A STUDY OF FUZZY BASED METHOD SYNCHRONOUS GENERATOR TERMINAL VOLTAGE CONTROL

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CERTIFICATE

I hereby certify that the work which is being presented in this thesis entitled, **"A study of fuzzy based Method synchronous Generator terminal voltage control"**, in partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Electronics Instrumentation and Control Engineering** submitted in Electrical & Instrumentation Engineering Department of Thapar University Patiala, is an authentic record of my own work carried out under the supervision and guidance of **Mr. M.D. Singh & Dr. Amjed Jalil**. The matter presented in this thesis has not been submitted anywhere for the award of any degree.

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This is to certify that the above statement made by the student is correct and true to the best of our knowledge and belief.

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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, conventional exciter type (IEEE DC1) 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.

In this thesis, 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.

The effect of changing the FL controller parameters on the dynamic performance of SG has been considered. The type of MF, number of MFs and knowledgebase elements are selected as the design parameters for this assessment. For specified knowledge-based elements and fixed number of MFs, the performance of intelligent controller has been evaluated based on type of MF and the duration length of load exertion. The simulation revealed that the FL controller based on triangular function could give best dynamic performance than that with other MFs. However, the FL controller based on Gaussian MF could give stable behavior to a longer fault period.

The effectiveness of FL controller is also examined by different fuzzification methods. Mamdani and Sugenio fuzzification methods have been selected to synthesize the FL controller and performance comparisons are assessed in terms of ISE measure and the ability of controller to withstand longer fault exertion interval.

The simulation shows that the performance of FL controller based on Sugenio method outperforms that based on Mamdani.

The work also elaborates in detail the modeling and analysis of the Synchronous Generator that is connected to the steam-turbine. The modeling of Synchronous Generator and Steam turbine has been done in MATLAB/SIMULINK by integrating all the sub-models which include exciter, turbine, governor and the electrical part of Synchronous Generator.

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List of Abbreviations

AC	Alternating Current.
AI	Artificial Intelligence.
ANN	Artificial Neural Network.
AVR	Automatic Voltage Regulator.
BOA	Bisector of area.
COA	Center of Area.
COLA	Center of largest area.
COS	Center of sums.
CV	Control valve.
DC	Direct Current.
DEH	Digital Electro Hydraulic Control.
EHC	Electro Hydraulic Control.
FLC	Fuzzy logic controller.
FM	First of Maximal.
HP	High pressure.
IEEE	Institute of Electrical and Electronic Engineers.
IP	Intermediate pressure.
ISE	Integral Square Error.
IV	Intercept valve.
LP	Low pressure.
MF	Membership Function.
MHC	Mechanical –Hydraulic Control.
MIMO	Multi-input multi-output.
MOM	Mean Of Maxima.
MSV	Main inlet stop valve.
N	Negative membership function.

NL	Negative Large membership function.
NM	Negative Medium membership function.
NN	Neural Network.
NS	Negative Small membership function.
P	Positive membership function.
PI	Proportional Integral controller.
PID	Proportional Integral Derivative controller.
PL	Positive Big membership function.
PLU	Power load unbalance.
RSV	Reheat stop valve.
SG	Synchronous generator.
SISO	Single- input single-output.
WtAver	Weighted Average.

List of Symbols

Pe	Electrical output power.
v_t	Generator terminal voltage.
v_{td}	d axis component of terminal voltage.
v_{tq}	q axis component of terminal voltage .
I_d	d axis armature current.
I_q	q axis armature current.
E_d'	d axis transient voltage.
E_q'	q axis transient voltage .
T_{d0}'	d axis open circuit time constant.
T_{q0}'	q axis open circuit time constant .
E_{fd}	d axis field voltage.
K_E	Exciter gain.
T_E	Exciter time constant.
Vs	Stabilizing transformer voltage .
K_F	Stabilizer circuit gain.
T_F	Stabilizer circuit time constant .
T_{SR}	Speed relay time constant .
T_{SM}	Servomotor time constant .
T_{CH}	Steam chest time constant.
T_{RH}	Reheater time constant.
K_{RH}	Reheater gain.
S	Laplace derivation operator.
Pr	Speed relay output power .
P_h	Servomotor output power.
Pc	Steam chest output power.

Pm	Generator input power.
K_G	Speeds relay gain.
δ	Rotor angular position.
ω	Angular speed.
ω_0	Base angular speed.
ω_r	Governor reference speed.
D	Damping coefficient.
M	Inertia constant of generator.
R_a	Armature resistance.
Re	Equivalent resistance of transmission lines.
x_e	Equivalent reactance of transmission lines.
x_d	Synchronous reactance.
$x_d^{'}$	Transient reactance.
x_q	q axis reactance of generator .
V	Infinitive bus voltage.
P	Real power.
Q	Reactive power.
Δ	Change from nominal values.
V_{tr}	Reference value of the terminal voltage.

Chapter- 1

Introduction and Literature Review

1.1. Introduction:

The synchronous generator represents the main equipment in major electric power systems. It is 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 Survey of 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), which is device that automatically adjusts the output voltage of the generator in order to maintain it at a Comparatively constant value. This is achieved by comparing the output voltage with a reference voltage and, from the difference (or error); it makes the needed adjustments in the field current to bring the output voltage nearest to the required value .Older AVRs 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 now 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. Intelligent controllers are based on artificial intelligence (AI) rather than on a plant model.

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].

1.2. Literature Review:

Many different studies have been developed by many researchers to find out different solutions to the control and stability problems for a power system. Because of the structure complexity of power system; a wide variety of models have been used and several control techniques have been proposed in recent years. Therefore, a literature survey for many previously published studies is presented as follows:

- **H. Hamdaoui Y. Ramdani et. al. (2003).**

Presented a new structure of SMES (Super-conducting Magnetic Energy Storage) using a PWM Current Source Inverter (CSI). Two independent f fuzzy controllers are assigned, one for the frequency control and another for the terminal voltage control. The inputs of fuzzy Frequency controller (FFC) are Speed deviation ($\Delta\omega$) and acceleration $(\Delta\boldsymbol{\omega}')$, the terminal voltage deviation (ΔV_t) and its derivative ($\Delta V_t'$) are considered as the input of the Fuzzy Voltage Controller (FVC). This method of control can guarantee transient stability of a single-machine-infinite-bus system under a large sudden fault [5].

- **R. Goma and et. Al (2004).**

A feedback control Proposed for transient stabilization and voltage regulation, when large and abrupt faults occur to the transmission line. An adaptive nonlinear controller used at real-time application of for the prevention of an electric power system losing synchronism after a large abrupt fault, and to achieve a good post-fault regulation of the generator terminal voltage. . The efficiency of the suggested controller has been compared to the performance of the standard linear controllers such as the automatic voltage regulator (AVR) and power stabilizer (PSS) [6].

- **D. Z. Fang,et, al (2004).**

The oscillation energy function origin method Proposed for developing an efficient static VAR compensator (SVC) Complementary damping controller. The fuzzy-logic adaptive SVC control scheme been developed. An extra fuzzy-logic control unit is used to enhance the performance of the damping controller by adjust the control gain factor in real time accordance with the magnitude of system oscillations at every moment. The drawback of fuzzy-logic control schemes with constant gain factor to overcome by adaptive approach [7].

- **Neven Bulic and et. al (2007).**

A Networks' (NN) based excitation control Presented on single machine infinite bus. The proposed feed forward neural network integrates a voltage regulator and a power system stabilizer. It is trained on-line and a modified error function used for training the neural network by the back propagation algorithm uses the reference and terminal voltage as controlling voltage and active power deviation to provide stabilization. The fixed point DSP used in execution of the complete control algorithm [8].

- **Dong-Hee Lee et, al (2007).**

A variable gain control planner Presented of DAVR (Digital Automatic Voltage Regulator) for AC brushless generator. A PID controller with a simple gain adjustor is used to enhance dynamic response and steady state performance, the terminal voltage and load current used to update the gains of PID controller. The gain is grown in proportional to load current and terminal voltage by used simple linear function [9].

- **Jenica Ileana Corcau et, al (2007).**

The controller is proposed in this paper is an fuzzy PID controller. Fuzzy logic controllers are based on trial control rules. The development of a fuzzy logic based power system stabilizer in order to maintain stability and improve the closed-loop performance of a power system. Transfer function simulations have been carried in order to subject it to several types of large disturbances using a SMIB power system. Comparison studies have also been performed between the classical proportional integral power stabilizers and the fuzzy PID [10].

- **Sukumar Kamalasadan, (2008).**

Provided optimal control of power with stable voltage profile at the synchronous generator terminals using two controllers, a hybrid coordinated control architecture implemented by an Implicit Model Adaptive Controller (IMAC) in parallel with a Radial Basis Function Neural Network (RBFNN) neuro-controller .The adaptive controller centrally controls the voltage, while systems dynamics constantly monitors by a RBFNN based neuro-controller [11].

- **Lingyan Hu et, al (2008).**

The controller is proposed in this paper can adjust the excitation current by adjusting duty circle of the PWM wave, in order to keep the terminal voltage at the desired value. To solve the classic PID algorithm problems, the duty circle of the PWM wave is calculated by PID and fuzzy integrated algorithm which can employ different control algorithm to adapt to the different case. In addition, ARM920T microcontroller-S3C2410A has been used as CPU, so the high speed and real-time performance can be ensured [12].

- **Tianchai Suksri et, al (2008).**

The design and implementation of the two degree of freedom (T-DOF) technique Presented to design control system for a reactive power and voltage regulation of the synchronous generator.

The T-DOF PID controller design by root locus technique is also introduced to the system for regulates and tracking terminal voltage response. The proposed controller will be a Proportional Integral Derivative (PID) controller. The overall control system is implemented on DSPACE DSP DS1104 controller board [13].

- **Ndubisi Samuel. N (2008).**

The controller is proposed in this paper is the fuzzy model reference learning (FMRLC) scheme for automatic voltage regulation of synchronous generators. This controller can tune the parameters and recall what it tuned before, because of that it is superior to classic AVR .The behavior of the generator is controlled by identifying (11×11) rules which Cared of most nonlinear operating conditions which wouldn't have been a problem by convectional adaptive and non-adaptive controllers[14].

- **Darabi et, al (2008).**

Presented a digital fuzzy based AVR of a synchronous generator in balanced and unbalanced load operating conditions .The performances of a digital fuzzy AVR evaluated for a wide range of unbalanced loads operating conditions [15].

- **Miguel Ramirez et, al (2008).**

The controller is proposed in this paper is a neurofuzzy controller (NFC) with adaptive input link weights (ILWs) and acting as a as an adaptive power system stabilizer. The controller Composed of a neuro identifier to track the dynamic behavior of the plant and an NFC to damp the low-frequency power system oscillations. The performance by adaptation of the consequent parameters (CPs) and the input membership functions (IMFs). Examined operation conditions and disturbances in a SMIB system and a multi machine power system demonstrate the enhancement in the dynamic performance of the system with the proposed adaptive neurofuzzy power system stabilizers [16].

- **Xiaoqing HANet, al (2009).**

Provided an assessment method on voltage stability of power system using Back Propagation (BP) Neural Network, the index of assessment is the Voltage Collapse Proximity Indicator (VCPI). The load flow calculation based training results of the static models can reflect the nonlinear relation between power flows and voltages on load bus with given load increasing mode. Networks used three-layer BP for classification and prediction on system, respectively [17].

- **Sang-Hoon Parket, al (2009).**

Implemented a Permanent Magnet Generator (PMG) type digital AVR using MOSFET on a synchronous generator for ships. Besides, the digital AVR implemented was improved for user convenience by building a monitoring system using the Lab view software. This method with period is slower than a converter composed of MOSFET or IGBT [18].

- **B.Selvabala and D.Devaraj (2010).**

The optimal tuning of AVR controller and PSS parameters in the synchronous machine is proposed in this paper. To solve the optimization problem Differential Evolution Algorithm is applied for obtaining the optimal parameters of AVR gains and PSS controller parameters simultaneously. The suitability of this method has been demonstrated by computer simulation in a Single Machine Infinite Bus (SMIB) system and compared with Genetic Algorithm (GA) based method [19].

- **A.G .Abro and J.M.Saleh, (2011).**

Model free estimation based adaptive and nonlinear approach is proposed to replace classical controller compensated automatic voltage regulator. Thus reduces complexity and risk implied in indirect adaptive online trained neurocontrollers used to drive dynamical systems. Trial at different conditions was implemented to investigate non-linear and model-free adaptability of well generalized neurocontroller. The neurocontroller with top performance although neurocontroller trained without helpe of auxiliary stabilization signal and any time delayed inputs and let generators to be operated near to their steady state stability limits. But it not answer question on how the proposed neurocontroller will behave with fault simulation with different transmission line impedance, and at different operating power factors impedance [20].

- **R.Ramya and K.Selvi, (2011).**

This work aims to develop a controller based on fuzzy adding power system stabilizer; it will restrain and damp the oscillation when the generator is subjected to disturbances. The performance of Fuzzy Logic power system stabilizer is evaluated on a single machine to infinite bus power system under different operating conditions and disturbances to demonstrate its effectiveness. Fuzzy Logic Power System Stabilizer arrive the desired value of active power at 1.33 seconds where classical Power System Stabilizer achieved it at 1.46 seconds. This Prove that Fuzzy Logic Power System Stabilizer quicker than Conventional Power System Stabilizer for achieve the settling time. Logic to simulate an automatic voltage regulator in analyzes transient stability power system [21].

1.3. Objectives of the Work:

The objectives of this thesis could be summarized in the following points:-

1- Developing an intelligent control technique based on fuzzy logic controller to control the terminal voltage for a transient stability investigation.
2- Study and check the powerfulness of both controllers first one is based on conventional DC1 exciter and the other is the intelligent and based on fuzzy logic theory under different load conditions.
3- Check the robustness of two type of controller due to short circuited fault.
4- Studying and investigating the performance of FL controller itself for specified machine condition and for different controller parameters.
5- Built the fuzzy logic controller using m-file to grant it a dynamic programming power and to qualify it for adaptation purposes.

1.4. Structure of Thesis:

This thesis contains five chapters as follows:

- Chapter one includes an introduction, literature survey of the research subjects, Objectives of the Work and thesis organization.
- Chapter two shows modeling and simulation with MATLAB/SIMULINK, Synchronous Generator construction and characteristics with brief explanation of frequency, real power, reactive power and voltage control. The excitation systems explained with Review of types. Explains steam turbines and the Synchronous Generator modeling.
- Chapter three deals with types of controllers and fuzzy logic system along with its advantages and disadvantages. It as well presents the general fuzzy controller structures accompanied by

fuzzification and defuzzification strategies. Finally fuzzy based synchronous generator terminal voltage controller implemented with MATLAB/SIMULINK.

- Chapter four simulation results of the designed Fuzzy based synchronous generator terminal voltage controller presented in chapter three compared with traditional DC1 controller under external load variation, also simulation results for different fuzzy controller parameters.
- Chapter five presents the Conclusions of the performed work, and provides some suggestions for future work.

Chapter -2

Modeling and simulation of synchronous generator

2.1 <u>Introduction:</u>

Nearly all of the electric power used throughout the world is generated by synchronous machines driven either by hydro or steam turbines or by combustion engines.

The equations that describe the behavior of synchronous machines are nonlinear and can be solved only with aid of a computer. However, considerable insight can be gained regarding the small-excursion behavior from the linearized version of these equations. The machines can then be treated as linear differential equations with regarding to small disturbance.

The linearized model of the synchronous machine's dynamic can be represented in the form of Laplace domain, which in turn can be built by connecting appropriate function blocks. Simulating the complete model requires detailed transient analysis of the synchronous machine, addition of new sub-models to model the operation of various control functions. These sub-models are used in the calculation of various values related to the synchronous machine such as the steady state, turbine governor model, exciter loop, and the currents.

2.2<u>Modeling and Simulation with MATLAB/SIMULINK:</u>

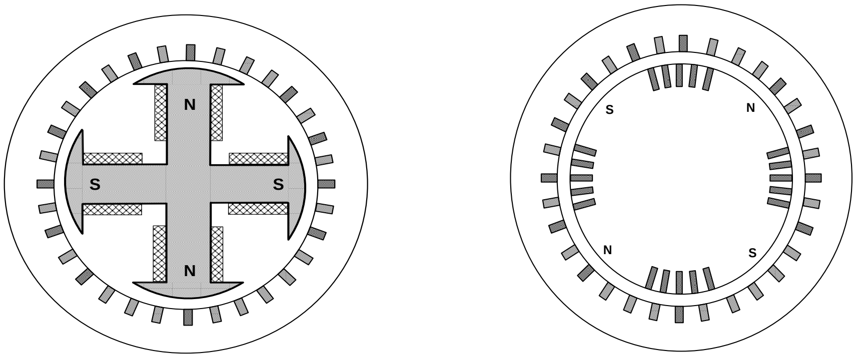
SIMULINK is a toolbox extension of MATLAB program. It is a program for simulating dynamic systems. Prior to setting up a system model in SIMULINK, one may need to have a mathematical description of the system that to be simulated. A typical mathematical description of a dynamic system may consist of a mix of integral and algebraic equations. These equations may have to be manipulated further to eliminate potential algebraic loops. Rewriting the integral equations with the dependent-state variable expressed as some integral of a combination of independent variables and dependent variables. Construction of the SIMULINK model can then follow the rearranged mathematical description of the model.

In SIMULINK, model definition is facilitated by the graphical interface and the library of templates or function blocks that are commonly used in mathematical descriptions of dynamic systems. A variety of function blocks or templates are grouped under the different library blocks. A template can be copied from a library block onto the SIMULINK model screen by first selecting the template and then dragging it to the desired location in the SIMULINK model screen, or by a sequence of copy paste commands, which are found under the edit menu. Many templates have internal parameters which one must specify before one can use these templates in a simulation. After one has created a SIMULINK model of a system and before one starts the simulation, one will need to choose an integration method and specify some run conditions. Under the parameter sub-menu of the main menu heading simulation, one can select one of several integration methods and enter the values of simulation parameters, such as tolerance and minimum and maximum step size. In this thesis, SIMULINK/MATLAB is used to obtain a schematic model of a synchronous machine by means of basic function blocks. This method is better than using a compilation of program code.

2.3 Synchronous Generator construction and characteristics:

The stator of synchronous machines consists of a Suit of laminated ferromagnetic core with internal slots, to place the stator windings inside, and an external frame with end shields and bearings for the rotor shaft. The turns of the stator windings are equally distributed over pole-pairs, and the phase axes spaced $2\pi/3$ electrical radians apart.

The rotor can be salient or cylindrical. Salient pole always used in low-speed applications .Salient pole synchronous machines are usually used in hydro generators to fit with the low operating speed of the hydraulic turbines. Salient here, refer to the prominent poles; the alternating configuration of pole iron and inter polar gap in preferred directions of magnetic flux paths or magnetic saliency. Figure (3.1) shows the cross–sections of salient and cylindrical rotor synchronous machines with four poles.



Salient rotor round rotor

Figure (2.1) *circuit representation of an idealized machine*

The cylindrical rotor construction is chosen in high–speed applications to keep mechanical stresses from centrifugal forces within acceptable level. Two- and four pole cylindrical rotor synchronous machines are used in steam generators to efficiently match high operating speed of steam turbines. Direct current excitation to the field winding can be supplied through a pair of secluded slip rings mounted on the rotor shaft. Alternatively, the dc excitation can be obtained from the rectified output of a small alternator mounted on the same rotor synchronous machines. The second excitation method without slip rings and is called brushless excitation.

In the basic two-pole representation of synchronous machines, the axis of the North Pole is called the direct or *d-axis*. The quadrature, or *q*-axis, is defined in the direction 90 electrical degrees ahead of the direct axis. Under no-load operation with only field excitation, the field mmf will be along the *d*-axis, and the stator internal voltage, $d\lambda_{af}/dt$, will be along the *q*-axis.

The mathematical model developed in this work is based on the concept of an ideal synchronous machine with two basic poles. The fields produced by the winding currents are assumed to be synchronous machines around the air gap. This assumption of sinusoidal field distributed ignores the space harmonics. It is also assumed that the stator slots cause no remarkable variation of any of the rotor winding with rotor angle. Although saturation is not explicitly taken into account in this model, it can be accounted for by adjusting the reactance along the two axes with saturation factors or by introducing a compensating component to the main field excitation.

A damper winding is usually fitted in slots at the pole surface for improve the stability of the machine as shown in Fig. (2.2). Also, the damper windings can represent physical armortisseur windings, or the damping effects of eddy currents in the solid iron portion [22].

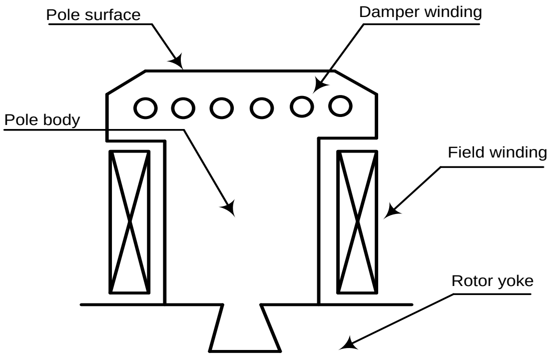


Figure (2.2), *Salient-pole rotor construction.*

Figure (2.3) shows a circuit representation of an idealized machine model of synchronous machine commonly used in the analysis [23].

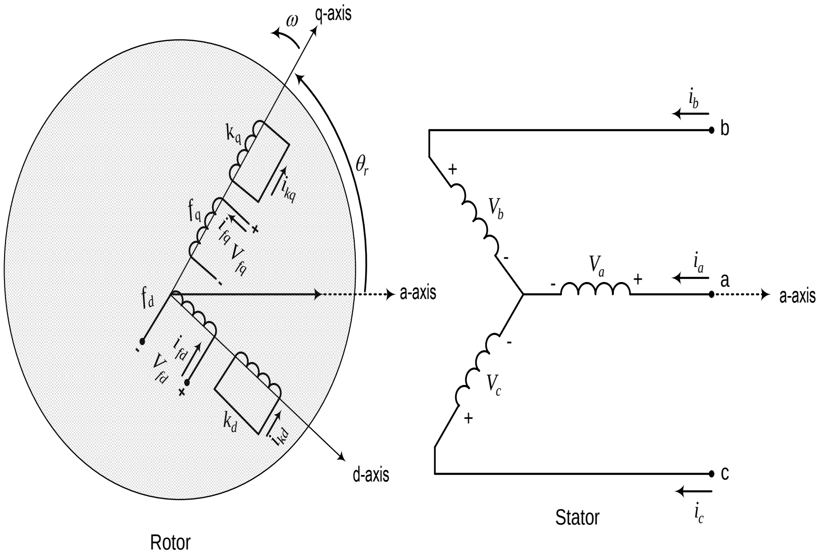


Figure (2.3) *circuit representation of an idealized machine.*

When rotor is driven by prime mover, the induced alternating voltage in the armature windings of the stator with voltages and currents frequencies depends on the speed of rotating magnetic field produced in the rotor winding. The frequency of the stator electrical quantities and the rotor mechanical speed are synchronized. The stator voltages and currents frequencies of all interconnected synchronous machines must have the same value. Therefore, rotors of all interconnected machines must be in synchronism.

There is reaction between stator and rotor fields. In generator an electromagnetic torque opposes rotor rotation results from the tendency of the two fields to align them so that to sustain rotation the mechanical torque must be applied by the prime mover. Increasing the input mechanical torque will advance the rotor to a new position relative to the revolving stator magnetic field .Under steady–state operation conditions; the both fields have the same speed. However, the angular separation between the two fields will depend on the output electrical torque of the generator [2].

2.4 Power Control of Synchronous Generator:

Two power can be discriminated in synchronous generator; active and reactive powers. Both active power and reactive power flow in a network independently and only influenced by different control actions. The reactive power control is related to voltage control, but active power is related to frequency control. The determining quality of power supply factors are constancy of frequency and voltage.

2.4.1 Active power and frequency control:

The generator frequency should remain nearly constant and its drop could result high magnetizing currents in induction motors or transformers. The change of active power demand is reflected by a change in frequency. A speed governor provides the primary function of speed control and then active power. The speed governing basic concepts can be illustrated in Figure (2.4).

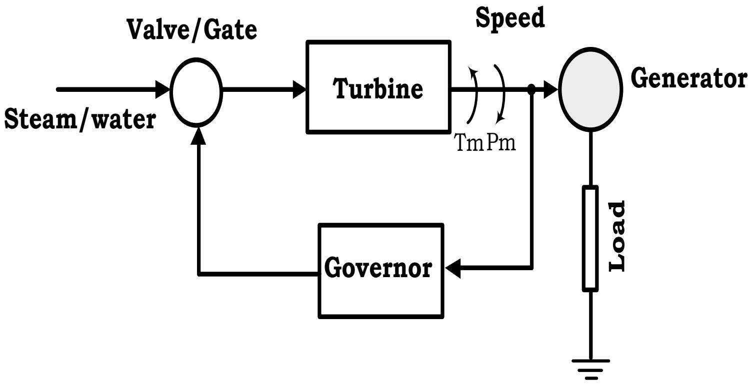


***Figure (2.4)**, Generator with speed governor.*

It is clear from Figure (2.4) that the change in SG speed would directly affect the speed of governor which in turn leads to a change in valve opening, and then the input power to the SG will change accordingly to compensate the varied speed [24].

2.4.2 Reactive power and voltage control:

Synchronous generators can generate or absorb reactive power depending on the excitation; they supply reactive power when overexcited, and absorb it when under excited. The capability of absorption or supply reactive power limited by the armature current, field current and end–region heating limits. For reliable and efficient power system operation, the voltage and reactive power control should satisfy the following objectives:

1. Terminal voltage for all systems equipment within acceptable range. All equipment are designed to operate at a certain voltage rating, when the equipment operate outside the allowable voltage range for a long time will affect their performance and can damage them.
2. The control of reactive power and voltage has significant impact on the stability of the system; the stability of the system is much enhanced if the transmission system utilization is to be maximized.
3. The reducing of (RI^2) and (XI^2) losses can also be minimized by the reactive power flow.

2.4.3 The Automatic Voltage Regulator :

The synchronous generators terminal voltage affected by the armature reaction, the stator winding voltage drop caused by the winding resistance and flux leakage, which would appear as a leakage inductance in the electric circuit of the stator. The voltage drop also affected by the phase angle between stator currents and voltages; lagging currents produce larger drop, while leading currents cause a negative drop. The change of the excitation current of the rotor field necessary to maintain the output voltage (for load conditions) to constant reference value [24]. The automatic voltage regulator is closed-loop based control principle. Its dynamic response is characterized by fast transient decay and its time constant is much smaller than the prime mover time constant and, therefore, load frequency control is not affected [25,26].The schematic diagram of AVR circuit is shown in Figure(2.5).

