P^a, K_I^a are the continuous proportional and integral gains, and $E(s)$ is the tracking error signal. Eq. (7) can be transformed to discrete version by applying the bilinear transformation: $s = \frac{2(z-1)}{T(z+1)}$ [14], where $T > 0$, is the non-pathological sampling period. Substituting by the bilinear transformation, Eq. (7) can be written as:

$$U_{PI}(z) = \left(K_p^a + \frac{K_I^a}{\frac{2(z-1)}{T(z+1)}}\right)E(z) \tag{8}$$

Eliminating the denominator and rearranging yield:

$$U_{PI}(z) = \left(K_p^a - \frac{TK_I^a}{2} + \frac{K_I^a T}{1-z^{-1}}\right)E(z) \tag{9}$$

Let $K_P^d = K_P^a - K_I^a \frac{T}{2}, K_I^d = K_I^a T$, where K_P^d, K_I^d are the discrete gains of the PI controller.

Eq. (9) can be converted back to a discrete-time domain using the inverse z transform, rearranging it and dividing each term by T yield:

$$\Delta U_{PI}(k) = K_P^d \Delta e(k) + K_I^d e(k) \tag{10}$$

$$\Delta U_{PI}(k) = \left(\frac{U_{PI}(k) - U_{PI}(k-1)}{T}\right) \tag{11}$$

$$\Delta e(k) = \left(\frac{e(k) - e(k-1)}{T}\right) \tag{12}$$

where $\Delta U_{PI}(k)$ stands for the incremental control output of the PI controller and $\Delta e(k)$ stands for the rate of change of the error signal. Eq. (11) can be written as;

$$U_{PI}(k) = -U_{PI}(k-1) + K_u^{PI} \Delta U_{PI}(k) \tag{13}$$

where K_u^{PI} is a scaling factor of the PI fuzzy controller which will be estimated in Section 4.

3.2. Derivation of the discrete fuzzy D controller

The control signal of the derivative continuous controller can be written as:

$$U_D(s) = sK_D^a Y(s) \tag{14}$$

where K_D^a is the continuous derivative gain, and $Y(s)$ is the frequency in S-domain of the plant output. Eq. (14) in discrete form using bilinear transform can be written as:

$$U_D(z) = \left(\frac{z-1}{\frac{T(z+1)}{2}}\right)K_D^a Y(z) \tag{15}$$

Eq. (15) can be written in discrete-time domain using the inverse z transform as;

$$\Delta U_D(k) = K_D^d \Delta y(k) \tag{16}$$

$$\Delta U_D(k) = \left(\frac{U_D(k) + U_D(k-1)}{T}\right) \tag{17}$$

$$\Delta y(k) = \left(\frac{y(k) - y(k-1)}{T}\right) \tag{18}$$

$$K_D^d = \frac{2K_D^a}{T} \tag{19}$$

where $\Delta U_D(k)$ is the incremental output of the D controller, $\Delta y(k)$ is the rate of change of the output, and K_D^d stands for the discrete gain of the D controller. Eq. (15) is modified to describe an actual fuzzy logic controller by adding a signal $ky_d(k)$ to its right-hand side representing the input error signal term [15] where;

$$Ky_d(k) = y(k) - y_{ref}(k) = -e(k) \tag{20}$$

where $y_{ref}(k)$ is the reference signal of the output $y(k)$ and k equals unity in our study. Eq. (16) can be written as:

$$U_D(k) = -U_D(k-1) + K_u^D \Delta U_D(k) \tag{21}$$

where K_u^D stands for scaling factor of the D fuzzy controller which will be designed in Section 4.

4. Discrete fuzzy *PID* control structure

Combination of both the output of the fuzzy PI controller and the output of the fuzzy D controller given by Eq. (13) and Eq. (21), respectively, gives the final output of the fuzzy PID controller as:

$$U_{PID}(k) = U_{PI}(k) + U_D(k) \tag{22}$$

Eq. (22) can be written in a simplified form as;

$$U_{PID}(k) = -U_{PI}(k-1) + K_u^{PI}\Delta U_{PI}(k) - U_D(k-1) + K_u^D \Delta U_D(k) \tag{23}$$

Eq. (23) gives the final discrete controller equation to be used in our control scheme. A special fuzzy logic routine of Eq. (23) will be developed later to yield a more powerful and robust controller for the power system under study which is considered nonlinear due to the fluctuation of the load conditions. For the case of power system, the problem of the defect in mathematical modeling can be solved using good associative decision rule.

