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Simulation of Synchronous Generator with Fuzzy based Automatic Voltage Regulator

R. Ramya, K. Selvi
Department of EEE, Thiagarajar College of Engineering, Madurai, India.

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ABSTRACT

This paper presents a linear mathematical model of a Synchronous Generator with excitation system for small signal stability analysis. This work aims to develop a controller based on fuzzy logic to simulate an Automatic Voltage Regulator (AVR) for a synchronous generator in order to achieve better stability of the closed loop system and fulfil the requirements of good excitation control. The performance of fuzzy based AVR is tested on Single Machine connected to an Infinite Bus bar system (SMIB) in the MATLAB/SIMULINK platform and the results are compared with the IEEE Exciter model.

Corresponding Author:

R.Ramya, K.Selvi
Department of EEE, Thiagarajar College of Engineering, Madurai, India.
e-mail: rramyame@gmail.com, kseee@tce.edu

1. INTRODUCTION

The quality of power supply must meet certain minimum standards with regard to the following factors: (a) constancy of frequency, (b) constancy of voltage and (c) level of reliability. The function of the excitation control is to regulate generator voltage and reactive power output. The control objectives are dependent on the operating state of the power system. Under normal conditions, the control objective is to operate as efficiently as possible with voltages and frequency close to nominal values. When an abnormal condition develops, new objectives must be met to restore the system to normal operation [1]. Many investigations in the area of AVR of an isolated power system have been reported and a number of control schemes like Proportional and Integral (PI), Proportional, Integral and Derivative (PID) and optimal control have been proposed to achieve improved performance [2]. The conventional method exhibits relatively poor dynamic performance as evidenced by large overshoot and frequency oscillations. These conventional fixed gain controllers based on classical control theories in literature are insufficient because of change in operating points during a daily cycle. In order to elevate this problem, various techniques have been presented in the literature. Synchronous machine simplified modeling for transient stability analysis is described in ref [3]. Ref [4] presents a linear mathematical model of the synchronous generator with excitation system for power system stability in state space form. Ref [5] demonstrated the design and stability analysis of Lyapunov technique approach for the transient stability of a SMIB power system based on the complete seventh order model of the generator system. Ref [6] presents a study of fuzzy logic power system stabilizer for stability enhancement of a single machine power system. The fuzzy reference learning scheme is applied for automatic voltage regulation of third order synchronous generator model and it achieves better time domain performance [7]. Ref [8] presents simulation and experimental study aimed at investigating the effectiveness of an adaptive artificial neural network stabilizer on enhancing the damping torque of a synchronous generator. An evolutionary computing approach for determining the optimal values for the PID controller parameters of LFC and AVR system of single area power system using the particle swarm optimization technique is presented [9]. A combined genetic algorithm and fuzzy logic approach is presented to determine the optimal PID controller parameters in AVR system [10]. Thus, an efficient methodology to achieve better stability and excitation control for synchronous generator is an active research area. In this paper, a detailed seventh order synchronous generator model with three damper windings is developed to reduce the oscillations. The effect of magnetic saturation is included in the design. Small signal stability analysis is done for the system with and without damper windings. Fuzzy based AVR is designed for detailed synchronous generator.

2. MATHEMATICAL MODELLING

2.1 Modelling of Synchronous Machine

The equations of central importance in power system stability analysis are the rotational inertia equations describing the effect of unbalance between the electromagnetic torque and the mechanical torque of the individual machines. The usual conventions are adopted in this work.

Mechanical Equations

The acceleration equations are

$$\Delta\dot{\omega}_r = (1/2H)(T_m - T_e - K_D\Delta\omega_r) \text{ and } \dot{\delta} = \omega_o\Delta\omega_r \tag{1}$$

Electrical Equations

The change in air-gap torque,

$$\Delta T_e = \psi_{ad0}\Delta i_q + i_{q0}\Delta\psi_{ad} - \psi_{aq0}\Delta i_d - i_{d0}\Delta\psi_{aq} \tag{2}$$

The dynamic characteristics of the system expressed in terms of K constants,

$$\Delta T_e = K_1\Delta\delta + K_2\Delta\psi_{fd} \tag{3}$$

The field circuit dynamic equation is

$$\dot{\psi}_{fd} = (\omega_o R_{fd} / L_{adu})E_{fd} - \omega_o R_{fd} i_{fd} \tag{4}$$

