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Fuzzy-Swarm Controller for Automatic Voltage Regulator of Synchronous Generator

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ABSTRACT

The main objective of this work is to propose Artificial Intelligence (AI) controller to enhance the performance of Automatic Voltage Regulator (AVR) of a Synchronous Generator (SG) during different loading conditions. The proposed mathematical model of the SG with saturation nonlinearities is connected to different loads in two ways. The first each load is connected individually and the second the SG loads change during the operation to ensure the robustness of controller for wide load variations. Two types of controllers are used. The first controller is the Proportional-Integral (PI) based on Particle Swarm Optimization (PSO) technique to obtain optimal gains. The second controller is Fuzzy PD+I with gains and Membership Functions (MFs) tuned by PSO technique. The results show the improvement of PI-PSO performance on conventional PI controller; also show the improvement in the performance of Fuzzy PD+I using PSO technique on PI-PSO. The simulation of SG is performed using MATLAB program version 7.10.0.499 (R2010a).

Keywords: Synchronous Generator (S.G.), Automatic Voltage Regulator (AVR) system, PI controller, fuzzy PD+I controller and Particle Swarm Optimization (PSO).

مسيطر الحشد الضبابي لمنظم الجهد الالي للمولد التزامني

الخلاصة

الهدف الاساسي من هذا العمل هو اقتراح مسيطر الذكاء الاصطناعي **(AI)** لتحسين اداء منظم الجهد الذاتي **(AVR)** للمولد المتزامن **(SG)** اثناء ظروف التحميل المختلفة. تم ربط النموذج الرياضي المقترح للمولد المتزامن مع اشباع لاخطي مع احمال مختلفة بطريقتين.الطريقة الاولى تم ربط كل حمل بصورة منفردة اما الطريقة الثانية فان الاحمال المربوطة للمولد المتزامن تتغير اثناء عمل المولد وذلك لضمان متانة المسيطر لمدى واسع من تغيير الاحمال. كما تم استخدام نوعان من المسيطرات. المسيطر الاول هو تناسبي-تكاملي **(PI)** و المعتمد على تقنية افضلية الحشد الجزيئي **(PSO)** للحصول على امثل قيم لمتغيرات **(gains)** المسيطر. المسيطر الثاني هو من نوع **(Fuzzy PD+I)** مع متغيرات **(gains)** ودوال عضوية **(MFs)** ضبطت بواسطة تقنية افضلية الحشد الجزيئي. اظهرت النتائج تحسين اداء مسيطر **PI-PSO** على مسيطر **PI** التقليدي, و اظهرت ايضا التحسين لاداء مسيطر **Fuzzy PD+I** والمعتمد على تقنية افضلية الحشد الجزيئي على مسيطر **PI-PSO**. ان نظام المحاكاة للمولد التزامني تم باستخدام برنامج **MATLAB** من اصدار **(R2010a) 7.10.0.49** .

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INTRODUCTION

Voltage stability and power quality of the electrical systems depend on proper operation of the AVR of generators. Nowadays, design technology of the AVRs is being broadly improved, according to wide range operating conditions of the generators and loads. According to the standards, the voltage profiles should be kept within the certain limits. Since the voltage profile is consistently varied by load fluctuations so it should be controlled permanently by AVR. For the generators, an increase in load or reactive power demand yields some decreases in terminal voltage. This voltage reduction is compensated by some increments in the field current and generating more field current through AVR and exciter machine [1].

Synchronous generators are nonlinear systems which are continuously subjected to load variations and the AVR design must cope with both normal load and fault condition of operation. Evidently, these conditions of operation result to considerable changes in the system dynamics [2].

Numerous control methods such as proportional-integral-derivative (PID) controller, adaptive control, neural control, and fuzzy control have been studied. Among them, PID has been widely used in the industry because of its simple structure and robust performance in a wide range of operating conditions. Unfortunately, it has been quite difficult to tune properly the gains of PID controllers because many industrial plants are often burdened with problems such as high order, time delays, and nonlinearities. Over the years, several heuristic methods have been proposed for the tuning of PID controllers. The first method used the classical tuning rules proposed by Ziegler and Nichols [3]. In general, it is often hard to determine optimal or near optimal PID parameters with the Ziegler-Nichols formula in many industrial plants. For these reasons, now days, PSO is used for optimal tuning of PID controller, it is highly desirable to increase the capabilities of PID controllers by adding new features. Fuzzy logic has been widely applied to improve of PID controller performance [4].

MATHEMATICAL MODEL OF THE SYNCHRONOUS GENERATOR

The mathematical model of synchronous generator with only one field winding in the d-axis and a pair of damper winding in the d- and q- axis is determined by the following equations of the winding flux linkages are as follows [5]:-

$$\Psi_q = \omega_b \ \{V_q - \frac{r}{\quad} \Psi_d + \frac{r_s}{x} (\Psi_{mq} - \Psi_q)\}.\,dt \quad \ldots(1)$$

$$\Psi_d = \omega_b \ \{V_d + \frac{r}{\quad} \Psi_q + \frac{r_s}{x} (\Psi_{md} - \Psi_d)\}.dt \quad \ldots(2)$$

$$\Psi'_{kq} = \frac{b*r}{\qquad} \{(\Psi_{mq} - \Psi'_{kq})\}.dt \quad \ldots(3)$$

$$\Psi'_{kd} = \frac{b*r}{\qquad} \{(\Psi_{md} - \Psi'_{kd})\}.dt \quad \ldots(4)$$

$$\Psi'_f = \frac{\omega_b * r'_f}{x_{md}} \{E_f + \frac{x_{md}}{x'_{lf}} (\Psi_{md} - \Psi'_f) \}. dt \quad ...(5)$$

$$\Psi_{mq} = XMQ*(\frac{\Psi_q}{x_{ls}} + \frac{\Psi'_{kq}}{x'_{lkq}}) \quad ...(6)$$

$$\Psi_{md} = XMD*(\frac{\Psi_d}{x_{ls}} + \frac{\Psi'_{kd}}{x'_{lkd}} + \frac{\Psi'_f}{x'_{lf}}) \quad ...(7)$$

Where, $\frac{1}{xMQ} = \frac{1}{x_{mq}} + \frac{1}{x'_{lkq}} + \frac{1}{x_{ls}}$ & $\frac{1}{xMD} = \frac{1}{x_{md}} + \frac{1}{x'_{lkd}} + \frac{1}{x'_{lf}} + \frac{1}{x_{ls}}$

The subscript, d & q referred to the quantities on the direct and quadrature axis respectively, md & mq referred to magnetizing on direct and quadrature axis respectively, kd & kq referred to damper winding on direct and quadrature axis respectively and f referred to field on direct axis, Ψ referred to flux linkage, ω_b referred to base electrical angular frequency, ω_r referred to rotor speed, r_s referred to stator winding resistance, x_{ls} referred to stator winding leakage reactance, x'_{lf} referred to d-axis field winding leakage reactance and E_f referred to steady state field excitation voltage.

