Performance Comparison of Two Controllers for AVR SG system

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ABSTRACT

The voltage stability and power quality of the electrical system depend on proper operation of Automatic Voltage Regulator (AVR). Nowadays, the design technology of AVR is being broadly improved. Nonlinearities, parametric uncertainty, ill-defined mathematical model are an evitable problem faced in controlling the output voltage of Synchronous Generator (SG) leading to greater complexities in the design of the control system. Therefore, the application of Artificial Intelligence based controllers in electric power systems is becoming an important field of research. In the present work, the standard direct current exciter type (DC1A) and an intelligent controller have been suggested to replace the excitation circuit for improving the dynamic performance of the AVR SG system. The performance comparison between two suggested controllers is based on how well these controllers improve the dynamic responses of SG when exerting to different loading conditions and different durations of fault application. The results show that the intelligent controller can give better dynamic behavior than its competitor. Moreover, when applying worst fault condition (short circuit case), it is seen that the fuzzy logic (FL) controller can keep satisfactory and stable dynamic characteristic to longer fault exertion time interval.

مقارنة أداء مسيطرين لمنظومة السيطرة الطوعية للمحرك التزامني

الخلاصة

أن استقرارية الفولتية ونوعية القدرة للمنظومة الكهربائية تعتمد على عملية التشغيل الصحيحة لمنظم الفولتية الطوعي (AVR). شـهدت تقنية التصـميم للمنظم الفولتية الطوعي في الوقت الحاضـرتحسـنا" كبيرا". ان اهم المشـاكل الحتمية التي تواجه عملية السيطرة على المحرك التزامني هي وجود اللاخطية العالية واحتمالية التغير في معلمات المحرك اثناء الاشـتغال وصـعوبة تحديد الانموذج الرياضـي الدقيق للمحرك، مما ادى الى زيادة التعقيد في تصـــميم منظومة الســيطرة للمحرك التزامني. واصـــبح من الضروري اقتراح المسيطرات ذو الذكاء الاصطناعي كاحد الحلول لتلك المشاكل.

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تم اقتراح نمذجين من المسـيطرات لغرض تحسـين الاداء الداينميكي لمنظومة السـيظرة الطوعية وهما: النوع التقليدي ذو التيار المســتمر (DC1A) والنوع الاخر هو المســيطر الضــبابي (Fuzzy Logic Controller).

مقارنة الاداء بين المسيطرين تعتمد على قابلية كل من تلك المسيطرات لتحسين الاداء الداينميكي لمنظومـة المحرك التزامني في حـال تعرض المنظومـة الى حـالات اختلاف الحمل وحـالات العطـب المفاجئة.

أثبتت النتائج بان المســيطر الذي يعتمد النظرية الضــبابية يعطي افضــل اداءا" من نظيره. حيث اثبت المســطر اضــبابي بانه يحافظ على خواص داينمنيكية للمنظومة اكثر اســتقرارا" من المســيطر التقليدي ولاســيما عندما تتعرض منظومة المحرك التزامني الى اســوأ حالات العطب وهي الدائرة القصـيرة، حيث يمكن ملاحظة بأن المسيطر الذكي يحافظ على الاداء المطلوب لفترة طويلة من العطب (Fault).

INTRODUCTION

Synchronous generator represents the main equipment in major electric power systems, due to its active role within the system - being used to supply electric power and to adjust the voltage and for handling active and reactive power. Synchronous generators are responsible for the bulk of the electrical power generated in the world today. They are mainly used in power stations and are mostly driven either by steam or hydraulic turbines. These generators are usually connected to an infinite bus where the terminal voltages are held at a constant value. The synchronous generator control systems can almost be divided into two sections: voltage regulation and speed governing. Both control elements contribute to the stability of the machine in the presence of disturbances [1].

Power system stability may be defined as that a characteristic of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [2]. Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load variations occur continually, the system must be able to adjust to the changing conditions and operate in a satisfactory manner. It must also be able to survive various disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator. A large disturbance may lead to structural changes due to the separation of the faulted elements [3].

A reliable control system set is essential for the safe operation of generators. There are various ways of controlling a synchronous generator and stability will depend on the type of machine, its application and the operating conditions. For instance, the voltage regulation of an electromagnet synchronous generator is usually achieved by controlling the field excitation current. The voltage regulation system in an electromagnet synchronous generator is called an automatic voltage regulator (AVR); a device that automatically adjusts the output voltage of the generator in order to maintain it at a comparatively constant value. It compares the output voltage to the reference voltage and based on this difference the field current of SG is adjusted to bring the output voltage nearest to the required value. Older AVRs are belonging to a category of electromechanical devices. They are generally slow acting and have regions of insensitivity known as dead bands [1].

There is a wide variety of electromechanical AVR, are replaced with continuously acting electronic regulators that are much faster and do not possess dead bands, which is implemented in various methods like Proportional Integral (PI), Proportional Integral Derivative (PID), digital technique and intelligent technique. In many instances, the mathematical model of the plant is simply unknown or ill defined, leading to greater complexities in the design of the control system. It has been proposed that intelligent control systems give a better performance in such cases.

Artificial Intelligence (AI) is an attempt to replace human intelligence with machine intelligence. An intelligence control system combines the techniques from the field of AI with those of control engineering to design autonomous system that can sense, reason, plan, learn and act in an intelligent manner, that offer an alternative to classic controllers, which is good at identifying and controlling nonlinear system. AI can be classified into expert systems, fuzzy logic, artificial neural networks and genetic algorithms. They are appropriate for multivariable applications, where they can easily identify the interactions between the system's inputs and outputs such a system should be able to achieve sustainability of desired behavior under conditions of uncertainty, which include uncertainty in plant model, unreliable sensor information, and unpredictable enviromental change [4].