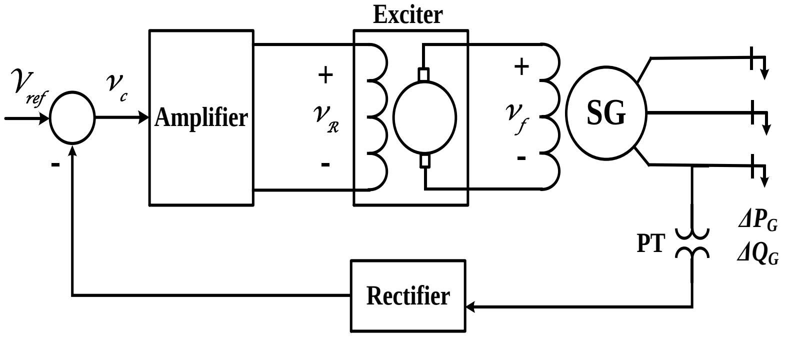


Figure (2.5): *Exciter with AVR.*

The (AVR) sense generator terminals voltage. The output voltage is converted through a potential transformer and rectifier to a low (D.C) voltage signal, this signal feedback and subtracted from a fixed reference voltage to produce an error signal (v_c), the error signal is processed and amplified to drive the rotor excitation current. A change in rotor excitation current will produce variation in terminal voltage. If large gain is used in AVR closed-loop, then a small error is required for necessary change in excitation current. However, high gain may lead to instability problems. To enhance the performance of the (AVR), adjustment potentiometers are used to vary the gains for each channel.

2.5 Excitation Systems:

The direct current supplied to the synchronous machine field winding is the main function of the excitation systems. It performs both the control and the protective functions. The control function enhances the system stability by controlling the voltage and reactive power flow, while the protective functions ensure that the excitation system, and other equipment are not exceeded the capability limits of the synchronous generator.

The factors which limits the capabilities of the generator are failure of rotor insulation due to high field voltage, rotor winding heating due to high field current, stator winding heating due the high armature current, the core end heating at unexcited operation, and the excess flux heating. In order to fulfill the above roles, the excitation system’s requirements as the following [2, 26]:

- The specified criteria of response must be met.
- The damage preventing of the excitation system.
- Meet the operation flexibility.

- The desired reliability and availability must meet, by the capability of internal fault detection and isolation.

The large synchronous generator has excitation control system with the following various subsystems:

1. *The Exciter*: The synchronous generator field winding provides with dc power by the exciter, which amplify the output signal of the regulator before exciting the field winding. Figure (2.6) shows block diagram transfer function for the exciter:

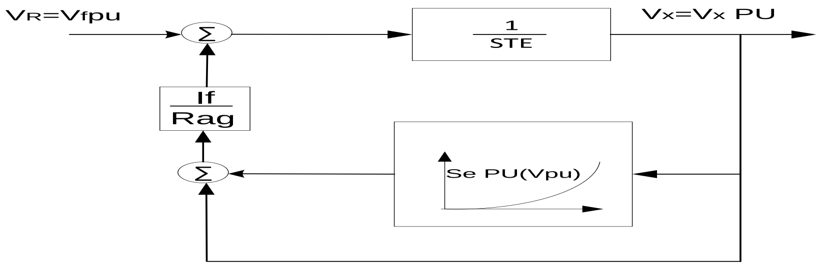


Figure (2.6): *Transfer function of dc exciter*.

2. *The Regulator*: The regulator consists of an error amplifier with limiter. The input control signals processes and amplifies by the regulator to level and form appropriate for the exciter. Its transfer function blocks shown in figure (2.7).

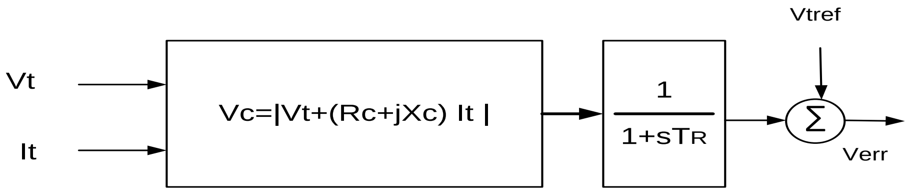


Figure (2.7): *Transfer function of the regulator.*

3. *The Terminal Voltage Transducer and Load Compensator*: The terminal voltage senses, rectifies, and filters to dc quantity, before compares it with reference value. The voltage transducer and rectifier modeled with unity gain and single time constant. Voltage transducer and load compensator is shown in Figure (2.8).

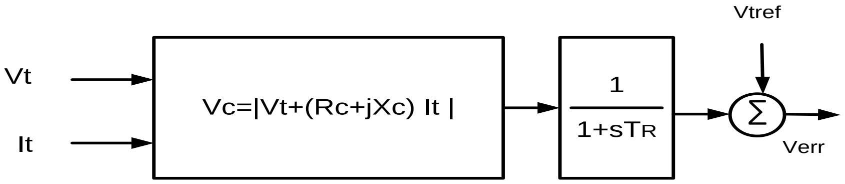


Figure (2.8): *Voltage transducer and load compensator circuit.*

4. *Power System Stabilizer*: The power system damped by additional input signal provides to the regulator, the signals are rotor speed or frequency deviation, and accelerating power. The stabilizer provides the phase advance needed to achieve the proper gain and phase margins in the regulator/exciter open loop frequency response. It is shown in figure (2.9).

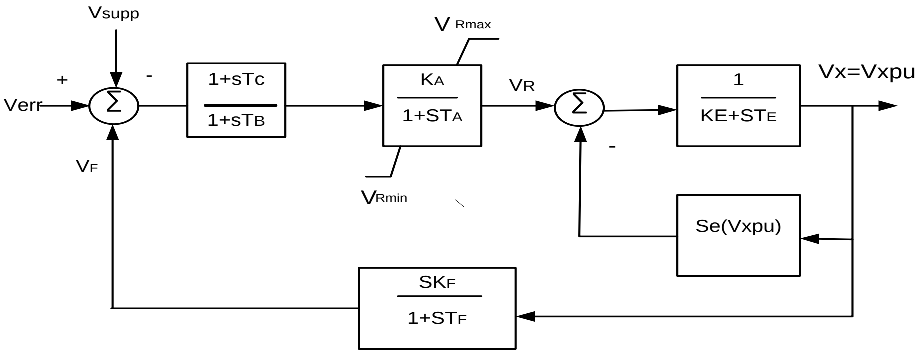


Figure (2.9): Stabilizer *for the regulator /exciter loop.*

5. *Limiters and Protective Circuits*: These circuits used to ensure that not exceeds the capability limits of the synchronous generator and also the exciter [22, 2]. The maximum excitation limiters are all limiters for under excitation, field current, terminal voltage, and volts per hertz. The functional block diagram of synchronous generator excitation control system with all its elements shown in Figure (2.10).

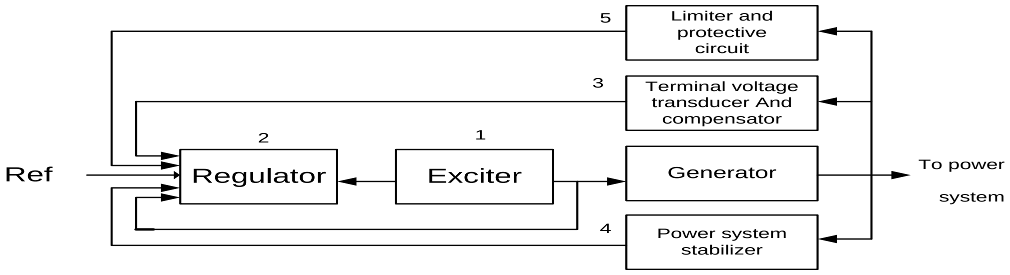


Figure (2.10): *Functional diagram of S.G control system.*

2.6 Types of Excitation Systems:

The excitation system based on excitation power source may be of the following types; dc excitation, ac excitation, and static excitation system.

The dc type provided current to the rotor by using dc generators through slip rings. The exciter driven by generator shaft, or by a motor, and may be self-excited or separately excited with a pilot exciter content a permanent magnet generator. The voltage regulators replaced by solid–state electronic regulator in some cases. Figure (2.11) shows a dc excitation system with an amplidyne exciter.

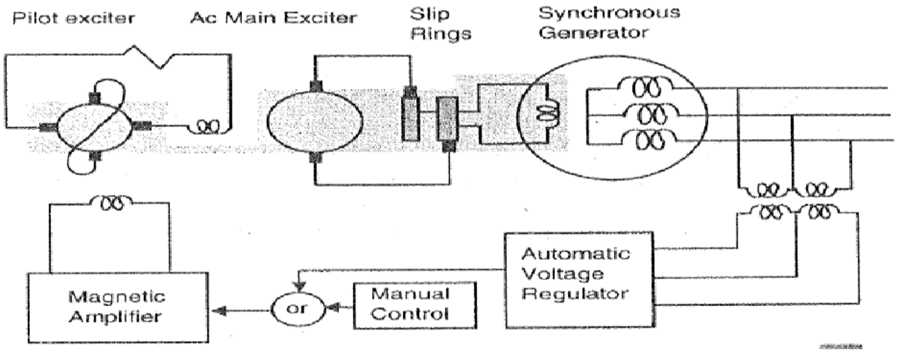


Figure (2.11): *Dc excitation system with an amplidyne exciter [22].*

The early excitation systems are of the ac rotary–or ac static type. The ac rotary type utilizes the output of a rotor ac alternator as source of the main generator excitation power. The ac output of the exciter is rectified by either controlled rectifiers or non-controlled rectifiers to produce the direct current needed for generator field. The rectifier is a thyristor controlled, whose dc output voltage controlled by adjusting the phase delay in turning on the thyristors of the bridge, and then dc excitation current can flow in one direction. When using two such bridges connected in anti-parallel the bi-directional dc excitation can be obtained. The slip rings used in order to connect the rectified dc bridge output to the main field winding of the synchronous generator. To avoid problems with the use of brushes when supplying very large generator with high field current, the brushless excitation system used with rotating rectifiers and the dc output is directly fed to the main generator field. The Ac brushless excitation system is shown in Figure (2.12).

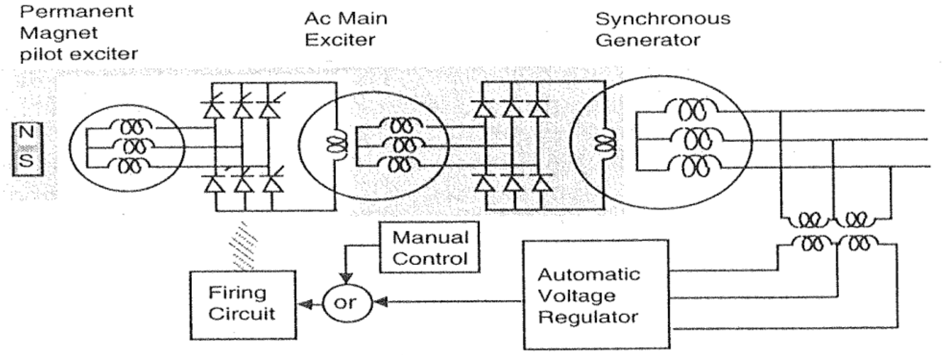


Figure (2.12): *Ac brushless excitation system (shadow for rotate parts) [22].*

The ac static–type exciters with static or stationary components draw their primary power from alocal ac bus.The controlled rectification used to provide the main field winding of the generator with an adjustable excitation. This system deversely effected by nearby faults.The ac static types are less expensive, more copact, and much quicker response than the ac rotory types.

2.6 Power System Voltage Stability:

The power system stability is the system's ability to remain in a state of operating equilibrium under normal operating conditions and regain an acceptable state of equilibrium after subjected to disturbance. The voltage stability will be of the work concern.

The voltage stability is the ability to maintain steady acceptable voltages at all system buses at normal operating and after disturbance. The voltage stability state enters by the system a disturbance, load demand increase, or change in system condition causes uncontrollable voltage drop. The system inability to meet reactive power demand causing instability, the problem occurs when voltage drop at flow of reactive power and active power through inductive loads. The system is voltage stable if (V-Q) sensitivity is positive for all buses and voltage unstable if (V-Q) is negative sensitivity for one bus at least [27]. The voltage stability can be classified into the following subclasses:

1. Large–disturbance voltage stability: The system's ability to control voltages after large disturbances such as loss of generation, or system faults. The determination of this stability requires the non-linear dynamic performance examination of the system at sufficient time period. The study period extend from a few seconds to ten minutes.
2. Small-disturbance voltage stability: The system's ability to control voltages after subjected to small disturbance such as incremental changes in the load of system [2].

2.7 Steam Turbines:

A steam turbine converts stored energy of steam with high temperature and pressure into rotating energy which then converted by generator into electrical energy. Steam turbines normally consist of two or more sections coupled in series, each one consists of a set of blades (buckets) attached to rotor and a set of stationary vanes (nozzles). The kinetic energy of the steam with high velocity will convert by the buckets into shaft torque.

The basic configuration of steam turbine with turbine elements is shown in Figure (2.13). The fossil–fuelled units consist of high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbine sections depending on turbine's configuration, also may be reheat type or non-reheat type. In first type, the steam upon leaving the (HP) section returns to the boiler, reheating improves efficiency, and some units have two reheat sections. The steam exhausted from turbine is condensed before returning to the boiler to repeat the cycle. The large steam turbines are equipped with four valves set:

- (MSVs) :Main inlet stop valves .
- (CVs) : Control valves (plug diffuser type).
- (RSVs): Reheat stop valves.
- (IVs) : Intercept valves (plug or butterfly type).

Many turbines have at least four controllers' valves operating in parallel or sequentially. The main inlet control valves (governor) modulate the flow of the steam through the turbine at normal operation. The control valves and intercept valves are responsive to increasing the speed after loss of the electrical load suddenly. The torque of the steam turbine is proportional to the steam flow rate, since.

$$T_m = K\,Q \tag{2.1}$$

Where K is a proportional constant and Q is steam flow rate.

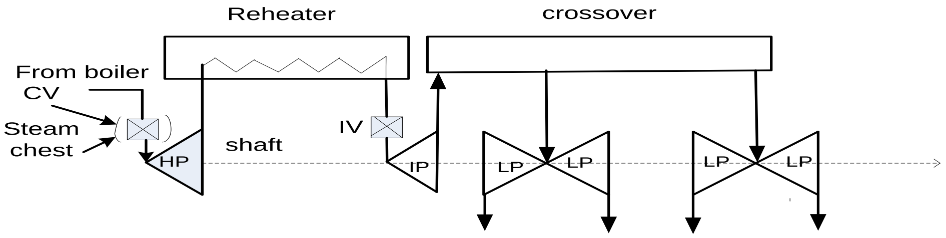


Figure (2.13): *steam turbine configuration.*

The steam enters the (HP) through the control valve (CV_S) and the inlet piping. The housing for the control valves is known as steam chest. The chest and inlet piping to the (HP) section is to store amount of steam. The steam exhausted from (HP) is passed through the reheat, then through the reheat intercept valve (IV) and inlet piping in to the (IP) section. The crossover piping provides steam path between (IP) section and (LP) inlet. Stop valves stopping steam flow. The response of steam flowed to change opening of control valve exhibits a time constant (T_{CH}) due to the time charging the steam chest and the inlet piping to the (HP) section. Time constant is in order of 0.25sec to 0.3sec. The intercept valve with non-linear characteristics is used for rapid control of the turbine's mechanical power at over speed. Time constant of reheat is (T_{RH}) in the range of 5sec to 10 sec. When steam flow in to (LP) additional time constant (T_{CO}) experienced. Per unit system is one with maximum turbine power as base power at rated main pressure of steam with fully open control valves [2, 27].

2.7.1 Steam Turbine Controls:

The steam turbines governing systems have three main functions: normal speed/load control, over speed control, and over speed trip, also with additional functions such as start-up/ shutdown controls, and auxiliary pressure control.

The over speed control used to limit the over speed that occurs on full or partial load rejection in order to return the steady–state condition of the turbine.

The over speed trip is protection element for failure of normal and over speed control to limit the speed of the rotor to a safe level. It functions fast closing the main reheat, reheat stop valves, and trips the boiler. The steam valves with highly non-linear characteristics are used to linearize the response of the steam flow with respect to control signal. Typically four or more parallel CV_S are used to admit steam through a nozzle section. The turbine governor design uses either mechanical hydraulic, electro hydraulic or digital electro hydraulic controls. In the present work, the mechanical turbine is used for governing a steam turbine [28].

2.7.2 Mechanical – Hydraulic Control (MHC):

The basic elements of an (MHC) system used for are a speed governor, speed relays and hydraulic servomotors. Speed governor is mechanical transducers which transform the shaft speed in to apposition, and it is operate on the fly ball basic principle. When rotor speed signal (w_r)converted to linear displacement by means of centrifugal forces opposed by a spring. The error signal is formed by comparing the speed governor output with speed reference used to controls (CV_S) and (IV_S). On very large turbines to move the steam valve using hydraulic servomotors needed for additional amplification to the energy level [29].

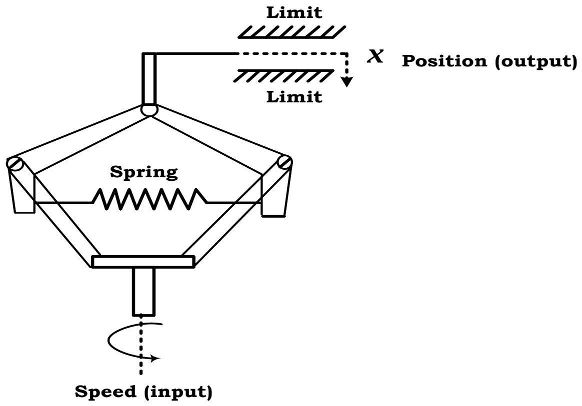


Figure (2.14): *Mechanical speed governor.*

The functional block diagram of MHC turbine governs system shown in figure (2.15).

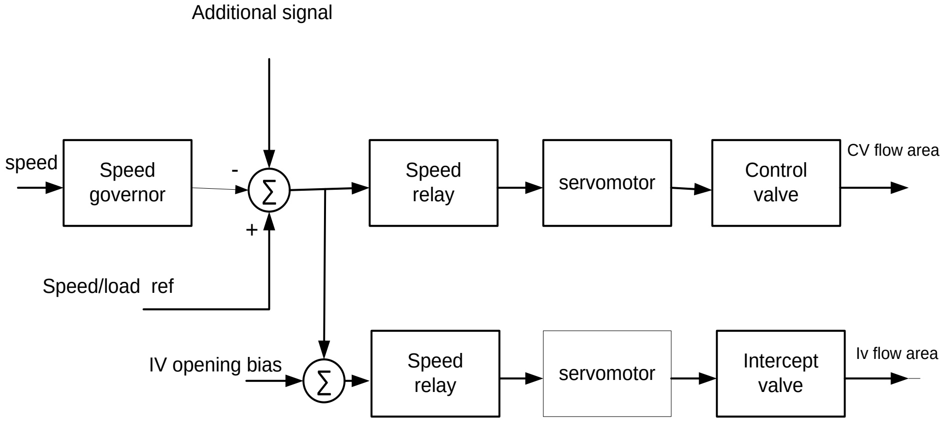


Figure (2.15): *Functional block diagram of MHC turbine governing system.*

2.8 Synchronous Generator Modeling:

A simplified model of the synchronous generator is given in this thesis 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 (2.16):

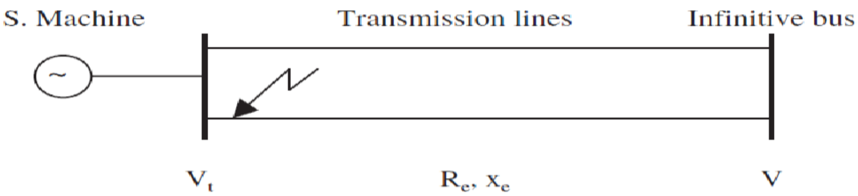


Figure (2.16)*: The considered single machine-infinitive bus system.*

2.8.1 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 (2.2) and (2.3). The considered system is given in Figure (2.17):

$$\Delta\omega = \frac{1}{D + sM}(P_m - P_e) \tag{2.2}$$

$$\delta = \omega_0 \frac{\Delta\omega}{S} \tag{2.3}$$

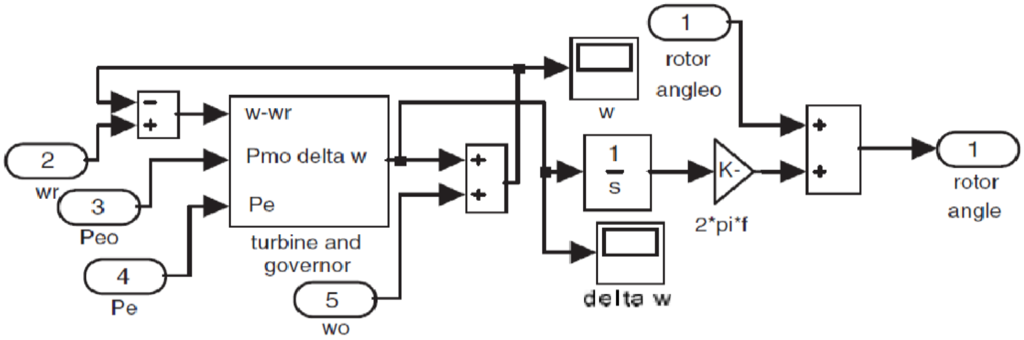


Figure (2.17), *Mechanical Part of the Synchronous Generator.*

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 [30].

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 (2.18):

$$\Delta P_r = \frac{K_G}{T_{SR}S + 1}\Delta\omega \tag{2.4}$$

$$\Delta P_h = \frac{1}{S\,T_{SM} + 1}\Delta P_r \tag{2.5}$$

$$\Delta P_C = \frac{1}{T_{CH}\,S + 1}\Delta P_h \tag{2.6}$$

$$\Delta P_m = \frac{S\,K_{RH}T_{RH}}{ST_{RH} + 1}\Delta P_C \tag{2.7}$$

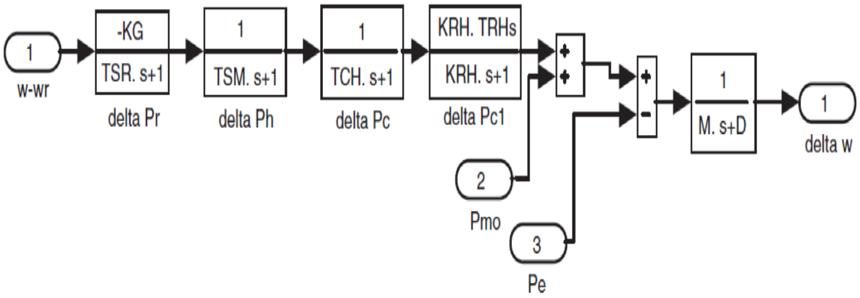


Figure (2.18): *Turbine and governor system configuration.*

2.8.2 The Excitation System:

The exciter is represented by the DC1A exciter model. The inside of the exciter block has an IEEE Type 1 excitation system. Integrators are used to build up the components of the exciter to keep the startup transients of the simulation to a minimum [22]. 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[32].The block diagram of the exciter DC1shown in Figure (2.19).