Having the values of the flux linkages of the windings and those of the mutual flux linkages along the d- and q- axis , we can determine the winding currents using :

$$i_q = \frac{\Psi_q - \Psi_{mq}}{x_{ls}} \quad ...(8)$$

$$i_d = \frac{\Psi_d - \Psi_{md}}{x_{ls}} \quad ...(9)$$

$$i'_{kd} = \frac{\Psi'_{kd} - \Psi_{md}}{x'_{lkd}} \quad ....(10)$$

$$i'_{kq} = \frac{\Psi'_{kq} - \Psi_{mq}}{x'_{lkq}} \quad ...(11)$$

$$i'_f = \frac{\Psi'_f - \Psi_{md}}{x'_{lf}} \quad ...(12)$$

The electromechanical torque developed by a machine with p-pole in generating conversion is:

$$T_{em} = \frac{3}{2} * \frac{P}{2*\omega_b} *(\Psi_d * i_q - \Psi_q * i_d) \quad ...(13)$$

Where p=number of poles, T_{em} is the electromechanical torque.

The net acceleration torque can expressed by :

$$T_{em(pu)} + T_{mech(pu)} - T_{damp(pu)} = 2H. \frac{d(\frac{\omega r}{\omega_b})}{dt}$$

$$= 2H. \frac{d[\frac{\omega r - \omega e}{\omega b}]}{dt} \quad ... (14)$$

3-EXCITER MODEL

The basic function of an excitation system is to provide direct current to the synchronous machine field winding. In addition, the excitation system performs control and protective functions essential to the satisfactory performance of the power system by controlling the field voltage and thereby the field current [6].

The transfer function of the exciter is:

$$G(s) = \frac{K_e}{(1 + sT_e)}$$

Where T_e is the time constant of the static exciter & K_e is the gain of static exciter. Since the time constant (T_e) of static exciter is very small, then equivalent transfer function is became as gain circuit connected between controller and SG, used to gain low control signal [7].

$$G(s) = K_e \qquad \ldots(15)$$

4-SENSOR MODEL

The terminal voltage of the SG is being fed back by using a potential transformer that is connected to the bridge rectifiers [8].

A sensor may be represented by a simple first-order transfer function, given by

$$\frac{Vs(s)}{Vt(s)} = \frac{K_R}{1+sT_R} \qquad \ldots.(16)$$

Where K_R is the gain of the sensor, T_R is the time constant of the sensor. Normal (T_R) is very small, ranging from of 0.001 to 0.06 s [9].

5- OVERVIEW OF PARTICLE SWARM OPTIMIZATION (PSO)

Particle Swarm Optimization, first developed by Kennedy and Eberhart, is one of the modern heuristic algorithms. It was inspired by the social behavior of bird and fish schooling, and has been found to be robust in solving continuous nonlinear optimization problems. This algorithm is based on the following scenario: a group of birds are randomly searching food in an area and there is only one piece of food. All birds are unaware where the food is, but they do know how far the food is at each time instant. The best and most effective strategy to find the food would be to follow the bird which is nearest to the food. Based on such scenario, the PSO algorithm is used to solve the optimization problem. In PSO, each single solution is a “bird” in the search space; this is referred to as a “particle”. The swarm is modeled as particles in a multidimensional space, which have positions and velocities. These particles have two essential capabilities: their memory of their own best position and knowledge of the global best. Members of a swarm communicate good positions to each other and adjust their own position and velocity based on good positions according to equation (17.a & b).

$$v(k+1)_{i,j} = w.v(k)_{i.j} + c_1r_1(gbest - x(k)_{i,j}) + c_2r_2(pbest_j - x(k)_{i,j}) \quad \ldots(17.a)$$

$$x(k+1)_{i,j} = x(k)_{i,j} + v(k)_{i,j} \qquad \ldots(17.b)$$

Where $v_{i,j}$: Velocity of particle i and dimension j, $x_{i,j}$: Position of particle i and dimension j, c_1,c_2: Acceleration constants, w: Inertia weight factor, r_1,r_2 : Random numbers between 0 and 1, pbest: Best position of a specific particle, gbest: nBest particle of the group[10]. The flow chart of Figure (2) shows the PSO algorithm .

PID CONTROLLER

The PID controller is used to improve the dynamic response of the system as well as to reduce or eliminate the steady-state error. The derivative controller adds a finite zero to the open-loop plant transfer function and improves the transient response. The integral controller adds a pole at the origin, thus increasing system type by one and reducing the steady-state error due to a step function to zero. The transfer function of PID controller is:

$$C(s)= K_p + \frac{K_i}{s} + K_d\, s \qquad \ldots.(18)$$

Where K_p, K_i and K_d are the proportional, integral and derivative gains respectively of PID controller [2].

PERFORMANCE INDICES

Performance index is defined as a quantitative measure to depict the system performance of the designed PID controller. Using this technique an ‘optimum system’ can often be designed and a set of PID parameters in the system can be adjusted to meet the required specification. For a PID- controlled system, there are often four indices to depict the system performance [11]:

$$\text{Integral Square Error (ISE)} = \int_0^\infty e^2(t).dt \qquad \ldots(19)$$

$$\text{Integral Absolute Error (IAE)} = \int_0^\infty |e(t)|.dt \qquad \ldots(20)$$

$$\text{Integral Time Absolute Error (ITAE)} = \int_0^\infty t.|e(t)|.dt \quad \ldots(21)$$

$$\text{Integral Time Square Error (ITSE)} = \int_0^\infty t.e^2(t).dt \qquad \ldots(22)$$

Therefore, for the PSO-based PID tuning, these performance indices (Equations19-22) will be used as the objective function. In other word, the objective in the PSO-based optimization is to seek a set of PID parameters such that the feedback control system has minimum performance index.

FUZZY LOGIC

The fuzzy logic use has received a lot of attention in the recent years because of its usefulness in reducing the model's complexity in the problem solution, it employs linguistic terms that deals with the causal relationship between input and output constraints. This logic was developed based on Lotfi Zadeh's 1960s fuzzy set theory [12], The fuzzy controller is composed of the following four elements:

1) A rule-base (a set of If-Then rules), which contains a fuzzy logic quantification of the expert’s linguistic description of how to achieve good control.
2) An inference mechanism (also called an “inference engine” or “fuzzy inference” module), which emulates the expert’s decision making in interpreting and applying knowledge about how best to control the plant.
3) A fuzzification interface, which converts controller inputs into information that the inference mechanism can easily use to activate and apply rules.
4) A defuzzification interface, which converts the conclusions of the inference mechanism into actual inputs for the process [13] .