In terms of K constants,

$$\Delta\psi_{fd} = (K_3 / 1 + pT_3)\lfloor \Delta E_{fd} - K_4\Delta\delta \rfloor \tag{5}$$

where,

$$K_3 = ((L_{ds} + L_{fd}) / L_{adu}) * (1/1 + (X_{Tq} / D)(X_d - X'_d)),\ K_4 = L_{adu}(L_{ads} / (L_{ads} + L_{fd})) * (E_B / D)(X_{Tq}\sin\delta_o - R_T\cos\delta_o) \tag{6}$$

The perturbation in the terminal voltage can be expressed as

$$\Delta E_t = (e_{d0} / E_{t0})\Delta e_d + (e_{q0} / E_{t0})\Delta e_q \tag{7}$$

In terms of K constants, $\Delta E_t = K_5\Delta\delta + K_6\Delta\psi_{fd}$ (8)

The excitation system variable,

$$\Delta\dot{v}_1 = (K_5 / T_R)\Delta\delta + (K_6 / T_R)\Delta\psi_{fd} - (1/T_R)\Delta v_1 \tag{9}$$

Linear model of SMIB

By linearizing the above equations on at operating point we have the state variable model of a single machine to infinite bus as

$$\dot{x} = Ax + Bu\ ,\ y = Cx + Du \tag{10}$$

$$\begin{bmatrix} \Delta\dot{\omega}_r \\ \Delta\dot{\delta} \\ \Delta\dot{\psi}_{fd} \\ \Delta\dot{v} \end{bmatrix} = \begin{bmatrix} \frac{-K_D}{2H} & \frac{-K_1}{2H} & \frac{-K_2}{2H} & 0 \\ \omega_0 & 0 & 0 & 0 \\ 0 & \frac{-\omega_0 R_{fd}}{L_{fd}} m_1 L'_{ads} & \frac{-\omega_0 R_{fd}}{L_{fd}}\left[1 - \frac{L'_{ads}}{L_{fd}} + m_1 L'_{ads}\right] & \frac{-\omega_0 R_{fd}}{L_{adu}} KA \\ 0 & \frac{K_5}{T_R} & \frac{K_6}{T_R} & \frac{-1}{T_R} \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\psi_{fd} \\ \Delta v_1 \end{bmatrix} + \begin{bmatrix} \frac{1}{2H} & 0 \\ 0 & 0 \\ 0 & \frac{\omega_0 R_{fd}}{L_{adu}} \\ 0 & 0 \end{bmatrix} [\Delta T_m] \tag{11}$$

A fourth-order model is considered for the synchronous generator. The system matrix A is function of the system parameters, which depends on the operating conditions. The perturbation matrix B depends on the system parameters only. The perturbation signal u is ΔT_m. The output matrix C relates the desired output signals vector y to the state variables vector x.

Inclusion of amortisseurs windings

In order to reduce the oscillations, amortisseurs windings are included in the modelling of synchronous generator. Three amortisseurs windings are considered, one on d-axis and two on q-axis. The equivalent circuit of the synchronous machine model given in [1] is considered in this paper.

Rotor circuit equations with inclusion of damper winding,

$$\dot{\psi}_{fd} = (\omega_o R_{fd} / L_{adu}) E_{fd} - \omega_o R_{fd} i_{fd} \tag{12}$$

$$\dot{\psi}_{1d} = -\omega_o R_{1d} i_{1d}, \; \dot{\psi}_{1q} = -\omega_o R_{1q} i_{1q}, \; \dot{\psi}_{2q} = -\omega_o R_{2q} i_{2q} \tag{13}$$

The expression for electromechanical torque and terminal voltage is given by

$$\Delta T_e = \psi_{ad0} \Delta i_q + i_{q0} \Delta \psi_{ad} - \psi_{aq0} \Delta i_d - i_{d0} \Delta \psi_{aq} \text{ and } \Delta E_t = K_5 \Delta\delta + K_6 \Delta\psi_{fd} + K_{61} \Delta\psi_{1d} + K_{62} \Delta\psi_{1q} + K_{63} \Delta\psi_{2q} \tag{14}$$

