Fuzzy logic controller for synchronous generators in a stand-alone multi-machine power system

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***Abstract*— This paper will deal with the design and development of fuzzy logic based controller implemented in synchronous generator excitation system that serves in isolated multi-machine power system. The controller is developed and simulated for a system containing nine generators with two types of prime movers (diesel engine and gas turbine systems) which feeds a variety of linear as well as non-linear loads. MATLAB/ SIMULINK based models are developed for observing steady state as well as dynamic performance for the study system. The simulation results are compared with others obtained for the system equiped with PID controllers. The results illustrate the effectiveness of the fuzzy controller over the PID controller. All the data acquired are from a real working oil production and refinery site.**

Keywords: Fuzzy logic, Excitation system, Stand-Alone, Decision making

INTRODUCTION

The existence of remote isolated loads is inevitable due to some industrial needs such as the extraction of minerals, petroleum sites, marine industries and the spread of populace in remote areas. Technical and economic difficulties prevent connecting them to the main grid which forces us to provide for these loads with high quality voltage and frequency.

OIL related industries are often supplied by remote stand-alone power system and usually the generators in these systems are driven by a prime mover (engine-turbine) which operates on the gas delivered from wells directly. Isolated power systems have characteristics significantly different from those found in large-scale power system. These systems often have very large induction motors that require being started direct-on-line. Small stand-alone systems are relatively weak, have low inertia and short-circuit levels, high R/X ratios and are much more affected by dynamic load changes. Load variations, disturbances and unbalances produce higher levels of power quality deviations in these systems [1-3].

The design, transmission, dispatching, operation, and control of such power systems offer many challenging problems. The most important one among them is probably the stabilization of the power system especially under transient conditions.

SYSTEM CONFIGURATION

The system under study is a working oil production and refinery field located in Ras-shukair near Hurghada city, Egypt.

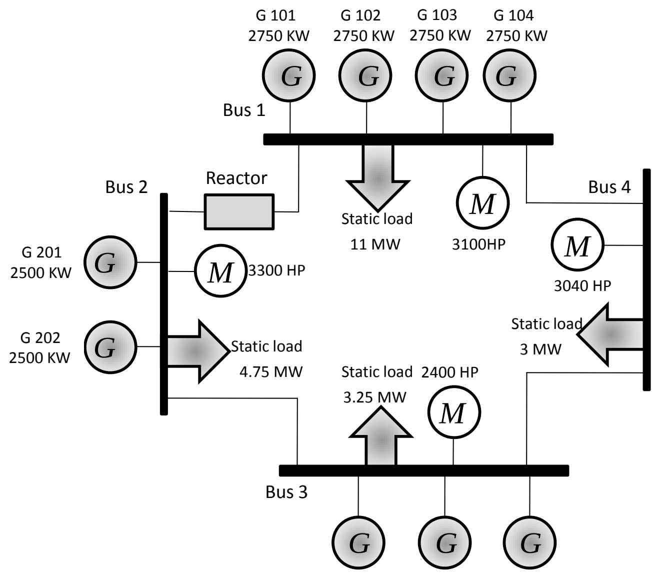


Figure (1) Schematic diagram of the system

Bus 1 is considered as slack bus, the other five generators are identical and have the same rating 2500 KW with different prime movers as mentioned in Table (1), they are distributed as two on Busbar 2 and three on Busbar 3, Motors on each bus are represented by a large new equivalent motor.

Table (1) Generating unit arrangement

Generator	Prime-mover	Bus-bar	(KW)	(V)
101-102 -103-104	Gas turbine	1	2750	4160

201-202	Diesel Engine	2	2500	4160
301-302-303	Gas turbine	3	2500	4160

1- SYSTEM MODELING

A. SYNCHRONOUS GENERATOR

The following equations synchronous generator is represented by, i.e. with a field circuit and one equivalent damper winding on q-axis these equations are known as the electro-mechanical swing and the generator internal voltage equations [4, 5]:

$$\frac{d\omega}{dt}=\frac{1}{M}\left[T_m-D(\omega-1)\right] \quad (1)$$

$$\frac{d\delta}{dt}=\omega_b(\omega-1) \quad (2)$$

$$\frac{dE'_q}{dt}=\frac{1}{T'_{do}}\left[-E'_q-i_d\left(x_d-x'_d\right)+E_{fd}\right] \quad (3)$$