FUZZY PID CONTROLLER

The design of a fuzzy-PID controller can be achieved in different ways. One way is to build a fuzzy controller with three inputs: the error (proportional action), the delta error (derivative action) and the sum of the error (integral action). The inconvenience for such a controller is that the number of rules will grow making the tuning task very difficult. A more efficient solution is to divide the controller in two controllers, one that is the PD equivalent and another one that provides the integral action. It will reduce the number of rules (see Figure (3)) [14].

SIMULATION AND RESULTS

In this work, a salient pole synchronous generator of rated (2 MVA, 400 V, 50Hz, 1500 r.p.m and 4 poles) are used. Four different loads applied to the generator to test the controller behavior for different loading conditions, and to show the ability of the AVR to control the SG terminal voltage for a wide range of loading. The generator loading conditions are :

1- The SG loaded at (0.2 P.U) of it's rated current as a light load.
2-After (4 second) the SG loaded at (0.5 P.U) of it's rated current as medium load.
3- After (6 second) the SG loaded at full load (1 P.U).
4- After (8 second) the SG loaded at (1.1 P.U) of it's rated current as over loading conditions.

Due to the very small time constant of the static exciter, the model of exciter can be representing by a gain and limiter to limit the exciter output.

Pi-Pso Controller

The generator circuit with PI-PSO controller is shown in Figure (4). The PI-controller gains for trial and error method chosen as $K_p = 0.5$ and $K_i = 13$. The step responses of the SG with PI-controller tuned by trial and error method for different loads applied individually are shown in Figure (5). The time specifications of the terminal voltage step response of the SG with PI-controller tuned by trial and error method are shown in Table (1).

The step response of SG with PI- controller tuned by trial and error method for different loading conditions is shown in Figure (6).

The PSO tuning method in this work depends on ITAE performance index with iteration number = 20 (stopping condition). The used values of PSO parameters values that achieved better solution are listed in Table (2). The optimal PI-controller gains tuned by PSO method are: $K_p = 2.9368$ and $K_i = 20.0022$.

PSO parameters of the algorithm used for tuning the PI controller are shown in Table (2). The swarm movement depends on self recognition and social behavior which leads the swarm to converge during iteration and the swarm convergence will increase as the iterations number increase.

Figure (7) illustrates the swarm behavior for different iterations. The tuned values of PI controller gains are K_p = 2.9368 and K_i = 20.0022.

The step responses of SG with PI- controller tuned by PSO for different loads applied individually are shown in Figure (8).

The time specifications of the terminal voltage step response of the SG with PI-controller tuned by PSO are shown in Table (3). The step response of SG with PI-controller tuned by PSO for different loading conditions is shown in Figure (9).

Figure (10) shows step response of SG with PI controller which gains tuned by trial and error and PSO for different loads applying during operation.

The PI tuned by PSO controller shows an improvement in response for different loading conditions and shows best performance than trial and error tuning method, so the PI controller tuned by PSO method shows superiority on the PI controller tuned by trial and error method.

Fuzzy Pd+I -Pso Controller

The SG with AVR using Fuzzy PD+I-PSO controller is shown in Figure (11).The controller have two fuzzy blocks. The first block has two inputs (error and change of error), 7 membership functions for all the inputs and output and (49) rules. While the second block has one input (error), (3) membership functions for both input and output, and (3) rules. PSO used for tuning gains of the fuzzy PD+I and optimize the parameters of fuzzy block membership functions.

The PSO parameters of the algorithm used for tuning the Fuzzy PD+I-PSO controller are shown in table (4).

The tuned values of the controller gains are :

Kp = 3.4645 , Ki= 15.1088 , Kd = 0.00162 , and K1 = 4.0633.

Tables (5) and (6) show the used rules for I and PD controller respectively.

Figure (13) shows the step responses of the SG with Fuzzy PD+I-controller with gains and MFs tuned by PSO for different loads applied individually.

The time specifications of the terminal voltage step response of the SG with Fuzzy PD+I controller are shown in Table (7) below.

The step response of SG with Fuzzy PD+I-controller with gains and MFs tuned by PSO for different loading conditions is shown in Figure (14).

The terminal voltage step response of the Fuzzy PD+I controller tuned by PSO controller shows best response than the other controller for different loading conditions. Figures (15) and (16) show a comparison in step response between the different controllers with different loads. The comparison in time specifications of the terminal voltage step response for SG with proposed controllers are shown in Tables (8), (9), (10) and (11).

CONCLUSIONS

The PI controller is normally used in the industry due to it's simple structure, and the ability to apply for a wide range of situations. The selection of the controller gains are difficult and time consuming. To overcome this difficulty the PSO is used for optimal gains. PSO tuning technique consumes less time and has fast convergence than trial and error method. The PSO tuning method make the controller superior than controller with trial and error tuning method.

The Fuzzy PD+I controller has the difficulties in selection the gains and parameters of MFs of the Fuzzy PD+I controller which can be overcame by using PSO technique. The use of the PSO technique can improve the performance of AVR with Fuzzy PD+I controller compared with PI-PSO controller.

Using two AI techniques (Fuzzy logic and PSO) and using PSO for gains and MFs tuning make Fuzzy PD+I controller superior on other controllers for AVR.

The final results of the proposed controllers for AVR system shows the superiority of the Fuzzy PD+I controller based on PSO versus the other proposed controllers, which is improved the time specification of the response which make this controller more robust to variation in load other than the rest controllers.

The proposed controllers can be arranged according to the performance in the simulation of this work as bellow:

1) Fuzzy PD+I controller with gains and MFs tuned by PSO.
2) PI-controller tuned by PSO.
3) PI-controller tuned by trial and error method.