The order of the system is increased by three with the inclusion of three amortisseurs windings. The equation for terminal voltage is derived and constants (K_{61},K_{62},K_{63}) are determined. The system equation is given by

$$\begin{bmatrix} \Delta\dot{\omega}_r \\ \Delta\dot{\delta} \\ \Delta\dot{\psi}_{fd} \\ \Delta\dot{\psi}_{1d} \\ \Delta\dot{\psi}_{1q} \\ \Delta\dot{\psi}_{2q} \\ \Delta\dot{v} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & 0 \\ a_{21} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_{32} & a_{33} & a_{34} & a_{35} & a_{36} & (-\omega_0 R_{fd} / L_{ad}) K_A \\ 0 & a_{42} & a_{43} & a_{44} & a_{45} & a_{46} & 0 \\ 0 & a_{52} & a_{53} & a_{54} & a_{55} & a_{56} & 0 \\ 0 & a_{62} & a_{63} & a_{64} & a_{65} & a_{66} & 0 \\ 0 & K_5 / T_R & K_6 / T_R & K_{61} / T_R & K_{62} / T_R & K_{63} / T_R & -1 / T_R \end{bmatrix} \begin{bmatrix} \Delta\omega_r \\ \Delta\delta \\ \Delta\psi_{fd} \\ \Delta\psi_{1d} \\ \Delta\psi_{1q} \\ \Delta\psi_{2q} \\ \Delta v \end{bmatrix} + \begin{bmatrix} b_{11} & 0 \\ 0 & 0 \\ 0 & b_{32} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} [\Delta T_m]$$

2.2 Excitation Controller

IEEE Exciter

The IEEE type2, the rotating rectifier system incorporates damping loops that originate from the regulator output rather than from the excitation voltage since, being brushless, the excitation voltage is not available to feedback. Two time constants appear in the damping loop of this system, T_{F1} and T_{F2}, one of which approximates the exciter time delay and is considered "major damping", with the second or "minor damping" being present to damp higher frequencies [11]. The IEEE Exciter available in ref [11] is used in this paper.

Fuzzy Logic Controller

Fuzzy control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system [12]. The fuzzy controller block diagram is given in Fig.1a, where we show a fuzzy controller embedded in a closed-loop control system. The plant outputs are denoted by $y(t)$, its inputs are denoted by $u(t)$, and the reference input to the fuzzy controller is denoted by $r(t)$. Defining the input and output variables is one of the important steps in the fuzzy controller design. In this study, the output voltage error and its rate of change are defined as input variables and increment of the voltage exciter is the controller output variable. The linguistic variables for fuzzy inputs are VN, LN, BN, MN, SN, ZE, SP, MP, BP, LP and VP which stands for very large negative, large negative, big negative, medium negative, small negative, zero, small positive, medium positive, big positive, large positive and very large positive respectively. Triangular membership functions are used to define the degree of membership (Fig.1b).

The rule base adjusts the excitation voltage of the synchronous generator based upon the changes in the input of the FLC. The rule base includes 121 rules, which are based upon the eleven linguistic variables. For this system, max-min composition is used for the inferencing. Defuzzification is done using centre of gravity method to generate nonfuzzy control signal for change in excitation voltage of the synchronous generator.

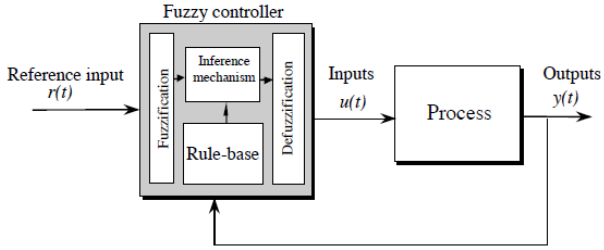

Figure 1a. Fuzzy controller architecture

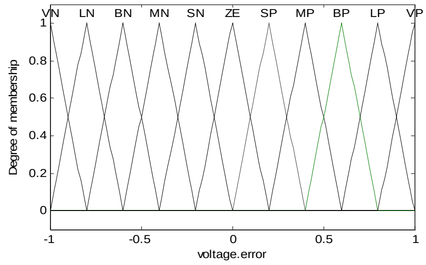

Figure 1b. Membership functions

3. NUMERICAL EXAMPLE

In this paper, a detailed dynamic model of a power system, named a single machine infinite bus (SMIB) power system is considered [1]. This model is consisted of a single synchronous generator connected through a parallel transmission line to a very large network approximated by an infinite bus. Fig.2 shows the system representation applicable to a thermal generating station consisting of four 555 MVA, 24 KV and 60 Hz units which is considered in this paper. The network reactances shown in Fig.2 are in per unit on 2220 MVA, 24 KV base referred to the LT side of the step-up transformer. All the parameters of the machine are converted on this same base value. Resistances are assumed to be negligible. The objective of this paper is to analyze the small- signal stability characteristics of the system about the steady-state operating condition following the loss of circuit2 and also to analyze the performance characteristics of the system with fuzzy based AVR. The post fault system condition in per
unit are P=0.9, Q=0.3, E_t=1∟36º and E_B=0.995∟0º