SYNCHRONOUS GENERATOR MODELING

A simplified model of the synchronous generator is given in this work for a transient stability investigation. The complete model consists of mechanical part, Steady State Operation sub-model, exciter System, electrical part, and fault sub-model. The considered single machine-infinitive subsystems given in Figure (1) [5]:

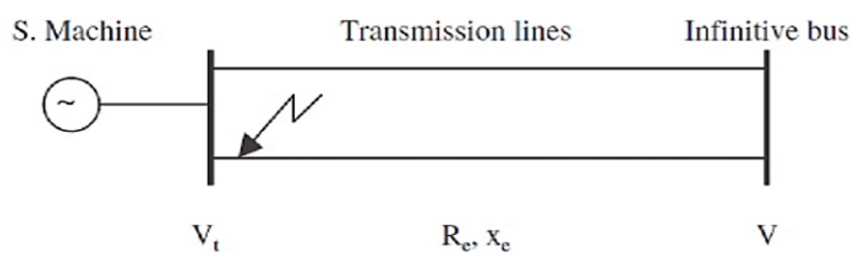


Figure (1): The considered single machine-infinitive bus system.

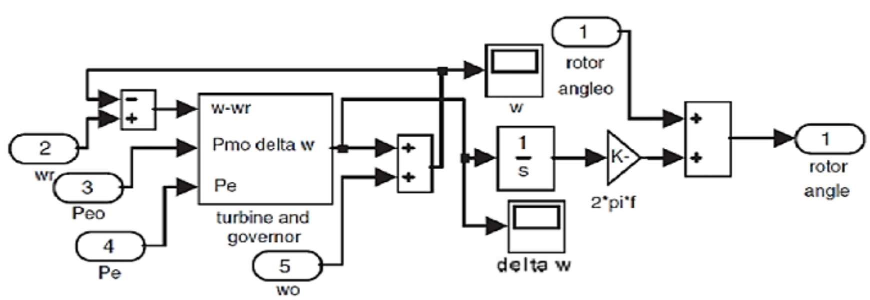


Figure (2) Mechanical Part of the Synchronous Generator.

THE MECHANICAL SUB-MODEL OF THE SYNCHRONOUS GENERATOR

The system includes a turbine and governor sub-system and the blocks of the relationships among rotor angle δ, deviation of angular speed Δω, and steady state value of angular speed, ω_0, as given in equation (1) and (2). The considered system is given in Figure (2) [5]:

$$\Delta\omega = \frac{1}{D + sM}(P_m - P_e) \qquad (1)$$

$$\delta = \omega_0\,(\Delta\omega/s) \qquad (2)$$

The sub-model includes five inputs, steady state value of rotor angle in radian, reference value of angular speed, the steady state and instantaneous values of real electrical power and steady state value of angular speed, in per-unit values. It has one output rotor angle in radians [5]. The sub-model of the turbine and governor system contains three inputs, the difference between the reference value and instantaneous value of angular speed, the steady state value of mechanical power, instantaneous value of electrical power, in per-unit, and one output, the deviation of angular speed in per-unit. All inputs and output are shown in Figure (3) [:

$$\Delta P_r = \frac{K_G}{T_{SR}\, s + 1}\Delta\omega \qquad (3)$$

$$\Delta P_h = \frac{1}{T_{SM}\, s + 1}\Delta P_r \qquad (4)$$

$$\Delta P_C = \frac{1}{T_{CH}\ \ s + 1}\Delta P_h \qquad (5)$$

$$\Delta P_m = \frac{(K_{RH}T_{RH}\,)\, s}{T_{RH}\, s + 1}\ \Delta P_C \qquad (6)$$

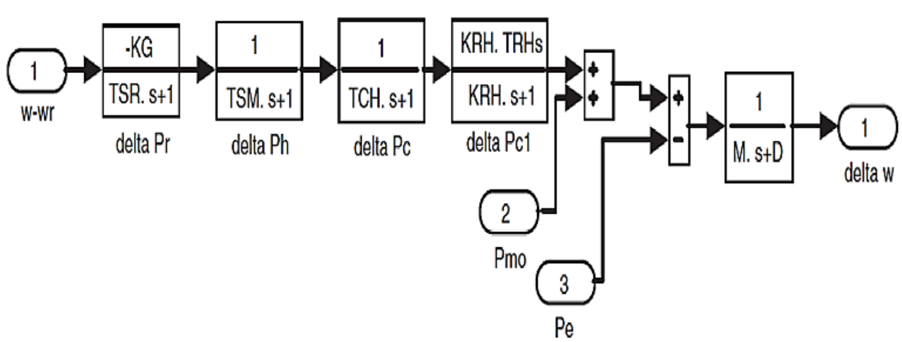


Figure (3) Turbine and governor system configuration.