The basic configuration of fuzzy logic control comprises four principal stages: fuzzification stage, knowledge base stage, decision making logic stage, and defuzzification stage. A comprehensive survey of fuzzy logic control, which becomes one of the most successful areas for the application of fuzzy set theory, can be found in [18]. In this work, the first step is to specify controller input and output variables. The main input variables to the proposed controller are the $y(k)$ which is the generator speed and its derivative (see Fig. 2). The individual inputs to the fuzzy PI and D controllers are derived as follows:

PI controller

$$X_1(k) = K_I^d(\omega_b(k) - \omega(k)) \tag{24}$$

$$X_2(k) = K_P^d\left(\frac{\Delta\omega(k) - \Delta\omega(k-1)}{T}\right) \tag{25}$$

D controller

$$X_1(k) = k(\omega(k) - \omega_b(k)) \tag{26}$$

$$X_2(k) = K_D^d\left(\frac{\omega(k) - \omega(k-1)}{T}\right) \tag{27}$$

where ω_b is the base speed and k is a constant equal 1.

The fuzzy output terms $U_{PI}(k)$ and $U_D(k)$ are functions in $[X_1(k), X_2(k)]$, where $X_1(k)$, and $X_2(k)$ are considered as inputs to discrete fuzzy PID controller.

Table 1 Fuzzy associative matrix for the excitation control signal.

	X_1						
X_2	NB	NM	NS	Z	PS	PM	PB
NB							Z
NM				NM	NS	Z	PS
NS	NB	NM	NM	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	
PS			Z		PM	PM	
PM		Z	PS	PM	PM	PB	PB
PB	Z						

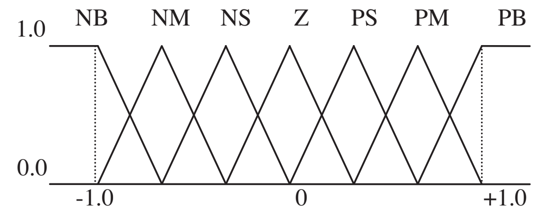

Figure 3 Triangular membership functions for inputs and outputs of *PI* and *D* controllers.

The fuzzy set values of the input and output fuzzy variables are specified. A universe of discourse is selected for the linguistic values, in our study $(-1, +1)$ is selected as a universe of discourse. The universe of discourse can be quantized into overlapping fuzzy set values. Control fuzzy variables, with their respective fuzzy set values are shown in Table 1. In our scheme, seven linguistic values are used. The fuzzy set values of the linguistic values are chosen in the way as follows: X_1: [NB Negative Big; NM Negative Medium; NS Negative Small; Z Zero; PS Positive Small; PM Positive Medium; PB Positive Big].

The same procedure can carry out for the input variable $X_2(k)$. Each term of the linguistic values has an associated membership functions as follows [μ_{NB} μ_{NM} μ_{NS} μ_{Z} μ_{PS} μ_{PM} μ_{PB}]. Each membership function is a map from the real line to the interval $[0, 1]$. Fig. 3 shows a plot of the membership functions used for the inputs. In practice, the quantizing fuzzy sets are usually symmetric triangular or trapezoids, centered about some representative values. The density of fuzzy sets must be highest around the optimal control point of the system and should be thin out as the distance from this point increases. Output membership functions are chosen to be identical with triangular function for both the fuzzy *PI* and *D* controllers as shown in Fig. 3. Fig. 3 uses a triangular membership functions with height one, which occurs at points -1, $-.65$, $-.33$, 0.0, 0.33, 0.65, and 1. In fuzzification stage, transformation of the inputs $X_1(k)$ and $X_2(k)$ into the setting of linguistic values are done. The input $X_1(k)$, and $X_2(k)$ are first normalized by scaling them and then converted to fuzzy sets. In each step k, we have two membership values μ_1 $(k_1, X_1(k))$ and $\mu_2(k_2, X_2(k))$, where k_1 and k_2 are scaling factors for the two inputs of the fuzzy *PI* controller, respectively. Similar notation for the fuzzy *D* controller is considered.

A set of decision rules relating controller inputs to the output can be constructed from expert knowledge and experience. This stage is considered as the core of the fuzzy logic control. With specific reference to the characteristic of the power system, we construct the fuzzy control rule table tabulated in Table 1, where the 28 rules are used. The rule in column 4 and row 2 for the fuzzy *PI* controller can be written as:

IF X_1 is Zero **AND** X_2 is Negative Medium **THEN** *PI* output = Negative Medium.