The electrical torque can be represented in terms of d-axis and q-axis components of the armature current, and the terminal voltage, as follows:

$$T_e=v_d\cdot i_d+v_q\cdot i_q \quad (4)$$

Voltages can be expressed as follows:

$$V_t=\sqrt{v_d^2+v_q^2} \quad (5)$$

$$v_d=x_d\cdot i_q \quad (6)$$

$$v_q=E'_q-x'_d\cdot i_d \quad (7)$$

B. PRIME MOVER

B.1-Gas Turbine

The gas turbine under study in the site is a single shaft light industrial gas turbine. As shown in Figure (2), The model consists of Speed error sensing circuit, Power amplifier, Governor compensation, Fuel valve mechanism lag and Fuel valve limits [6].

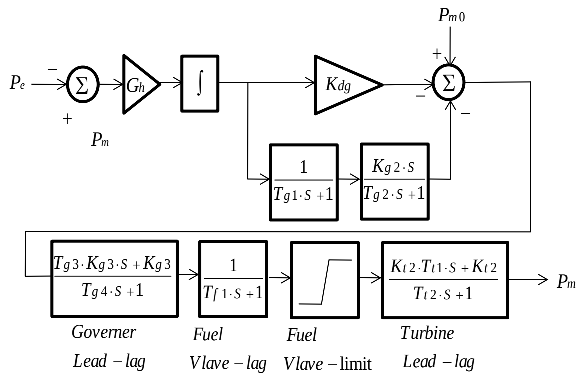


Figure (2) Gas turbine model

B.2-Diesel Engine

In this model, the controller is modeled as a first order system; the diesel engine is modeled as a pure delay [7],as shown in Figure (3).

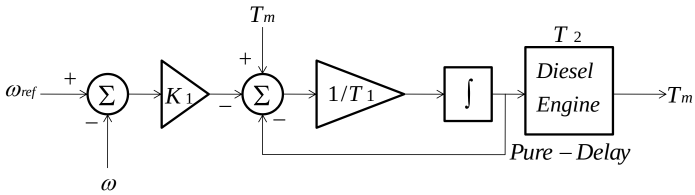


Figure (3) Diesel Engine and governor model

C. TRANSMISSION SYSTEM AND LOAD

-The transmission system is treated as a short transmission '< 8

0KM', and is taken into consideration as an additional resistive and inductive load as the longest transmission line is 20 KM long.

-Loads are also represented in both forms static and dynamic, Motors are represented as one relatively large motor about 2500 HP rating which is represented in a separate model associated with the power system, static loads are also represented as resistance and inductance.

C.1 Induction motor

A squirrel cage induction motor (2500 KW) is modeled through a fast approach in which four differential equations of voltage and current in rotor reference frame along with the torque equation is used to model the motor in state space form [8], The equations are in synchronous reference frame.

$$\begin{bmatrix}V_{qs}\\V_{ds}\\0\\0\end{bmatrix}=\begin{bmatrix}(R_s+L_sp) & \omega L_s & L_mp & \omega L_m\\ -\omega L_s & (R_s+L_sp) & -\omega L_m & L_mp\\ L_mp & -(\omega-\omega_r)L_m & (R_r+L_rp) & (\omega-\omega_r)L_r\\ -(\omega-\omega_r)L_m & L_mp & -(\omega-\omega_r)L_r & (R_r+L_rp)\end{bmatrix}\cdot\begin{bmatrix}i_{qs}\\i_{ds}\\i_{qr}\\i_{dr}\end{bmatrix} \quad (8)$$

Where, $L_s = L_{1s} + L_m$

$L_r = L_{1r} + L_m$

$p = \frac{d}{dt}$

Equation (8) is presented in state space form as follows:

$$p[i] = -[L]^{-1}([R] + \omega_r [G])[i] + [L]^{-1}[V] \quad (9)$$

Where;

$$[i] = [i_{qs} \quad i_{ds} \quad i_{qr} \quad i_{dr}]^T$$

$$[V] = [V_{qs} \quad V_{ds} \quad 0 \quad 0]^T$$

A MATLAB-SIMULINK for the induction motor model is shown in Figure (4)

$$[R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix}$$

$$[L] = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \qquad [G] = \begin{bmatrix} 0 & L_s & 0 & L_m \\ -L_s & 0 & -L_m & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

Mechanical equations: $T_e = 1.5 P L_m (i_{qs} i_{dr} - i_{ds} i_{qr})$ (10)

$$\dot{\omega}_m = -F \cdot \omega_m + (T_e - T_L)/J_m \quad (11)$$

D. INITIAL CONDITION AND LOAD FLOW CALCULATIONS

The next step was to perform the initial condition and load flow calculations this can be done By using MATLAB M-File especially built to calculate the initial values of all system variables i.e., power flow (active and reactive power), bus voltages, currents and load angles etc. the load flow is done according to the system nodes self-admittance and mutual-admittance which include the lines resistances and reactances, The iterative used algorithm for the load flow is Newton–Raphson approach, This approach will be repeated until an acceptable tolerance is reached.