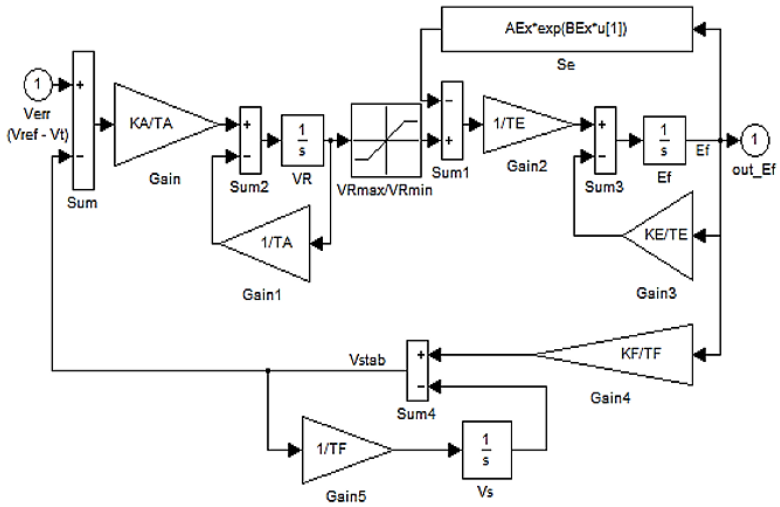


Figure (4): DC1A-Type exciter block diagram.

THE EXCITATION SYSTEM

The exciter is represented by the DC1A exciter mode; the inside of the exciter block has an IEEE Type 1 excitation system [8]. Integrators are used to build up the components of the exciter to keep the startup transients of the simulation to a minimum [5,6]. The sub model has two inputs, v_{tr} and v_r, reference and instantaneous values of terminal voltage, respectively and one output E_{fd} in per unit values [9]. The block diagram of the exciter DC1A shown in Figure (4).

THE STEADY-STATE SUB-MODEL OF THE SYNCHRONOUS GENERATOR

The steady state values are calculated separately according to the block diagram of Figure (5). The function blocks given in this figure which correspond to initial values of current, load angle, rotor angle, electromotor force in the machine, terminal voltage, real power, exciter voltage, and reference terminal voltage are calculated using the following equations [5, 9]:

$$V_{t0=}\sqrt{(V_0 + R_e I_0 \cos\varphi_0 + x_e I_0 \sin\varphi_0)^2 + (x_e I_0 \cos\varphi_0 - R_e I_0 \sin\varphi_0)^2} \quad (7)$$

$$E'_{q0} = E_{fd0} + (x_d - x'_d) I_{d0} \quad (8)$$

$$E'_{d0} = -(x_q - x'_d) I_{q0} \quad (9)$$

$$P_{e0} = E'_{d0} I_{d0} + E'_{q0} I_{q0} \quad (10)$$

$$V_{tr} = \frac{E_{fd0}}{K_E} + V_{tro} \quad (11)$$

$$P_{m0} = P_{e0} \quad (12)$$

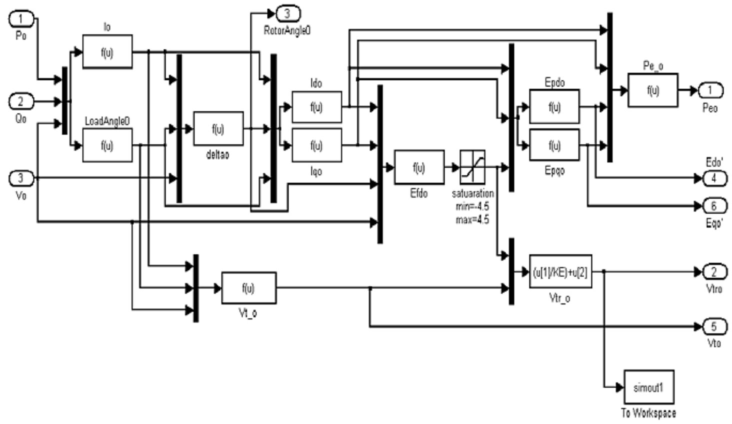


Figure (5): The electrical parts of the machine for continuous operation [5,9].

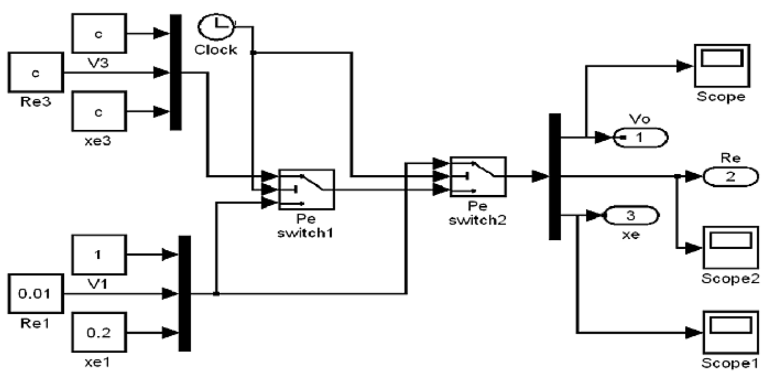


Figure (6): The fault sub-model with switch Configuration [5,9].

THE FAULT SUB-MODEL OF THE SYNCHRONOUS GENERATOR

It used for transient stability analysis of a synchronous generator. It is assumed that different types three-phase fault at the sending terminal of one of the parallel lines has occurred at 0.6 s and the fault has continued for different fault time intervals, when the fault cleared by change the switch state then the system return to the pre-fault configuration [5,9]. The fault sub-model and complete model of the synchronous generator shown in the Figures (6) and (7):

SIMULATED RESULTS

It has been mentioned earlier that two control structures (or configuration) of synchronous generator exciter have been employed in the present work. The first one is classical and based on DC1A and the other is intelligent and based on FL theory. In this section, the robustness of these controllers against variation of machine parameters has been assessed. How well the controller does work depends on its ability to how quickly it can manage the parameter change without any adverse effect. The machine parameters and coefficients are listed in Appendix (A) [5].