This rule can be explained as; if the input X_1 is a member of the zero and the input X_2 is a member of the negative medium, then the output of the *PI* controller is a tendency for negative medium. Where ***AND*** operation is realized by "min" operation, i.e. $= \min\ (\mu(x_1), \mu(x_2))$ and other rules can be interpreted in the same way. Similar rules from Table 1 can be written for the fuzzy *D* controller. The 28 rules for the fuzzy *PI* controller and the same number of rules for the fuzzy *D* controller altogether yield the control actions for the fuzzy *PID* controller. For the power system these rules are structured in such away that avoid overshooting and an obtained acceptable significant amount of positive damping.

The resulting fuzzy set must be converted to a number that can be sent to the excitation summing point as a supplementary control signal. This operation is called defuzzification. The resulting fuzzy set is thus defuzzified into a crisp control signal. The method of center of gravity is used in this study to transform the fuzzy value into a crisp value [18]. The crisp output value U_{PID} is given by:

$$U_{PID}(k) = \frac{\sum_i \mu(x_i) x_i}{\sum_i \mu(x_i)} \qquad (28)$$

where x_i is a running output in a discrete universe, and $\mu(x_i)$ is its related membership value in the membership function. The expression can be interpreted as the weighted average of the elements in the support set.

5. Results of the discrete fuzzy *PID* controller simulations

To demonstrate the efficiency of the proposed discrete fuzzy *PID* controller, several simulations were performed. Following the design procedures explained in Sections 3 and 4, the output of the discrete fuzzy *PID* controller can be obtained and injected to the summing point in the excitation system of the single-machine infinite-bus system as shown in Fig. 1. A nonlinear model of 14 orders is used for representation of the system. A complete system representation and detailed data are given in Appendix B [17]. Results of three study cases are presented in this paper. These are step change in the mechanical load for lagging, step change in the mechanical load for leading power factor and 3-phase short circuit. The maximum excitation voltage was specified to be 5.0 pu. The sampling time was chosen to be 0.02 s, while the time step of numerical integration of the differential equation (solved by using fourth order Runge-Kutta method) was specified as 0.001 s. For the purpose of comparison the response curves for the same system variables, when using conventional *PID*, discrete fuzzy *PID* controller, fuzzy *PID* controller and the case of without control are shown in Figs. 4–9.

5.1. Case A1: Load test with lagging power factor

Initially, the generator operating at a power of 0.8 pu, 0.87 power factor lag, then it was subject to a 15% step increase

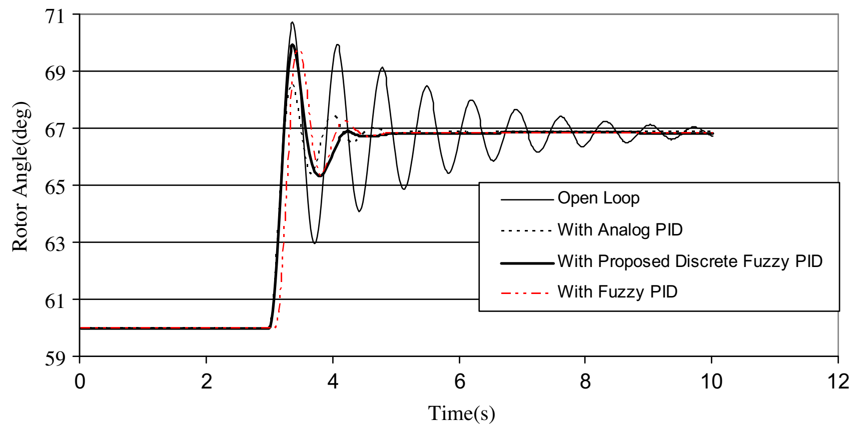

Figure 4 Rotor angle responses to 15% step increase in mechanical torque with lagging power factor.