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Table (1): Time specifications of the terminal voltage step responses

PI- controller tuned by trial and error	**Rise time (sec)**	**Maximum over shoot**	**Settling time(sec) at $e_{ss} \le 1\%$**
Light load	0.2525	0.5437	2.65
Medium load	0.2661	0.4123	2.142
Full load	0.3272	0.1227	1.01
Over load	0.3527	0.0730	0.992

Table (2): Parameters of PSO algorithm for tuning gains of PI-controller

	NO. of birds	NO. of iteration	C1	C2	W
PI-PAO	10	5	1.1	1.3	0.9

Table (3): Time specifications of the terminal voltage step response of the SG

PI- controller tuned by PSO	**Rise time (sec)**	**Maximum over shoot**	**Settling time (sec) at $e_{ss} \le 1\%$**
Light load	0.1693	0.2137	0.8901
Medium load	0.1792	0.1674	0.8688
Full load	0.2297	0.0356	0.8528
Over load	0.2625	0.0071	0.9251

Table (4)

	No. of birds	No. of iterations	C1	C2	W
FuzzyPD+I-PSO for MFs tuning	5	5	1.2	1.2	0.9
FuzzyPD+I-PSO for gain tuning	20	20	2	2	0.5

Table (5): I-controller rules

Input	Output
N	N
Z	Z
P	P

Table (6): PD- controller rules

e / Δe	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NM	NM	NS	NS	Z
NM	NL	NM	NM	NS	NS	Z	PS
NS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NS	NS	Z	PS	PS	PM
PS	NS	NS	Z	PS	PS	PM	PM
PM	NS	Z	PS	PS	PM	PM	PL
PL	Z	PS	PS	PM	PM	PL	PL

Table (7): Time specifications of the terminal voltage step response of the SG

FuzzyPD+I controller tuned by PSO	Rise time (sec)	Settling time (sec) at $e_{ss} \leq 1\%$
Light load	0.1593	0.1567
Medium load	0.1684	0.1651
Full load	0.2061	0.1964
Over load	0.2168	0.2071

Table (8): Time specifications of the terminal voltage step response of the SG at light load

At light load	Rise time (sec)	Maximum over shoot	Settling time (sec) at $e_{ss} \leq 1\%$
PI based trial and error	0.2525	0.5437	2.65
PI based PSO	0.1693	0.2137	0.8901
Fuzzy PD+I based PSO	0.1593	0	0.1567

Table (9): Time specifications of the terminal voltage step response of the SG at medium load

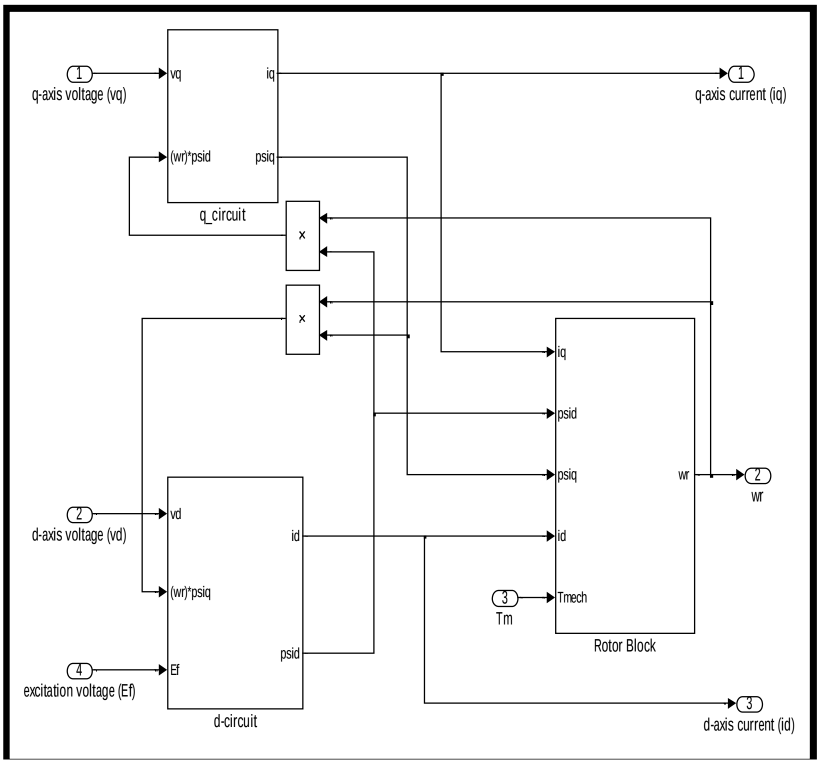
At medium load	Rise time (sec)	Maximum over shoot	Settling time (sec) at $e_{ss} \leq 1\%$
PI based trial and error	0.2661	0.4123	2.142
PI based PSO	0.1792	0.1674	0.8688
Fuzzy PD+I based PSO	0.1684	0	0.1651

Table (10): Time specifications of the terminal voltage step response of the SG at full load

At full load	Rise time (sec)	Maximum over shoot	Settling time (sec) at $e_{ss} \leq 1\%$
PI based trial and error	0.3272	0.1227	1.01
PI based PSO	0.2297	0.0356	0.8528
Fuzzy PD+I based PSO	0.2061	0	0.1964

Table (11): Time specifications of the terminal voltage step response of the SG at over load

At over load	Rise time (sec)	Maximum over shoot	Settling time (sec) at $e_{ss} \leq 1\%$
PI based trial and error	0.3527	0.0730	0.992
PI based PSO	0.2625	0.0071	0.9251
Fuzzy PD+I based PSO	0.2168	0	0.2071



Figure(1): Simulink program of SG.