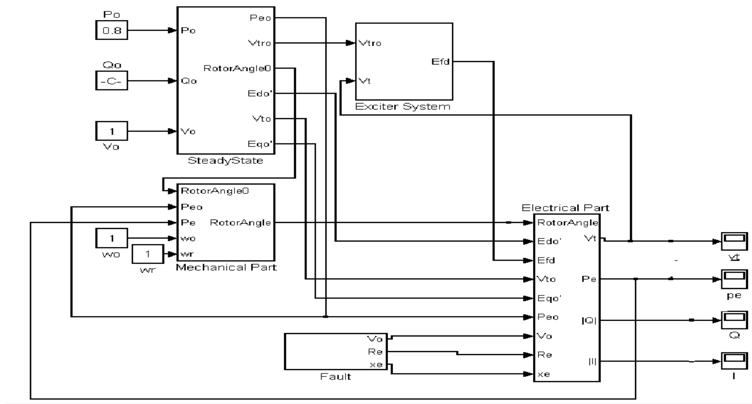


Figure (7): The electrical parts of the machine for continuous operation.

The FL controller is built using m-function block in Simulink library, while its action has been coded in m-file. Appendix (B) lists Matlab code of FL controller including the processes of fuzzification and defuzzification. In this project, seven triangular membership functions (MF) have been used for both the inputs and the output. The center of gravity (COG) has been used for aggregation and to generate the crisp output.

The objective of these tests is to study and to check the powerfulness of both FL and DC1A controllers under different load conditions. In all results below, a load change (or a fault) in transmission line occurs at time 0.6 seconds and is cleared at 0.72 seconds.

Figures (8a) -(8f) show the traces of terminal voltages, voltage errors, stator currents, active and reactive powers, and rotor angle respectively, resulting from both suggested controllers. In these figures, a sudden load (transmission line) change of about 25% of rated load has occurred at 0.6 second and vanished at 0.72. Also, the terminal voltage V_t has been decreased to 75% of its rated value at the same time duration such that the equivalent impedance elements becomes;

$$V_t\text{=0.75, } R_e\text{=0.0075, } X_e\text{=0.15}$$

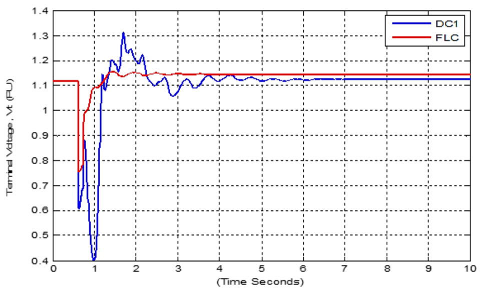
It is clear from the figures that the fuzzy controller shows a better response than DC1A one. This is evident from voltage errors of Figure (8-b), where the actual voltage response based on DC1A shows a large error than that based on intelligent controller. The Integral Square Error (ISE) criterion tells that its value is equal to 0.1603 in case of DC1A controller-based response and equal to 0.02284 based on FL controller.

In Figures (9-a) -(9-f), the load impedance of the transmission line are decreased to 50% (R_e =0.005, X_e =0.1) from their rated values, respectively. The same above discussion can be argued here, where the response based on the FL controller shows better characteristics than its counterpart. For Figure (9), the ISE criterion gives the value of 0.1105 for DC1A-based controller and 0.04428 for the FL-based controller.

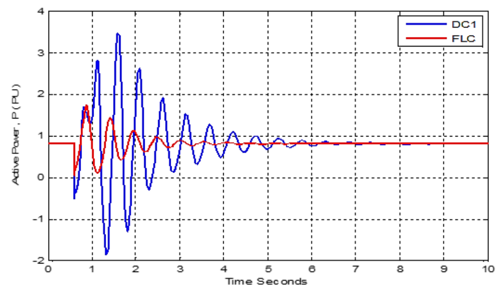
The worst load condition (transmission line) occurs when the load is short circuited, i.e., $Ze = R_e + jX_e = 0$.The effectiveness of both controllers will be tested at this severe condition and the different measurements under supervision of both controllers are shown in Figure (10). As it is evident from the figure, the FL controller still again outperforms the DC1A controller. The ISE criterion records the value of 0.1899 for the DC1A controller and the value of 0.1596 for the FL controller case.

So far, all load changes has been exerted at time period of 0.6-0.78 seconds. It is interesting to investigate the effectiveness of both controllers when the time duration is changed over the above time interval. In Figure (11), the short circuit condition is applied, but the end time of fault exertion is extended to be 0.76 rather than 0.72 second. In this case the responses based on the FL controller are still a little better than those based on DC1A controller. The ISE measure gives the value of 0.2144 in case of FL controller and the value of 0.2532 in case of the other one.

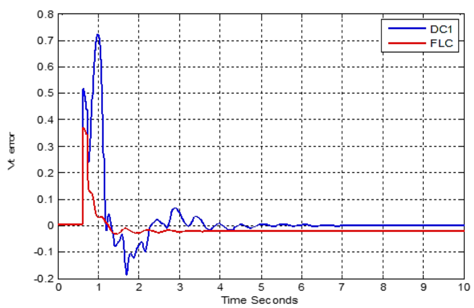
The next test will consider the case when the exertion time interval is increased up to 0.79. At this critical value, the responses due to DC1A controller would show unstable characteristics, while those based on FL controller could keep their satisfactory behaviors. All these new scenes can be clarified in Figure (12). One can easily see that the load angle change increase without bound.