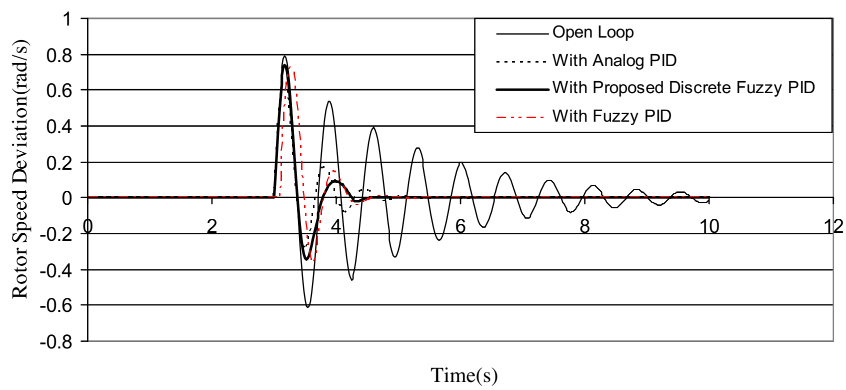

Figure 5 Rotor speed deviation responses to 15% step increase in mechanical torque with lagging power factor.

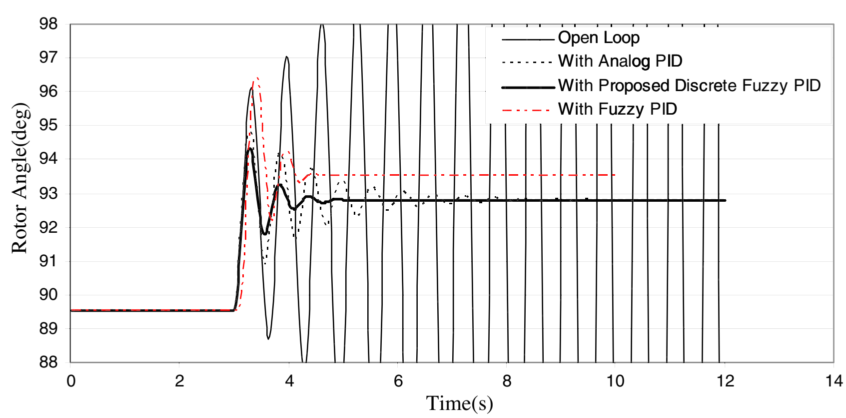

Figure 6 Rotor angle responses to 15% step increase in mechanical torque with leading power factor.

in the mechanical torque reference at $t = 3$ s. Figs. 4 and 5 represent rotor angle and rotor speed deviation for the nominal loading condition of active power 0.8 pu, reactive power of 0.26 pu. The parameters of the analog *PID* controller is fixed to $K_P^a = 1.3$, $K_I^a = 40.0$, and $K_D^a = -0.0001$. In the case of discrete fuzzy *PID* controller the output scaling parameters are adjusted to $K_u^{PI} = 0.0002$ and $K_u^D = 0.04$. The weights of both the *PD* and *PI* controllers for the fuzzy *PID* are adjusted to 0.008. The comparison between the response curves corresponding to the discrete fuzzy *PID* controller with those when analog *PID* and fuzzy *PID* controllers are applied show that the transient system performance is highly improved. The

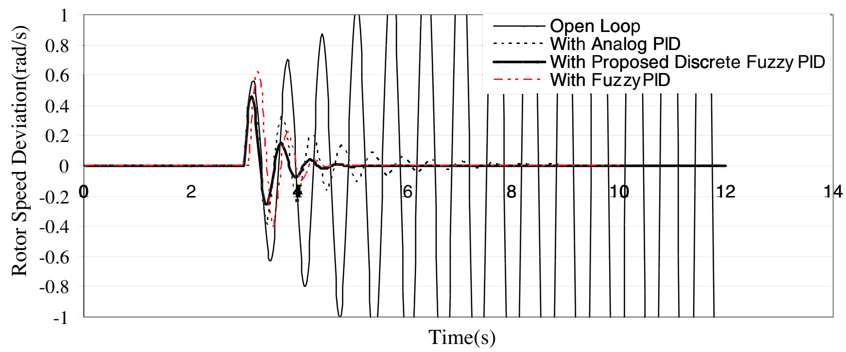

Figure 7 Rotor speed deviation responses to 15% step increase in mechanical torque with leading power factor.

