Study the Robustness of Automatic Voltage Regulator for Synchronous Generator Based on Neural Network

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Abstract – Artificial Neural Networks (ANN) can be used as intelligent controllers to control non-linear dynamic systems through learning, which can easily accommodate the non linearity's, time dependencies, model uncertainty and external disturbances. Modern power systems are complex and non-linear and their operating conditions can vary over a wide range. The Nonlinear Auto-Regressive Moving Average (NARMA-L2) model system is proposed as an effective neural networks controller model to achieve the desired robust Automatic Voltage Regulator (AVR) for Synchronous Generator (SG) to maintain constant terminal voltage. The concerned neural networks controller for AVR is examined on different models of SG and loads. The results shows that the neuro-controllers have excellent responses for all SG models and loads in view point of transient response and system stability compared with conventional PID controllers. Also shows that the margins of robustness for neuro-controller are greater than PID controller.

Keywords – Synchronous Generator (SG), Automatic Voltage Regulator (AVR) system, NARMA-L2 controller, PID controller, Robust AVR.

1. Introduction

The robust control problem is to find a control law which maintains system response and error signals within prescribed tolerances despite the effects of uncertainty on the system [1].

In general, however, robust control system design uses an idealized or nominal model of the plant. Uncertainty in the nominal model is taken into account by considering a family of models that include all possible variations. The control system is said to have robust stability if a controller can be found that will stabilize all plants within the family. However, on its own, robust stability is not enough, since there may be certain plants within the family that are on the verge of instability. A controller is said to have robust performance if all the plants within the family meet a given performance specifications [2,3].

The main function of the electric power system is to supply electric energy to the end customer in an efficient way. This power system is dynamic and non linear in nature and works in a changing environment. The main control function of the excitation system is to regulate the generator terminal voltage which is accomplished by adjusting the field voltage with respect to the variation of the terminal voltage [4,5].

Synchronous generators are used almost exclusively in power systems as a source of electrical energy [6]. SGs are nonlinear, fast acting; multi-input multi-output (MIMO) 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 [7]. The excitation voltage is supplied from the exciter and is controlled by the AVR [8]. Fig.1. shows a block diagram of AVR system [9].

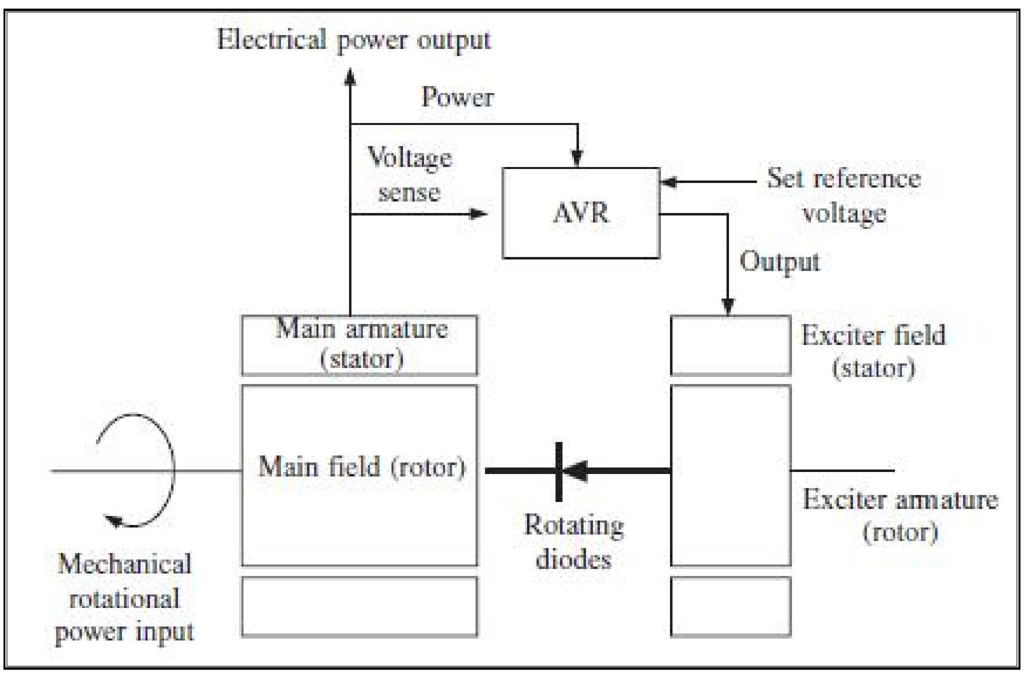

Fig. 1. Block diagram of a synchronous generator and AVR.

Artificial neural networks (ANN's) can be used as intelligent controllers to control non-linear, dynamic systems through learning, which can easily accommodate the non-linearity's and time dependencies called neuro-controllers [10,11]. The intelligent controllers were being developed using (ANN's) are used for same model for each controller and system continuously subjected to load variations [12,13]. This paper is focused on the design of many AVRs for different types of non-linear SGs models and loads then each controller subjected for different types of synchronous generators models.