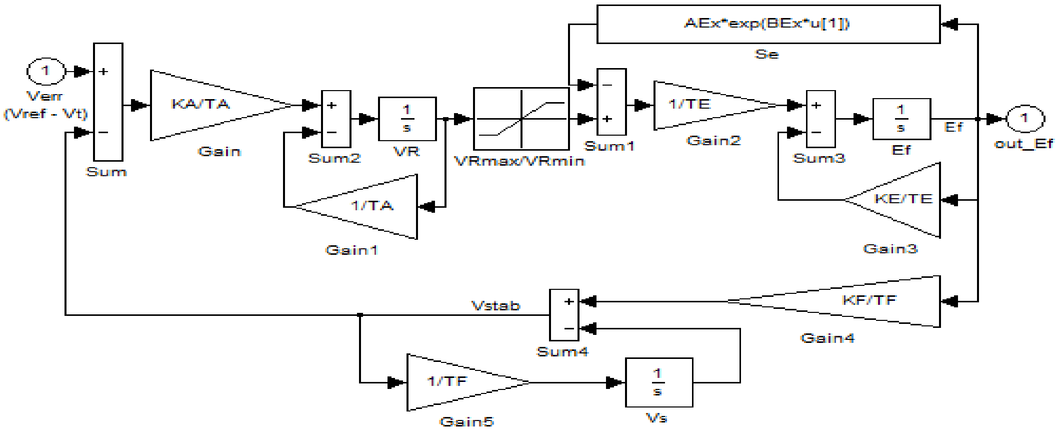


Figure (2.19): *DC1A-Type exciter block diagram.*

2.8.3 The steady-state sub-model of the synchronous generator:

The steady state values are calculated separately according to the block diagram of Figure (2.20). 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 equations [30] given below:

$$\mathrm{V}_{t0=}\sqrt{(\mathrm{V}_0 + R_e I_0 \cos\varphi_0 + x_\mathrm{e} \mathrm{I}_0 \sin\varphi_0)^2 + (x_\mathrm{e} I_0 \cos\varphi_0 - R_\mathrm{e} I_0 \sin\varphi_0)^2} \qquad (2.8)$$

$$E_{q0}^{'} = \mathrm{E}_{fd0} + (x_d - x_d^{'})I_{d0} \qquad (2.9)$$

$$E_{d0}^{'} = -(x_q - x_d^{'})I_{q0} \qquad (2.10)$$

$$P_{e0} = E_{d0}^{'}I_{d0} + E_{q0}^{'}I_{q0} \qquad (2.11)$$

$$V_{tr} = \frac{\mathrm{E}_{fd0}}{K_E} + V_{tro} \qquad (2.12)$$

$$P_{m0} = P_{e0} \qquad (2.13)$$

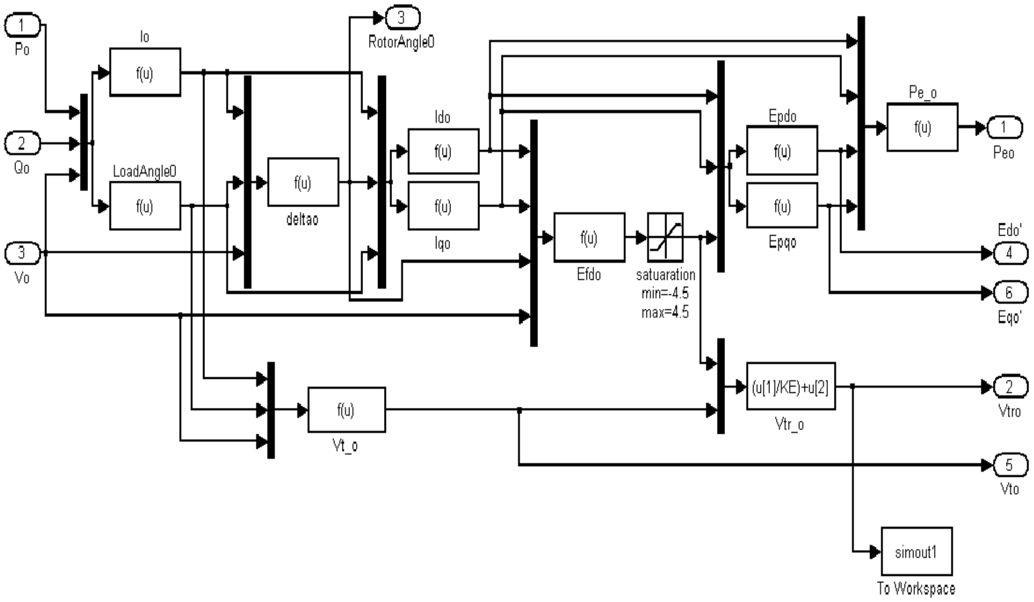


Figure (2.20): *Steady State Operation Model.*

2.8.4 The electrical sub-model of the synchronous generator:

The sub-model in Figure (2.21) represents continuous operation of the electrical parts of the machine. The initial values which will be used until a fault occurs are provided by four switches in the sub-model. The inputs of the sub-model are δ,$E_{d0}^{'}$,E_{fd}, V_{t0}, $E_{q0}^{'}$, P_{e0} , V_0 , R_e , X_e ,and the outputs are *Vt*, *Pe*, Q, I .The sub-models terminal equations as the following [31]:

$$\mathrm{E}_d^{'} = \frac{x_d^{'} - x_q}{ST_{q0}^{'} + 1} I_q \tag{2.14}$$

$$E_q^{'} = \frac{x_d^{'} - x_d}{1 + s\,T_{d0}^{'}}\, I_d + \frac{\mathrm{E}_{fd}}{1 + s\,T_{d0}^{'}} \tag{2.15}$$

$$V_{td} = E_d^{'} - R_a I_d - x_d^{'} I_q = -V_0 \sin\delta + R_e I_d + x_{\mathrm{e}} I_q \tag{2.16}$$

$$V_{tq} = E_q^{'} - R_a I_q + x_d^{'} I_d = V_0 \cos\delta + R_e I_q - x_{\mathrm{e}} I_d \tag{2.17}$$

$$V_t = \sqrt{V_{td}^2 + V_{tq}^2} \tag{2.18}$$

$$P_e = E_d^{'} I_d + E_q^{'} I_q \tag{2.19}$$

$$|Q| = E_q^{'} I_d - E_d^{'} I_q \tag{2.20}$$

$$|I| = \sqrt{I_d^2 + I_q^2} \tag{2.21}$$

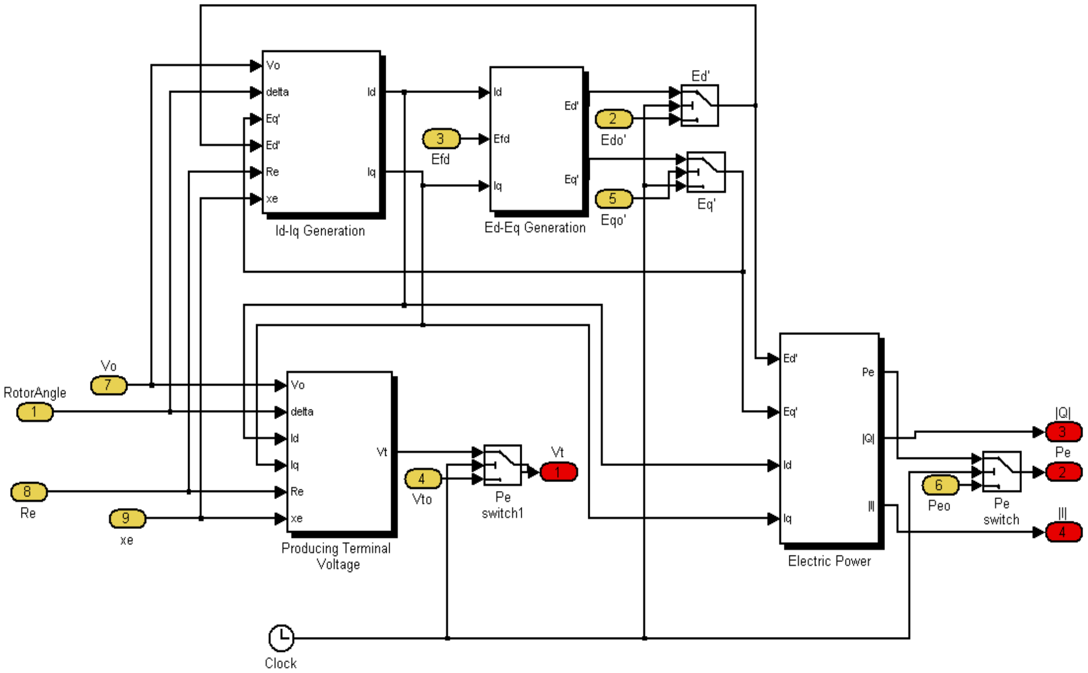


Figure (2.21): *The electrical parts of the machine for continuous operation.*

2.8.5 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 [30].The fault sub-model and complete model of the synchronous generator shown in the Figures (2.22), (2.23):

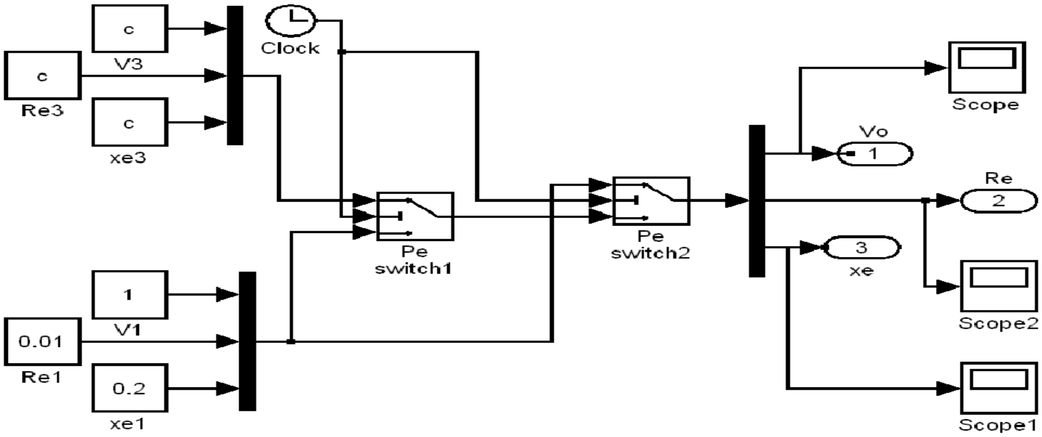


Figure (2.22):*The fault sub-model with switch configuration.*

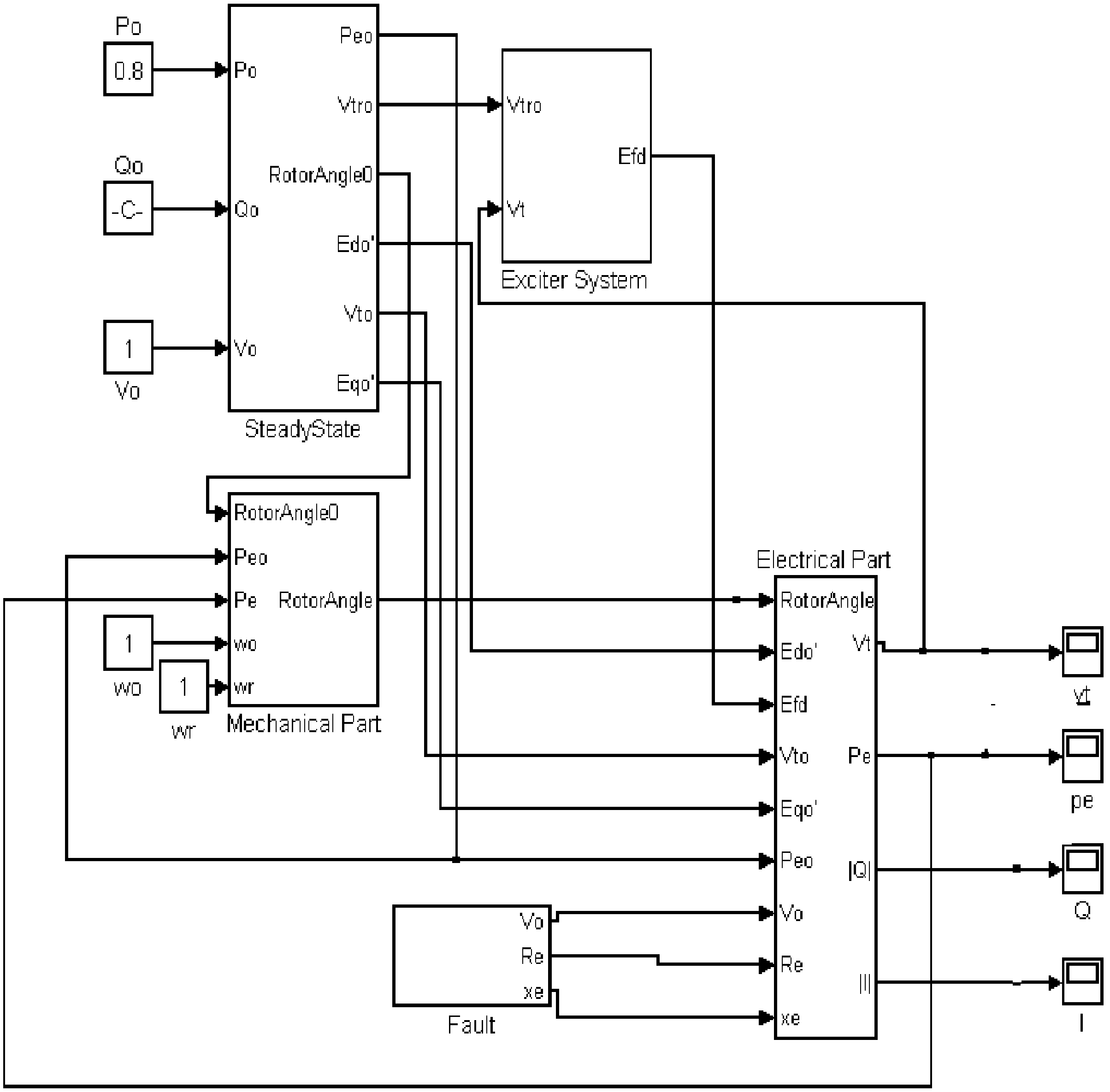


Figure (2.23): *The complete model of the system in SIMULINK.*

Chapter -3

FUZZY CONTROLLER

3.1 Introduction:

Control theory is historically divided into a classical and modern control theory. First one deals with linear time invariant single- input single-output (SISO) system because it is entirely powerless for multi-input multi-output (MIMO) systems and for complicated behavior such as hard nonlinearities. Modern control theory is suitable to (MIMO) system, which may be linear, nonlinear, time invariant and time varying.

Intelligent control is considered now one of the important classes of control theory. This technique provides alternatives to conventional Methods by borrow the ideas from intelligent biological systems; such ideas can either come from humans who are, like experts at manually solving the control problem or by observing how a biological system operates and using analogous techniques in the solution of control problems.

The proportional-integral-derivative (PID), controller is the most popular controller in the field of control process. It is simple both in the design and the parameter tuning point of view. PID controller now controls many industrial processes.

3.2 Types of Controller:

The nature of the plant model and the operating conditions decide the kind that should be used of controller. Industrial automatic controllers may be classified according to their control action as: two-positions or on-off, proportional, integral, proportional-plus-integral, proportional-plus-derivative and proportional plus integral-plus-derivative controllers (PID) [32]. In the following some common types of controllers will be presented with brief description.

3.2.1 PID Controller:

The most use in control at the present time is PID controllers. This is because PID controllers are easy to understand, and easy to implement. Figure (3.1) shows control system with PID controller. The three parameters that must be determined for a given process: proportional gain, integral gain and derivative gain as shown below.

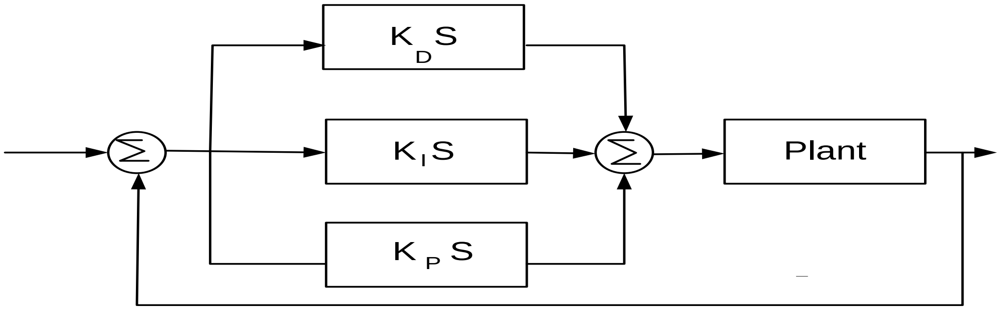


Figure *(3.1), Control system with PID controller.*

The time domain from of PID controller is

$$u(t) = K_p e_f(t) + K_i \int_0^T e_f(t)dt + K_d \frac{de_f(t)}{dt} \tag{3.1}$$

Where $e_f(t)$, $u(t)$, K_p, K_d, K_I are feedback error signal, controller output signal, proportional gain, derivative gain, and integral gain respectively .

Proportional plus integral plus derivative control is essentially a compromise between the advantages of proportional-integral control that eliminates the offset and the proportional-derivative control that brings the system to final steady-state value in the shortest time with the smallest overshoot [33].

3.2.2 Adaptive Controller:

Adaptive control is an approach that deals with dynamic systems, which have a known structure but uncertain or slowly varying parameters. In other direction, the adaptive control also defines an approach which continuously and automatically measures the dynamic characteristic of plant, and compares them with the desired dynamic characteristic, and uses the difference to vary an adjustable controller parameters, or generate an actuating signal so that a desired performance can be maintained regardless of environmental changes [34].

3.2.3 Intelligent Systems:

A machine or an industrial system is considered as intelligent system, if it is able to improve its performance or maintain an acceptable level of performance in the presence of uncertainty. The main attributes of intelligence are learning or generally adaptation, fault tolerance and self-repair and self-organization [35]. The ability of machine to examine and modify its behavior in a limited sense is usually achieved by using the following techniques:

1- Artificial Neural Networks (ANNs).
2- Genetic Algorithms (GAs).
3- Expert Systems also called Knowledge-Based Systems.
4- Fuzzy Logic System (FLS).

3.3 Fuzzy Logic System :

The Fuzzy logic was conceived by Lotif Zadah as a way of processing data by allowing an element with partial membership of set. The theory of " Fuzzy Sets " is a step forwards a rapprochement between classical mathematics and the imprecision of real world [39]. Fuzzy systems have been used in a wide variety of applications in engineering, science, business, medicine, psychology, and other fields. The Fuzzy control can use where there is no explicit process model available, or in which the analytical model is too difficult to evaluate or when the model is too complicated to evaluate in real time [36].

3.3.1 Fuzzy logic advantages:

There are many advantages for FLC as listed below:

1. Fuzzy logic is inherently robust, for this it does not require precise.
2. Low overall system cost and complexity because inexpensive and imprecise sensor can be used.
3. Flexible. With any given system it is easy to manage it. Also can modify easily to improve, add, or alter performance of the system.
4. Inputs noise free and when system components fail like destroy or quits feedback sensor will degrades gradually.
5. System can be easily designed for any reasonable number of inputs and outputs, because it is rule based operation. But with large number of inputs and outputs the rule base

defining becomes complex. In order to break the system in to smaller parts, use several smaller modules of fuzzy distributed on the system, with more limited responsibilities for each one.

6. Create fuzzy system to match any set of input –output possible
7. Focuses on problem solution not on its analysis.
8. Fuzzy logic can control non-linear system that would be difficult or impossible to model mathematically.
9. It can store the knowledge data base using the knowledge of experts, but with neural networks require training data and generate opaque.
10. Work well on conventional microprocessors.
11. It is easy to understand because its ability of processing linguistic information.
12. Fuzzy system not replaces conventional methods and it can combine with them. In many cases fuzzy system simplify the conventional control implementation [37].

3.3 .2 Fuzzy Logic disadvantages:

There are some limitations of fuzzy logic, which are unavoidable. There can be summarized as follows:

1- Highly dependent on domain expert's knowledge, the fuzzy logic technique translates the expert knowledge into a collection of machine understandable rules. Unlike neural networks and genetic algorithms, problem is solved through training process. A well-defined knowledge base is needed in fuzzy logic to solve any kind of problems. If the domain experts provide wrong information, then the system may not be functioning well as required.

2- Insufficient design standard or methodology, they usually use heuristic or trial and error approach in selecting the types of membership functions, inference engine and defuzzification methods, since it is time-consuming. Thus, a systematic design methodology is needed in order to obtain satisfactory results for fuzzy systems and reduce the development time constraints.

3- Lack of information. If there is enough information or relevant knowledge about the process and its control strategies fuzzy control can be applied. Solving a totally unknown or impossible job that even human experts cannot accomplish is rather difficult to be accomplished using fuzzy logic technique [38].

3.3 .3 Classical Set (Crisp Set):

Crisp Set are special case of fuzzy sets as collection of objects all having the same characteristics without ambiguity in their boundaries. A set can be described by naming all its members (List Set) [41]. Let E be a set and A, a subset of E:

$$A \subset E \tag{3.2}$$

It usually indicates that an element *x of* E is a member of A using the symbol:

$$x \in \mathrm{A} \tag{3.3}$$

In order to indicate this membership another concept can be used, a characteristic function $\mu_A(x)$, whose value indicates (yes or no) whether x is a member of A [38].

$$\begin{cases} \mu_A(x) = 1 \text{ if } x \in A \\ \mu_A(x) = 0 \text{ if } x \notin \mathrm{A} \end{cases} \tag{3.4}$$

The boundary of the set A is rigid and sharp and performs a two-states only (i.e.,$x \in A$or $x \notin A$). Consider eight elements:

$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8$

Let E be a finite set:

$$\mathrm{E} = \{x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8\}$$

And let A be classical set, it is with two values 0 or 1 only.

$A = \{x_2, x_6, x_8\}$

So

$\mu_A(x_1)=0$, $\mu_A(x_2)=1$, $\mu_A(x_3)=0$, $\mu_A(x_4)=0$, $\mu_A(x_5)=0$, $\mu_A(x_6)=1$, $\mu_A(x_7)=0$, $\mu_A(x_8)=1$.

This allows representing A by accompanying the elements of E with their characteristic function values:

A = {(x_1 ,0) ,(x_2 , 1) , (x_3 , 0) , (x_4 , 0) , (x_5 ,0) , (x_6 , 1) , (x_7 , 0) , (x_8 , 1)}

Recall the well-known properties of a Boolean binary algebra, Let Ā be the complement of A with respect to E [42]:

$$A \cap \bar{A} = \Phi \tag{3.5}$$

$$A \cup \bar{A} = E \tag{3.6}$$

Where Φ null set, as the set containing no element. And if $x \in A$, $x \notin \bar{A}$, and $\mu_A(x) = 1$ is written and $\mu_{\bar{A}}(x) = 0$. Considering the example above, it seen:

$\mu_{\bar{A}}(x_1) = 1$, $\mu_{\bar{A}}(x_2) = 0$, $\mu_{\bar{A}}(x_3) = 1$, $\mu_{\bar{A}}(x_4) = 1$, $\mu_{\bar{A}}(x_5) = 1$, $\mu_{\bar{A}}(x_6) = 0$, $\mu_{\bar{A}}(x_7) = 1$, $\mu_{\bar{A}}(x_8) = 0$

And it is written:

Ā = { (x_1 ,1) , (x_2 , 0) , (x_3 , 1) , (x_4 , 1) , (x_5 , 1) , (x_6 ,1) , (x_7 , 1) , (x_8 , 0)}

3.3 .4 Fuzzy Set:

Fuzzy set is a set containing elements with varying degrees of membership and its transition in the universe between membership and non membership can be gradual.

Elements membership values of fuzzy set are mapped to the universe by using a function-theoretic form [43]. A fuzzy set A in the universal set E is a set of ordered pairs of generic x and its membership degree $\mu_A(x)$ as [39]:

$$\mathrm{A} = \{(x_i \, , \mu\mathrm{A}(x)\,)/\, x_i \in \mathrm{E}\} \tag{3.7}$$

In classical set, the subset A is of E. The eight elements x_1 *to* x_8 belong or do not belong to A (true or false). The membership function takes only the value 0 or 1, and called "Crisp Set". In fuzzy set, the membership function can be written as [38]:

$$0 \le \mu\mathrm{A}(x) \le 1 \tag{3.8}$$

Where $\mu\mathrm{A}(x)$ is called the membership function (or characteristic function) of A and$\mu_A(x)$ is the grade (or degree) of membership of x in A, which indicates the degree that x belongs to A.

3.3 .5 Membership Function Types:

In fuzzy set section, it is tacked symbol idea of membership function, it is the cover (curve) that defines how each point in the input space is mapped to a membership value or (degree of membership) between 0 or 1 [39].

The fuzzy membership function depends not only on the concept to be represented, but also on the context in which it is used. The graphs of the functions may have very different shapes, and may have some specific properties (e.g., continuity). Below are the functions and curves of some of the commonly used membership functions:

A. Trapezoidal function:

$$\mu_A(x) = \begin{bmatrix} 0 & if\ x < a \\ \frac{x-a}{m-a} & if\ x \in [a,m] \\ 1 & if\ x \in [m,n] \\ \frac{b-x}{b-n} & if\ x \in [n,b] \\ 0 & if\ x > b \end{bmatrix} \tag{3.9}$$

Where a, b, *n*, and m are real values in x-axis and *k* is slant

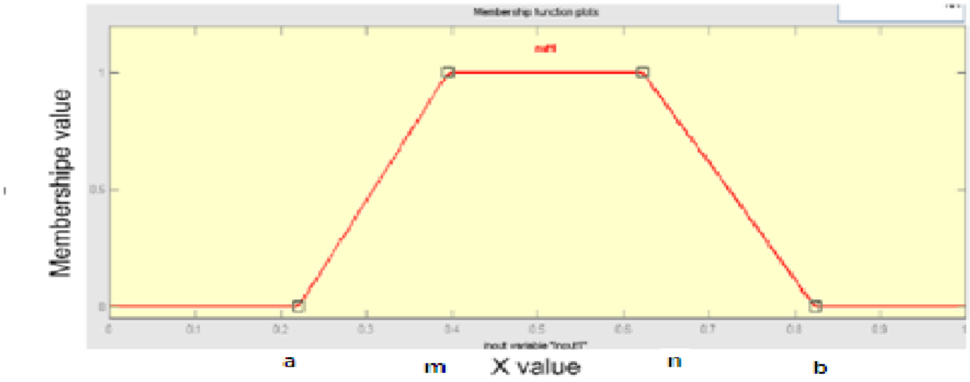


Figure (3.2): *A Trapezoidal function curve.*

B .S- Membership Function:

$$\mu_A(x) = \begin{bmatrix} 0 & if\ x \leq a \\ 2\left(\frac{x-a}{b-a}\right)^2 & if\ x \in [a,m] \\ 1-2\left(\frac{x-a}{b-a}\right)^2 & if\ x \in [m,b] \\ 1 & if\ x > b \end{bmatrix} \qquad (3.10)$$

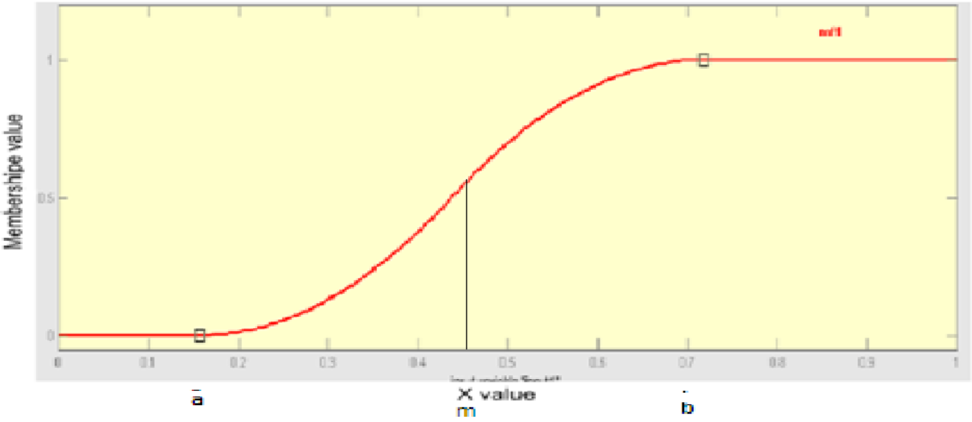


Figure (3.3) *An S- function curve*

C. Gaussian Membership Function:

$$(x) = \boldsymbol{e}^{-\boldsymbol{K}(\boldsymbol{x}-\boldsymbol{m})^{2}} \quad \text{where k} > 0 \tag{3.11}$$

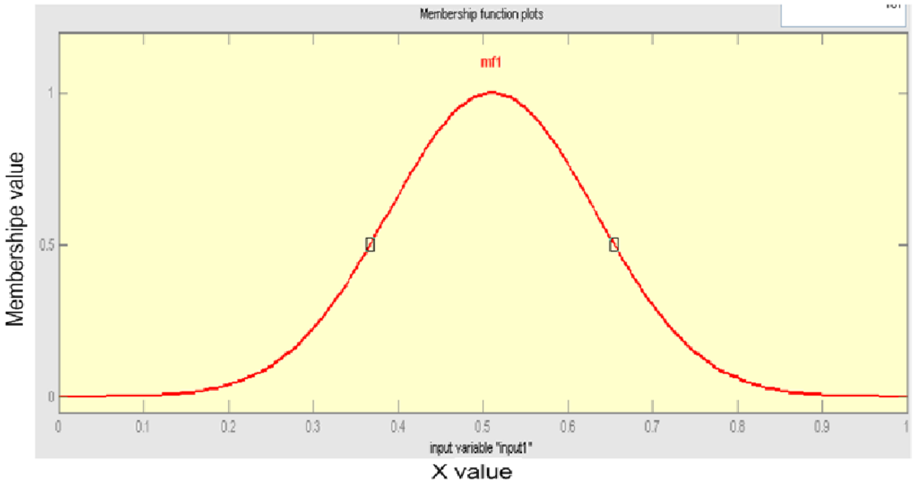


Figure (3.4): *A Gaussian membership function curve.*

D.Z-Membership Function:

$$\mu_A(x) = \begin{cases} 1 & , x \le x_l \\ \dfrac{1}{2} + \dfrac{1}{2}\cos\left(\dfrac{x - x_l}{x_r - x_l}\pi\right) & , x_l < x < x_r \\ 0 & , x \ge x_r \end{cases} \tag{3.12}$$

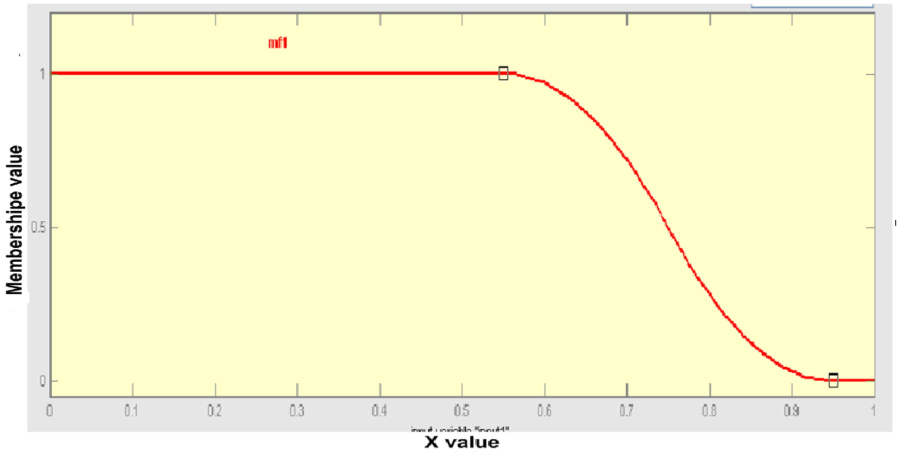


Figure (3.5)*: A Z-membership function curve*

E. Triangular Membership Function:

$$\mu_A(x) = \left[\begin{array}{ll} 0 & if\ x \le a \\ \dfrac{x-a}{m-a} & if\ x \in [a,m] \\ \dfrac{b-x}{b-m} & if\ x \in [m,b] \\ 0 & if\ x \ge b \end{array}\right] \tag{3.13}$$

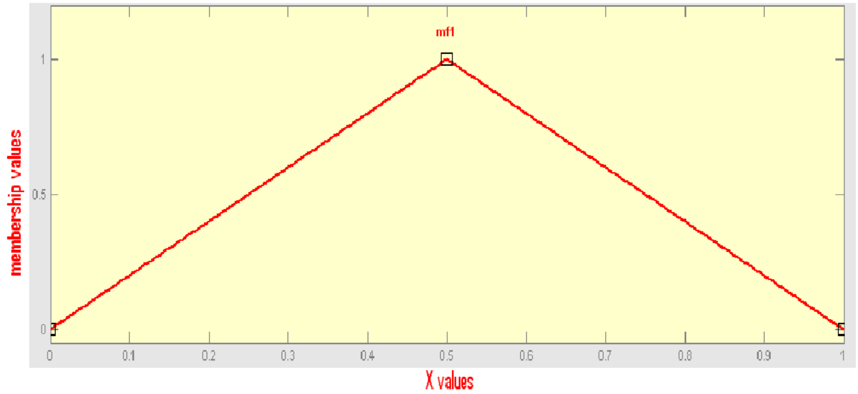


Figure (3.6): *A Triangular membership function curve.*

3.3.6 <u>Fuzzy Operations:</u>

Fuzzy logical operator is superset of standard Boolean logic which needed if convolution for more than one fuzzy set.