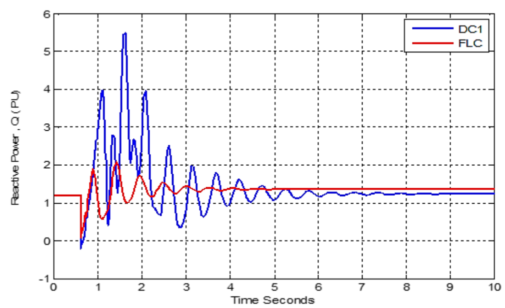
(a) Terminal voltage responses



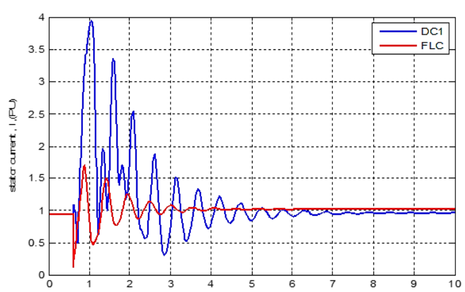
(d) Active Powers



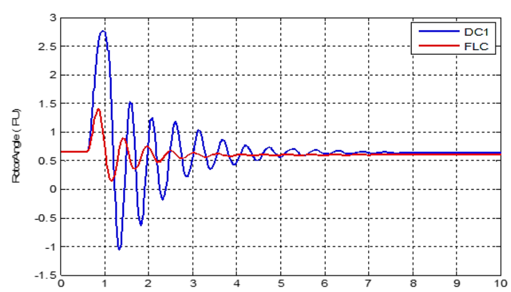
(b) Voltage errors (between reference and actual voltages)



(e) Reactive Power

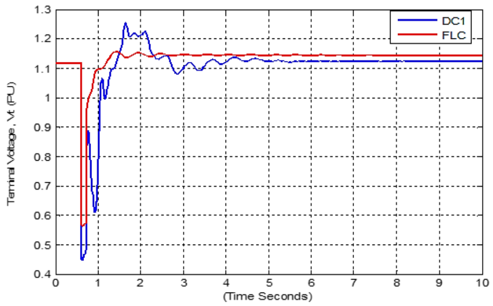


(c) Stator currents

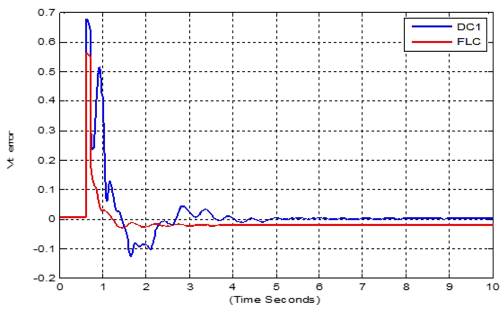


(f) Rotor angle change

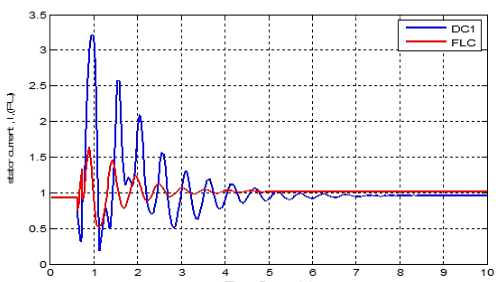
Figure (8) Different SG Responses due to load change starts at 0.6 and lasts at 0.78 seconds (R_e=0.0075,X_e=0.15).



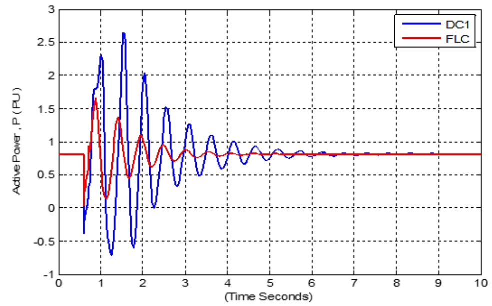
(a) Terminal voltage responses



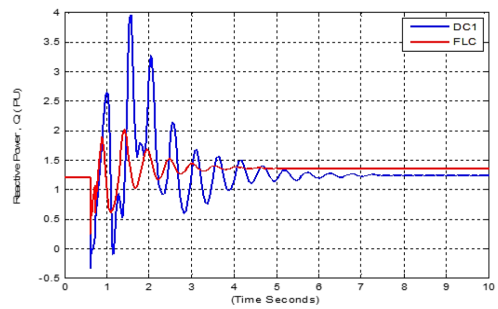
(b) Voltage errors (Between reference and actual voltages)



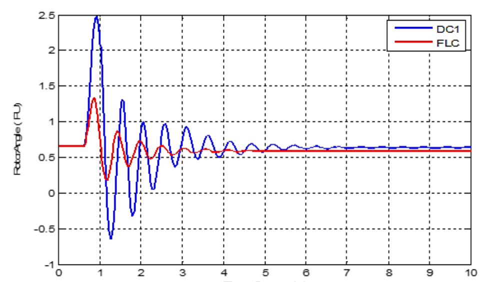
(c) Stator currents



(d) Active Power

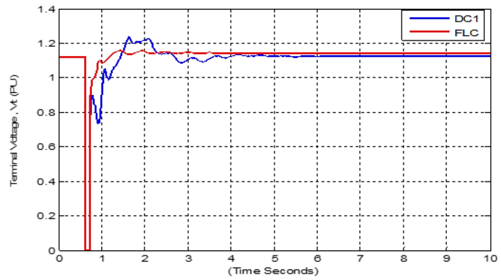


(e) Reactive Power

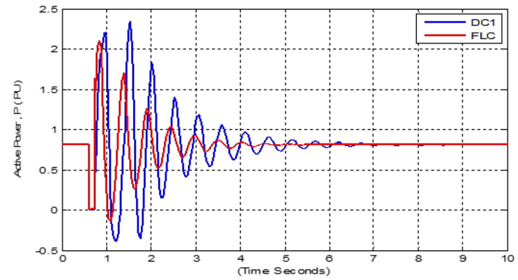


(f) Rotor angle change

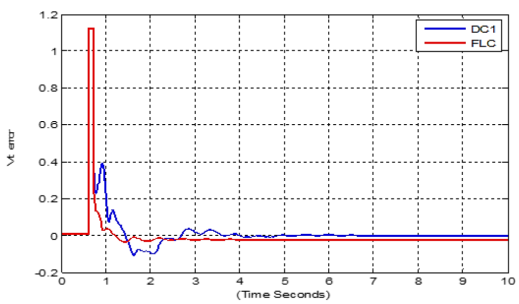
Figure (9) Different SG Responses due to load change starts at 0.6 and lasts at 0.72 seconds (R_e=0.005, X_e=0.1).