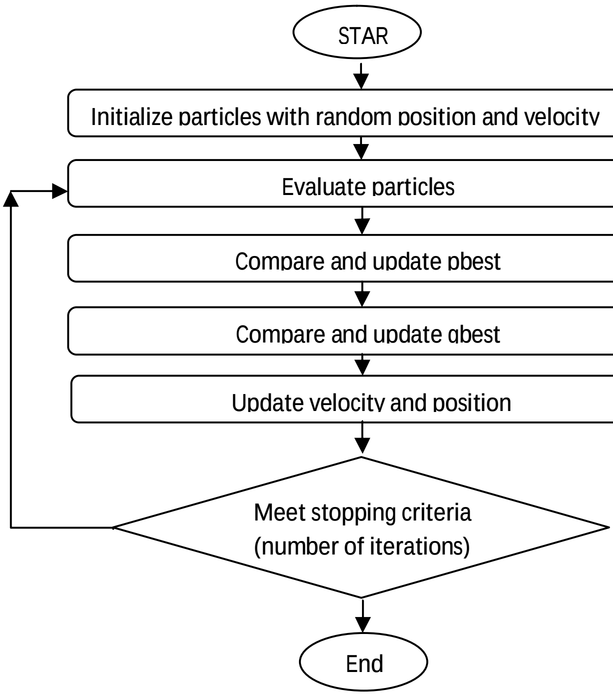


Figure (2): Flow chart of PSO algorithm

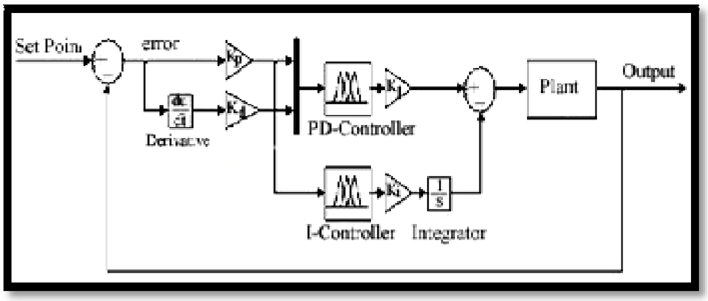


Figure (3): Fuzzy PD+I controlle

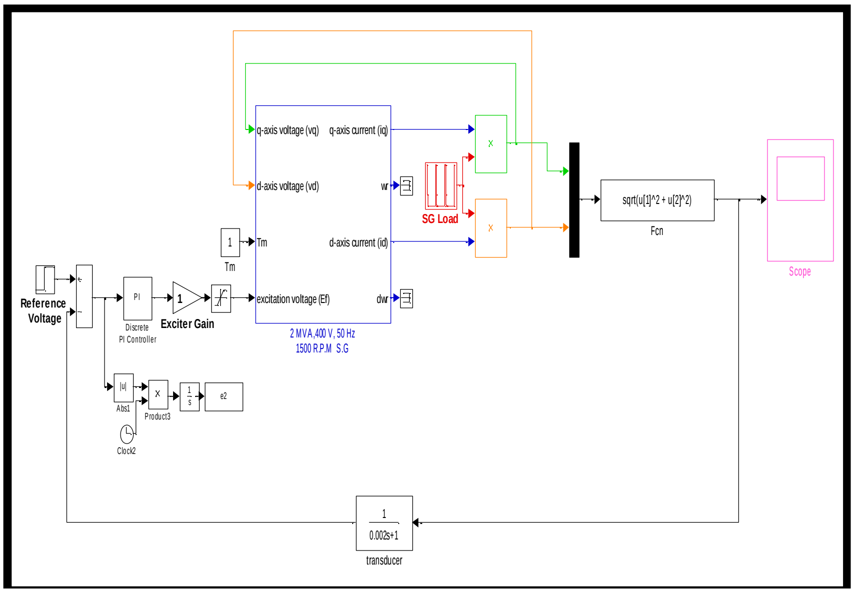


Figure (4): SG simulink program of SG with AVR using PI-controller

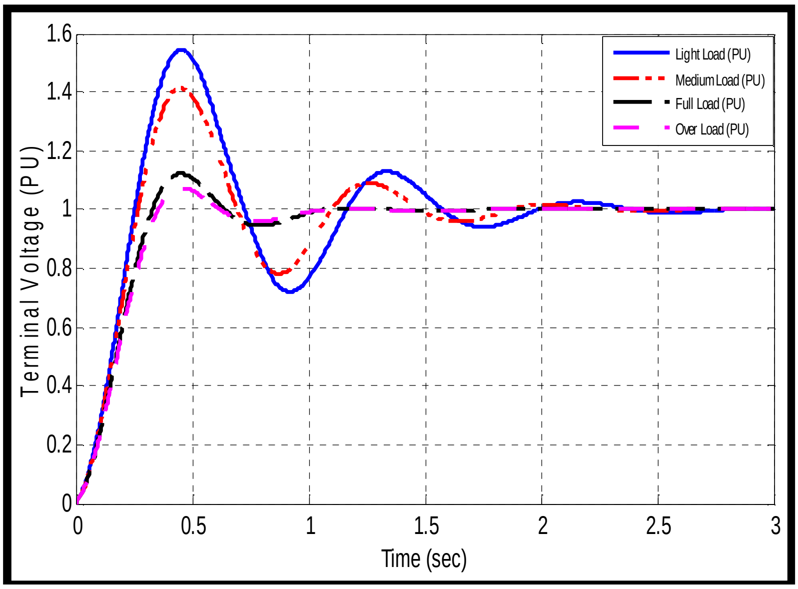


Figure (5): Terminal voltage step responses of SG with PI controller tuned by trial and error for different loads

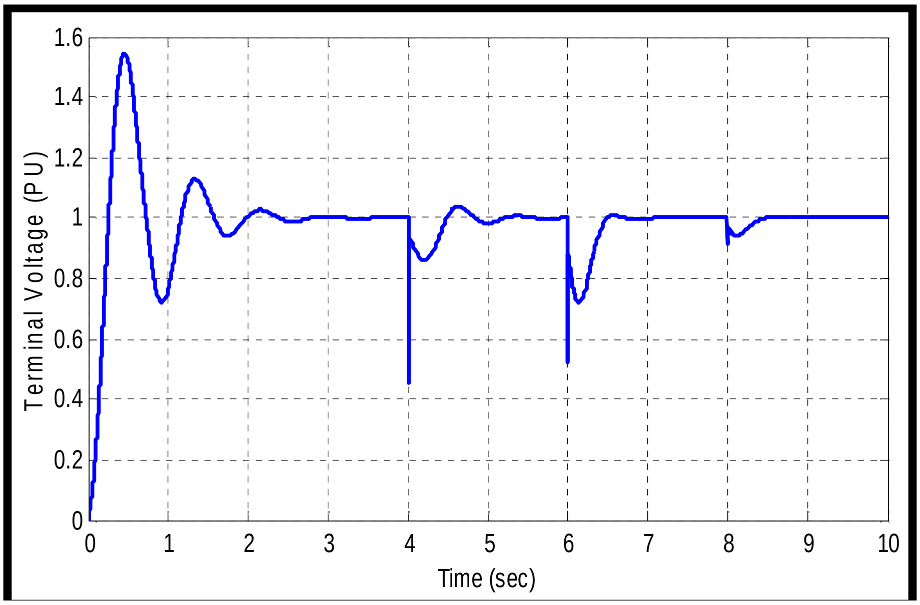
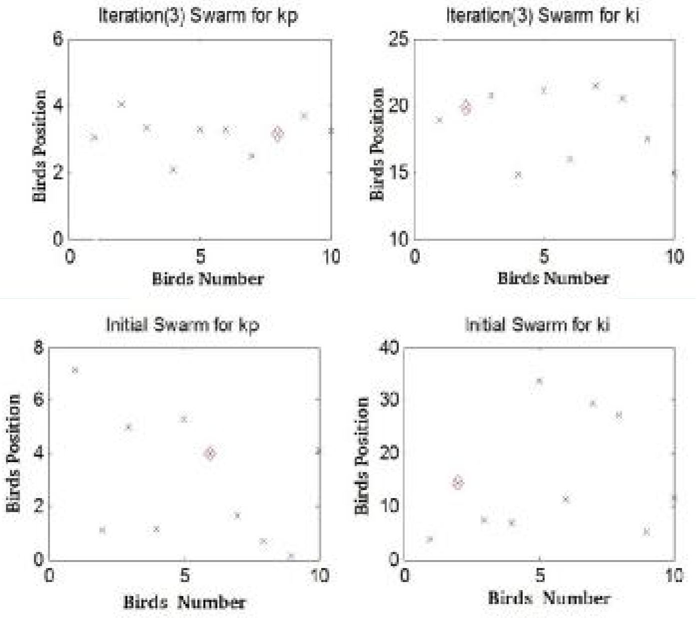


Figure (6): Terminal voltage step responses of SG with PI- controller tuned by trial and error method for load changes from light to over load.