E. STAND-ALONE MULTI-MACHINE REPRESENTATION

To implement more than one synchronous generator in a stand-alone system, the Busbar with the highest generating power should be taken as a slack bus. All the generators will be represented on a new D-Q axis. he MATLAB SIMULINK model is shown in Figure (5), which is built using the dynamic equations described in previous sections and the steady state equations are used to compute the initial conditions. In the simulation, the nonlinear system equations are solved using Runge-Kutta Fourth order integration technique with an integration step of 2ms.

F. EXCITATION SYSTEM

-The IEEE Type-ST1 excitation system including both AVR and PSS considered [9]. It can be described as:

$$\rho E_{fd} = \left[K_A (V_{ref} - v + u_{pss}) - E_{fd}\right] / T_A \quad (12)$$

2- DESIGN OF FUZZY LOGIC CONTROLLER

This paper is to present the application of fuzzy logic techniques to control the generator in multi-machine power systems. To demonstrate the generator control improvement, the simulation results are obtained in comparison with PID control system.

Any Fuzzy logic controller (FLC) will go through 3 stages, fuzzification, decision making and defuzzification (11,12) as shown in Figure (5). As shown in Figure (6), The input and output variables are thus represented as a collection of linguistic values L = {- ve, Z, + ve}. Each of the membership function is triangular type and the height of the membership functions is chosen to be one.

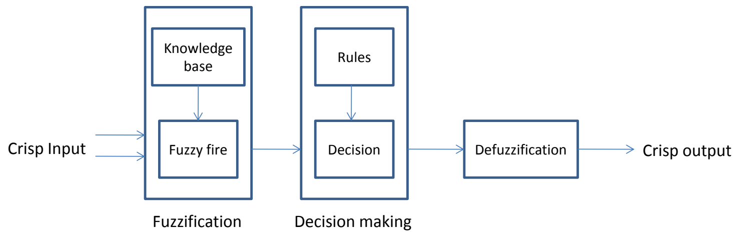


Figure (6) Fuzzy logic control scheme

G.1 Fuzzification

A process in which a crisp input variable transfers into an equivalent fuzzy variable. Two inputs will be assigned to FLC , speed error (ω) and its derivative ($d\omega/dt$).

The input and output variables are thus represented as a collection of linguistic values L = {- ve, Z, + ve}. Each of the membership function is triangular type and the height of the membership functions is chosen to be one.

G.2 Decision making

IF-then based rules, their number depend on the inputs and outputs and the number of membership functions. If the number of if-then fuzzy rules increases Complexity of fuzzy controllers increases Also, the number of rules increases exponentially as the number of input variables of fuzzy controllers increases [10].

Table (2),(3) shows the Rule table for Busbar 2 and Busbar 3 respectively

Table (2) Rule table for generators on Bus 2

$d\omega/dt$ \ ω	- ve	Zero	+ ve
- ve	+ve	+ve	-ve
Zero	-ve	Zero	Zero
+ ve	-ve	+ve	Zero

Table (3) Rule table for generators on Bus 3

$d\omega/dt$ \ ω	- ve	Zero	+ ve
- ve	+ve	-ve	+ve
Zero	-ve	Zero	+ve
+ ve	Zero	+ve	-ve