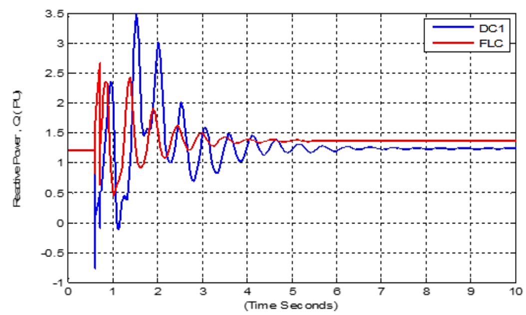
(a) Terminal voltage responses



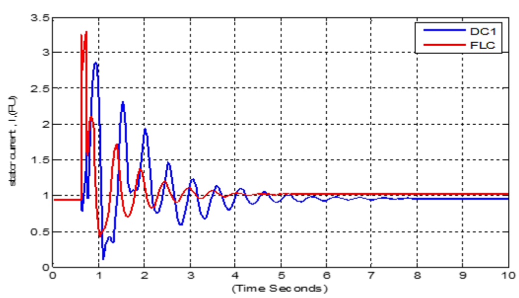
(d) Active Power



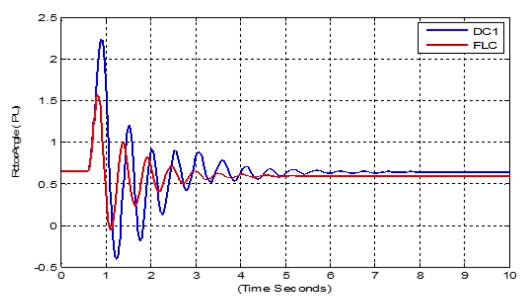
(b) Voltage errors (Between reference and actual voltages)



(e) Reactive Power

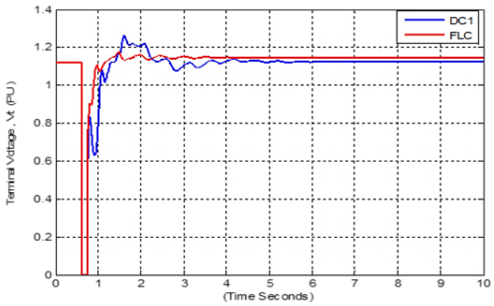


(c) Stator currents

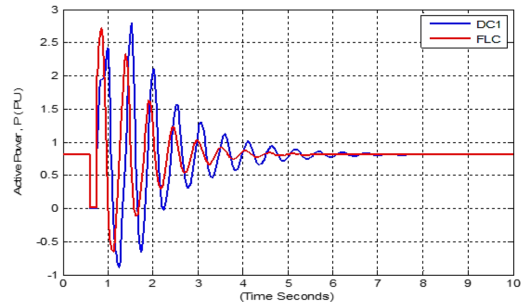


(f) Rotor angle change

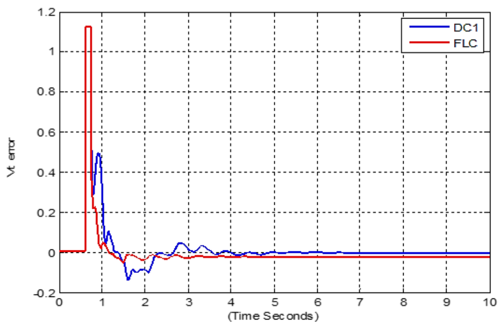
Figure (10) Different SG Responses due to short circuited fault occurs at 0.6 and lasts at 0.72 seconds (R_e= X_e=0).



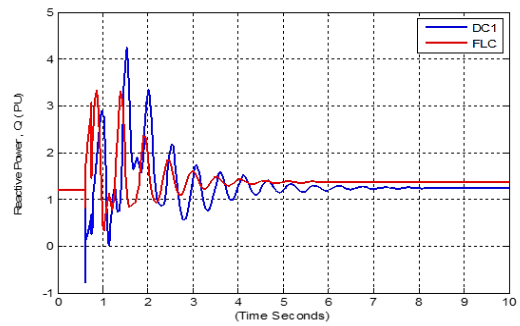
(a) Terminal voltage responses



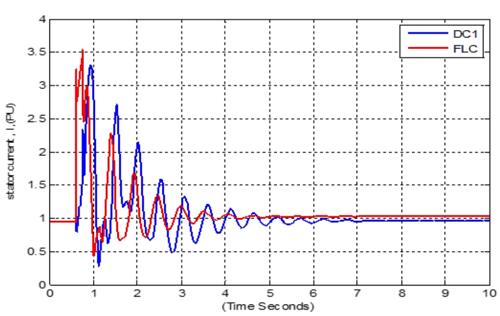
(d) Active Power



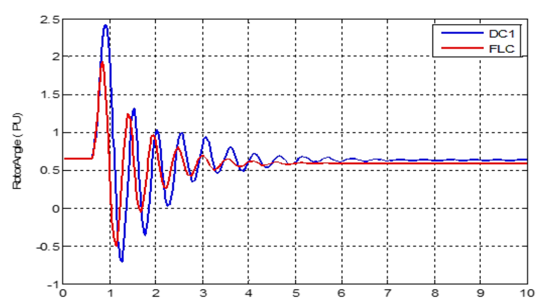
(b) Voltage errors (Between reference and actual voltages)