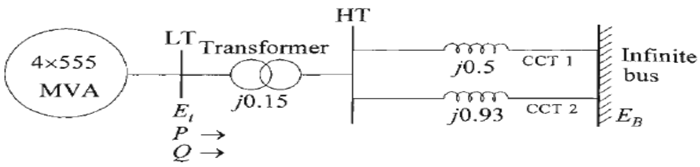

Figure 2. Single machine connected to an Infinite bus through transmission lines [1]

4. RESULTS AND DISCUSSION

To show the validity of the mathematical analysis and hence to investigate the performance of the proposed fuzzy excitation controller, simulation works are carried out for the Single Machine Infinite Bus system. In order to prove the robustness of the proposed controller, the results are compared with conventional IEEE type 2 AVR.

4.1 Small Signal Stability Analysis

4.1.1 System without amortisseurs winding - Computation of Heffron-Phillips constants

The K constants K_1 to K_6 are termed as Heffron-Phillips constants. They are dependent on the machine parameters and the operating conditions. Table 1 summarizes the K constants with variations in network parameter(X_e) at operating condition P=0.9 and Q=0.3.

Table 1. Heffron-Phillips constants with X_e Variations when P=0.9, Q=0.3, K_A=200

Constants/X_e	0.1	0.2	0.3	0.5	0.6	0.8
K1	1.8239	1.5238	1.2919	0.9443	0.8075	0.5814
K2	1.6864	1.4280	1.2559	1.0412	0.9697	0.8658
K3	0.2264	0.2676	0.3045	0.3678	0.3952	0.4432
K4	2.7536	2.3343	2.0550	1.7062	1.5901	1.4211
K5	0.0165	0.0021	-0.024	-0.088	-0.121	-0.182
K6	0.1637	0.2617	0.3270	0.4086	0.4357	0.4752

Generally K_1, K_2, K_3 and K_6 are positive. The field flux variations are caused by feedback of Δδ through the coefficient K_4 which is shown in Fig.5. This represents the demagnetizing effect of the armature reaction. K_4 is also mostly positive except for cases when R_e is high. K_5 can be either positive or negative. K_5 is positive for low to medium external impedances (R_e+jX_e) and low to medium loadings and it is usually negative for moderate to high external impedances and heavy loadings as shown in Fig3b. In this work, armature resistance is neglected and this refers to a lossless network on the stator side.