2. Mathematical Model of the Synchronous Generator

The dynamic response of SG in a practical power system is including much non linearity such as the magnetic saturation. The simulated model of the synchronous generator is represented in MATLAB/ SIMULINK. The central concept underlying the development of the mathematical models of ac machines is the representation of the variables for voltages, currents and fluxes by means of space vectors that are expressed in different reference frames. These reference frames or coordinate systems: the triplet [V_a V_b V_c] denotes a three-phase system attached to the stator while the pair [V_q V_d] corresponds to an equivalent two-phase system quadrature and direct phase The basic approach to modeling involves the transformation of the stator and rotor equations to a common reference frame [5]. MATLAB/SIMULINK toolbox synchronous generator model used in this work takes into account the dynamics of the stator, field, and damper windings. The equivalent circuit of the model is represented in the rotor reference frame (qd frame). All rotor parameters and electrical quantities are viewed from the stator. They are identified by primed variables. The subscripts used are defined as follows:

- *d,q*: d and q axis quantity
- *R,s*: Rotor and stator quantity
- *l,m*: Leakage and magnetizing inductance
- *f,k*: Field and damper winding quantity

The electrical model of the machine is:

$$V_d = R_s i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \quad (1)$$

Where $\varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd})$

and $\varphi_q = L_q i_q + L_{mq} i'_{kq}$

$$V_q = R_s i_q + \frac{d}{dt}\varphi_q + \omega_R \varphi_d \quad (2)$$

$$V'_{fd} = R'_{fd} i_{fd} + \frac{d}{dt}\varphi'_{fd} \quad (3)$$

Where $\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd})$

$$V'_{kd} = R'_{kd} i_{kd} + \frac{d}{dt}\varphi'_{kd} \quad (4)$$

Where $\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd})$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \quad (5)$$

Where $\varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \quad (6)$$

Where $\varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q$

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.

The transfer function of the exciter is:

$$G(s) = \frac{K_R}{(1+sT_R)} \quad (7)$$

Where T_R is the time constant of the static exciter & K_R is the gain of static exciter. Since the time constant (T_R) 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 [5].

$$G(s) = K_R \quad (8)$$

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

$$\frac{Vs(s)}{Vt(s)} = \frac{K_T}{1+sT_T} \quad (9)$$

Where K_T is the gain of the sensor, T_T is the time constant of the sensor. Normal T_T is very small, ranging from of 0.001 to 0.06 s [14].

5. NARMA-L2 Controller

The Nonlinear Auto-Regressive Moving Average (NARMA-L2) model was proposed by Narendra and Mukhopadhayay (1997) [15]. The neuro-controller described in this section is referred to by two different names: feedback linearization control and NARMAL-2 control. It is referred to as feedback linearization when the plant model has a particular form (companion form). It is referred to as NARMA-L2 control when the plant model can be approximated by the same form. The central idea of this type of control is to transform nonlinear system dynamics into linear dynamics by canceling the nonlinearities [16].

The advantage of the NARMA-L2 form is that you can solve for the control input that causes the system output to follow a reference signal as shown in Fig. 2. [15].

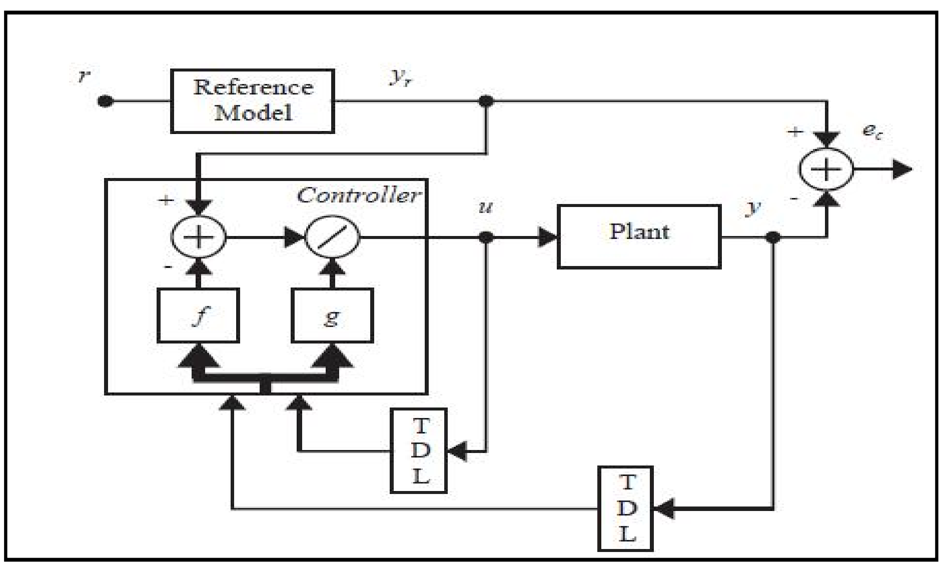

Fig. 2. Block diagram of NARMA-L2 controller

6. PID Controller

Proportional-integral-derivative or PID control has been the major control in industry for many years, the controller works by examining the instantaneous error between the process value and the set point. The proportional term produces a control action proportional to the size of the error input, and decrease the rise time of transient response, the integral term is used to decrease steady state error and the derivative term supplement the control action if the error is changing rapidly with time by damped the response or decrease the over shoot [9]. The values of the P-I-D terms depend on characteristics of the process and must be tuned accordingly yield satisfactory result. Properly tuned and maintained PID controllers provide adequate control for a large portion of industrial applications. This equation represents mathematical expression for PID controller [8].

$$p_t = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt} \quad (10)$$

Where; e is error signal, k_p is proportional gain, k_i is integral gain and k_d is derivative gain.