(e) Reactive Power

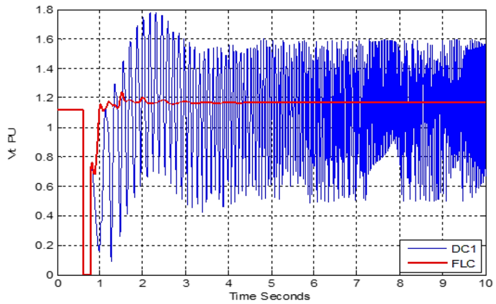


(c) Stator currents

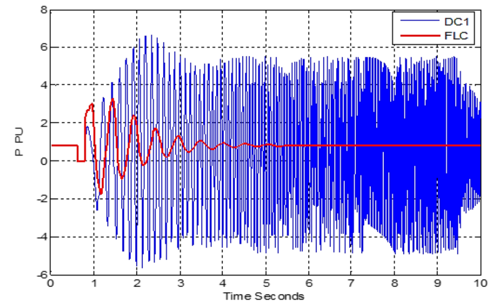


(f) Rotor angle change

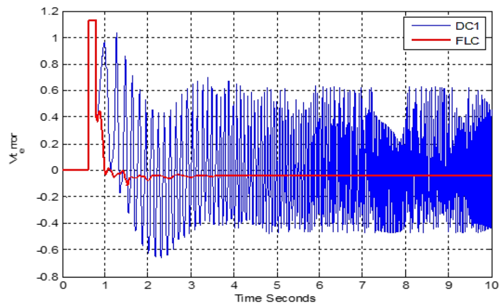
Figure (11) Different SG Responses due to short circuited fault (R_e= X_e=0) occurrence between 0.6 and 0.76 seconds.



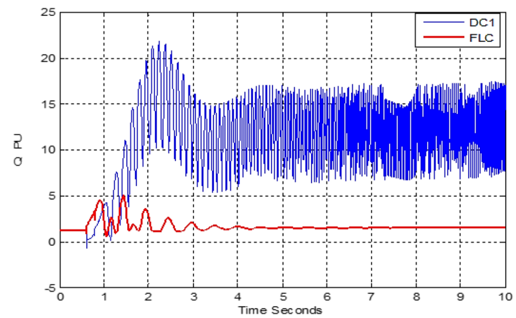
(a) Terminal voltage responses



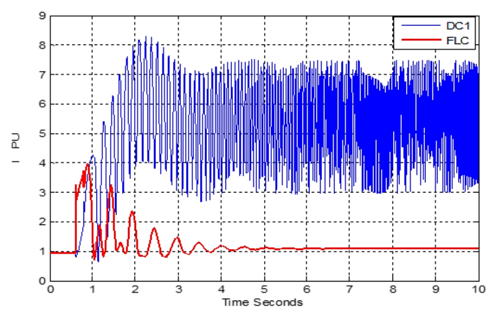
(d) Active Power



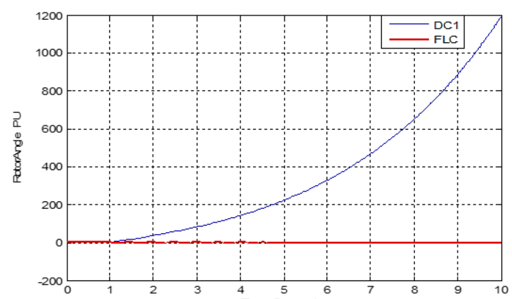
(b) Voltage errors (Between reference and actual voltages)



(e) Reactive Power



(c) Stator currents



(f) Rotor angle change

Figure (12) Different SG Responses due to short circuited fault (R_e= X_e=0) occurrence between 0.6 and 0.79 seconds.

CONCLUSION

In the present work, conventional and intelligent controllers have been suggested to replace the excitation circuit for improving the dynamic performance of the AVR SG system. The performance of the two controllers has been compared and assessed at different machine loading conditions. Also, the integral square error (ISE) measure is relied to evaluate the controller performances. Based on observations from simulated results, one can highlight the following conclusions:

1. If the fault duration is held fixed and different load changes of transmission line impedance has been exerted, one can conclude based on ISE indicator that FL controller could successively outperform the conventional controller.
2. If the fault duration time is again fixed and the short circuit case is applied to machine load (transmission line), the intelligent controller could give better dynamic performance than its counterpart. One can decisively conclude that for all load changes, even the worst one, and the FL controller shows better characteristics than DC1A controller.
3. Considering the worst loading machine condition (short circuit case), and the time interval of load exertion is allowed to be changed, the results showed that for certain time duration, the DC1A controller would fail to control the AVR system, meanwhile the FL controller still gives satisfactory performance. In other words, the intelligent controller could withstand longer time duration of load exertion than the other candidate.