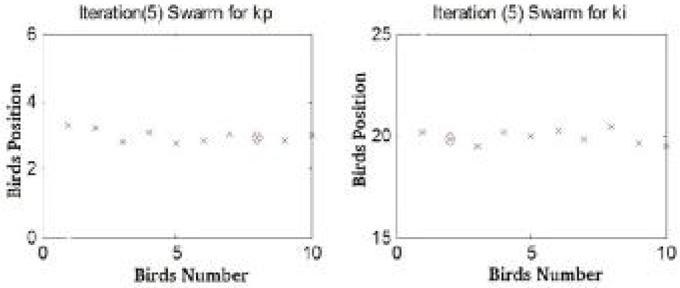


Figure (7): Swarm convergence behavior Represent the global best position

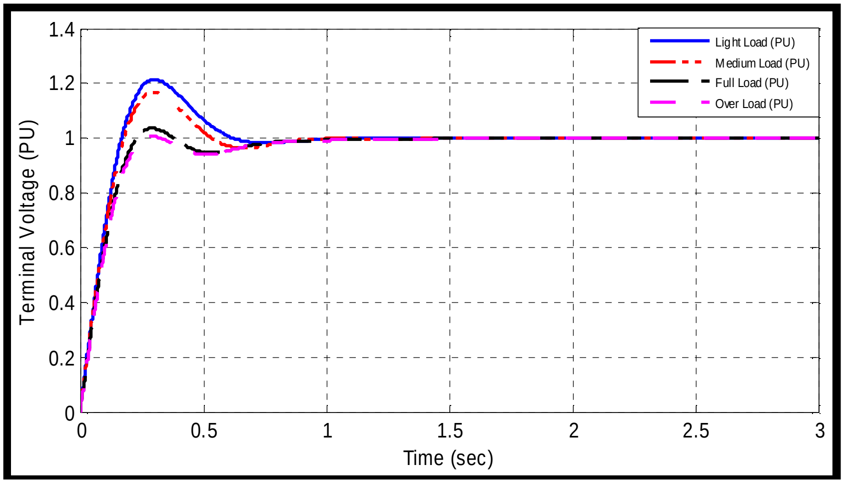


Figure (8): Terminal voltage step responses of SG with PI controller tuned by PSO for different loads applied individually

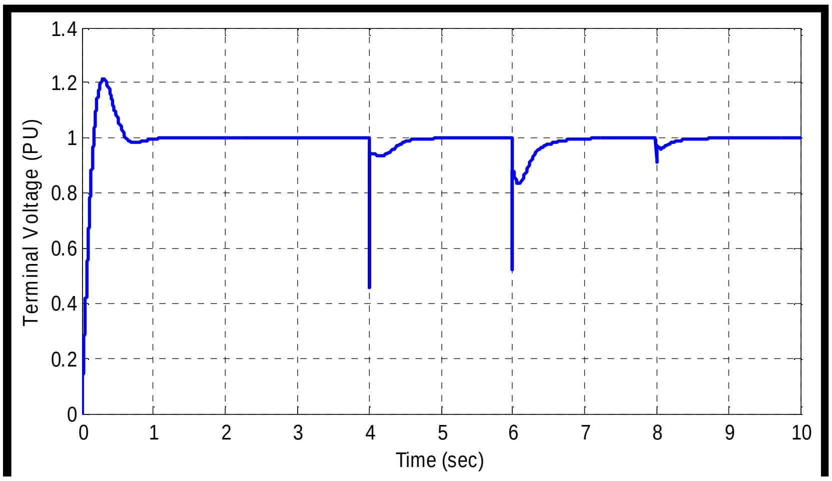


Figure (9): Terminal voltage step responses of SG with PI- controller tuned by PSO for load changes from light to over load.

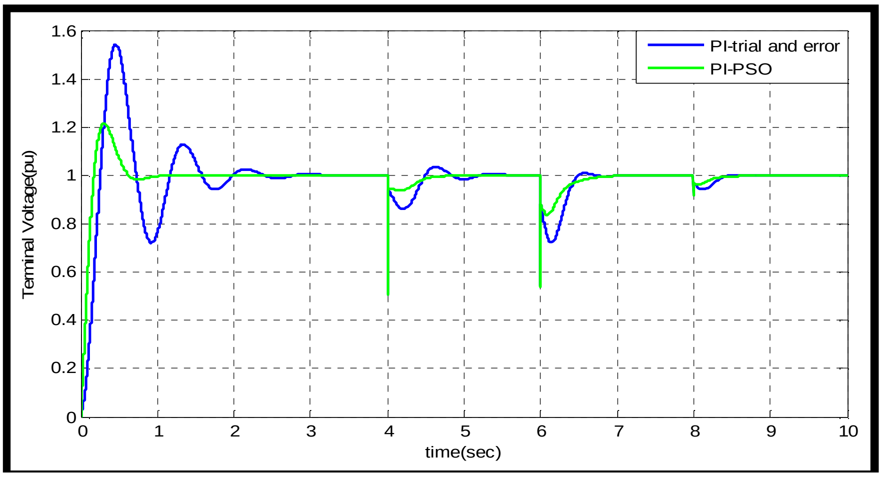


Figure (10): Terminal voltage step responses of SG with PI controller which gains tuned by trial and error and PSO for load changes from light to over load.