7. Simulation and Results

The first step in analysis and designing the controllers for the SG is to use the mathematical model of the SG which is more reality to the actual plant rather than linear transfer function model in the control design and studies. The simulation of SG is performed using MATLAB/SIMULINK implementation program version 7.10.0.499 (R2010a). In this work, salient pole synchronous generators of parameters listed in Appendix A are used.

The AVR was implemented by using tow type of controller. First the classical PID controller, adjusted to the nominal condition of the synchronous generator model as shown in Fig. 3.

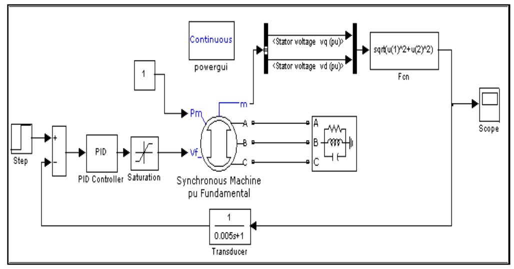

Fig. 3. Power unit with AVR using PID controller

Second the neuro-controller (NARMA-L2) shown in Fig. 4 was trained by using the data of PID controllers to the nominal condition of the synchronous generator model.

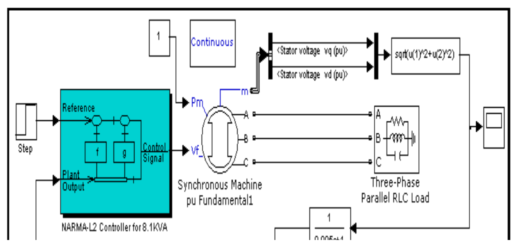

Fig. 4. Power unit with AVR using neuro-controller

The tuned parameters of PID controller for each SG model by trial and error with saturation of 3 (pu) and full load are listed in table 1.

Table 1 Tuned gains of PID controllers

SG model	Gains of PID controller		
	k_p	k_i	k_d
SG of 8.1KVA	20	60	0.25
SG of 31.3KVA	20	35	0.25
SG of 250KVA	20	14	0.4
SG of 2MVA	30	4	0.5

The designed AVRs with PID controllers which applied to the synchronous generator of 8.1KVA and full load are shown in Fig. 5.

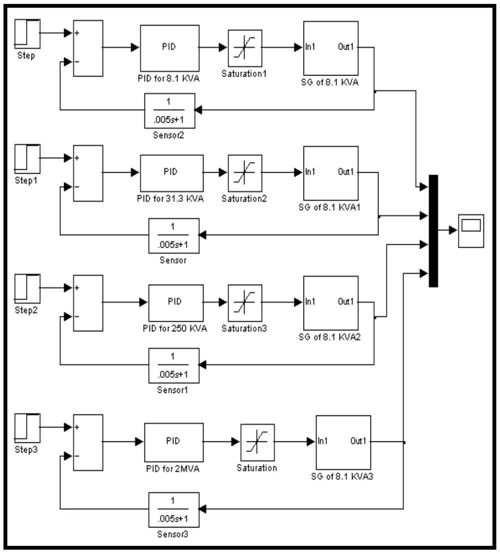

Fig. 5. Different PID controllers connected to SG of 8.1KVA

The time responses for the synchronous generator of 8.1KVA for various controllers are depicted in Fig. 6. Also the time responses for the synchronous generators of 31.3KVA, 250KVA, 910KVA, 2MVA, and 187MVA for various PID controllers are depicted in Fig. 7, 8, 9, 10 and 11 respectively.