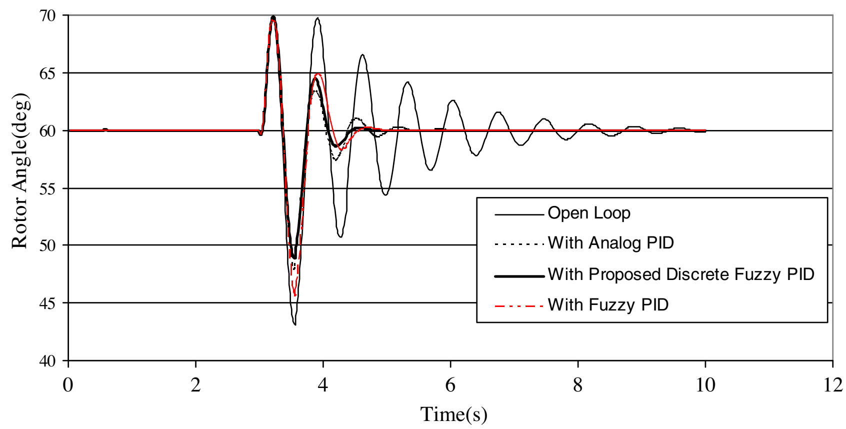

Figure 8 Rotor angle responses to a temporary (100 ms) three phase short circuit with lagging power factor.

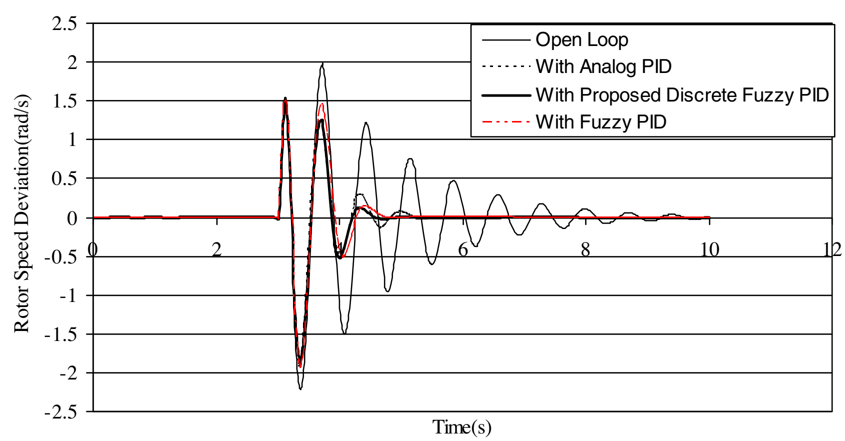

Figure 9 Rotor speed deviation responses to a temporary (100 ms) three phase short circuit with lagging power factor.

discrete fuzzy *PID* controller exhibits quickly settling time corresponding to the analog *PID* controller and the fuzzy *PID*, while the later has exhibits a time delay.

5.2. Case A2: Load test with leading power factor

With the generator operating at a power of 0.8 pu, 0.95 power factor lead, then it was subject to a 15% step increase in the mechanical torque reference at t = 3 s. Figs. 6 and 7 represent rotor angle and rotor speed deviation for the unstable loading condition, the reactive power is equal to −0.2629 pu. The operating point in this kind of disturbance is close to $\pi/2$ which means that power system works near unstable region. The parameters of the analog *PID* controller are fixed to $K_P^a = 1.3, K_I^a = 40$, and $K_D^a = -0.0001$ while the output scaling parameters of the discrete fuzzy *PID* controller are adjusted to

$K_u^{PI} = 0.0001$ and $K_u^D = 0.04$. Also, the weights of both the *PD* and *PI* controllers for the fuzzy *PID* controller are adjusted to 0.008. The discrete fuzzy *PID* controller is able to damp out the oscillations in this type of disturbance in approximately 1 s compared to analog *PID* and fuzzy *PID* controller. The discrete fuzzy *PID* controller exhibits low overshooting and quickly settling time corresponding to the analog *PID* controller. The fuzzy *PID* controller shows a significant value of steady error as well as time delay.

5.3. Case A3: Three phase short circuit test at generator bus

With the generator operating at a power of 0.8 pu, 0.87 power factor lag, a three phase short circuit on the generator bus was applied at $t = 3$ s and cleared in 100 ms. The parameters of the analog *PID* controller are fixed to $K_P^a = 1.3, K_I^a = 40$, and $K_D^a = -0.0001$ while the output scaling parameters of the discrete fuzzy *PID* controller are adjusted to $K_u^{PI} = 0.0001$ and $K_u^D = 0.04$. Also, the weights of both the *PD* and *PI* controllers for the fuzzy *PID* controller are adjusted to 0.09 and 0.03, respectively. Figs. 8 and 9 show response curves of rotor angle and speed deviation in the case of three phase short circuit on generator bus. This fault is considered as a severe disturbance and the discrete fuzzy *PID* controller returned the system to a stable case in two swings only with enough amount of positive damping compared to the analog *PID* and the fuzzy *PID*. These simulations clearly reveal that the discrete fuzzy *PID* controller has generally better steady state and transient responses, especially when the system under control is nonlinear or higher order linear. The weights of the *PD* and *PI* controllers for the fuzzy *PID* are adjusted to 0.09 and 0.03, respectively.