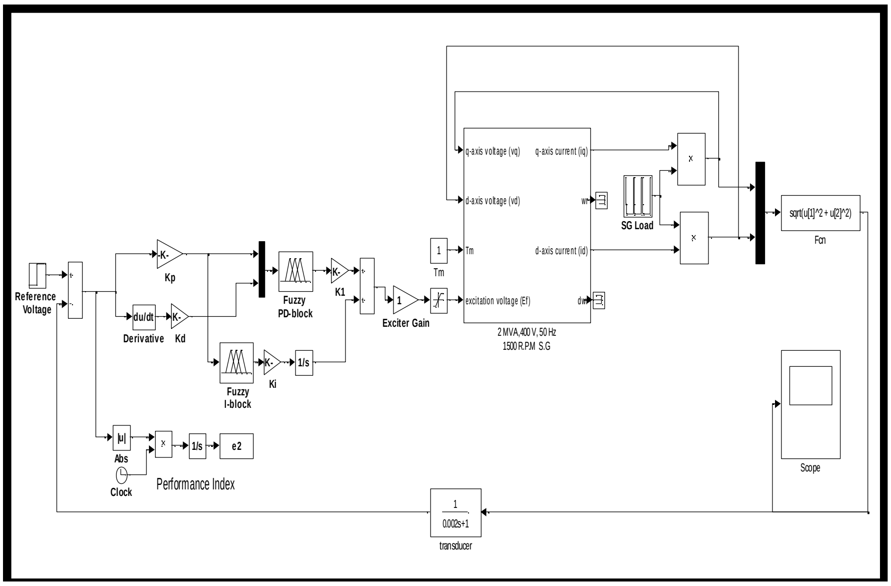
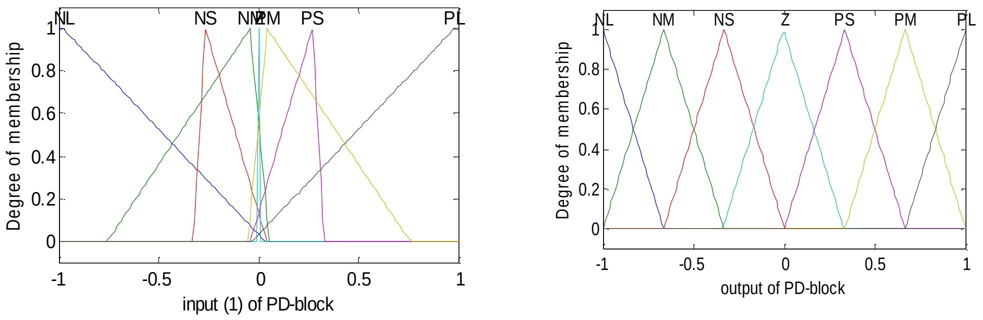
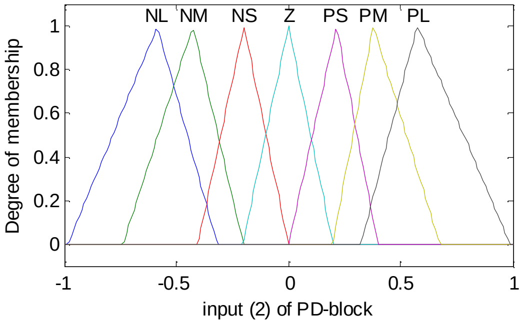


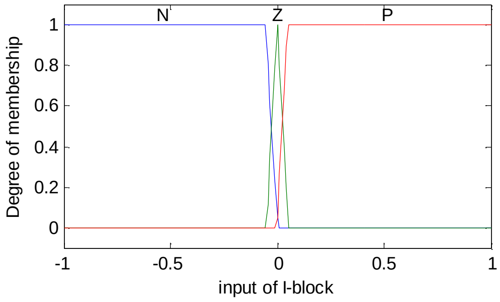
Figure (11): Simulink program of SG with AVR using Fuzzy PD+I- controller



(a) (b)

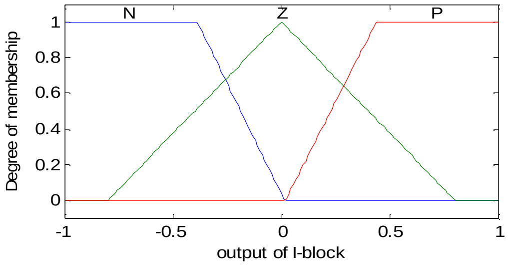


(c)



(d)

Figure (12): MFs of PD and I controller
(a): Input (1) MFs of PD controller
(b): Input (2) MFs of PD controller
(c): Output MFs of PD controller
(d): Input MFs of I controller
(e): Output MFs of I controller



(e)

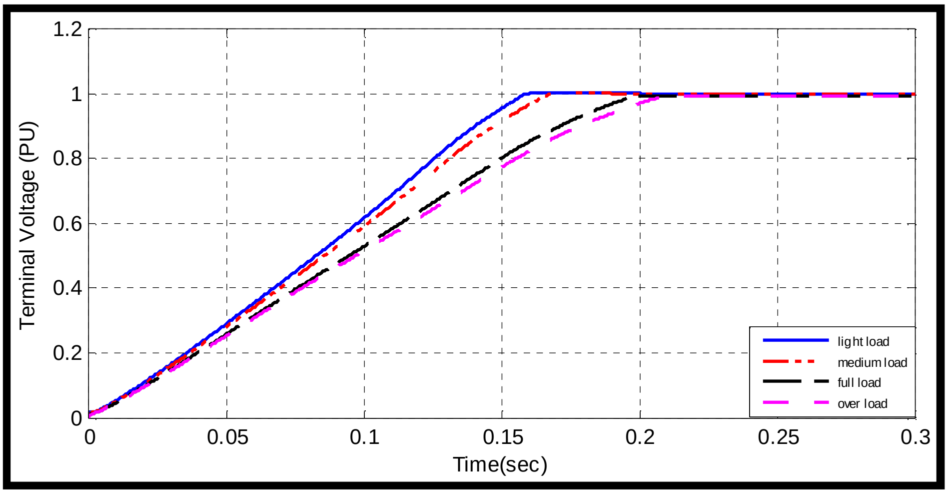


Figure (13): Terminal voltage step responses of SG with Fuzzy PD+I-controller which MFs and gains tuned by PSO with different loads.