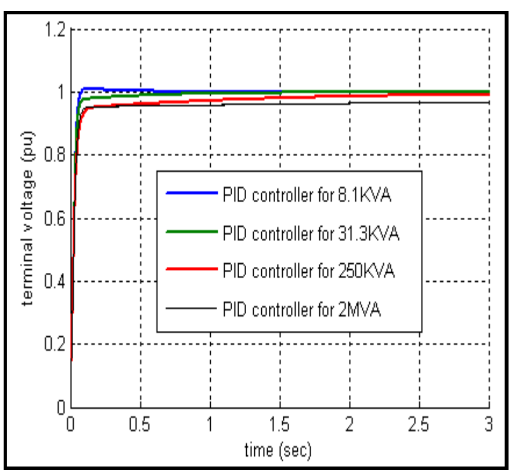

Fig. 6. Time responses for SG of 8.1KVA with different PID controllers

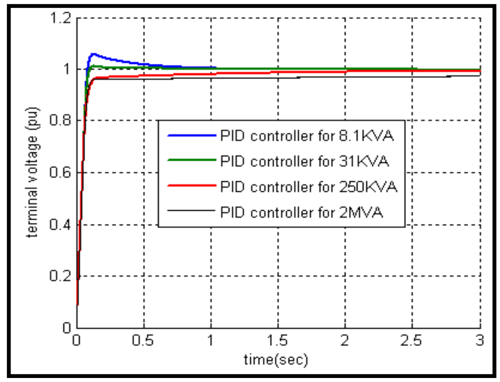

Fig. 7. Time responses for SG of 31.3KVA with different PID controllers

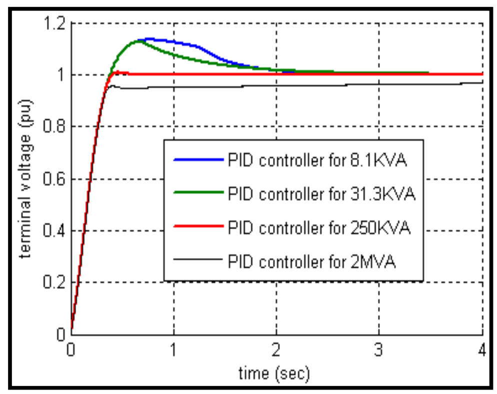

Fig. 8. Time responses for SG of 250KVA with different PID controllers

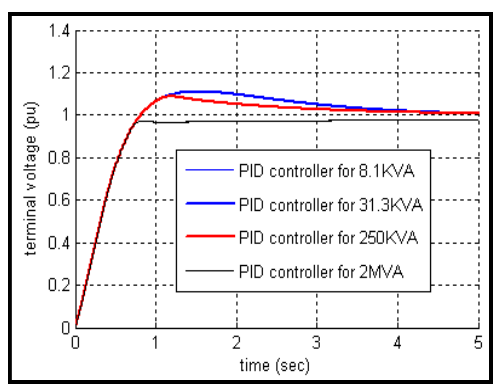

Fig. 9. Time responses for SG of 910KVA with different PID controllers

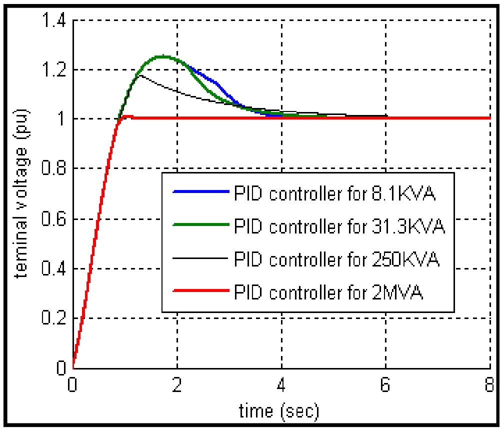

Fig. 10. Time responses for SG of 2MVA with different PID controllers

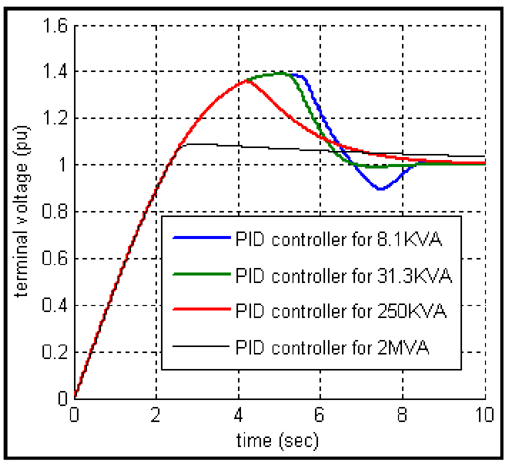

Fig. 11. Time responses for SG of 187MVA with different PID controllers

Figures 6, 7, 8, 9, 10, and 11, show that the over shoot increases when the power of SG is greater than the desired SG controller. The time responses of Fig. 6, 7, 8, and 10 shows the best response for each figure is the response of the controller designed for the same SG.

The neuro-controllers were trained using the data of PID controllers with saturation of 3 pu and full load. The neuro-controllers which applied to the synchronous generator of 8.1KVA and full load are shown in Fig. 12.