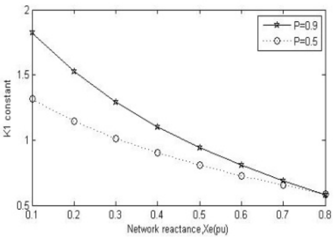

Figure 3a. Variations of K_1 with X_e

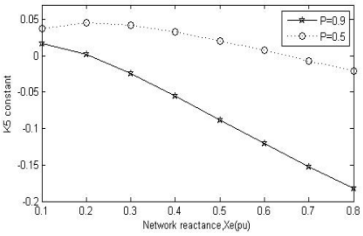

Figure 3b. Variations of K_5 with X_e

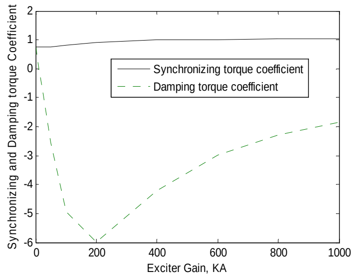

Figure 3c. Synchronizing and Damping torque coefficient with varying K_A

The synchronizing torque is responsible for restoring the rotor angle excursion while the damping torque damps out the speed deviations. The synchronizing and damping torques are usually expressed in terms of the torque coefficients K_S and K_D. The effect of AVR on damping and synchronizing torque components is primarily influenced by K_5 and exciter gain K_A. When K_5 is negative, the effect of AVR is to increase the synchronizing torque component and decrease the damping torque component. When K_5 is positive, the effect of AVR is to decrease the synchronizing torque component and increase the damping torque component. For the system considered in this paper a negative value of K_5 is employed. Since, high response exciter is beneficial in increasing synchronizing torque. Fig.3c shows the effect of AVR on K_S and K_D at ω=10 rad/s for different values of K_A. The effect of the AVR is to decrease K_D for all positive values of K_A. As can be seen from Fig.3c, the net damping is most negative with a value of -6 for K_A = 200. Thus, K_A is set at 200 for the model. From the equations discussed in section 2.1, the system matrix obtained is given by

$$A = \begin{bmatrix} -1.426 & -0.1065 & -0.1342 & 0 \\ 376.9911 & 0 & 0 & 0 \\ 0 & -0.2113 & -0.3360 & -27.4175 \\ 0 & -6.8440 & 22.3581 & -50.0000 \end{bmatrix}$$

The stability condition of the synchronous machine infinite bus system can be examined using eigen values of overall system matrix (A) in the MATLAB environment. The closed loop eigen values are -0.2106+i7.1521, -0.2106-i7.1521, -25.6716+i3.1641 and -25.6716-i3.1641 with exciter gain fixed as K_A=200. Then the sensitivity of eigen values to the elements of the state matrix has been examined by the participation matrix which combines the right and left eigen vectors. This is evaluated as a measure of the association between the state variables and the modes.

4.1.2 System with amortisseurs winding

The open loop eigen values are -0.9617+i6.3218, -0.9617-i6.3218, -0.1610, -1.7129, -22.0095 and -39.3760. The closed loop eigen values are -0.7777±i7.0231, -0.8841±i46.7559, -1.6775, -21.9877 and -88.1939. Table 2 shows the effect of varying exciter gain on the eigen values of the state matrix.

Table 2. Eigen values with varying exciter gain

K_A/ Eigen values	λ1,λ2	λ3	λ4	λ5	λ6	λ7
-	-0.961±6.321i	-0.161	-1.712	-22.00	-39.376	-
0.1	-0.956±6.318i	-0.219	-1.714	-22.00	-39.160	-50.164
10	-0.456±6.467i	-1.667	-8.443	-22.21	-23.870	-58.072
15	-0.410±6.648i	-15.209±6.6861i		-1.671	-21.929	-60.341
50	-0.622±6.994i	-10.156±24.458i		-1.676	-21.983	-69.964
100	-0.726±7.021i	-6.059±34.7118i		-1.677	-21.986	-77.947
125	-0.747±7.023i	-4.523±38.3530i		-1.677	-21.987	-80.977
150	-0.760±7.023i	-3.1792±41.485i		-1.677	-21.987	-83.638
200	-0.777±7.023i	-0.884±46.7559i		-1.677	-21.987	-88.193
230	-0.784±7.022i	0.3128±49.4770i		-1.677	-21.987	-90.574

It is observed from table 2, when K_A= 0.1 and 10, there are two oscillatory eigen values and the remaining are non-oscillatory. From K_A=15 to 200, there are four oscillatory modes since the real eigen values λ3 and λ4 are combined as a complex pair. With the further increase in K_A from 200, two oscillatory modes becomes positive, hence it indicates unstable condition. Therefore the value of K_A is set at 200. Plot for eigen value loci is shown in Fig.4 to give the effects of varying exciter gain. The damping frequency and its ratio for oscillatory eigen values is also detailed in Table 3 for various values of K_A.

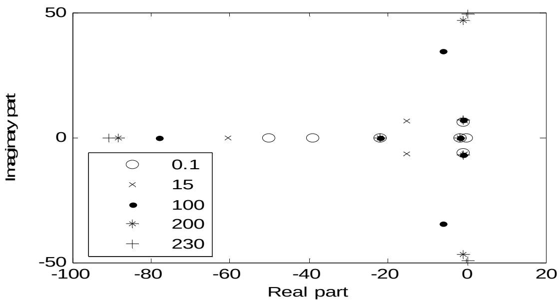

Figure 4. Eigen value loci for variations in exciter gain

Table 3. Damping frequency and ratio

K_A	Oscillatory Eigen values	Damping Frequency(Hz)	Damping ratio
-	-0.9617 ±6.3218i	1.0061	0.1504
10	-0.4569 ± 6.4674i	1.0293	0.0705
50	-0.6226 ±6.9945i	1.1132	0.0887
	-10.1567±24.4588i	3.8927	0.3835
100	-0.7261±7.0219i	1.1176	0.1029
	-6.0599±34.7118i	5.5246	0.1720
200	-0.7777±7.0231i	1.1178	0.1101
	-0.8841±46.7559i	7.4414	0.0189
250	-0.7878±7.0224i	1.1176	0.1115
	1.0537±51.1548i	8.1415	-0.0206