The binary AND, OR, and NOT are implemented by the function min, max, and complement respectively which also define the fuzzy intersection, fuzzy union and fuzzy complement [38]. Fuzzy logic the truth of any statement is a matter of degree to which an element is a member of the set and its value can vary between 0 and 1. Let A and B be two fuzzy sets with membership $\mu_A(x)$ and $\mu_B(x)$, respectively [42].

Definition 1: The union of the two sets, $A \cup B$, corresponds to the OR function and is defined by:

$$\mu_{A\cup B}(x) = max[\mu_A(x), \mu_B(x)] \tag{3.14}$$

Definition 2: The intersection of two sets , $A \cap B$, corresponds to the AND function and is defined by [42]:

$$\mu_{A\cap B}(x) = min[\mu_A(x), \mu_B(x)] \tag{3.15}$$

Definition 3: The NOT operator or the complement of a fuzzy set is defined by [40].

$$\mu'_A(x) = 1 - \mu_A(x) \tag{3.17}$$

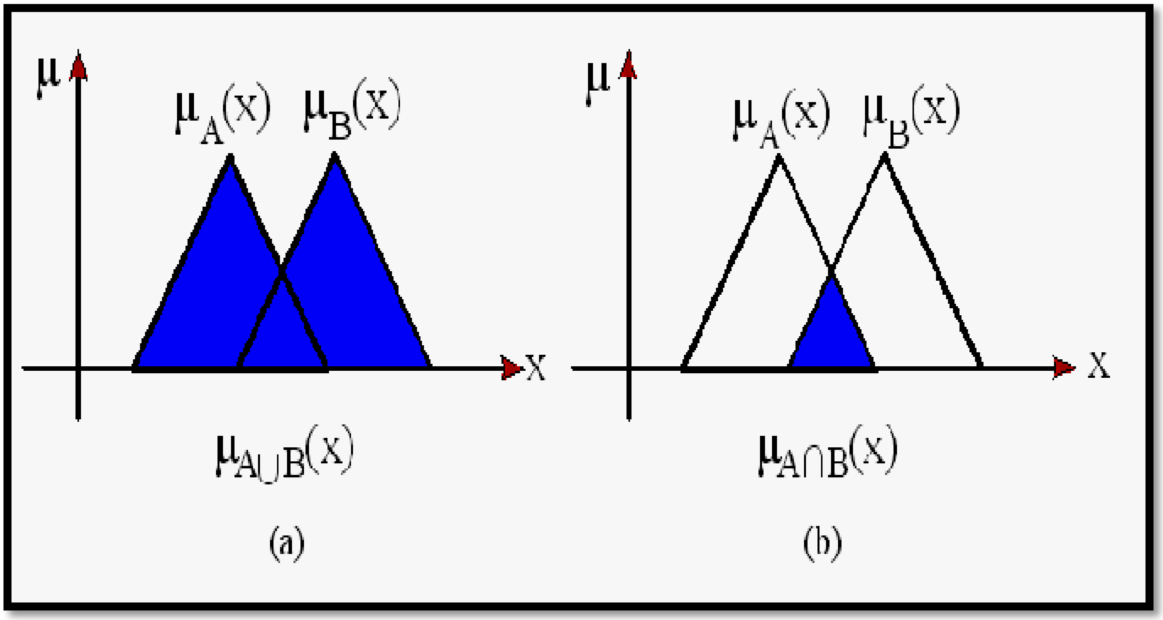


Figure (3.7): *Membership function of max. And min. for two function [43].*

3.4 General Fuzzy Controller Structures:

A control system is arrangement of hardware components, used to regulate or to command another system exhibits certain desired behavior or characteristics. It is open loop or close loop and sometimes divided in to regulatory type if maintain variable at constant value in the presence of disturbances. The second class is set point tracking controllers in which variable is required to follow desired time function. The fuzzy control provides a formal methodology for representing, manipulating, and implementing a human's heuristic knowledge about how to control a system [40]. The general fuzzy logic system is shown in Fig. (3.8):

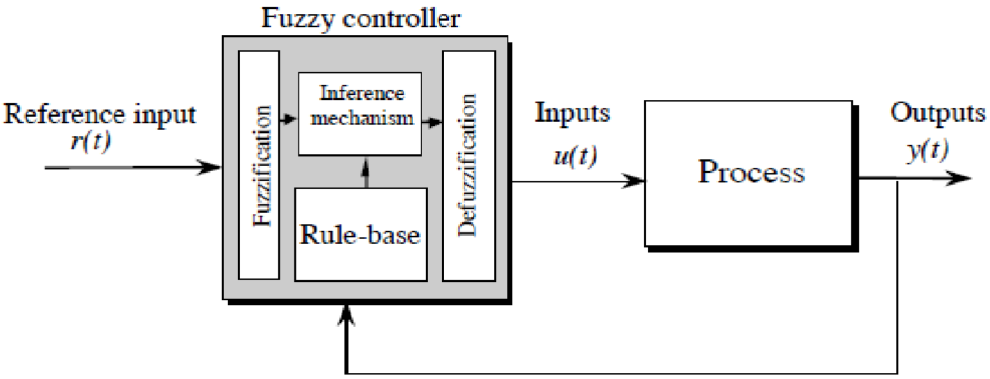


Figure (3.8): *Fuzzy logic system [40].*

The fuzzy system can be divided into single-input and single output (SISO), two-inputs and single-output, multi-inputs and single output, multiple-inputs and multiple-outputs (MIMO). The higher the dimension of fuzzy control is, the more precise the fuzzy control will be. But when the dimension is too high, the control rules and control calculation will be too complicated. On the premise of satisfying control performance, the input variable dimension should be minimized. So, the optimum fuzzy controller design should be no more than two inputs to take fast and easy design [1, 40].The close loop fuzzy controller shown in Fig (3.9).

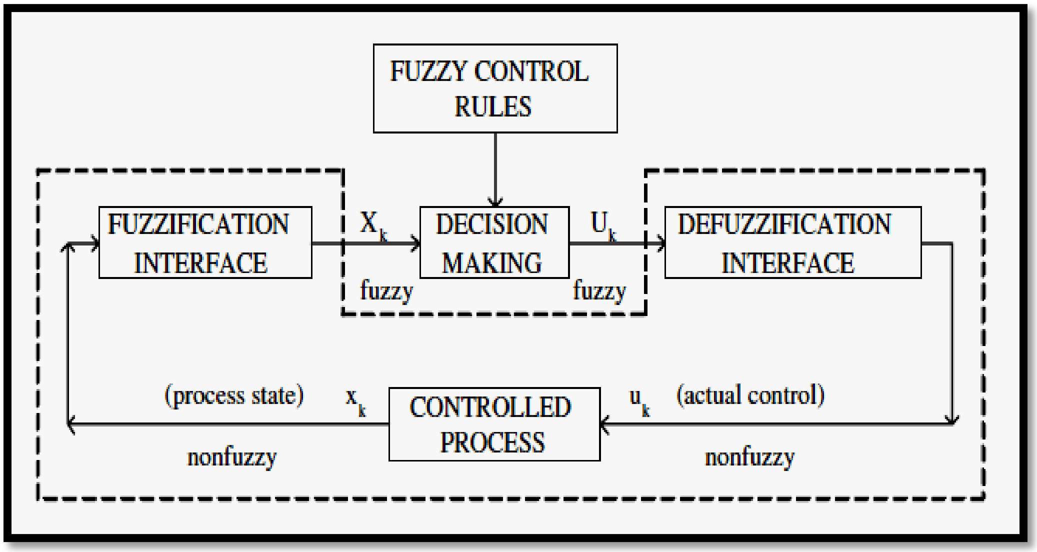


Figure (3.9): *Fuzzy closed-loop control system [44].*

The development of the control system based on fuzzy logic involves the following steps:

1- Preprocessing:
2- Fuzzification strategy.
3- Rule base elaboration.
4- Inference mechanism elaboration.
5- Defuzzification strategy.

3.4.1 Preprocessing:

This done by choose appropriate scaling factors for the input and output variables to normalize the variables to the interval [0,1] or [-1,1], In order to increase the sensitivity of an FLC the input values multiplied by a factor greater than one and vice versa.

3.4.2 Fuzzifcation strategy:

Fuzzification is the process of making a crisp quantity to fuzzy or converts controller inputs into information that the inference mechanism can easily use to activate and apply rules. The fuzzification output is degree of membership corresponding to the input numerical value defined by the qualifying linguistic set [45]. Since the first step is to establish the fuzzy variables of natural language form, and then to determine the fuzzy subsets of fuzzy variables [36, 46]. From figure (3.10) the input to fuzzification is crisp numerical value ($x_{K)}$, and ($X_{k)}$ its output.

3.4.3 Rule Base elaboration:

The (If – Then) rule statements are used to formulate the conditional statements that comprise fuzzy logic. Rules may be provided by experts or can be extracted from numerical data. Basically a linguistic controller contains rules in the ($if\ incident\ then\ conclusion$) format, but they can be presented in different formats. In many systems, the rules are presented as the form:

$$If\ Input1\ is\ (A)\ and\ Input2\ is\ (B)\ then\ Output\ is\ (C)$$

Where A, B, and C are linguistic values defined by fuzzy set for first and second inputs and the output respectively. It is clear, that the IF-THEN rule involves distinct parts: First evaluating the antecedent and second applying that result to the consequent. Another more compact representation illustrated below:

Table (3.1) *Rule base compact representation.*

Input1	**Input2**	**Output**
A	B	C

The first row the variables names, and the second row represents a rule, by this format can get an overview of the rule base quickly. A third formats the tabular linguistic format.

Table (3.2) *the tabular linguistic format.*

$Input2$ $Input1$	B
A	$\boldsymbol{C}$

It is more compact. The input variables outside with (dark background) but the output variables inside the table with (white background).If the inputs more than two the table grows to dimensions equal to the number of inputs.

3.4.4 Inference Mechanism elaboration:

The inference mechanism emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant. The inference mechanism has two basic tasks:

1. Determining the extent to which each rule is relevant to the current situation, as characterized by input u_i , $i = 1,2,3,\ldots,n$ (called matching).There are two steps to matching:
   Step 1: Combine inputs with rule premises.
   Step 2: Determine which rules are on .
2. Drawing conclusions using the current inputs u_i and the information in the rule-base (called inference step) [4].For performing the inference step use two alternatives:
   Alternative 1: Determine implied fuzzy set.
   Alternative 2: Determine the overall implied fuzzy set[1].

3.4.5 Fuzzification:

Defuzzification is a mapping of fuzzy space control action defined over an output universe of discourse to non fuzzy space (crisp) control actions.

The defuzzification aim is producing a crisp control action that best represents the possibility distribution of an inferred fuzzy control action. Because of there is no systematic procedure for choosing a good defuzzification strategy the selection of its procedure depends on the properties of the application. The various strategies reported in literature described as follows:

- **Center of Area (COA):** It is the most prevalent and physically appealing of all the defuzzification. This method selects the output crispy value corresponding to the center of gravity of the output membership function. This method is also called “Centroid” or “Center Of Gravity” (COG). It shown in figure (3.10).

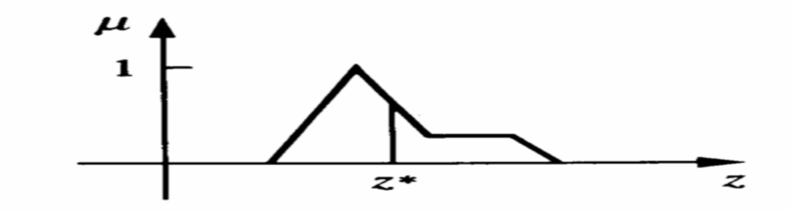


Figure (3.10): *Center of Area defuzzification*

$$z^* = \frac{\int \mu c(z).z\,dz}{\int \mu c(z).dz} \tag{3.18}$$

- **Weighted average method (WtAver)**: It is the most frequently used in fuzzy applications. It is computationally efficient methods but restricted to symmetrical output membership functions. Its algebraic expression:

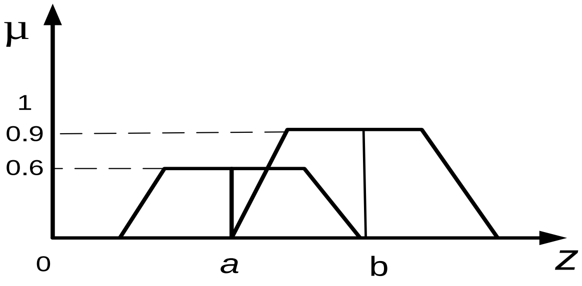


Figure (3.11): *Weighted average defuzzification.*

$$z^* = \frac{\sum \mu c(\acute{Z}).\acute{Z}}{\sum \mu c(\acute{Z})} \tag{3 .19}$$

- **Max membership principle:** It known as the height method and it limited to peaked output functions. This methods algebraic expression:

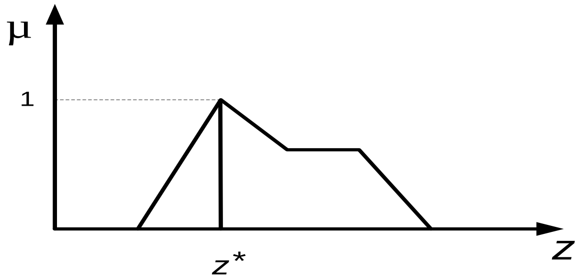


Figure (3.12): *Max membership defuzzification.*

$$\mu c(z^{*}) \geq \mu c(z) \qquad for\ all\ z = Z \tag{2.20}$$

- **Mean Of Maxima (MOM):** This method is closely related to max membership principle method except that the locations of the maximum membership can be non unique. Its expression given by:

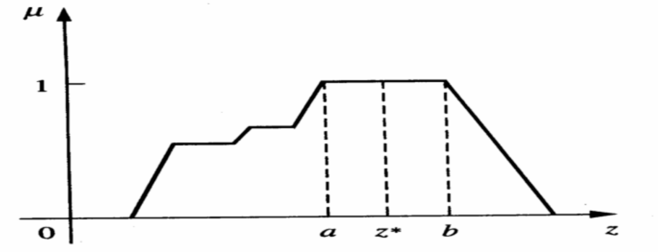


Figure (3.13): *(MOM) method.*

$$z^{*} = \frac{\sum_{i}\{Max\ [\mu_i(x)]\}}{n} \tag{3.21}$$

Where n is the number of membership functions.

- **First of Maximal (FM):**The union of the fuzzy sets used and takes the smallest value of the domain with maximum membership degree, it is expressed as :

$$z^{*} = \inf\{z \in \mathcal{Z} | \mu c_k\,(z) = hgt(c_k)\} \tag{3.24}$$

Where $hgt(c_k)$ is the highest membership degree of(z).

$$hgt(c_k) = sup\ \mu c_k(z) \qquad (3.25)$$

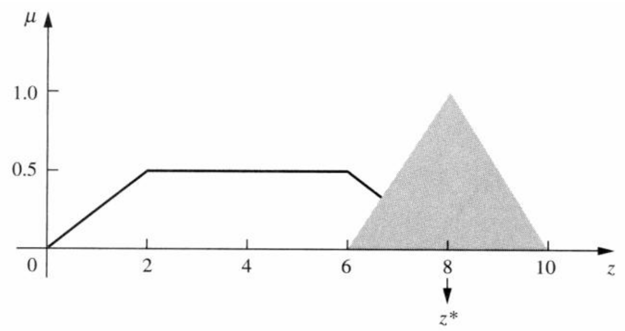


Figure (3.14): *(FM) method.*

- **Bisector of Area (BOA):** bisector of the area generates the action (z_o) which partitions the areas in to two regions with the same area.

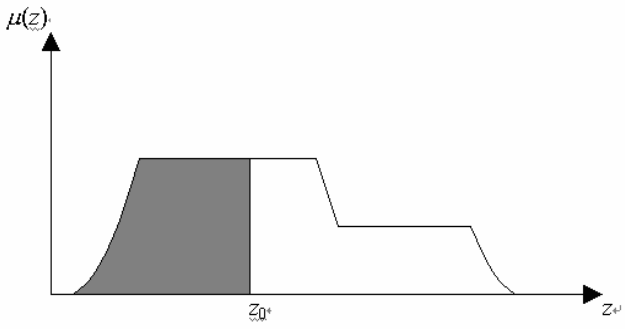


Figure (3.15): *(BOA) method.*

$$\int_{\alpha}^{zo} \mu c(z)\ dz = \int_{zo}^{\beta} \mu c(z)\, dz \qquad (3.30)$$

$$\alpha = \min\{z|z \in w\} \qquad (3.31)$$

$$\beta = ma\,x\{z|z \in w\} \qquad (3.32)$$

When use (MOM) method used, the performance of an FLC is similar to that of multilevel relay system, while the (COA) method yields results similar two these obtainable by use conventional PI controller. It can be expected that the 9COA) strategy can yield superior results, especially the steady-state performance [39, 46].

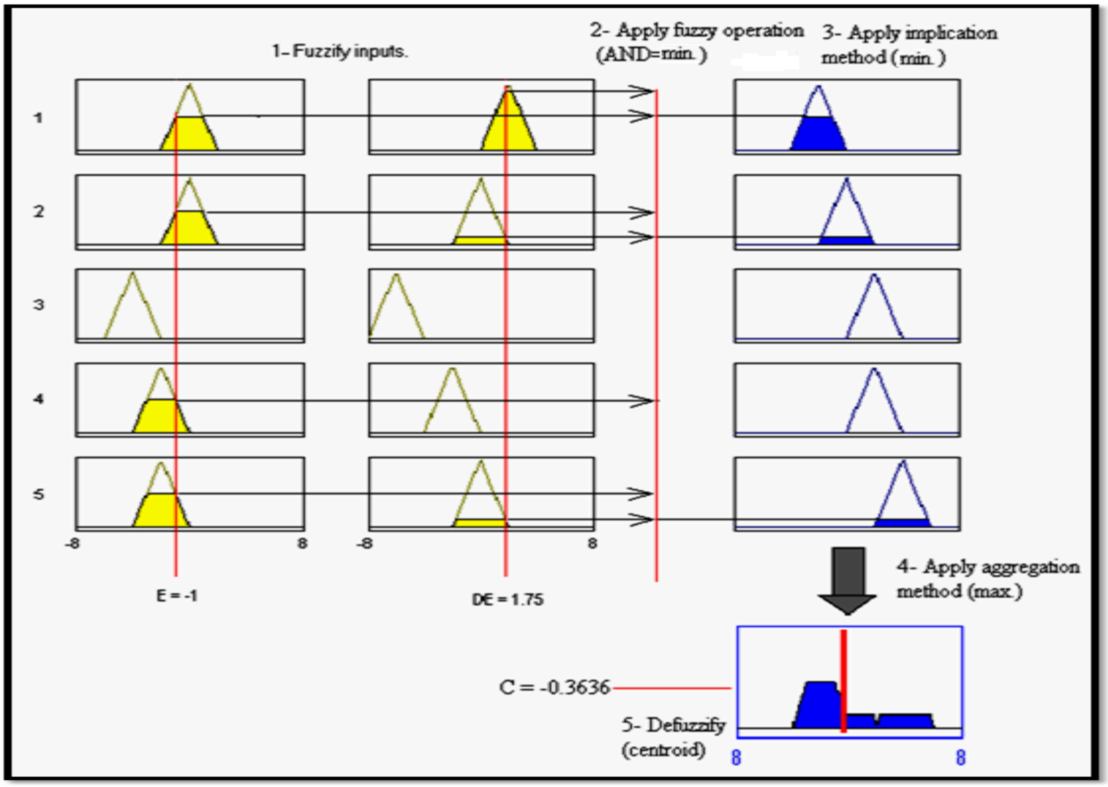


Figure (3.16): *Fuzzy control inference diagram.*

3.5 Takagi-Sugeno method:

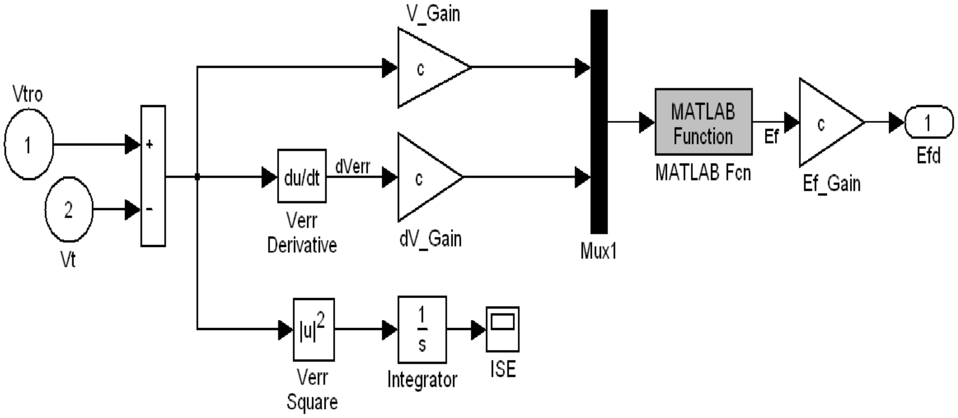
This is the second method of fuzzy logic control; it represents the output variables by using singleton values different from memdani method which represent output variables by fuzzy membership.

The Takagi-Sugeno models utilize the idea based on assumption of approximation of nonlinear models also TS model representation provides efficient and computationally attractive solutions to wide range of control problems introducing a powerful multiple model structure that is capable to approximate non-linear dynamics, multiple operating models and significant parameter and structure variations.

3.6 Fuzzy based synchronous generator terminal voltage controller:

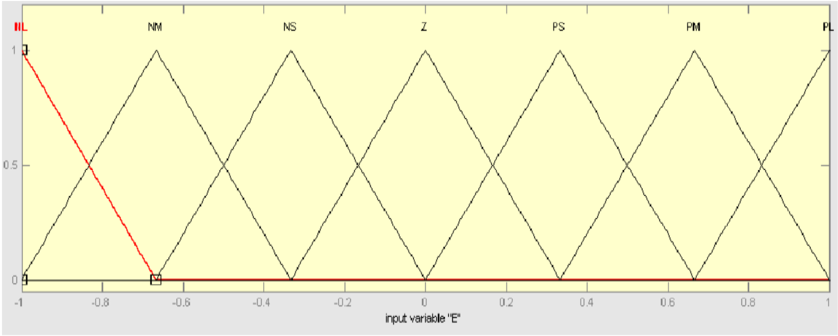
In this work to enhance the stability of reactive power a fuzzy logic-based controller has been designed and implemented to control the terminal voltage of a synchronous generator. The effectiveness of the proposed fuzzy automatic voltage regulator (AVR) is demonstrated by digital computer simulation.

The transient model of synchronous generator with DC1A excitation system controller illustrated in Figures (2.19),and(2.23),the classic DC1 excitation controller replaced by the fuzzy logic-based controller shown in Figure (3.17), this fuzzy based controller with two input the error presented by difference between reference and instantaneous values of terminal voltage, and the second input is change of error . Its output is only (Efd). The fuzzy controller does not require the knowledge of machine parameters and it is quite robust to parameter changes and load disturbance.