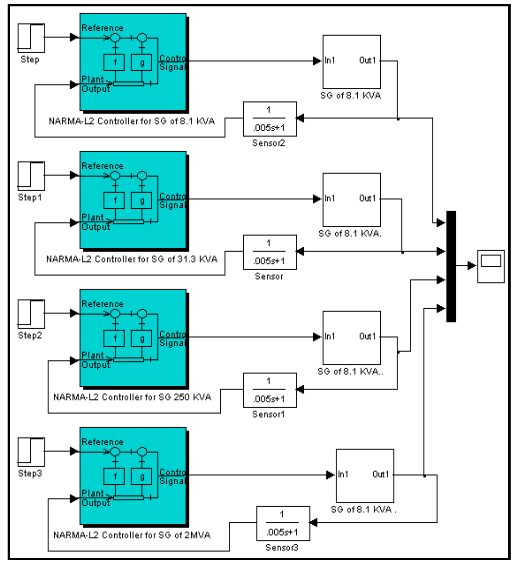

Fig. 12. Different NARMA-L2 controllers connected to SG of 8.1KVA

Time responses for the synchronous generators of 8.1KVA, 31.3KVA, 250KVA, 910KVA, 2MVA, and 187MVA for various NARMA-L2 controllers are depicted in Fig. 13, 15, 17, 19, 21 and 23 respectively. The responses shows that approximately same transient responses as depicted in Fig. 14, 16, 18, 20, 22 and 24 and tables 2,3,4 and 6, where the settling time (t_s) for approximately 3% of the error and rise time (t_r) from initial to 97% of the input signal.

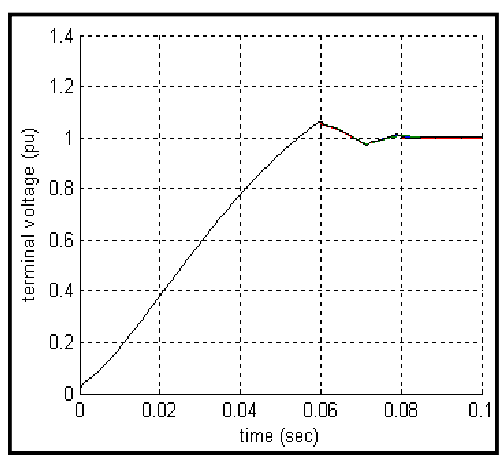

Fig. 13. Time responses for SG of 8.1KVA for different NARMA-L2 controllers

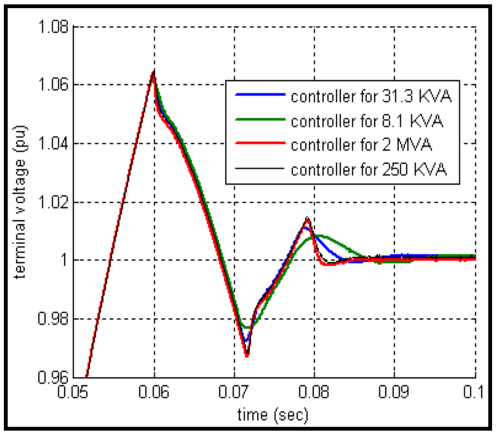

Fig. 14. Zoomed time responses of Fig. 13

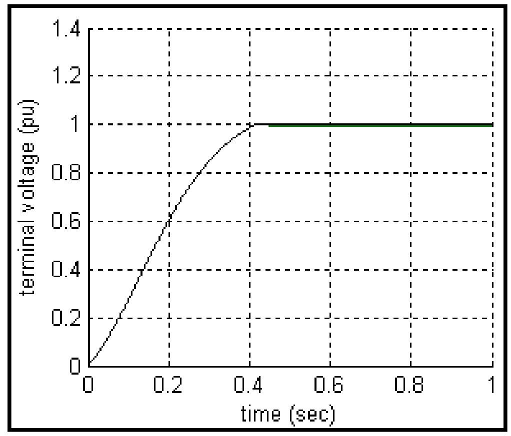

Fig. 17. Time responses for SG of 250KVA with different NARMA-L2 controllers

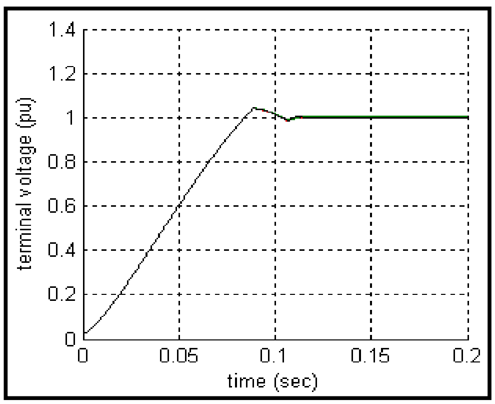

Fig. 15. Time responses for SG of 31.3KVA with different NARMA-L2 controllers

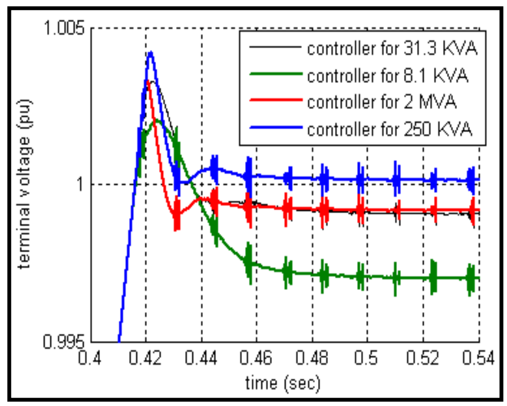

Fig. 18. Zoomed time responses of Fig. 17.