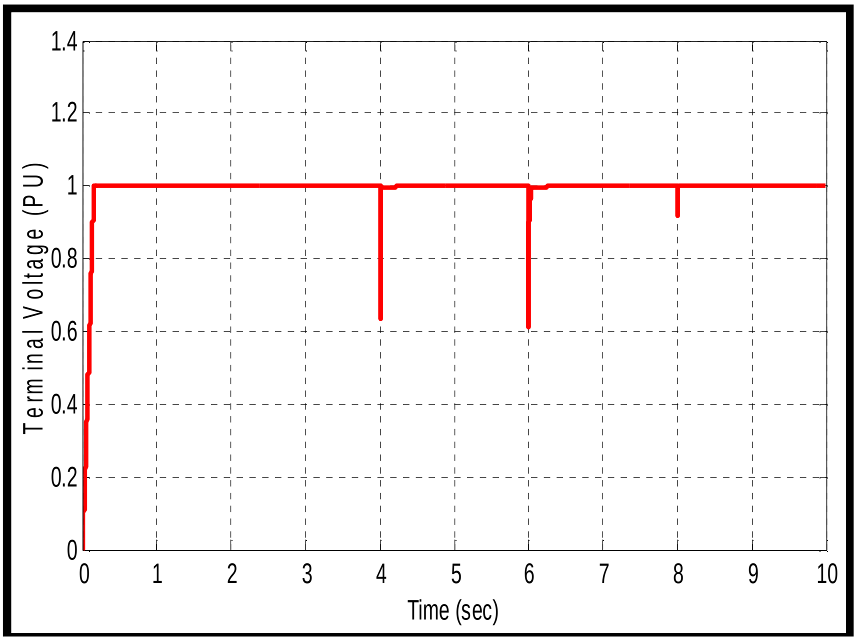
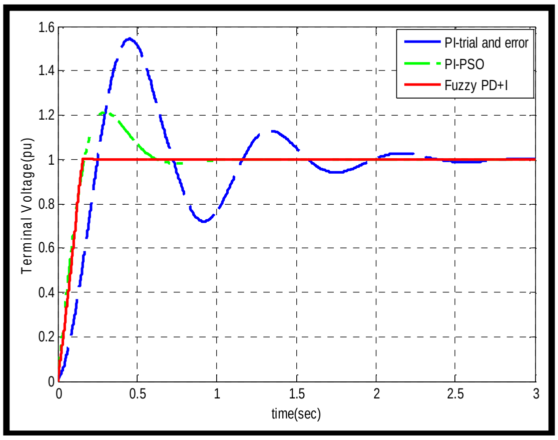
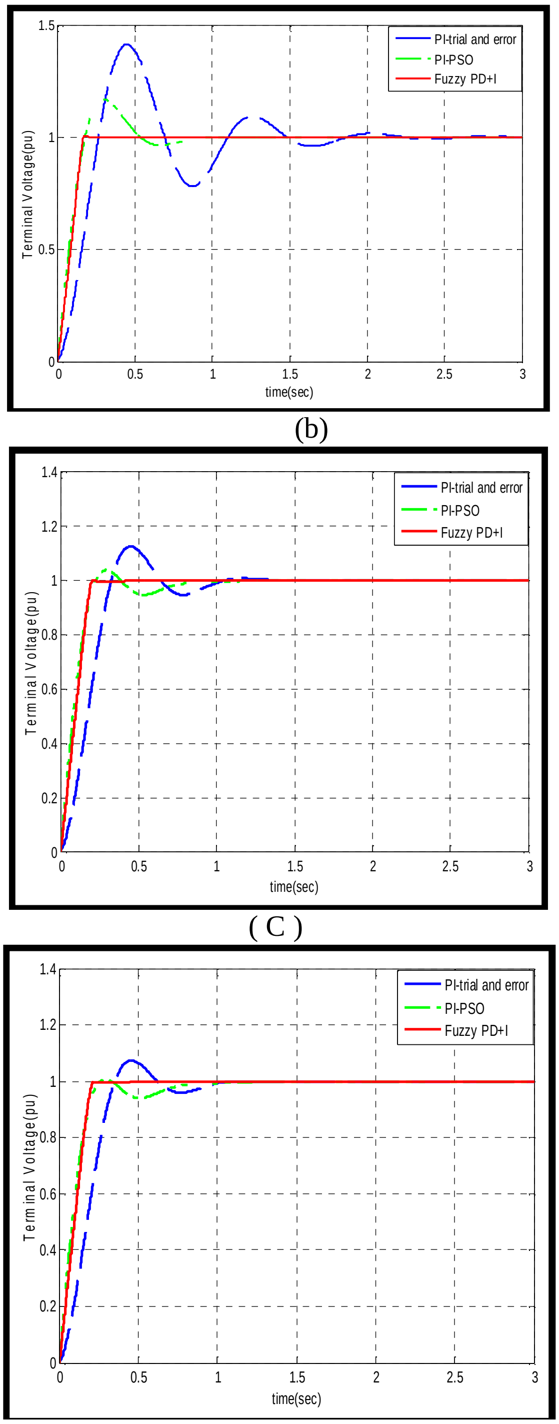


Figure (14): Terminal voltage step response of SG with Fuzzy PD+I- controller with gains and MFs tuned by PSO for load changes from light to over load.



(a)



(b)

(C)

(d)

Figure (15): Terminal voltage step responses of SG with different loads. (a) With light load. (b) With medium load. (c) With full load. (d) With over load.

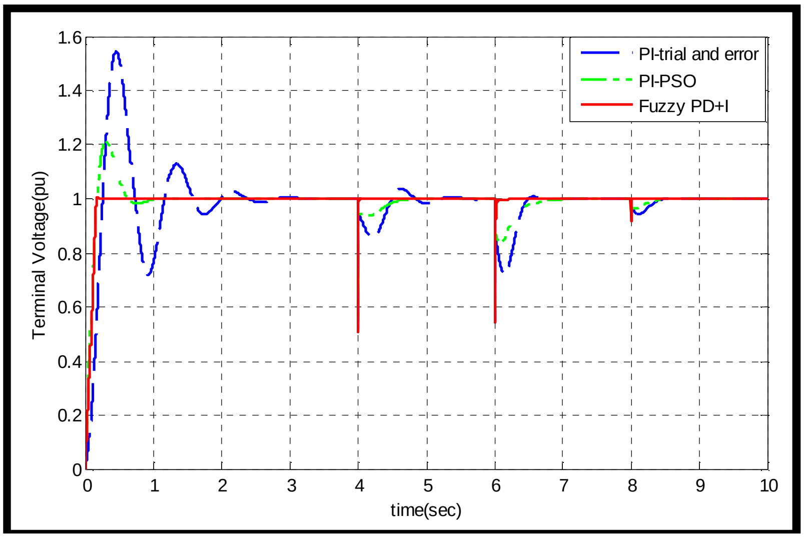


Figure (16): Comparison in terminal voltage step response of SG for load changes from light to over load.

Appendix A

The table below shows the (2 MVA) SG parameters taken from the Matlab simulink tool box which used in our simulation model.

Rated Power KVA	**2000**
Rated voltage V(L-L)	400
Rated frequency HZ	50
stator resistance(rs) pu	0.0095
stator leakage inductance (Lls) pu	0.05
mutual inductance of d-axis(Lmd) pu	2.06
mutual inductance of q-axis(Lmq) pu	1.51
field resistance on d-axis(rf') pu	.001971
field leakage inductance on d-axis(Llf') pu	0.3418
damper resistance n d-axis(rkd') pu	0.2013
damper leakage inductance on d-axis(Llkd')pu	2.139
damper resistance on q-axis(rkq') pu	0.02682
damper leakage inductance on q-axis(Llkq') pu	0.2044
Inertia coefficient (H) pu	0.3072