4.2 Controller Performance

The initial conditions of system parameters are calculated and model is created using Simulink in Matlab as in Fig.5. Nonlinear simulations are performed to test the efficacy of the designed controller. In order to test the performance of the proposed fuzzy controller under disturbances, it is tested on a single machine connected to infinite bus system for two different test cases as given below.

Test1: Changes in reference voltage (V_{ref}) and Test2: Changes in input mechanical torque (T_m)

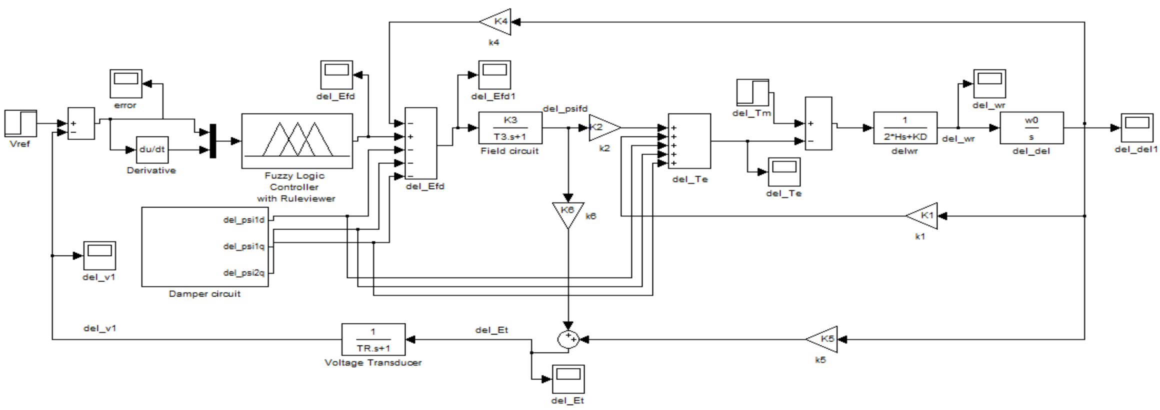

Figure 5. Linearized incremental model of Synchronous Generator with Fuzzy Logic Controller

Test1-Step change in reference voltage: In order to test the effectiveness of the controller in tracking the reference values, the system is subjected to a variation of reference voltage. In this case, the reference voltage is decreased from 1 pu to 0.5 pu at 20secs. The test results of proposed fuzzy controller are compared with IEEE exciter. The response of terminal voltage is shown in Fig.6. It is observed that with the use of fuzzy controller the oscillations are damped out quickly even reference voltage is decreased by 50%.

Fig.6 shows variations in rotor speed and rotor angle with respect to time. Though the rotor speed is not much disturbed by excitation control normally, it is obvious from the Fig.6(third from the top when moving in clockwise) that immediately after occurrence of disturbance, small oscillations in rotor speed is present in case of IEEE exciter, which is also nullified with the use of the developed fuzzy controller.