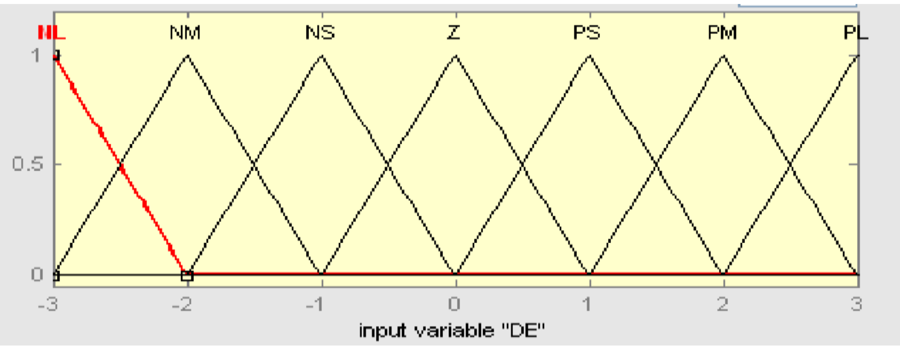


Figure(3.17) *fuzzy controller Model with MATLAB/SIMULINK.*

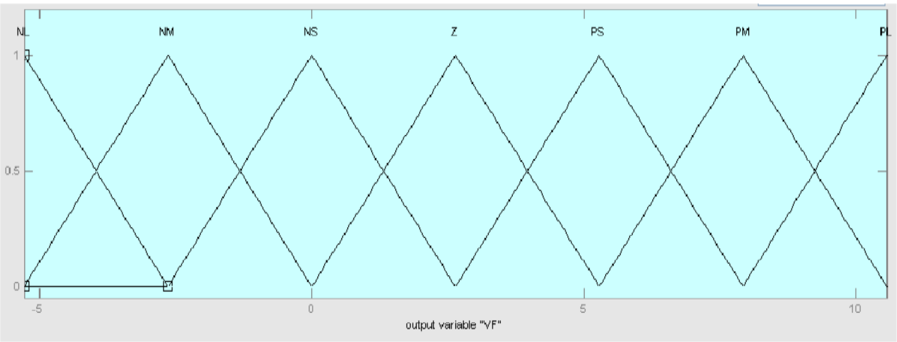
The fuzzy logic implemented with seven triangular membership functions for all inputs and the output, its rule table based on (49) roles, it build in m- file illustrated in Appendix-A .The fuzzy membership functions and its control surface are shown in figures (3.18),(3.19).



a) First input error (E)



b) Second input change error (DE).



C) Fuzzy controller output (E_{fd})

Figure (3.18): *Fuzzy controller membership functions.*

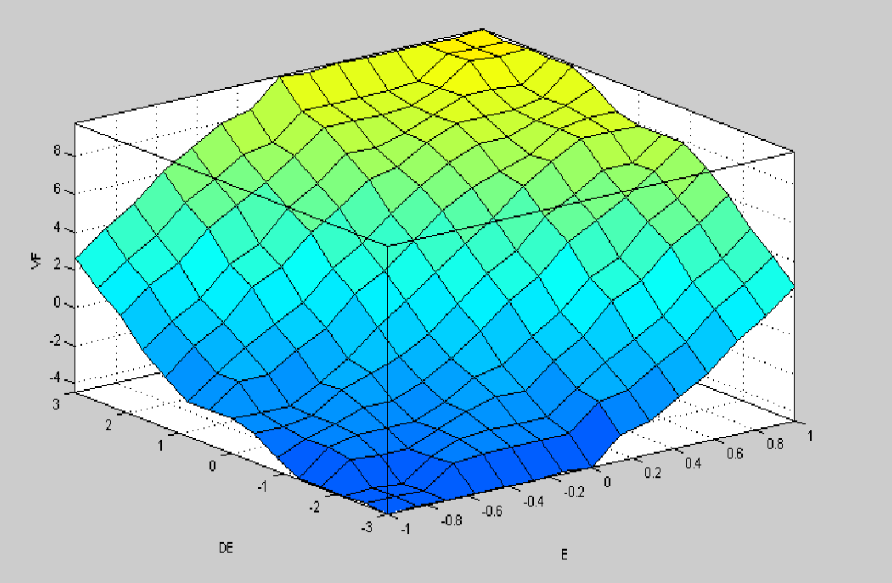


Figure (3.19): *Fuzzy control surface.*

Chapter- 4

Simulated Results

4.1 Introduction:

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 DC1 and the other is intelligent and based on FL theory. In this chapter, 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.

In this chapter, the performance of FL controller itself has been assessed for specified machine condition and for different controller parameters. The type and number of membership functions, elements or entries of knowledgebase table and type of fuzzification method are selected as design parameters for such assessment.

The FL controller is built using m-file, i.e., it is synthesized away from consulting MATALB/TOOLBOX. This would grant it a dynamic programming power and to qualify it for adaptation purposes. The m-file MATLAB code is listed in Appendix (A).The machine parameters and coefficients are listed in Appendix (B).

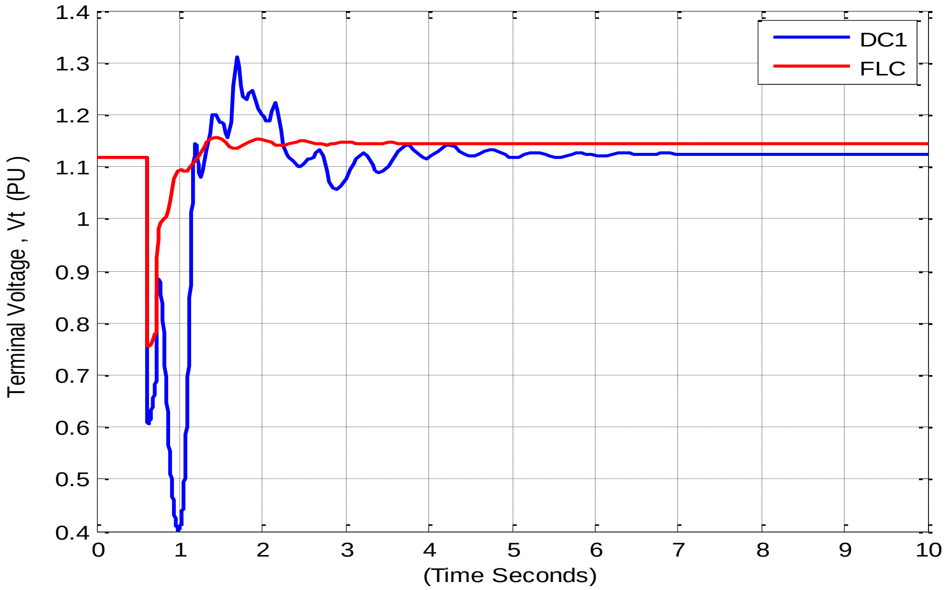
4.2 External Load Variation:

The objective of these tests is to study and to check the powerfulness of both FL and DC 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.

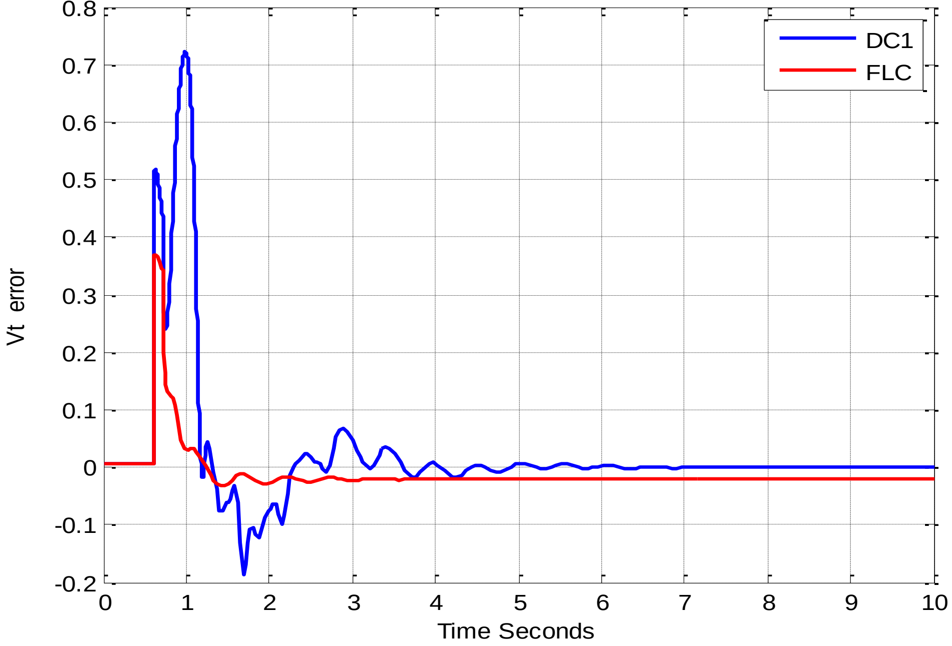
Figures (4.1a)-(4.1e) show the traces of terminal voltages, voltage errors, active and reactive powers, and rotor angle respectively, resulting from both suggested controllers. In these figures, a sudden load (transmission line) change of about 25% of rated load has occurred at 0.6 second and vanished at 0.72, i.e.:

R_e=0.0075, X_e=0.15

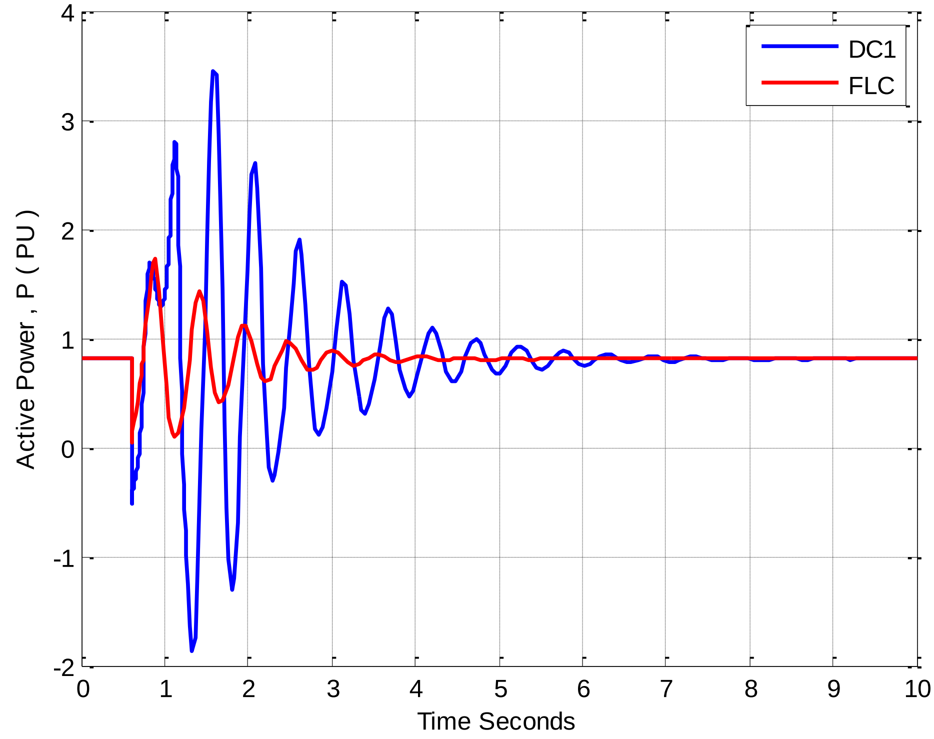
It is clear from the figures that the fuzzy controller shows a better response than DC one. This is evident from voltage errors of Figure (4.1-b), where the actual voltage response based on DC shows a large error than that based on intelligent controller. The Integral Square Error (ISE) criterion tells that its value is equal to 0.1603 in case of DC controller-based response and equal to 0.02284 based on FL controller.



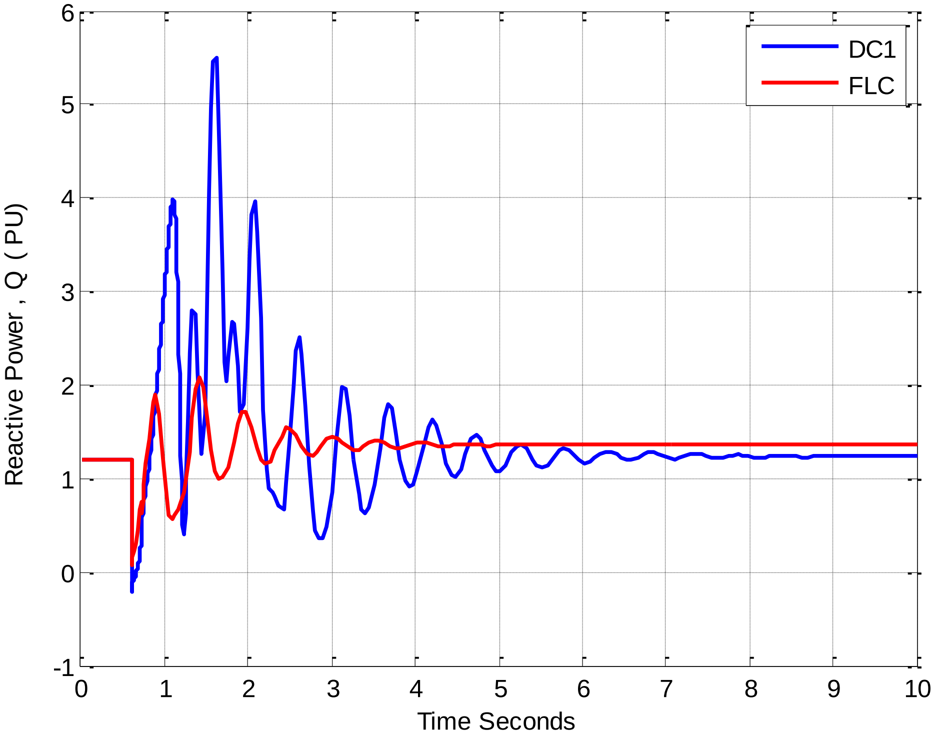
a)Terminal voltage responses.



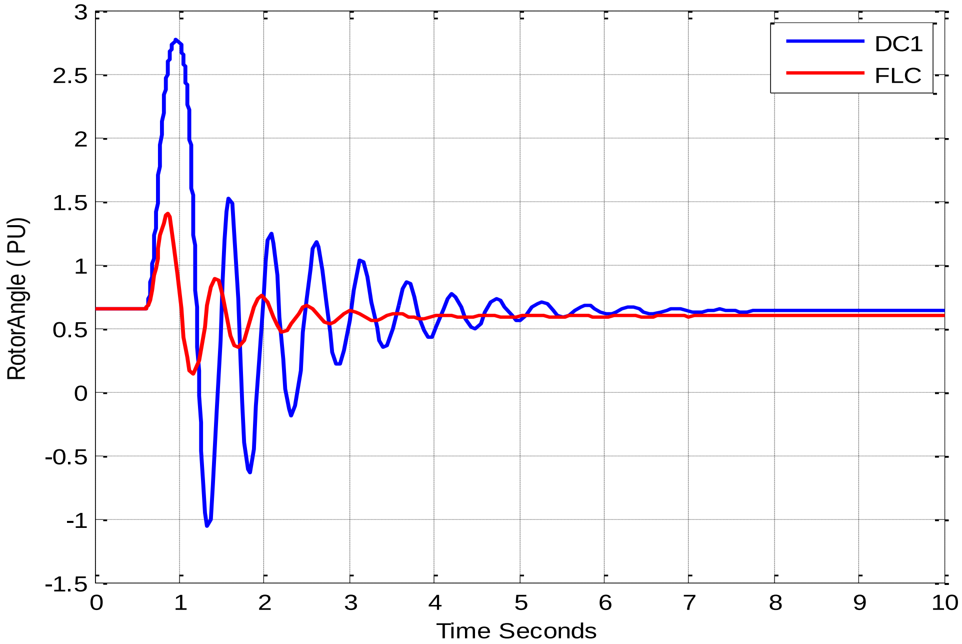
b)Voltage errors (between reference and actual voltages.



c) Active Powers



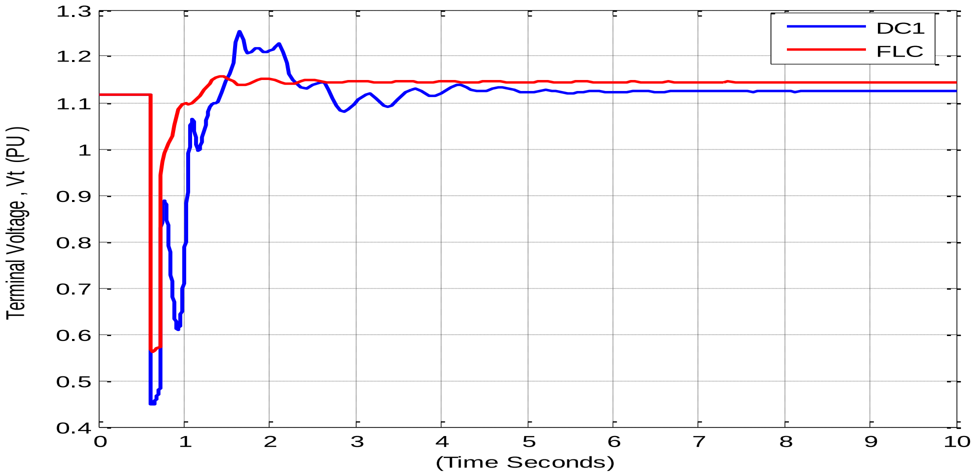
d) Reactive Power



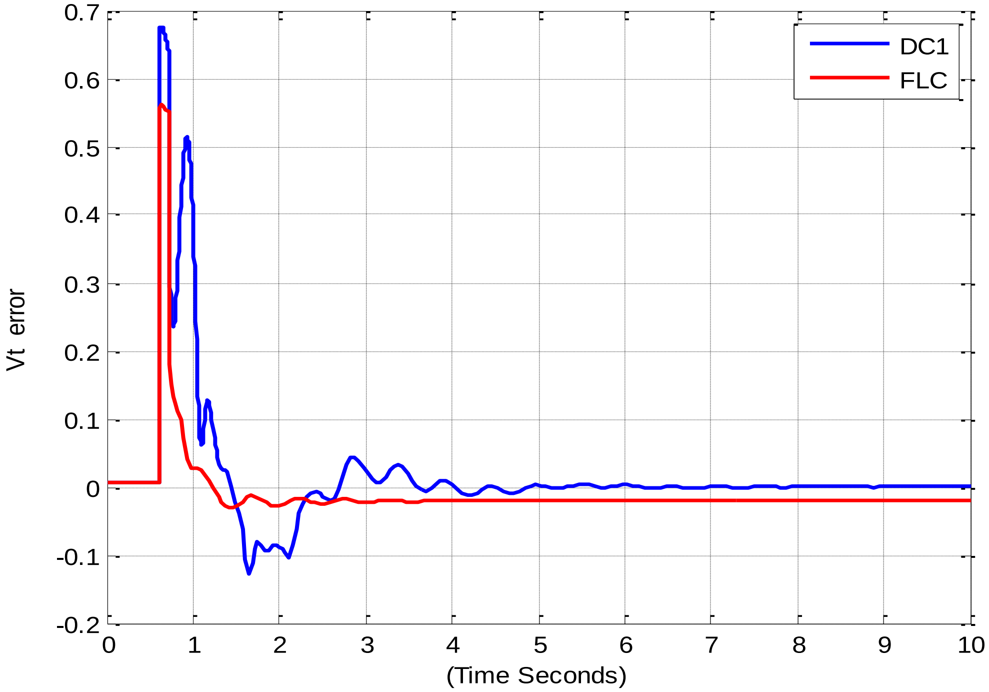
e) Rotor angle change.

Figure (4.1) *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)*

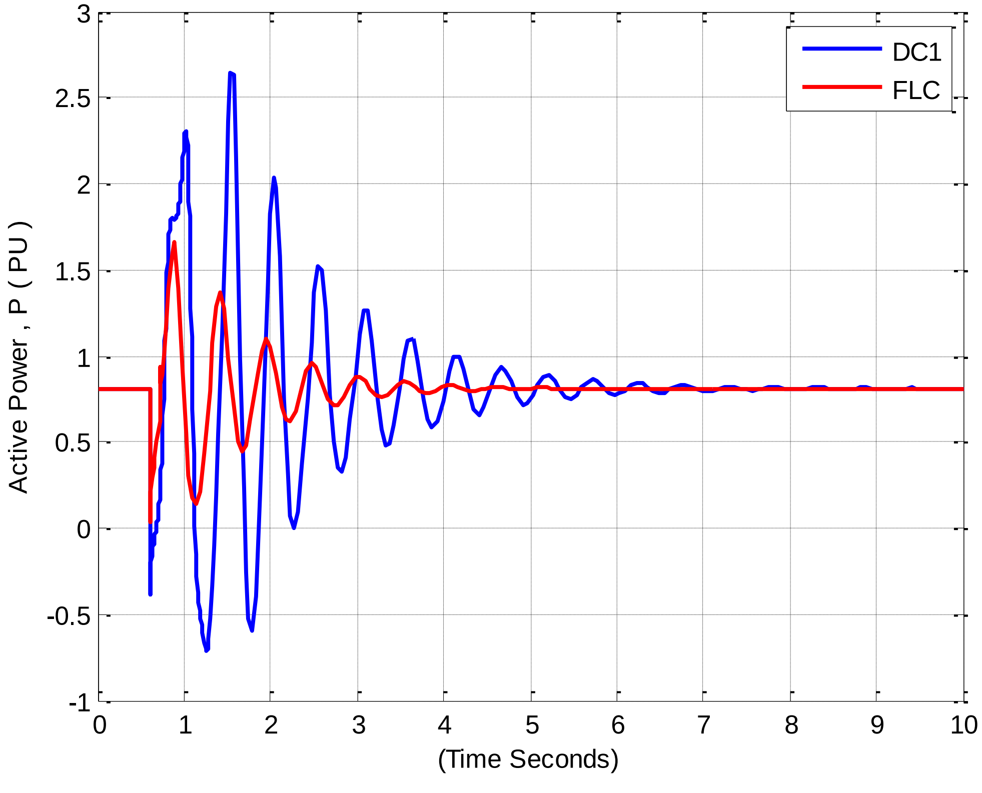
In Figures (4.2-a)-(4.2-e) and Figures (4.3-a)-(4.3-e), the load impedance of the transmission line are decreased to 50% (R_e=0.005, X_e=0.1) and 75% (R_e=0.0025, X_e=0.05) from their rated values, respectively. The same above discussion can be argued here, where the response based on the FL controller shows better characteristics than its counterpart. For Figure (4.2), the ISE criterion gives the value of 0.1105 for DC1-based controller and 0.04428 for the FL-based controller. On the other hand the ISE measure gives0.1331 for conventional controller and the value of 0.08407 for the intelligent controller of Figure (4.3).



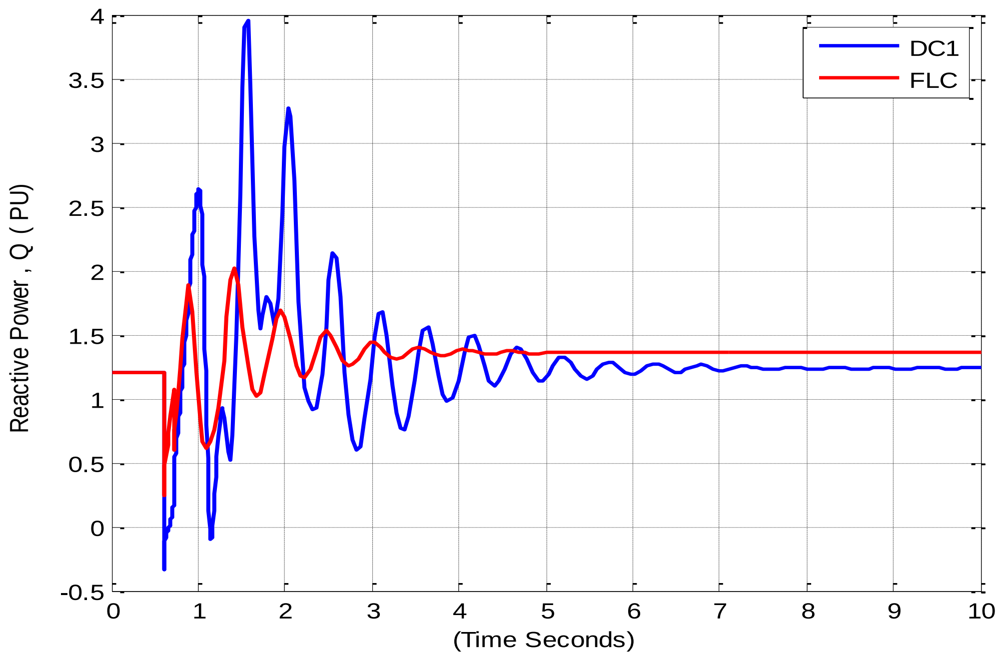
a)Terminal voltage responses.



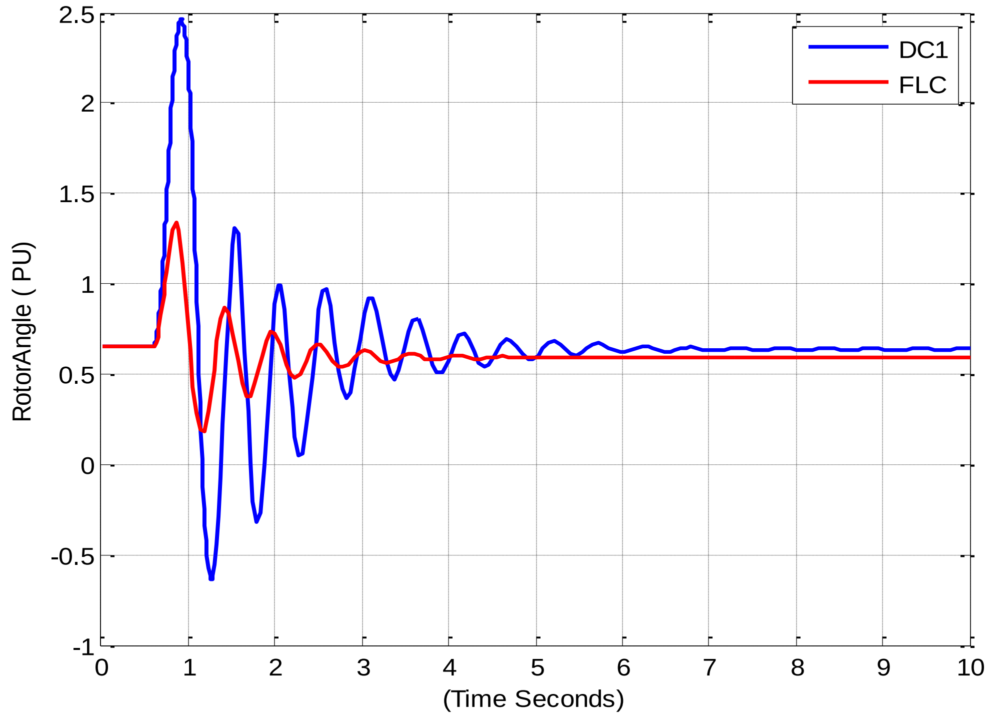
b) Voltage errors (between reference and actual voltages).



c) Active Powers.