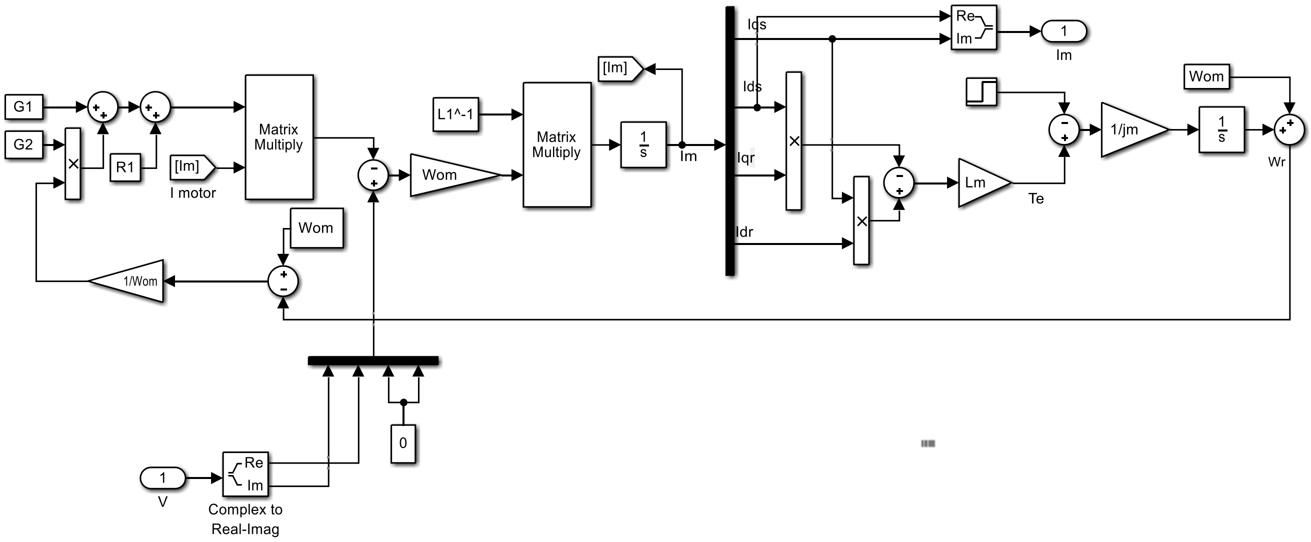


Figure (4) SIMULINK model of the induction motor

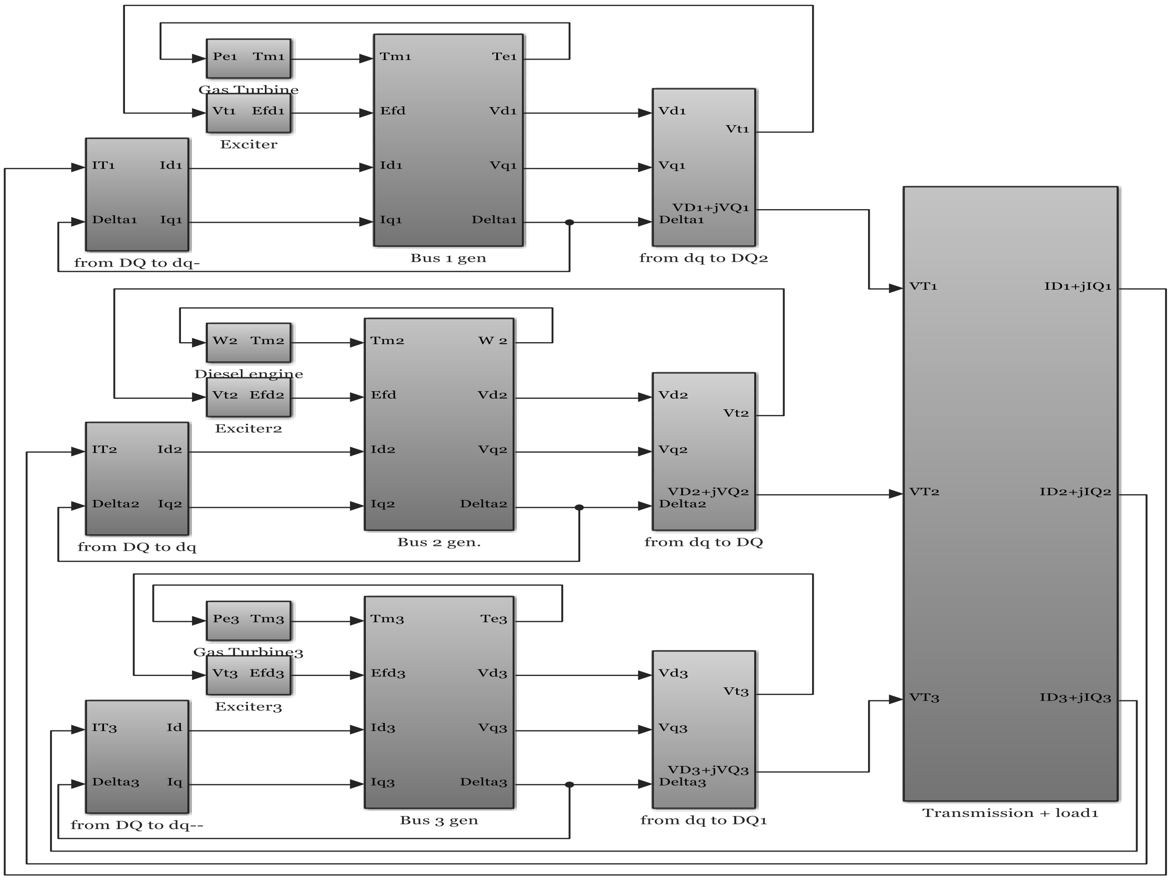


Figure (5) SIMULINK model of Multi-machine power system

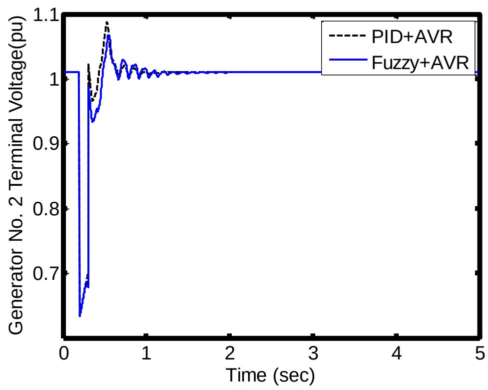
G.2 Defuzzification

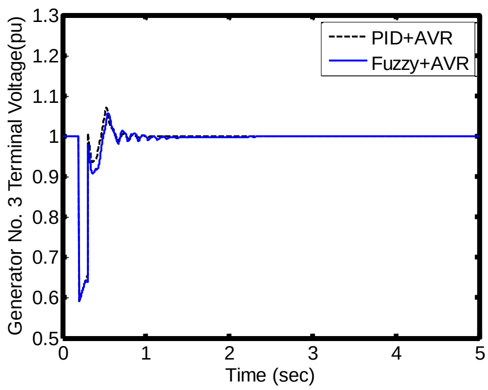
Defuzzification is the process of transferring the fuzzy values into a crisp output once again

3- PERFORMANCE AND RESULTS

The dynamic performance of the system is tested among many disturbances, A comparison between both the PID and FLC will be performed and the results will be shown.

Case 1: Six cycles (100 ms) 3-phase short circuit on Bus 4. Results are taken on bus 2 (Diesel engine) and bus 3 (Gas turbine).
As we can see on bus 2 results: 1-slight improvement on the terminal voltage swings 2-Speed deviation swings amplitude is reduced 3- Rotor angle have the same settling time but the swings amplitudes are increased.
Bus 3 results: 1-slight improvement on the terminal voltage swings 2- Speed deviation settling time is improved 3- Rotor angle have the a longer settling time but the swings amplitude is decreased.