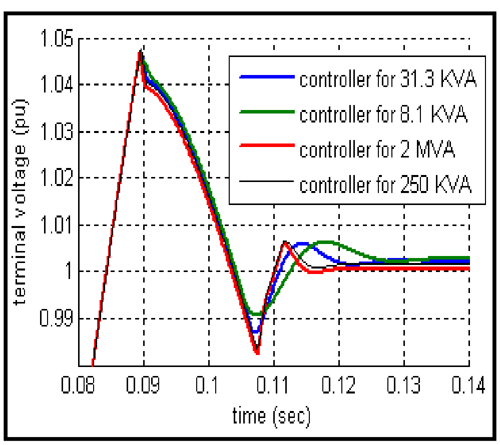

Fig. 16. Zoomed time responses of Fig. 15.

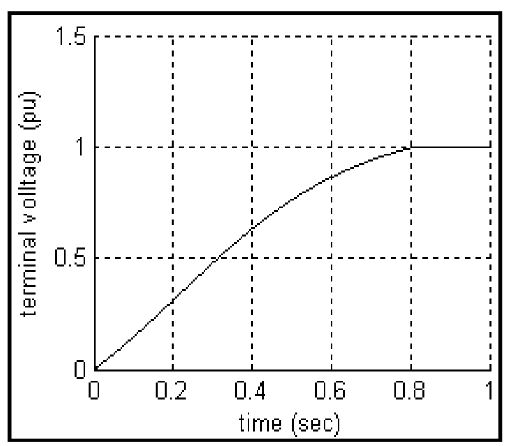

Fig. 19. Time responses for SG of 910KVA with different NARMA-L2 controllers

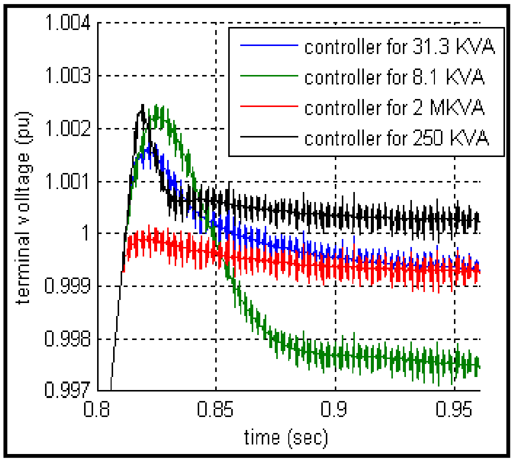

Fig. 20. Zoomed time responses of Fig. 19.

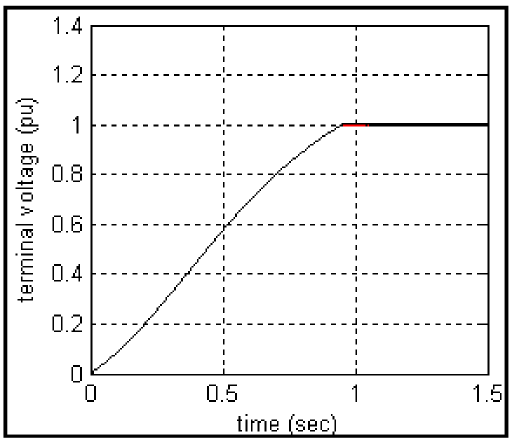

Fig. 21. Time responses for SG of 2MVA with different NARMA-L2 controllers

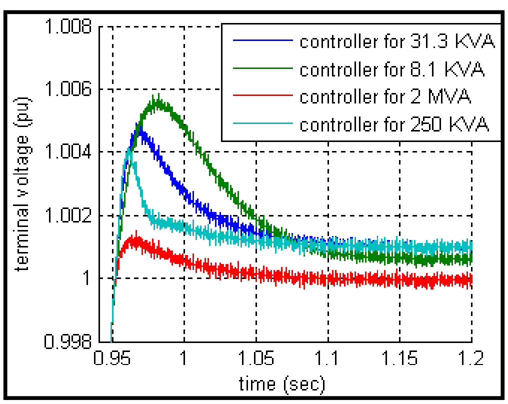

Fig. 22. Zoomed time responses of Fig. 21.