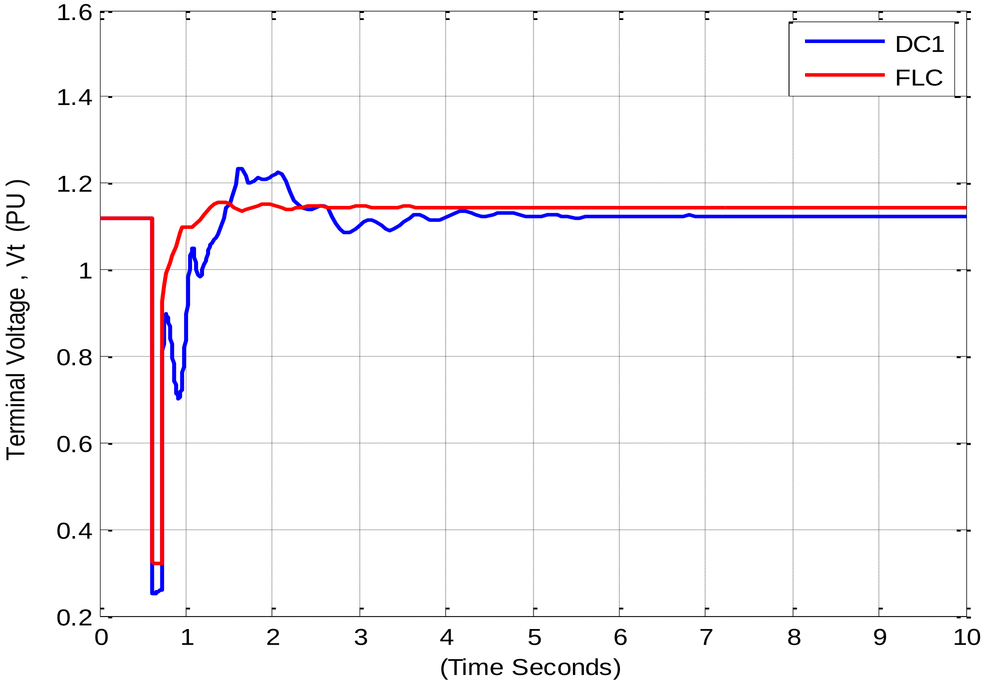


d) Reactive Power.

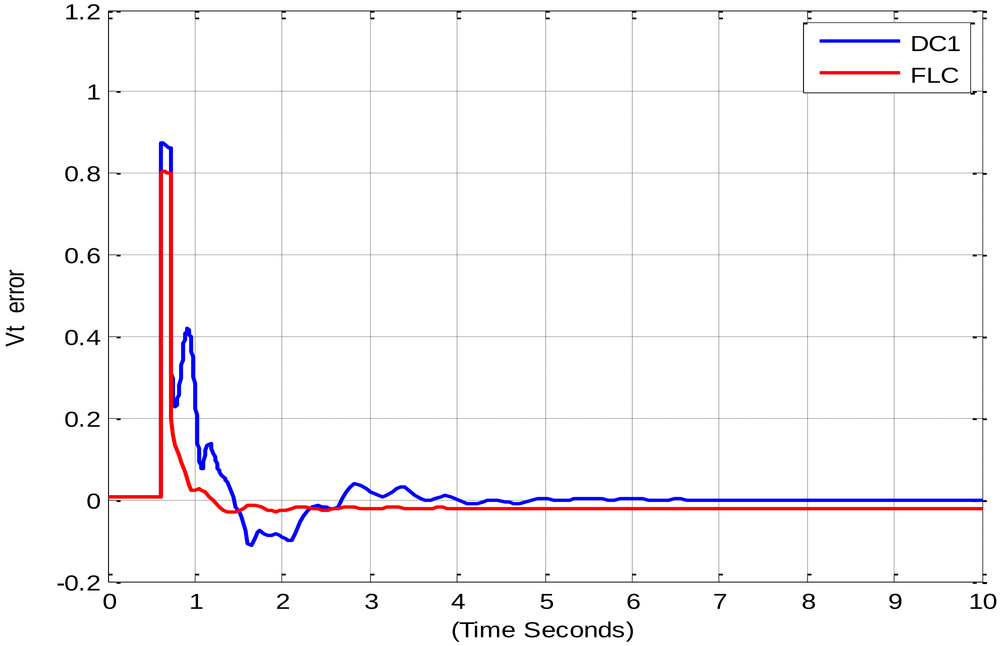


e) Rotor angle change.

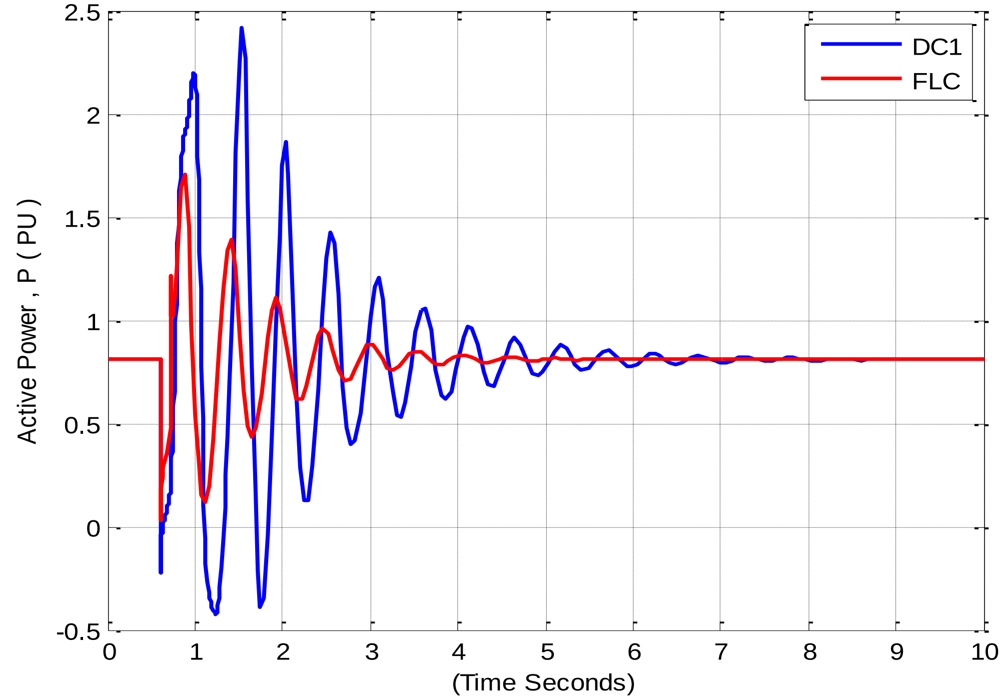
Figure (4.2) *Different SG Responses due to load change starts at 0.6 and lasts at 0.72 seconds* (R_e=0.005, X_e=0.1)



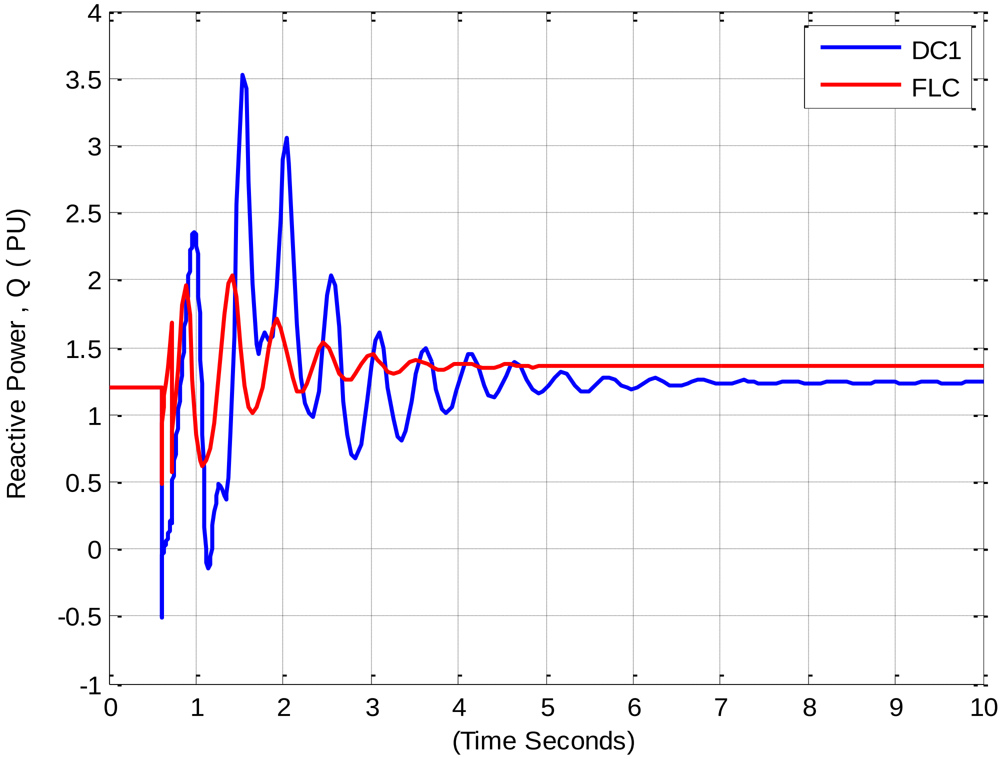
a)Terminal voltage responses



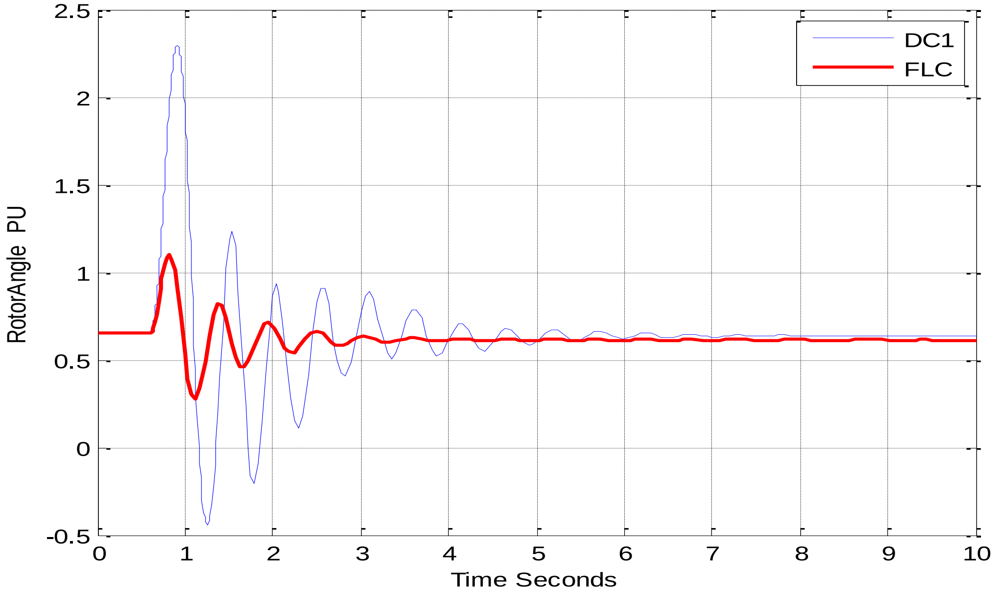
b) Voltage errors (between reference and actual voltages).



c) Active Powers



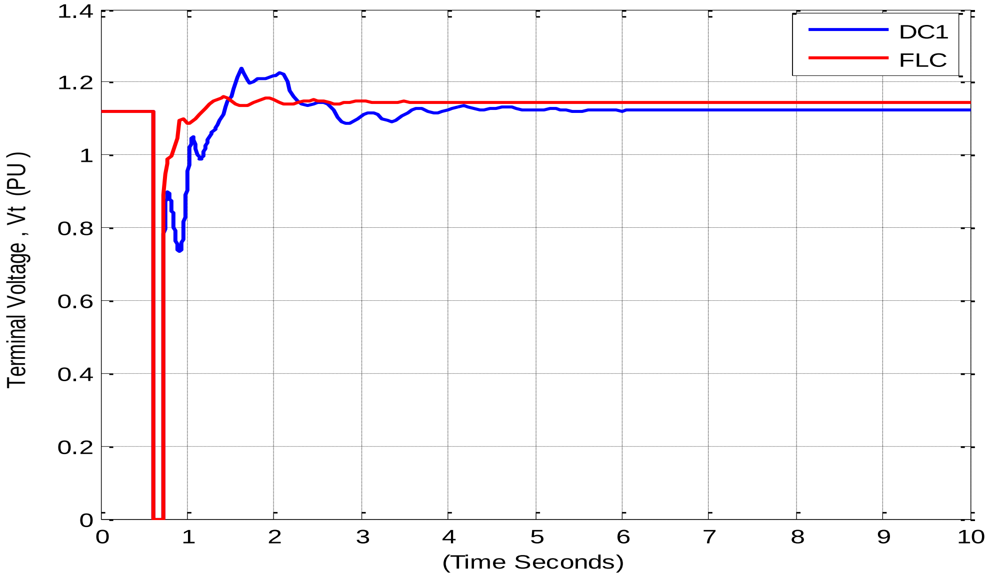
d) Reactive Powers.



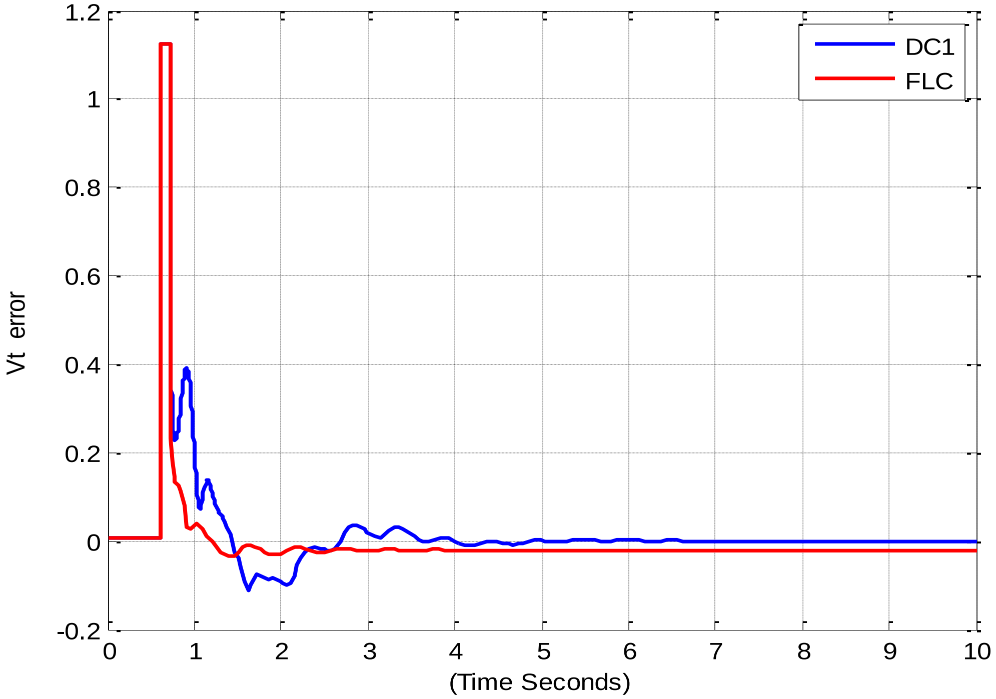
e) Rotor angle change.

Figure (4.3) *Different SG Responses due to load change starts at 0.6 and lasts at 0.72 seconds* (R_e=0.0025, X_e=0.05).

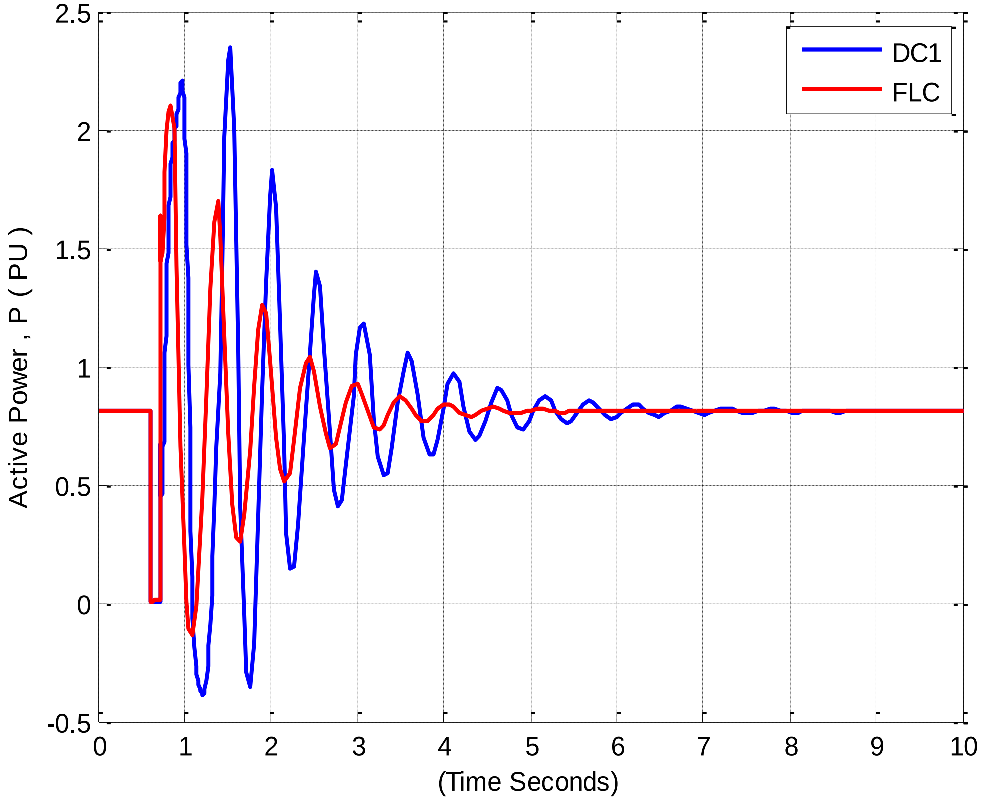
The worst load condition (transmission line) occurs when the load is short circuited, i.e., $Ze = R_e + jX_e = 0$.The effectiveness of both controllers will be tested at this severe condition and the different measurements under supervision of both controllers are shown in Figure (4.4). As it is evident from the figure, the FL controller still again outperforms the DC1 controller. The ISE criterion records the value of 0.1899 for the DC1 controller and the value of 0.1596 for the FL controller case.



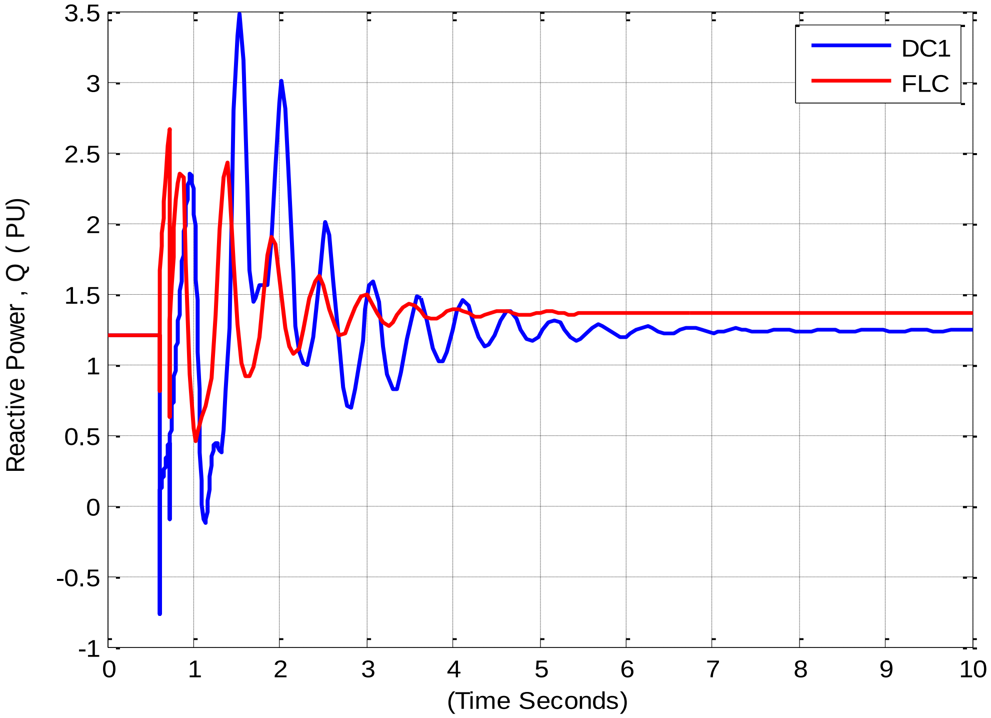
a)Terminal voltage responses.



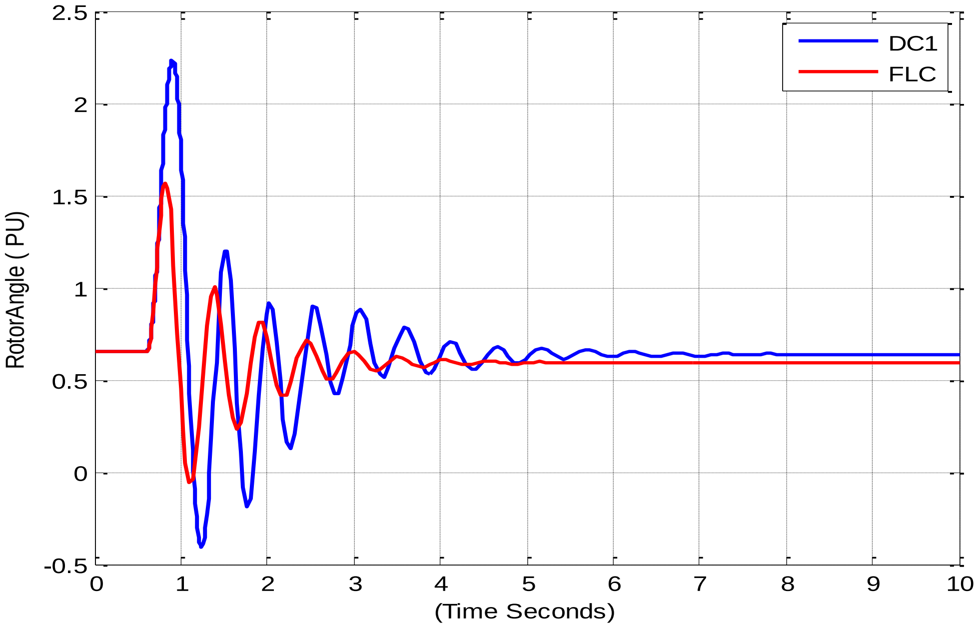
b) Voltage errors (between reference and actual voltages)



c) Active Powers



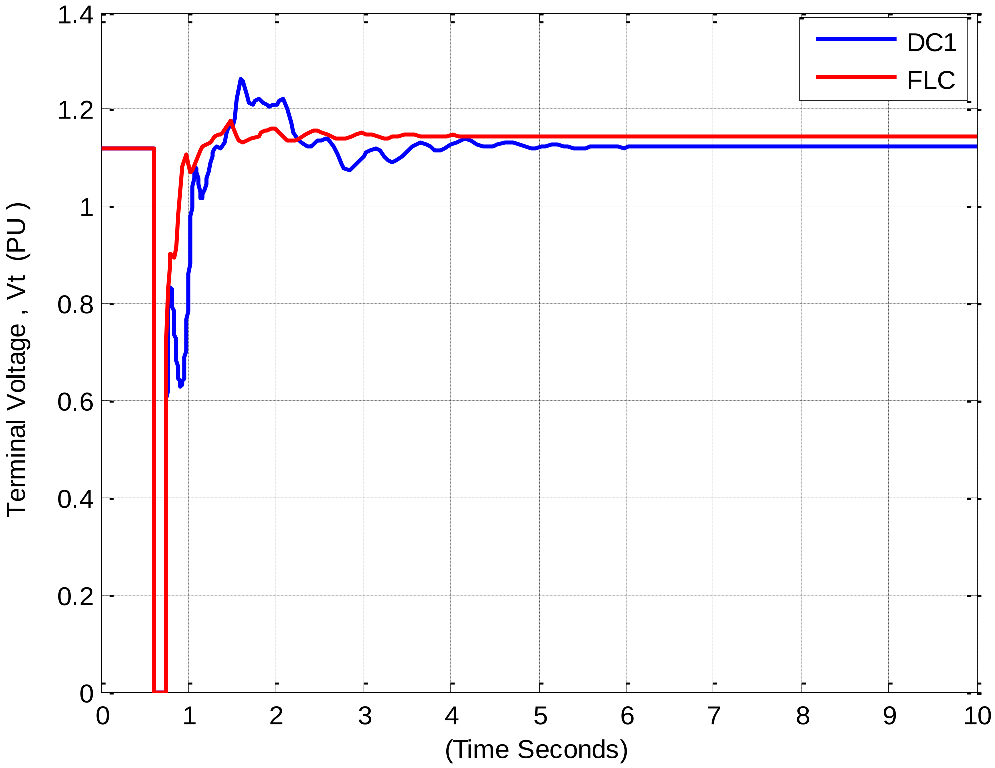
d)Reactive Powers



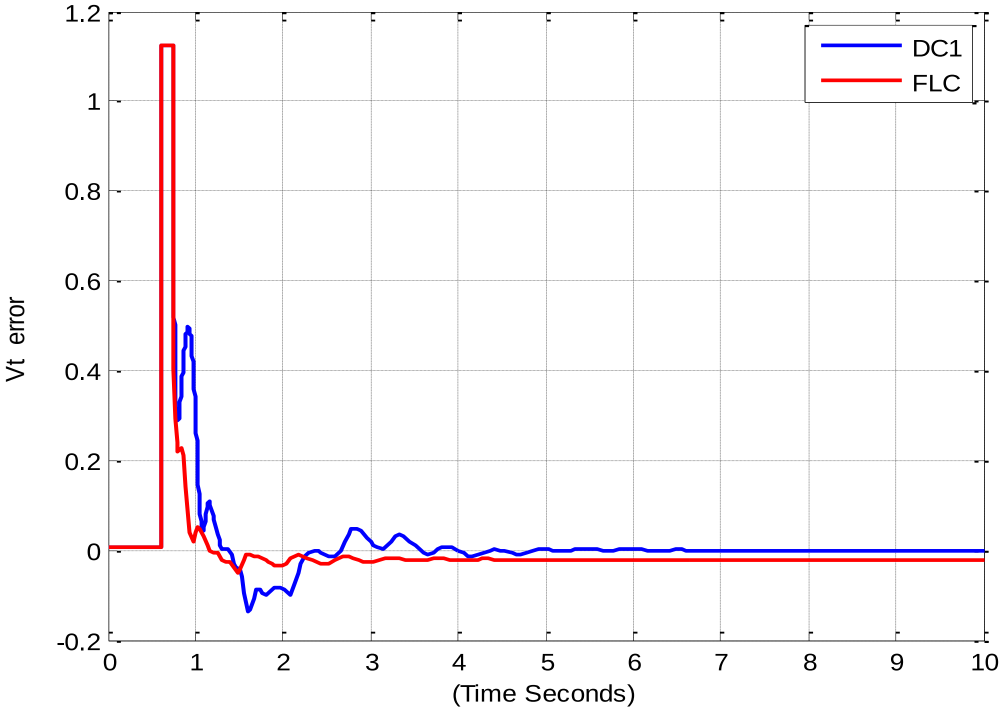
e) Rotor angle change.