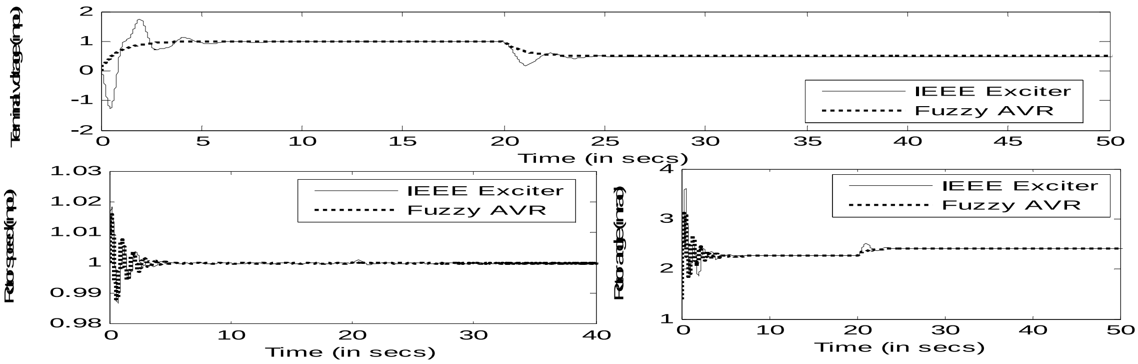

Figure 6. Response of the system for step change in V_{ref}

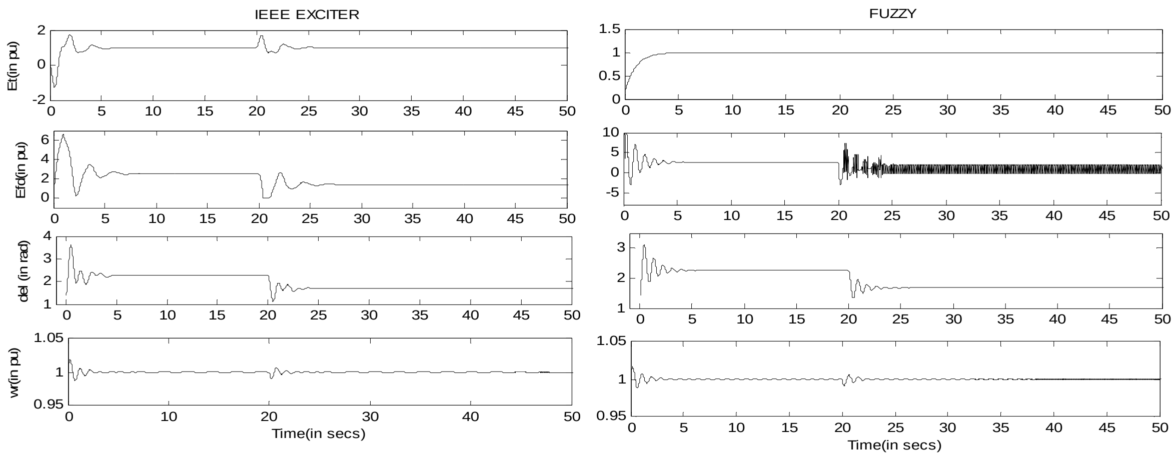

Figure 7. Response of the system for step change in T_m

Since, the system is tested for larger decrease in reference voltage intentionally, with the aim to prove the performance of the controller in extreme cases; rotor angle is increased in post disturbance settlement, as shown in Fig.6, (second from top when moving in clockwise direction). However, the better performance of the fuzzy controller over the conventional one in damping out the initial oscillations incurred is explicit.

Test2-Step change in T_m: In this case, the mechanical torque (T_m) is decreased from 1 pu to 0.5 pu at 20secs. The test results of the developed fuzzy controller are compared with IEEE exciter. The response of the system in Test2 is shown in Fig.7. The developed fuzzy controller shows good performance that is characterized by lower overshoot and faster response.

5. CONCLUSION

This paper reports on the design, development and validation of a fuzzy based AVR for a state space model of SMIB system. Response curves of terminal voltage, field voltage, rotor speed and angle were observed. The simulation results with two test cases demonstrate that generator excitation with the developed fuzzy controller can effectively damp out the oscillations and improve the small signal stability of power system. Hence, fuzzy controller guarantees the stability of the closed loop system and fulfils the requirements of good excitation control.

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BIOGRAPHIES OF AUTHORS

R. Ramya obtained B.E (EEE) and M.E (Power Systems) with Distin, from Anna University in the year 2007 and 2009 respectively. She is currently pursuing Ph.D in Anna University and working in Department of Electrical Engineering in Thiagarajar College of Engineering, Madurai, Tamil Nadu, India. Her research areas are Power System modelling and Simulation, Power System Stability and Control.

Dr. K. Selvi obtained B.E (EEE) with Honours, M.E(Power Systems) with Distin, from Madurai Kamaraj University in the year 1989 and 1995 respectively. She obtained Ph.D in Electricity Deregulation in June 2005 from Madurai Kamaraj University. She is currently working as Associate professor in Department of Electrical Engineering in Thiagarajar College of Engineering, Madurai, Tamil Nadu, India. Her research interests include Electricity deregulation, System modeling and simulation and Power plant economics.