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APPENDIX –A
The machine parameters and coefficients [5]

Parameter	Definition	Value
Pr	Rated power	160 MVA
Vr	Rated voltage	15 Kv
fr	Rated frequency	60 Hz
PO	Steady-state reactive power	0.8
Qo	Steady-state reactive power	0.496
VO	Steady-state terminal voltage	1
Ra	Armature resistance	0.001096
Re	Equivalent resistance of transmission lines	0.01
Xd	Synchronous reactance	1.7
Xq	q-axis reactance of generator	1.64
x'_d	Transient reactance	0.245
x_e	Equivalent reactance of transmission line	0.2
KRH	Re-heater gain	0.3
M	Inertia constant of generator	4.74
D	Damping coefficient	0
TRH	Re-heater time constant	8 sec.
TGH	Steam chest time constant	0.05sec.
TSR	Speed relay time constant	0.1 sec.
TSM	Servomotor time constant	0.2 sec.
ω_o	Base angular speed	1
ω_r	Governor reference speed	1
KE	Exciter gain	400
TE	Exciter time constant	0.052 sec.
TF	Stabilizer circuit time constant	1 sec.

APPENDIX –B
FUZZY CONTROLLER PROGRAM BY M. FILE MATLAB CODE

```
%Define function name
function [VF]=SGFC3(E,DE)
FLCVF=newfis('FUZZY31');
%%%to add input parameter of e into FIS
FLCVF=addvar(FLCVF,'input','E',[-1 1]*1);
FLCVF=addmf(FLCVF,'input',1,'NL','trimf',[-1 -1 -0.6667]);
FLCVF=addmf(FLCVF,'input',1,'NM','trimf',[-1 -0.6667 -0.3333]);
FLCVF=addmf(FLCVF,'input',1,'NS','trimf',[-0.6667 -0.3333 0]);
FLCVF=addmf(FLCVF,'input',1,'Z','trimf',[-0.3333 0 0.3334]);
FLCVF=addmf(FLCVF,'input',1,'PS','trimf',[0 0.3333 0.6667]);
FLCVF=addmf(FLCVF,'input',1,'PM','trimf',[0.3333 0.6667 1]);
FLCVF=addmf(FLCVF,'input',1,'PL','trimf',[0.6666 1 1]);
%figure(1);
%plotmf(FLCVF,'input',1);
%axis([-1 1 0 1.2]);
FLCVF=addvar(FLCVF,'input','DE',[-3 3]);
FLCVF=addmf(FLCVF,'input',2,'NL','trimf',[-3 -3 -2]);
```

```
FLCVF=addmf(FLCVF,'input',2,'NM','trimf',[-3 -2 -1]);
FLCVF=addmf(FLCVF,'input',2,'NS','trimf',[-2 -1 0]);
FLCVF=addmf(FLCVF,'input',2,'Z','trimf',[-1 0 1]);
FLCVF=addmf(FLCVF,'input',2,'PS','trimf',[0 1 2]);
FLCVF=addmf(FLCVF,'input',2,'PM','trimf',[1 2 3]);
FLCVF=addmf(FLCVF,'input',2,'PL','trimf',[2 3 3]);
%figure(2);
%plotmf(FLCVF,'input',2);
%define the output name, range ,and number.
FLCVF=addvar(FLCVF,'output','VF',[-5.282 10.564]);
FLCVF=addmf(FLCVF,'output',1,'NL','trimf', [-5.282 -5.282 -2.641]);
FLCVF=addmf(FLCVF,'output',1,'NM','trimf', [-5.282 -2.641 0]);
FLCVF=addmf(FLCVF,'output',1,'NS','trimf', [-2.641 0 2.641]);
FLCVF=addmf(FLCVF,'output',1,'Z','trimf', [0 2.641 5.282]);
FLCVF=addmf(FLCVF,'output',1,'PS','trimf', [2.641 5.282 7.923]);
FLCVF=addmf(FLCVF,'output',1,'PM','trimf', [5.282 7.923 10.564]);
FLCVF=addmf(FLCVF,'output',1,'PL','trimf', [7.923 10.564 10.564]);
%figure(3);
%plotmf(FLCVF,'output',1);
%%%to add input parameter into FIS
[Rule1]= [ 1 1 1 1 1;1 2 1 1 1; 1 3 1 1 1; 1 4 2 1 1; 1 5 2 1 1; 1 6 3 1 1; 1 7 4 1 1; 2 1 1 1 1; 2 2 1 1 1;
           2 3 2 1 1; 2 4 2 1 1; 2 5 3 1 1; 2 6 4 1 1; 2 7 5 1 1; 3 1 1 1 1; 3 2 2 1 1; 3 3 2 1 1; 3 4 3 1 1;
           3 5 4 1 1; 3 6 5 1 1; 3 7 6 1 1; 4 1 1 1 1; 4 2 2 1 1; 4 3 3 1 1; 4 4 4 1 1; 4 5 5 1 1; 4 6 6 1 1;
           4 7 7 1 1; 5 1 2 1 1; 5 2 3 1 1; 5 3 4 1 1; 5 4 5 1 1; 5 5 6 1 1; 5 6 6 1 1; 5 7 7 1 1; 6 1 3 1 1;
           6 2 4 1 1; 6 3 5 1 1; 6 4 6 1 1; 6 5 6 1 1; 6 6 7 1 1; 6 7 7 1 1; 7 1 4 1 1; 7 2 5 1 1; 7 3 6 1 1;
           7 4 6 1 1; 7 5 7 1 1; 7 6 7 1 1; 7 7 7 1 1 ];
%%% add Rule_base into FIS
FLCVF=addrule(FLCVF,Rule1);
ruleedit(FLCVF)
% showfis(FLCVF);
%showrule(FLCVF);
%figure(4);
%gensurf(FLCVF);
%plotfis(FLCVF);
%FLCVF_input=[E DE];
VF=evalfis([E DE],FLCVF);
```