6. Conclusion

In this paper, the application of a discrete fuzzy *PID* controller to power system is presented. The discrete fuzzy *PID* controller is applied to one machine infinite-bus system and it was tested for different operating points and different kinds of disturbances. In our study we describe the design principle and the tracking performance of the discrete fuzzy *PID* controller. The proposed controller is composed of two parts; a fuzzy *PI* and a fuzzy *D* controller; which preserves the simple linear structure of its conventional counterpart and enhances the self tuning control capability. It is found that the discrete fuzzy *PID* controller provides good damping enhancement and results in better response behavior to damp out the oscillations for various operating points. Results obtained with a few if-then rules instead of 49 if-then rules reveal the robustness of the proposed controller. It is observed that although the discrete fuzzy *PID* controller has the same linear structures as the analog, the discrete fuzzy *PID* controller gains are nonlinear with self tuning capability and better performances.

Appendix A

The parameter matrices R_1, X_1, G_1, and V_1 are given as follows:

$$R_1 = \begin{bmatrix} -r - R_e & 0 & 0 & 0 & 0 \\ 0 & -r - R_e & 0 & 0 & 0 \\ 0 & 0 & r_{kq} & 0 & 0 \\ 0 & 0 & 0 & r_{kd} & 0 \\ 0 & 0 & 0 & 0 & X_{md} \end{bmatrix}$$

$$X_1 = \begin{bmatrix} -X_q - X_e & 0 & X_{mq} & 0 & 0 \\ 0 & -X_d - X_e & 0 & X_{md} & X_{md} \\ -X_{mq} & 0 & X_{kq} & 0 & 0 \\ 0 & -X_{md} & 0 & X_{kd} & X_{md} \\ 0 & \frac{-X_{md}^2}{r_{fd}} & 0 & \frac{X_{md}^2}{r_{fd}} & X_{fd}\frac{X_{md}}{r_{fd}} \end{bmatrix}$$

$$V_1 = \begin{bmatrix} V_B \cos\delta \\ V_B \sin\delta \\ 0 \\ 0 \\ E_{fd} \end{bmatrix}$$

$$G_1 = \begin{bmatrix} 0 & -\omega_b(X_d - X_e) & 0 & -\omega_b X_{mq} & -\omega_b X_{mq} \\ \omega_b(X_q - X_e) & 0 & -\omega_b X_{md} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Appendix B

The parameters of the generating unit and the connected power system are given as follows:

- Generator

$\omega_b = 377$ rad/s, $X_d = 2.0$ pu, $X_q = 1.91$ pu,

$X_{fd} = 1.97$ pu, $X_{kd} = 1.94$ pu, $X_{kq} = 1.9$ pu, $R_a = 0.005$ pu,

$R_{fd} = 0.0015$ pu, $r_{kd} = 0.0078$ pu, $r_{kq} = 0.0084$ pu, $H = 3.25$,

$D = 0.0$

- Exciter

$T_e = 0.01$ s, $K_e = 100$, $-5 \le E_{fd} \le 5$ pu

- Turbine and governor system

$F_{HP} = 0.24$, $F_{IP} = 0.34$, $F_{LP} = 0.42$, $T_{HP} = 0.3$ s, $T_{RH} = 10$ s,

$TIP = 0.3$ s, $P_0 = 1.2$, $T_{GVM} = 0.1$ s, $T_{GVI} = 0.1$ s

Maximum opening and closing rates for both intercept and inlet valves are restricted to $= 6.7$ pu /s.

- Transmission line

$R_e = 0.063$ pu, $X_e = 0.4$pu

- Operating point

$P = 0.8$ pu, $Q = 0.45$ pu, $V_B = 1.0$ pu

- Conventional power system stabilizer

$K = 0.08$, $T_1 = 10$ s, $T_2 = 0.15$ s, $T_3 = 0.05$ s.

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