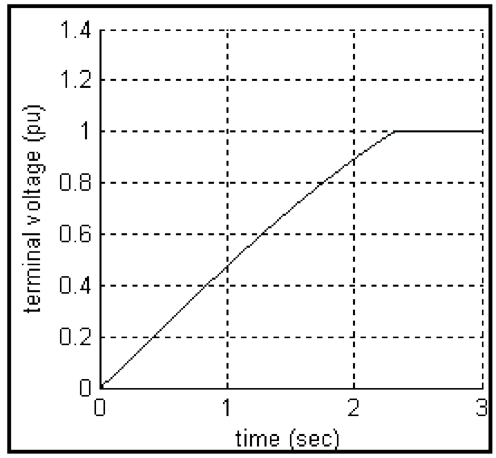

Fig. 23. Time responses for SG of 187MVA with different NARMA-L2 controllers

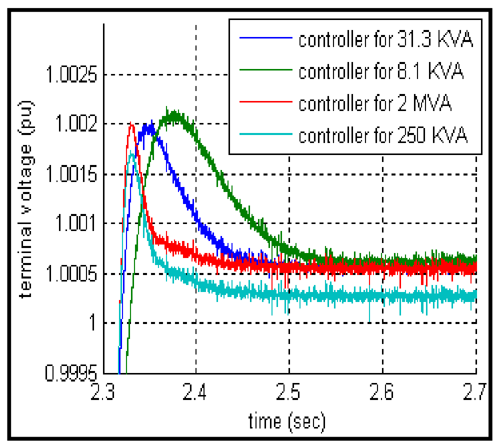

Fig. 24. Zoomed time responses of Fig. 23.

Table 2. Transient responses parameters for different SG model with controller for SG 8.1KVA

SG model	PID controller for SG 31.3KVA			NARMA-L2 controller for SG 31.3KVA		
	Rise time (sec)	Over shoot	Settling time (sec)	Rise time (sec)	Over shoot	Settling time (sec)
SG of 8.1KVA	.05	<0.05	.087	.0531	.068	.063
SG of 31.3KVA	.08	<0.05	.082	.08	<0.05	.096
SG of 250KVA	.35	0.13	1.6	0.35	<0.05	.35
SG of 910KVA	.73	0.11	3.6	0.73	<0.05	.73
SG of 2MVA	.85	0.25	3.6	0.85	<0.05	.85
SG of 187MVA	2.23	0.39	6.7	2.17	<0.05	2.17

Table 3. Transient responses parameters for different SG model with controller for SG 31.3KVA

SG model	PID controller for SG 2MVA			NARMA-L2 controller for SG 2MVA		
	Rise time (sec)	Over shoot	Settling time (sec)	Rise time (sec)	Over shoot	Settling time (sec)
SG of 8.1KVA	.05	<0.05	3.5	.0531	.069	.065
SG of 31.3KVA	.08	<0.05	2.3	.08	<0.05	.096
SG of 250KVA	.35	<0.05	5	0.35	<0.05	.35
SG of 910KVA	.73	<0.05	2	0.73	<0.05	.73
SG of 2MVA	.85	<0.05	.85	0.85	<0.05	.85
SG of 187MVA	2.23	.09	12	2.17	<0.05	2.17

Table 4. Transient responses parameters for different SG model with controller for SG 250KVA

SG model	PID controller for SG 8.1KVA			NARMA-L2 controller for SG 8.1KVA		
	Rise time (sec)	Over shoot	Settling time (sec)	Rise time (sec)	Over shoot	Settling time (sec)
SG of 8.1KVA	.05	<0.05	.05	.0531	.066	.065
SG of 31.3KVA	.08	0.6	.35	.08	<0.05	.096
SG of 250KVA	.35	0.135	1.7	0.35	<0.05	.35
SG of 910KVA	.73	0.11	3.6	0.73	<0.05	.73
SG of 2MVA	.85	0.25	3.5	0.85	<0.05	.85
SG of 187MVA	2.23	0.39	6.8	2.17	<0.05	2.4

Table 5. Transient responses parameters for different SG model with controller for SG 2MVA

SG model	PID controller for SG 250KVA			NARMA-L2 controller for SG 250KVA		
	Rise time (sec)	Over shoot	Settling time (sec)	Rise time (sec)	Over shoot	Settling time (sec)
SG of 8.1KVA	.05	<0.05	.9	.0531	.065	.065
SG of 31.3KVA	.08	<0.05	.35	.08	<0.05	.096
SG of 250KVA	.35	<0.05	.35	0.35	<0.05	.35
SG of 910KVA	.73	.09	2.9	0.73	<0.05	.73
SG of 2MVA	.85	.175	4.3	0.85	<0.05	.85
SG of 187MVA	2.23	.36	8.8	2.17	<0.05	2.17

Figures 25 and 26 show the time response for SG 187MVA for different loads with AVR using PID and NARMA-L2 controller of SG 8.1KVA respectively. The numerical values of transient response for Figures 25and 26 are depicted in Table 6. This table illustrates that big over shoot and large settling time for PID controller compared with NARMA-L2 controller.