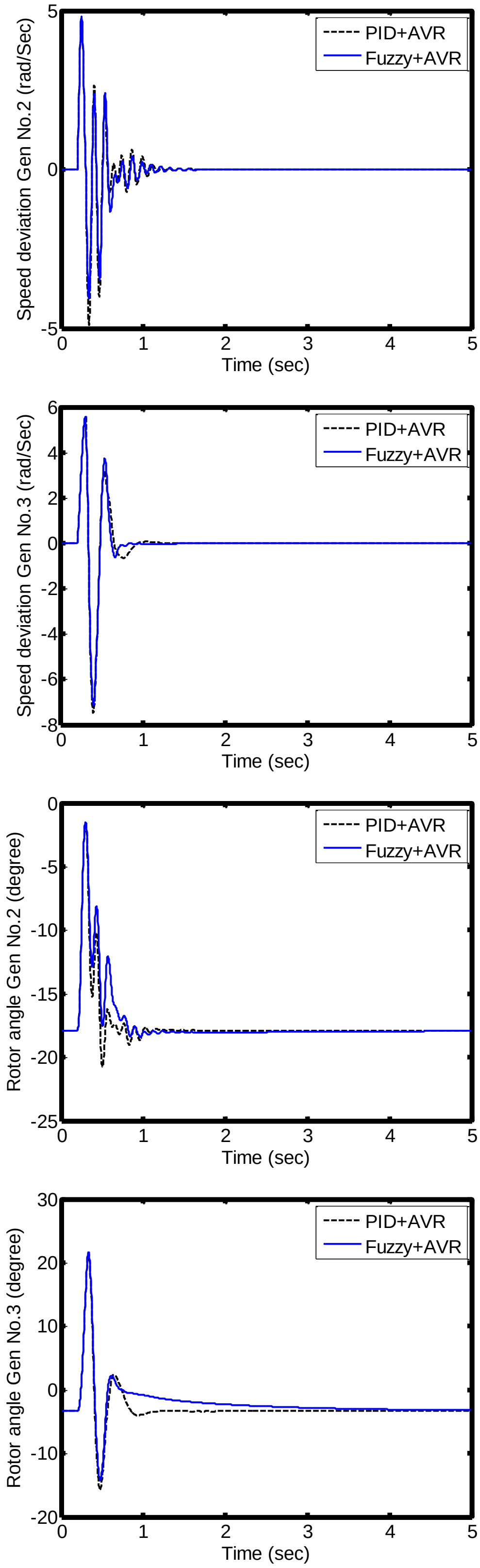
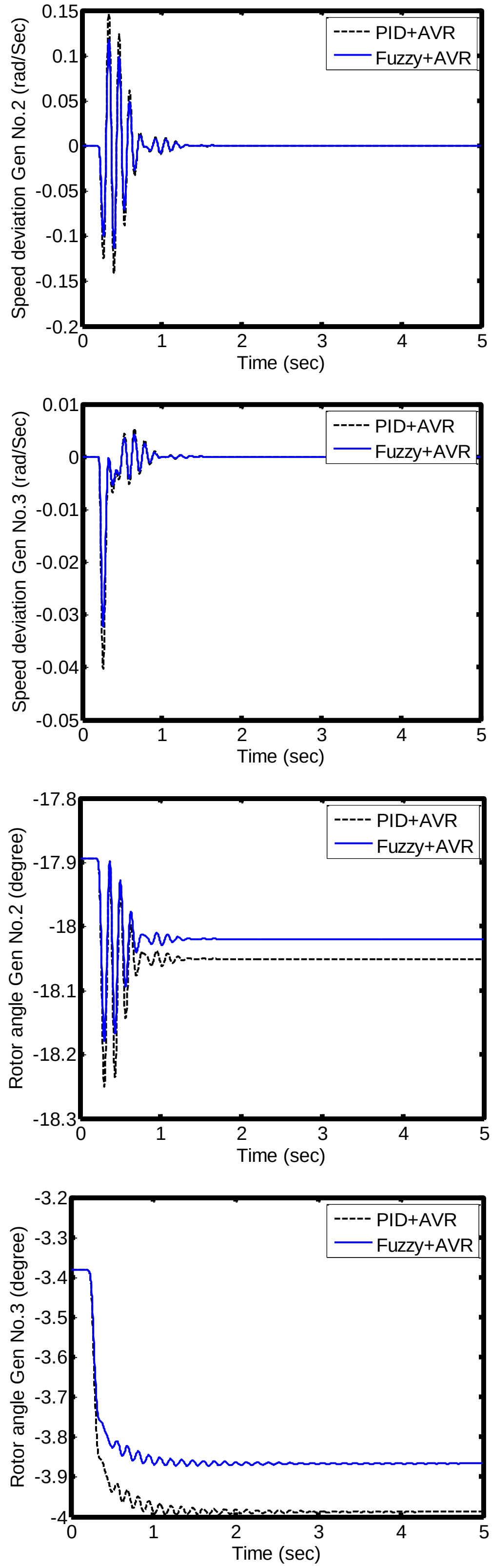


Figure (7) System response for 5% increase in gen.2 reference voltage for 1s

Case 2: 10% permanent increase in the motor load. As we can see on bus 2 and bus 3 results: 1-Speed deviation swings amplitude is reduced 2- Rotor angle have the same settling time but with a better settling value. It is also noticeable that the motor terminal voltage drops by a lower value in case of applying FLC same for motor speed final value