Figure (4.4) *Different SG Responses due to short circuited fault occurs at 0.6 and lasts at 0.72 seconds* ($R_e = X_e = 0$)

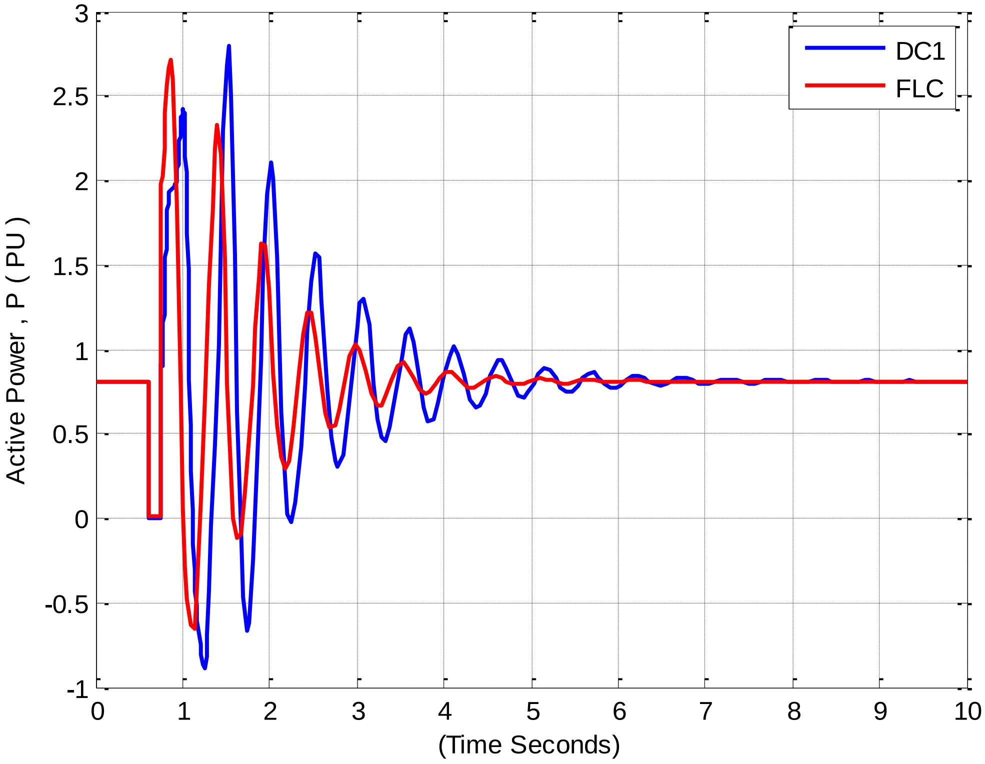
So far, all load changes has been exerted at time period of 0.6-0.78 seconds. It is interesting to investigate the effectiveness of both controllers when the time duration is changed over the above time interval. In Figure (4.5), the short circuit condition is applied, but the end time of fault exertion 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 DC1 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.



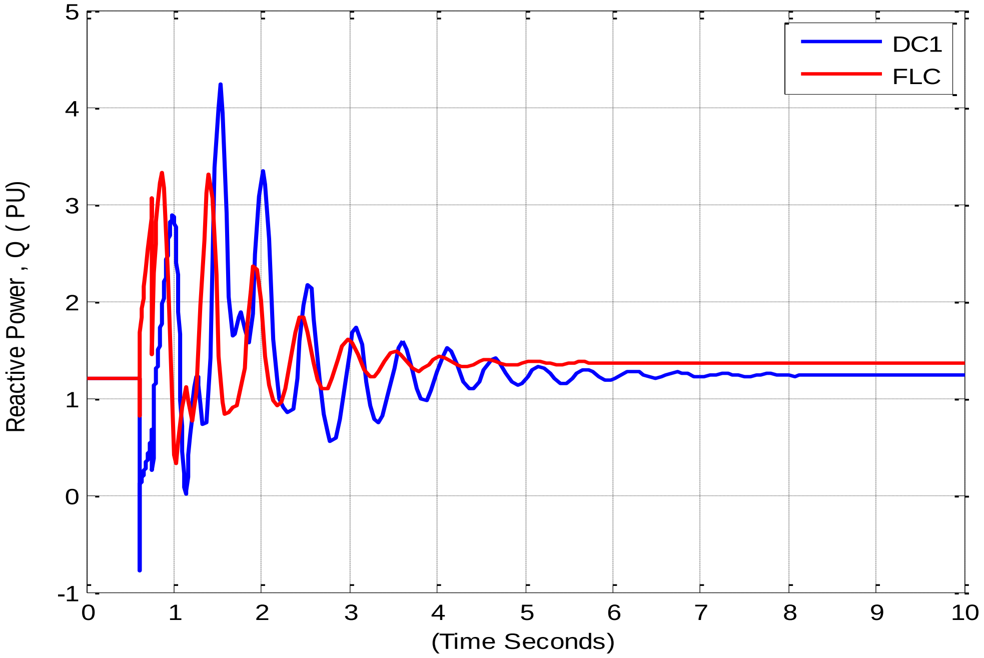
a)Terminal voltage responses.



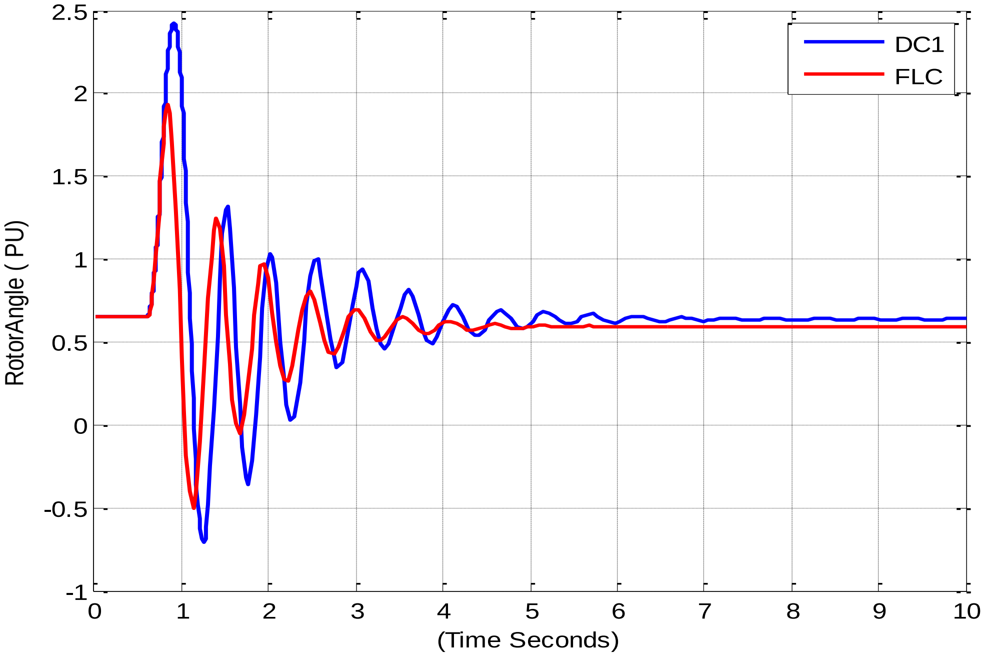
b) Voltage errors (between reference and actual voltages).



c) Active Powers.



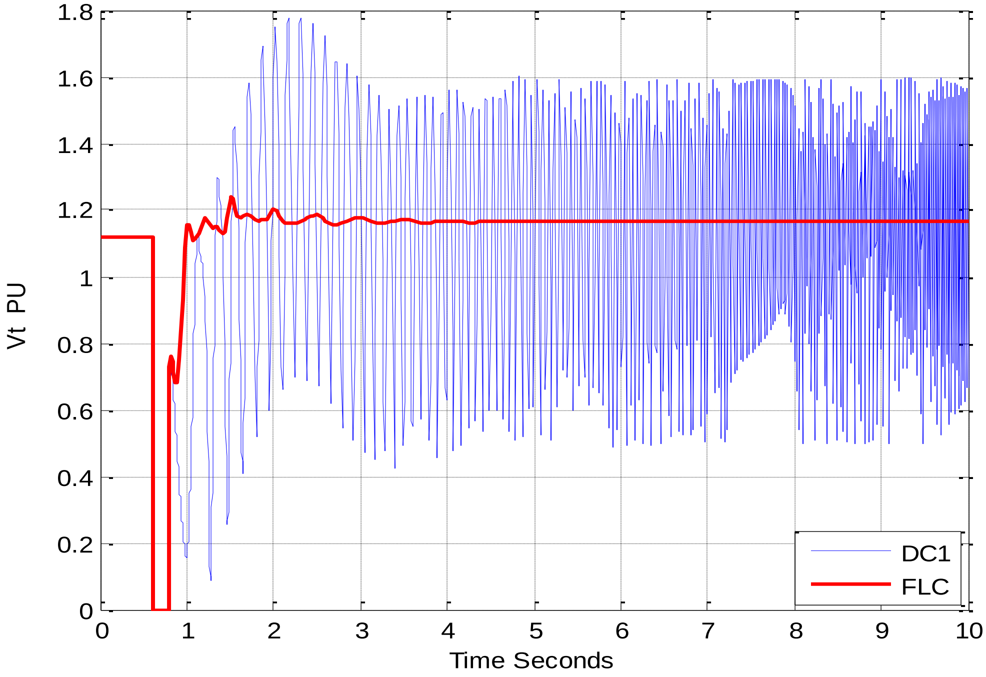
d) Reactive Powers.



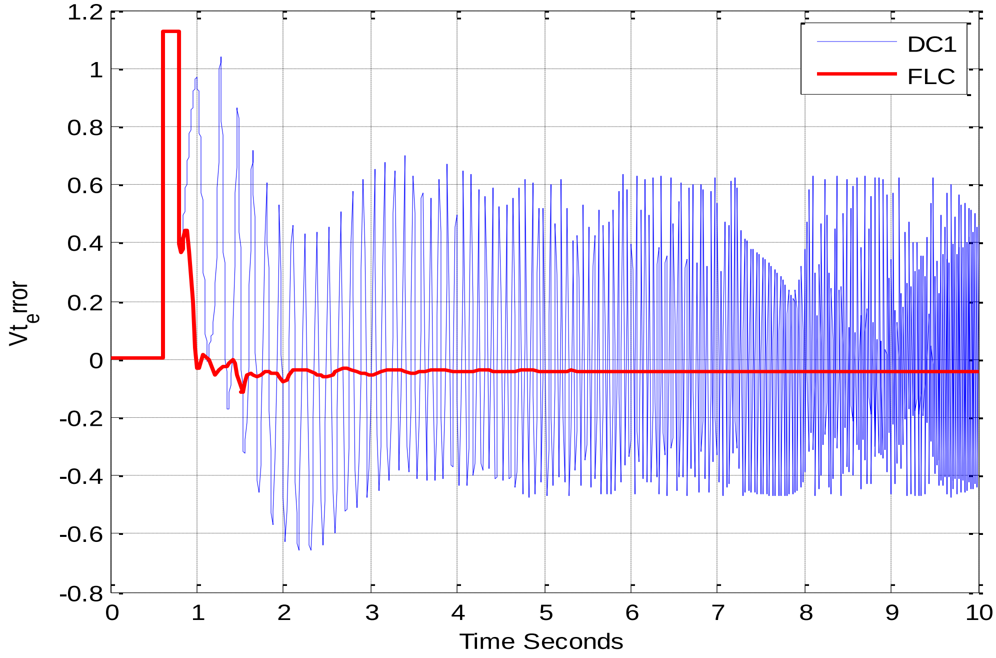
e) Rotor angle change.

Figure (4.5) *Different SG Responses due to short circuited fault (R_e= X_e=0) occurrence between 0.6 and 0.76 seconds.*

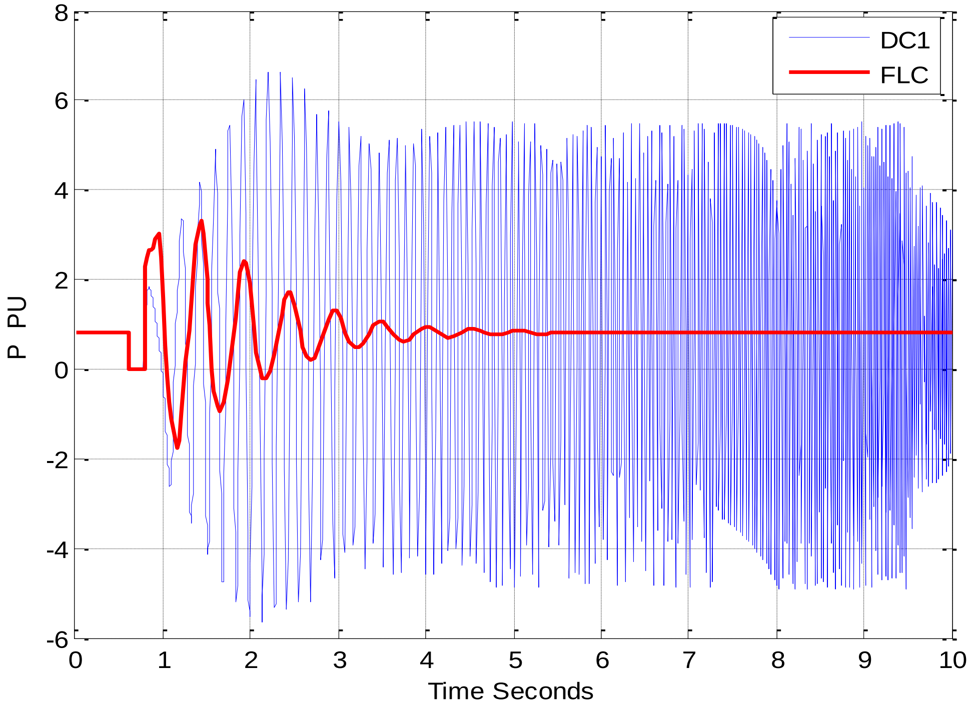
The next test will consider the case when the exertion time interval is increased up to 0.79. At this critical value, the responses due to DC1 controller would show unstable characteristics, while those based on FL controller could keep their satisfactory behaviors. All these new scenes can be clarified in Figure (4.6). One can easily see that the load angle change increase without bound.



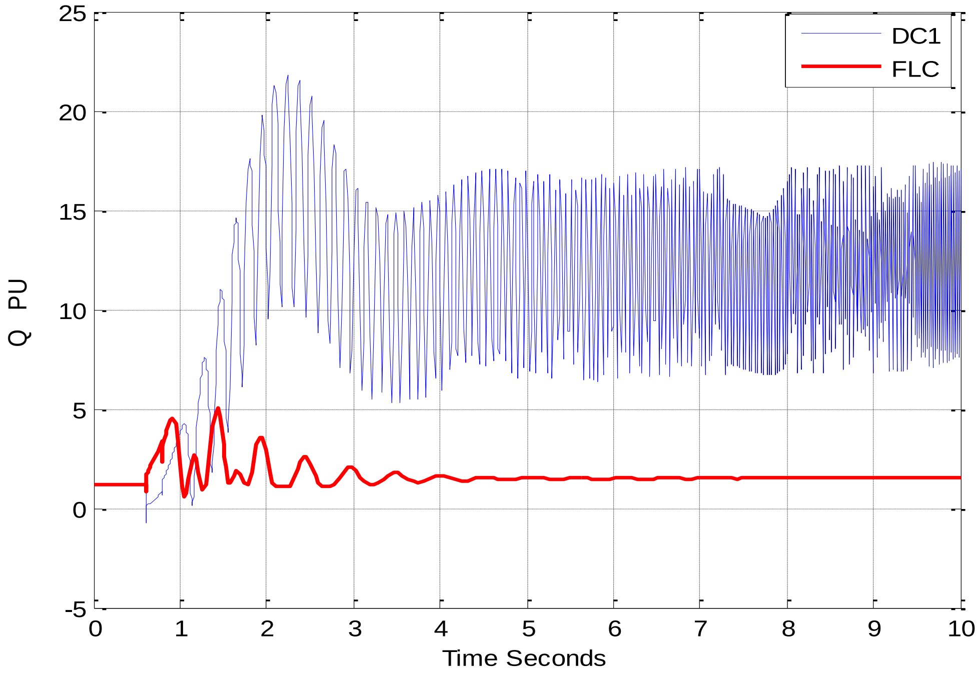
a)Terminal voltage responses.



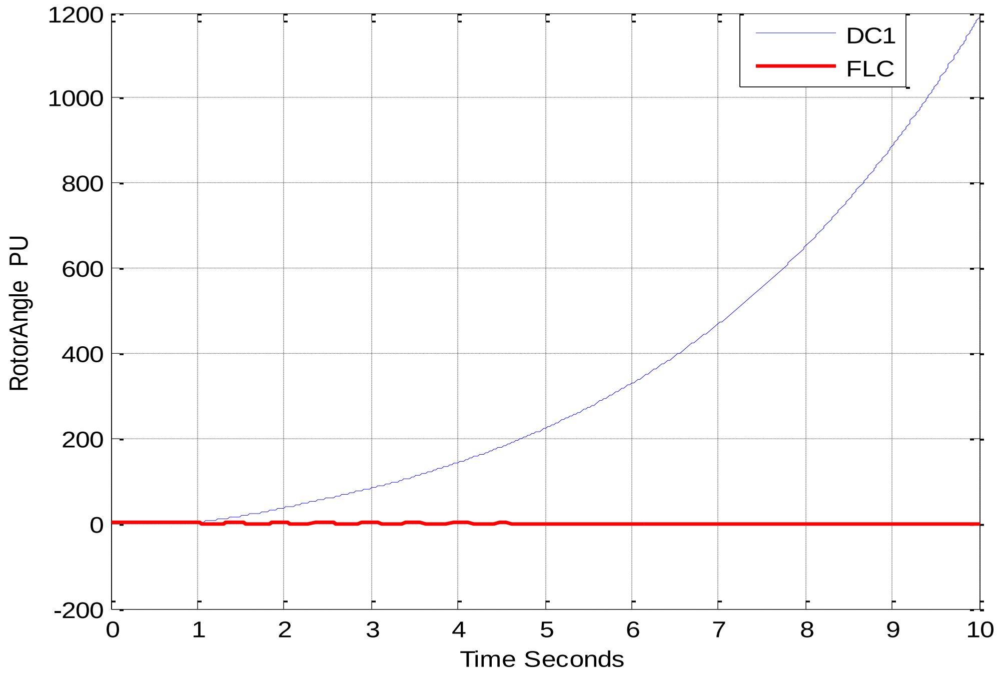
b) Voltage errors (between reference and actual voltages).



c) *Active Powers.*



d) *Reactive Powers.*



e) Rotor angle change

Figure (4.6) *Different SG Responses due to short circuited fault (R_e= X_e=0) occurrence between 0.6 and 0.79 seconds.*

4.3 Variation of FL controller Parameters:

For all the above discussion, the parameters of FL controller are fixed at seven membership function of triangular type for both input and output with knowledge base given by Table (4.1):

Table (4.1) *Knowledge base entries of FL controller*

		ΔE						
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NM	NM	NS	Z	PS
	NS	NL	NM	NM	NS	Z	PS	PM
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PM	PM	PL
	PM	NS	Z	PS	PM	PM	PL	PL
	PL	Z	PS	PM	PL	PL	PL	PL

Therefore, one can deduce that there are 49 rules can be deriving based on the above knowledge base.

For the purpose of dynamic response improvement, it is interesting to consider the effect of changing the FL parameters on the FL controller itself. The type of MF, number of MFs and knowledgebase elements will be considered as the design parameters for the workbench of simulation. Also, the effect of time duration length (at which the fault occurs and released) on the dynamic performance of SG states will be argued for specified FL parameters. It is worth to mention that the worst fault (short circuit)of load condition will be taken into account.

In Figures (4.7), (4.8), (4.9), (4.10) and (4.11) three types of MFs has been selected; triangular, trapezoidal and Gaussian function. In these figures, the time duration is changed as indicated in Table (4.2) and the ISE is evaluated at each type of MFs.

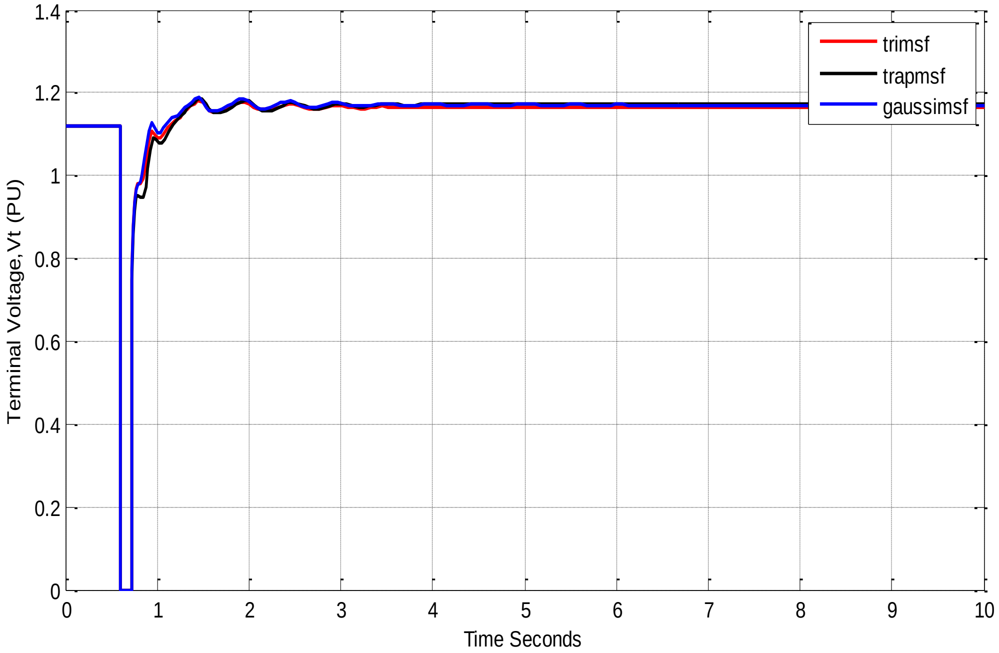
The capability of FL controller to give good behavior with these MFs against time length of fault exertion time duration will be considered. For space saving, the terminal and error voltages will be only monitored.

It is clear from Figures (4.7)-(4.9) and the results listed in Table (4.2) that the FL controller based on triangular MF gives the best dynamic responses than those based on other types of MFs. For all these figures, the ISE indicator gives the minimum value for triangular-based controller. However, the FL controller based on triangular function cannot withstand the increased change in fault time duration. This can be seen in Figure (4.10), where the behavior based on triangular MF-based controller will increase without bound when the end time of this interval reaches 0.8 seconds. On the other hand, the other two FL controllers still give satisfactory behaviors with this time limit.

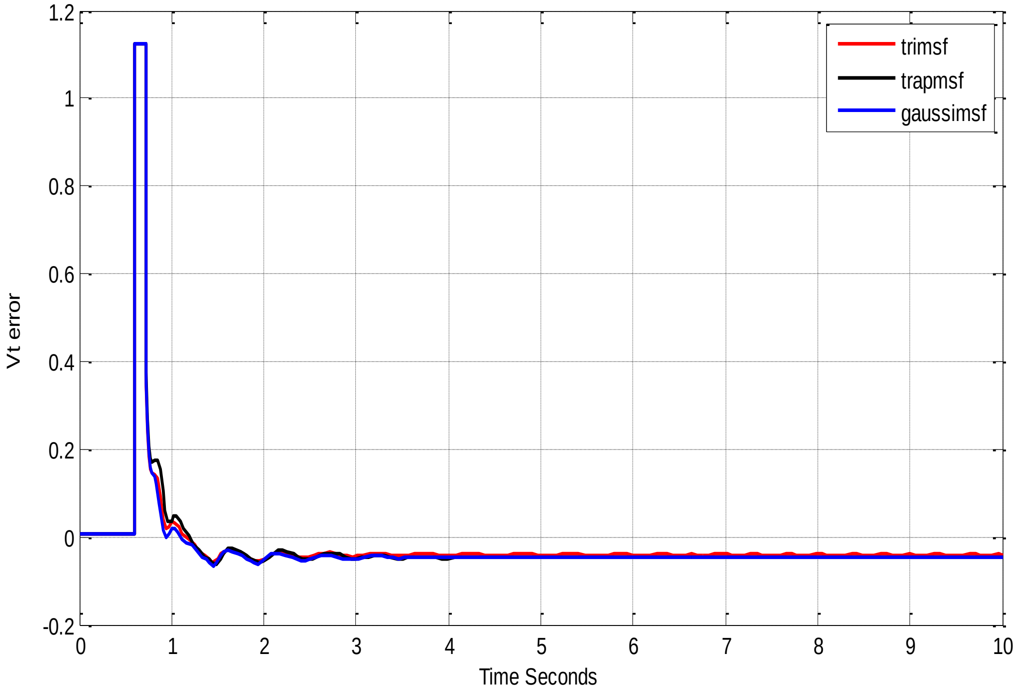
Table (4.2) *Evaluation of ISE for Each MF with different fault Interval for Exertion Time*

Figure No.	***Member function Type***	***ISE value***	***Time interval of Fault Exertion***
Figure (4.7)	***Triangular function***	0.1832	(0.6) to (0.73)
	Trapezoidal function	0.2146	
	Gaussian function	0.1874	
Figure (4.8)	***Triangular function***	0.225	(0.6) to (0.76)
	Trapezoidal function	0.2328	
	Gaussian function	0.2298	
Figure (4.9)	***Triangular function***	0.2827	(0.6) to (0.79)
	Trapezoidal function	0.2966	
	Gaussian function	0.2887	
Figure (4.10)	***Triangular function***	unstable	(0.6) to (0.8)
	Trapezoidal function	0.3511	
	Gaussian function	0.3288	
Figure (4.11)	***Triangular function***	unstable	(0.6) to (0.81)
	Trapezoidal function	unstable	
	Gaussian function	unstable	

Increasing the end time up to 0.81 seconds will lead to unsatisfactory behaviors resulting from all types of controllers. This critical time (0.81second) will shows unstable characteristics as shown in Figure (4.11).