Table 6. Transient responses parameters for SG 187MVA with different controllers and loads

Controller type	Rise time (sec)	Over shoot	Settling time (sec)	load
PID for SG 8.1KVA	1.92	.85	16	1MVA
	2.04	.66	10.3	100MVA
	2.24	.39	8.1	180MVA
NARMA-L2 for SG 8.1KVA	1.92	.011	1.92	1MVA
	2.04	.009	2.04	100MVA
	2.24	.005	2.24	180MVA

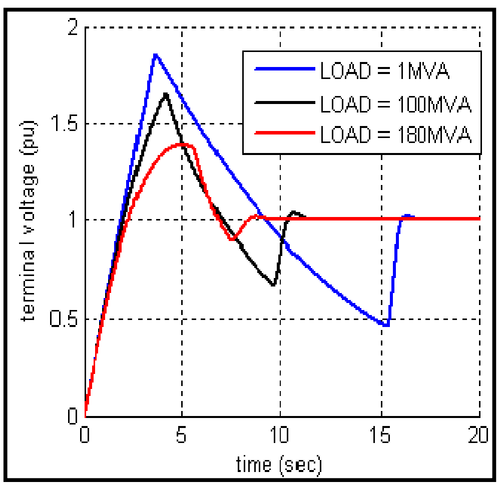

Fig. 25. Time responses for SG of 187MVA with PID controller for SG 8.1KVA

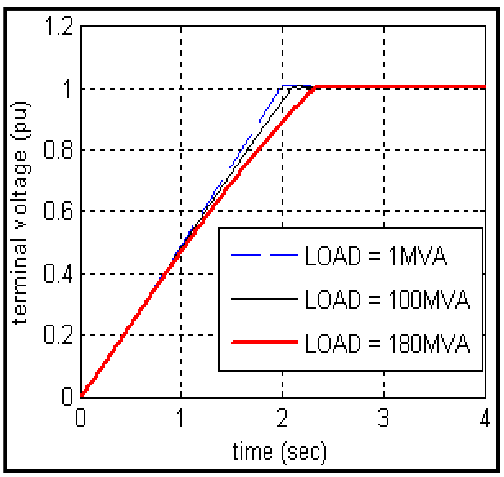

Fig. 26. Time responses for SG of 187MVA with NARMA-L2 controller for SG 8.1KVA

8. Conclusions

The main concluding remarks of SG terminal voltage response obtained by testing the proposed AVR using neuro-controller and the AVR using conventional PID controller can be summarized as follows:

- The settling times for different neuro-controllers are less than PID controllers except for the controller designed for same SG model this fact can be seen obviously by numerical values in tables 2,3,4 and 5 or by comparing Fig. 6 with Fig. 13, Fig. 7 with Fig. 15, Fig. 8 with Fig. 17, Fig. 9 with Fig. 19, Fig. 10 with Fig. 21, and Fig. 11 with Fig. 23.
- Approximately same over shoot for same SG model and different neuro-controllers as shown in tables 2,3,4 and 5 and Fig. 13 to 24, while for PID controllers the over shoot increase in case, when the controller designed for SG model of low power applied to SG model of higher power as shown in Fig. 7 to 11 and tables 2,3,4 and 5, where the over shoot for PID controller of SG 8.1KVA applied to different SG model are in the range from less than 5% to 39% see table 2.
- Neuro-controllers and PID controller have approximately same rise time from initial to 97% of the input signal.
- The response of SG model with different load for neuro-controller is better than PID controller as illustrated in Fig. 25 and 26 and table 6 where over shoot and settling time for PID controller reach the values 85% and 16 second respectively compared with 1.1% and 1.91 second for NARMA-L2 controller.
- From above remarks the margins of robustness for neuro-controller are greater than PID controller.

APPENDIX (A)

The table A below shows the parameters for different SG model taken from MATLAB/SIMULINK toolbox version 7.10.0.499 (R2010a) which used in our simulation models.

Table A. Parameters for different SG model taken from MATLAB/SIMULINK toolbox with

	Synchronous generator model					
	SG of 8.1KVA	SG of 31.1KVA	SG of 250KVA	SG of 910KVA	SG of 2MVA	SG of 187MVA
Rated Power (KVA)	8.1	31.3	250	910	2000	178000
Rated voltage V(L-L)	400	400	400	400	400	13800
Rated frequency (HZ)	50	50	50	50	50	60
stator resistance (pu)	.08201	.04186	.02594	.01706	0.0095	0.00285
stator leakage inductance (pu)	.0721	.0631	.09	.08	0.05	.114
mutual inductance (pu)	1.728	1.497	2.75	2.62	2.06	1.19
quadrature mutual inductance (pu)	.823	.707	2.35	1.52	1.51	.36
field resistance (pu)	.06117	.02306	.00778	.004686	.001971	.000579
field leakage inductance (pu)	.1801	.1381	0.3197	.4517	0.3418	.114
damper resistance (pu)	.1591	.1118	.2922	.2377	0.2013	.0117
damper leakage inductance (pu)	.1166	.1858	1.982	2.192	2.139	.182
damper resistance (pu)	.2416	.09745	.06563	.02186	0.02682	.0197
damper leakage inductance (pu)	.1615	.1258	.305	.09566	0.2044	0.384
Inertia coefficient (sec)	0.1406	.08671	.1753	.2717	0.3072	3.7
Friction factor (pu)	.02742	.02365	.o1579	.01356	.00987	0
Pole pair	2	2	2	2	2	20

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