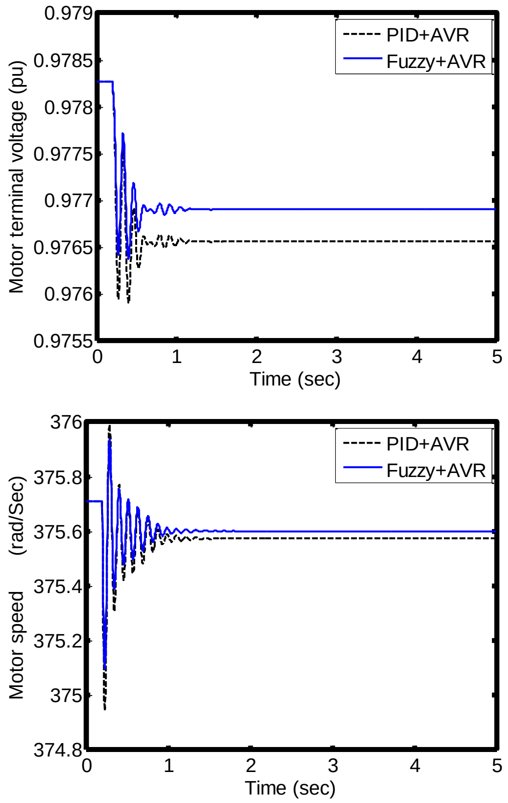


Figure (8) System response for 10% permanent increase in the motor load.

After comparing the graphs of conventional PID and fuzzy logic controller as shown in Figure (7- 10) it is clear that system performance with fuzzy logic controllers has a better overall dynamic performance ,small overshoot and faster response compared to conventional PId controllers.

The simulation results are obtained when using this control strategy under different disturbances.

Simulation results show that the proposed FLC scheme is more effective for enhancing the stability of mentioned isolated system.

3- CONCLUSION

In this paper, A complete isolated system has been represented including nine generators with different prime movers (Diesel engine and gas turbine), static load and transmission system are also taken into consideration. The control is implemented in the excitation loop with the speed deviation as the main controlling signal. For both FLC and PID controller. PID controller and FLC parameters are chosen based on try and error. The simulation results show that, FLC scheme is more effective for enhancing the dynamic performance on different disturbances compared with that of a conventional PID controller.

4- APPENDIX

Diesel engine parameters:

$\tau_1 = 0.02$ $\tau_2 = 0.05$

$K_1 = 1/0.04$

AVR and PSS parameters:

Bus 2	Bus 3
$K_a = 100$	$K_a = 200$
$T_a = 0.05$	$T_a = 0.034$
$T_{pss1} = 0.12$	$T_{pss1} = 0.24$
$T_{pss2} = 0.012$	$T_{pss2} = 0.024$
$K_{pss} = 0.2$	$T_{pss} = 0.09$

Gas turbine parameters:

$K_{dg} = .04$	$T_{t1} = 0.3$
$K_{g2} = 5$	$T_{t2} = 1.3$
$K_{g3} = 1$	$T_{f1} = 0.01$
$T_{g1} = .06$	$T_{g4} = 1$
$T_{g2} = .03$	$T_{g3} = 0.25$
	$K_{t3} = 0.9$

PID controller parameters:

Bus 2	Bus 3
$P_{pid} = 0.0010043$	$P_{pid} = 0.065269$
$I_{pid} = 0.959780$	$I_{pid} = 0.82612$
$D_{pid} = 0.0010994$	$D_{pid} = 0.0055816$

Induction motor parameters:

$P = 2$	$R_s = 0.029$
$W_{om} = 120 * pi$	$L_{ls} = 0.226$
$W_{em} = Wom / P$	$R_r = 0.022$
$J = 63.87$	$L_{lr} = 0.226$
$H_m = 0.5 * J * (Wem)^2$	$L_m = 13.04$
	$S = 0.0034$

Synchronous generator parameters:

$X_d = 1.464$ $\quad T_{do}' = 4.93$

$X_q = 0.757$ $\quad T_{qo}' = 0.3287$

$X_d' = 0.187$ $\quad R_f = 0.706$

$X_q' = 0.757$ $\quad R_a = 0.018$

$H = 0.657$ $\quad W_0 = 2 * pi * 60$

Static load "Assumed constant during the simulation":

Consumed power at Bus 1: 6.119 watt

Consumed power at Bus 2: 3.980 watt

Consumed power at Bus 3: 2.390 watt

Consumed power at Bus 4: 2.619 watt

Transmission network:

Reactor impedance (Z12): R12 = 0.032; L12 = 0.0849

Z23 = 0.09 + 0.05 OHM

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