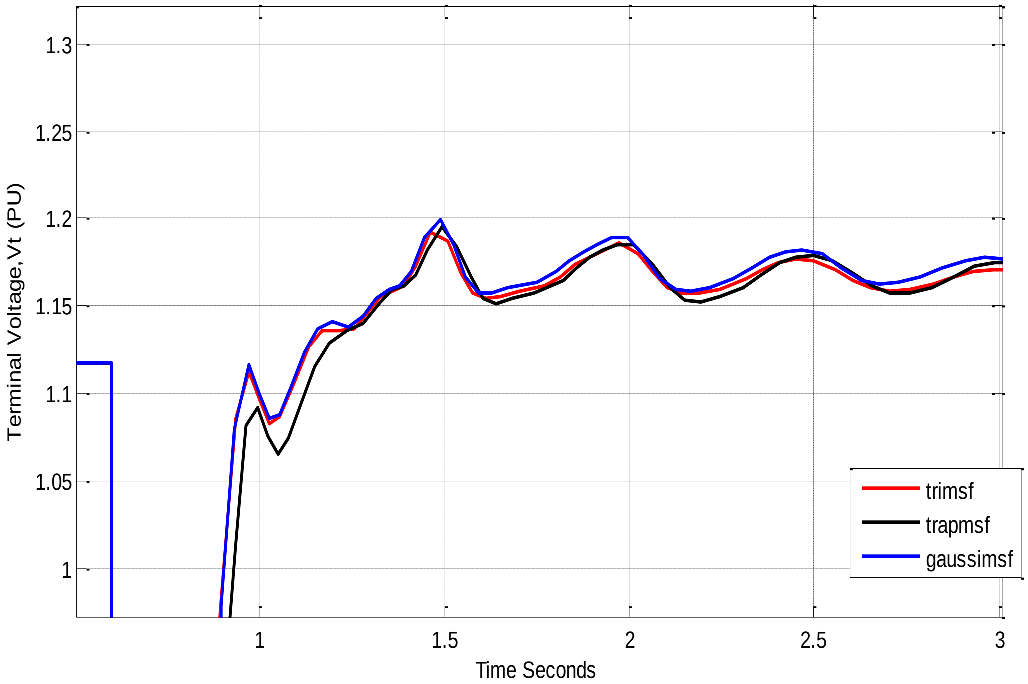


a)Terminal voltage responses.

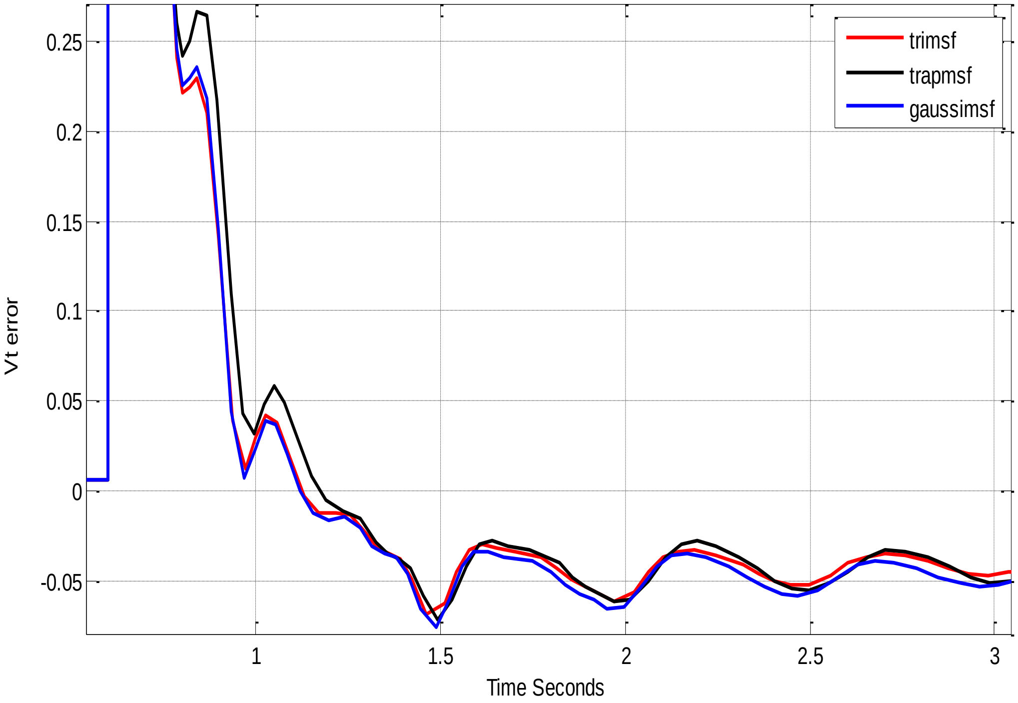


b) Voltage errors (between reference and actual voltages).

Figure (4.7) *Terminal and Error voltages Responses with different MFs at worst case of load condition* ($R_e = X_e = 0$)*and with time duration* (0.6) to (0.73) *seconds*

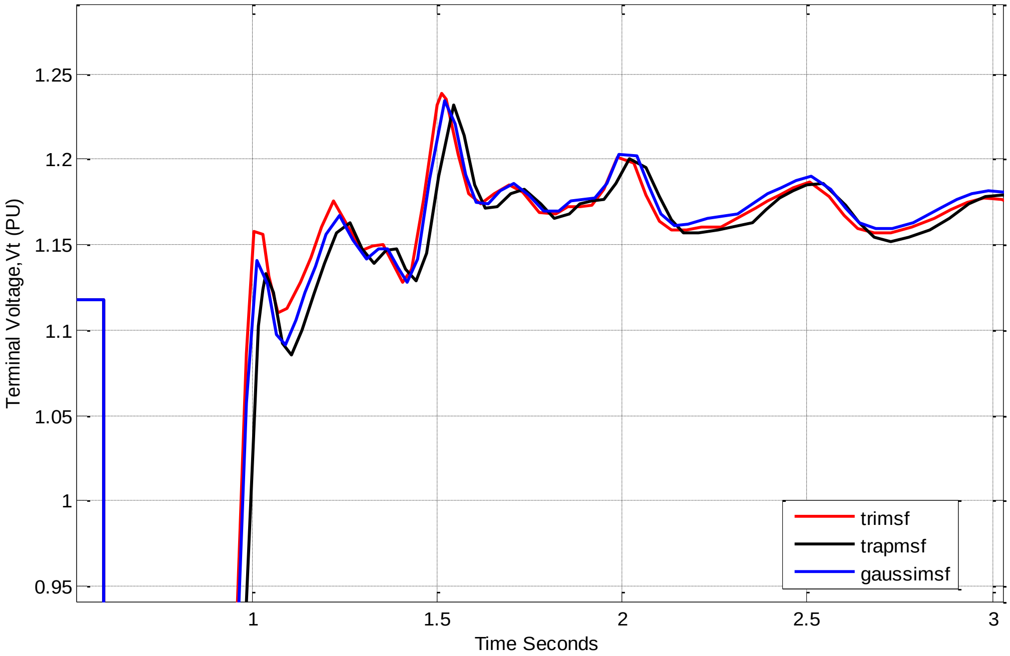


a)Terminal voltage responses.

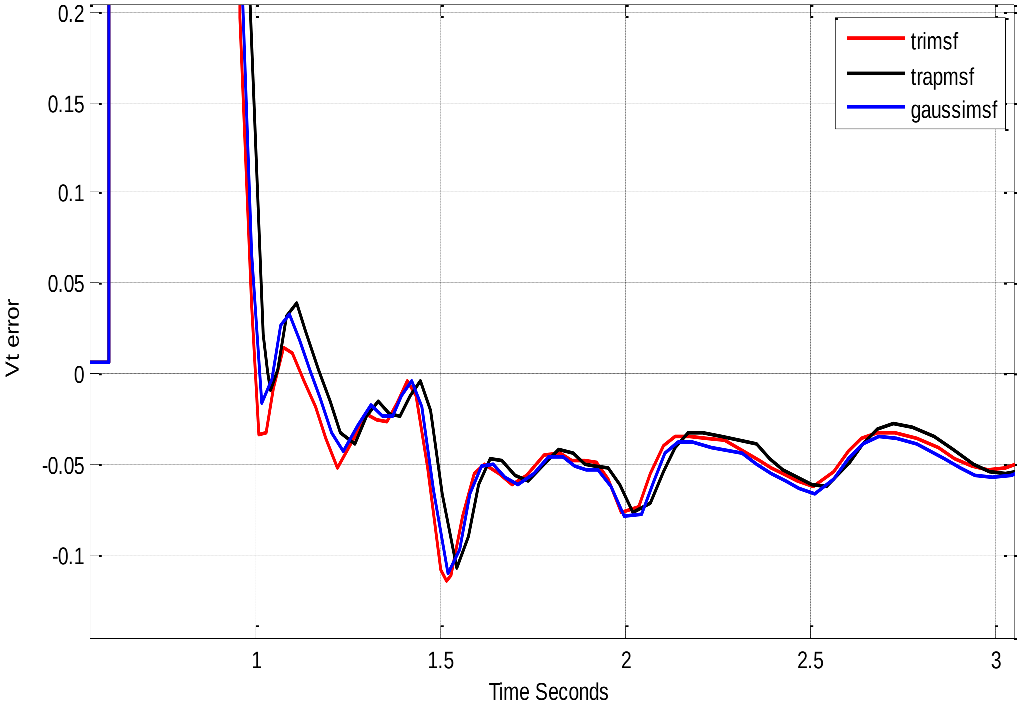


b) Voltage errors (between reference and actual voltages).

Figure (4.8) *Terminal and Error voltages Responses with different MFs at worst case of load condition* ($R_e= X_e=0$) *and with time duration* (0.6) to (0.76) *seconds.*

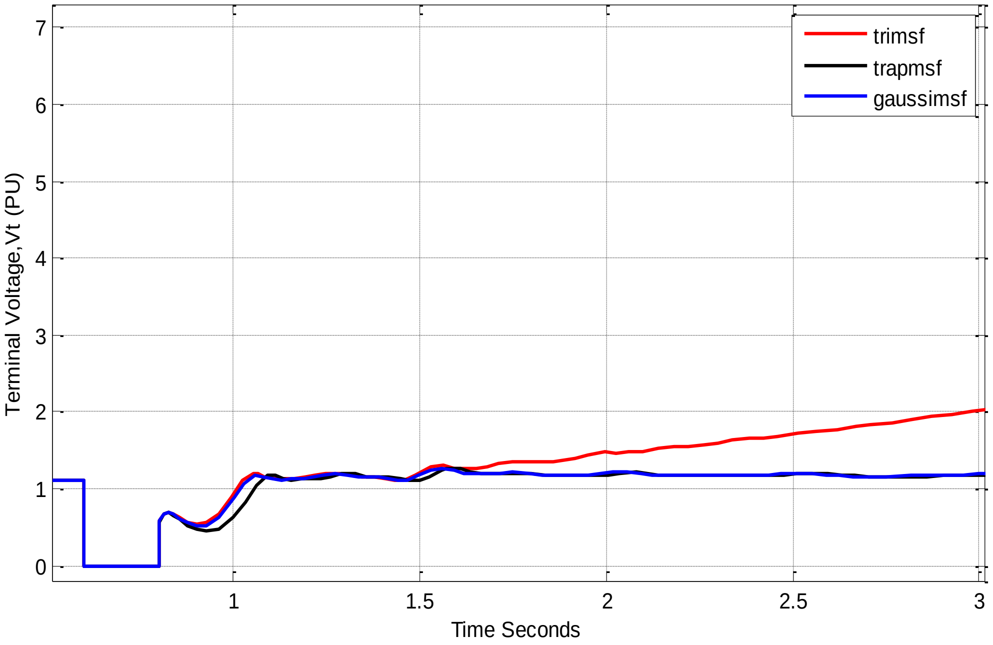


a)Terminal voltage responses.

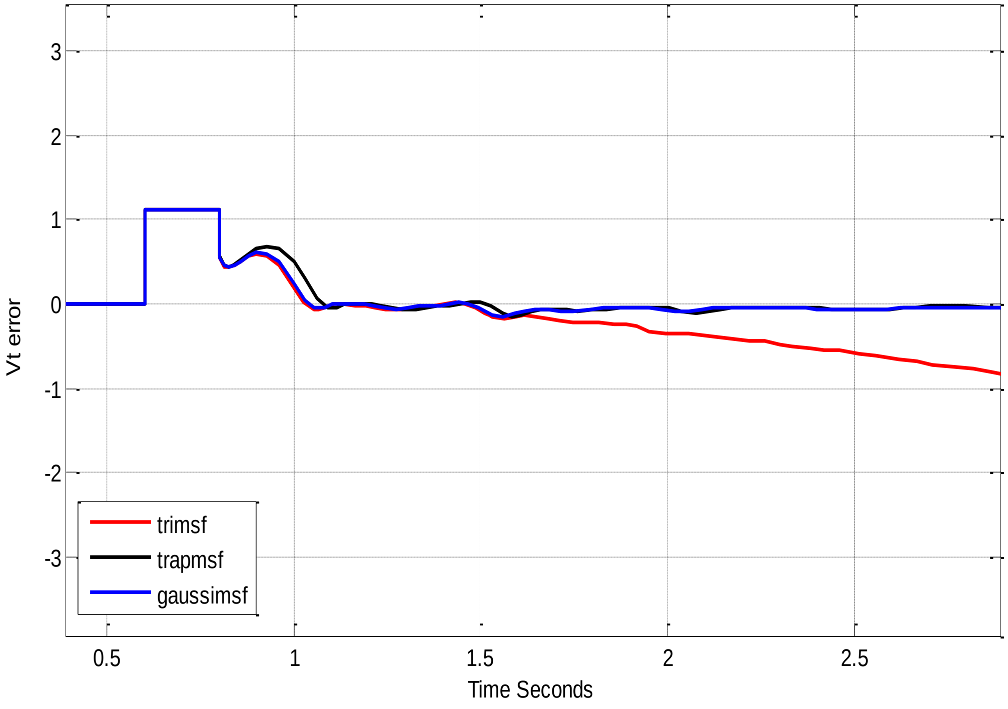


b) Voltage errors (between reference and actual voltages).

Figure (4.9) *Terminal and Error voltages Responses with different MFs at worst case of load condition* (R_e= X_e=0) *and with time duration* (0.6) to (0.79) *seconds.*

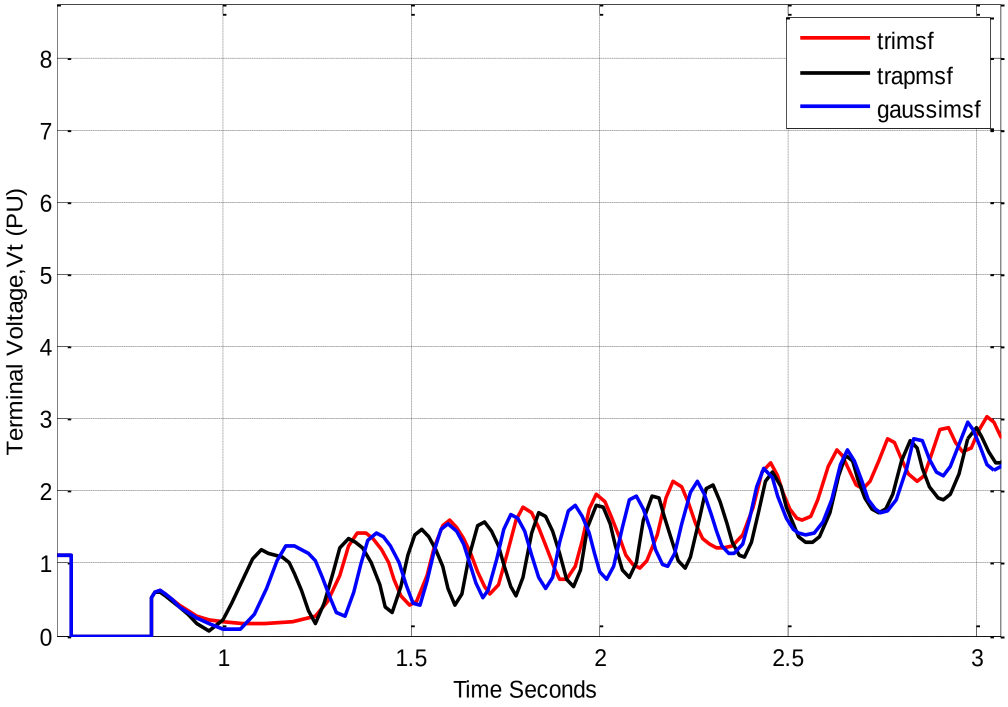


a)Terminal voltage responses.

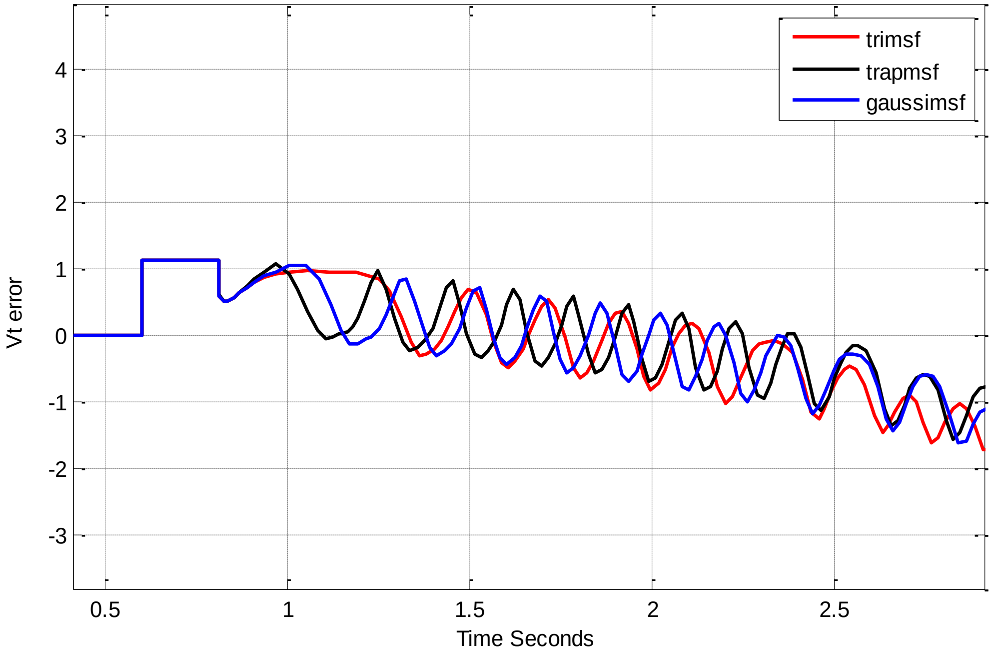


b) Voltage errors (between reference and actual voltages).

Figure (4.10) *Terminal and Error voltages Responses with different MFs at worst case of load condition* ($R_e= X_e=0$) *and with time duration* (0.6) to (0.8) *seconds.*



a)Terminal voltage responses.



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

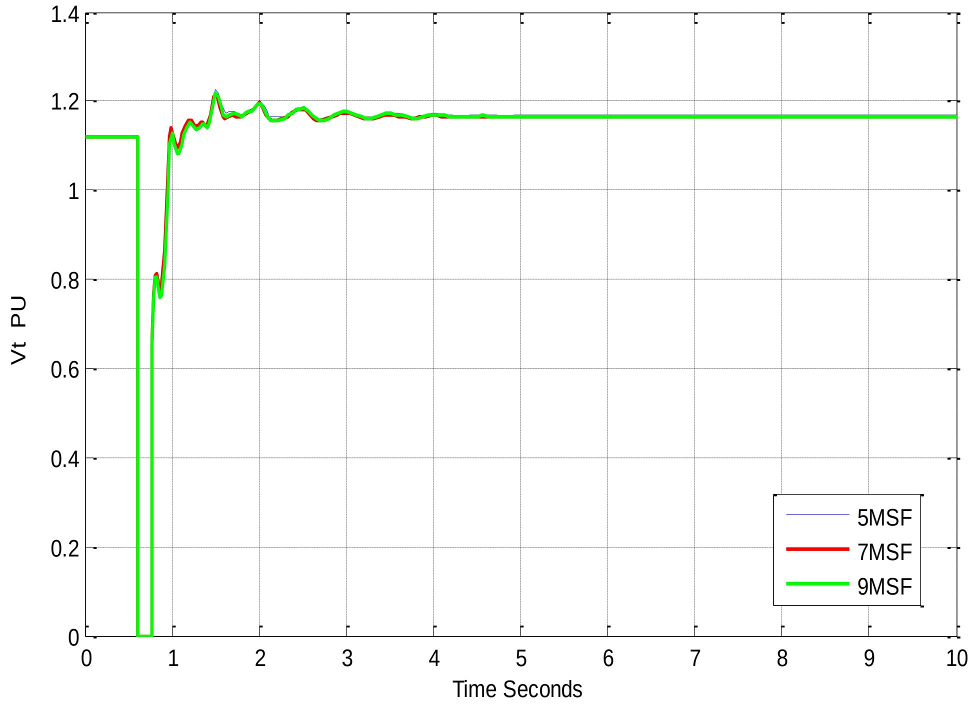
Figure (4.11) *Terminal and Error voltages Responses with different MFs at worst case of load condition* ($R_e = X_e = 0$) *and with time duration* (0.6) to (0.81) *seconds.*

The next test on FL-controller is to show the effectiveness of the controller when the number of MFs is changed for specified fault exertion duration and for specified type of MFs. The triangular function is elected as the function type of FL controller. The ISE reports are listed into Table (2.3). It has to be emphasized here that the short–circuit fault condition is again applied.

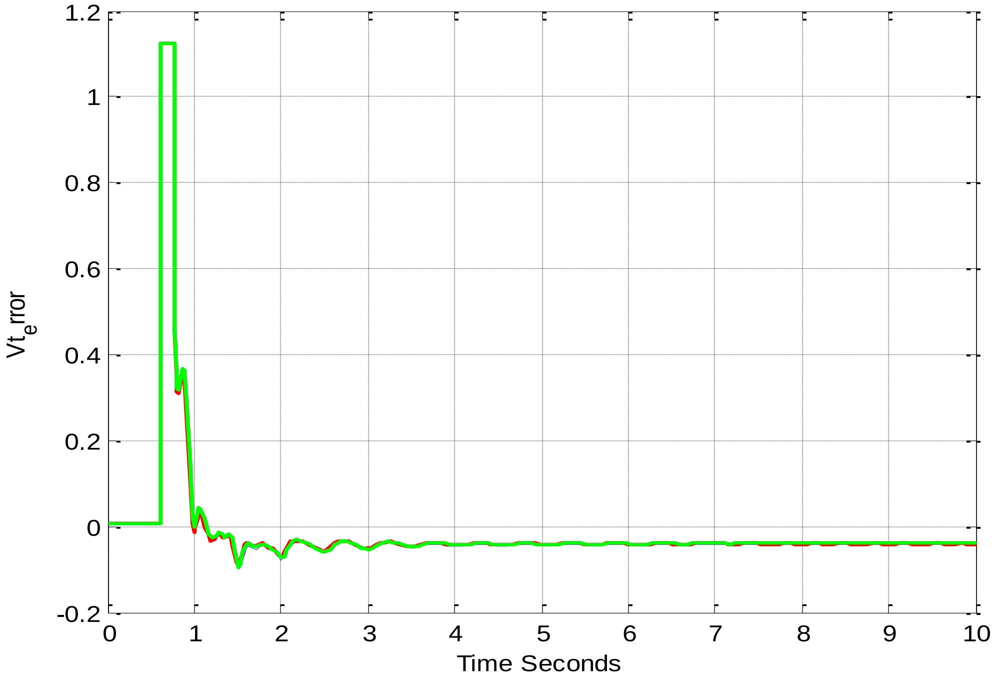
One can conclude from Figures (4.12), (4.13) and (4.14) and Table (4.3) that no significance difference is found in the voltage responses when the number of MFs is changed. Moreover, when fault exertion time width is extended to be [0.6, 0.8] seconds, the system comes into unstable behavior irrespective with number of MFs. In other words, the system response would increase without bound even with case that the FL controller has maximum number of 9 MFs.

Table (4.3) *Determination of ISE with different fault exertion times and different number of MF (The triangular function is selected)*

Figure No.	***Number of MFs***	***ISE***	***Time interval of Fault Exertion***
Figure (4.12)	**5**	0.264	(0.6 to 0.78) *sec.*
	7	0.2592	
	9	0.2614	
Figure (4.13)	***5***	0.2911	(0.6 to 0.79) *sec.*
	7	0.2827	
	9	0.2872	
Figure (4.14)	***5***	*unstable*	(0.6 to 0.8) *sec.*
	7	*unstable*	
	9	*unstable*	

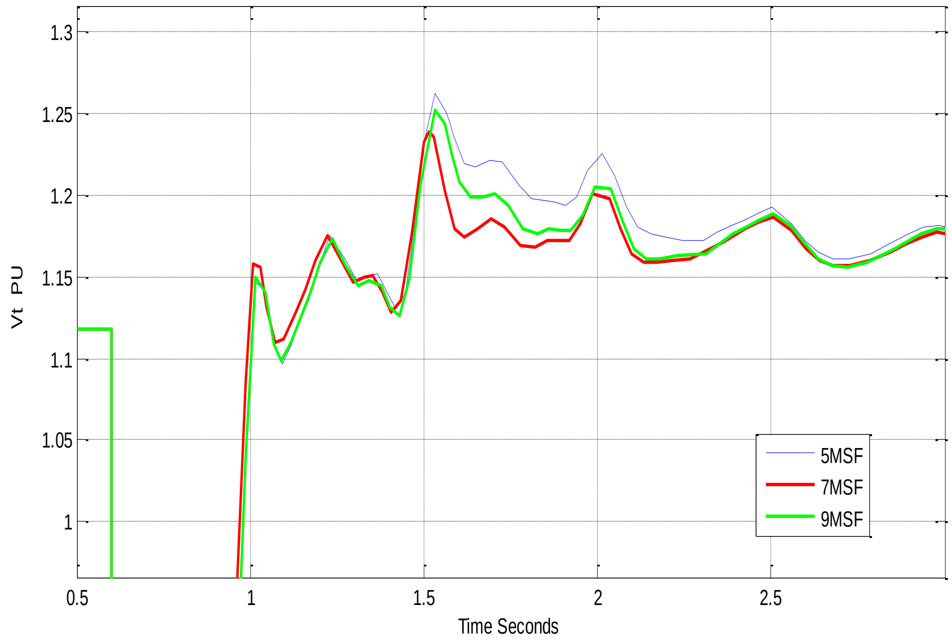


a)Terminal voltage responses.

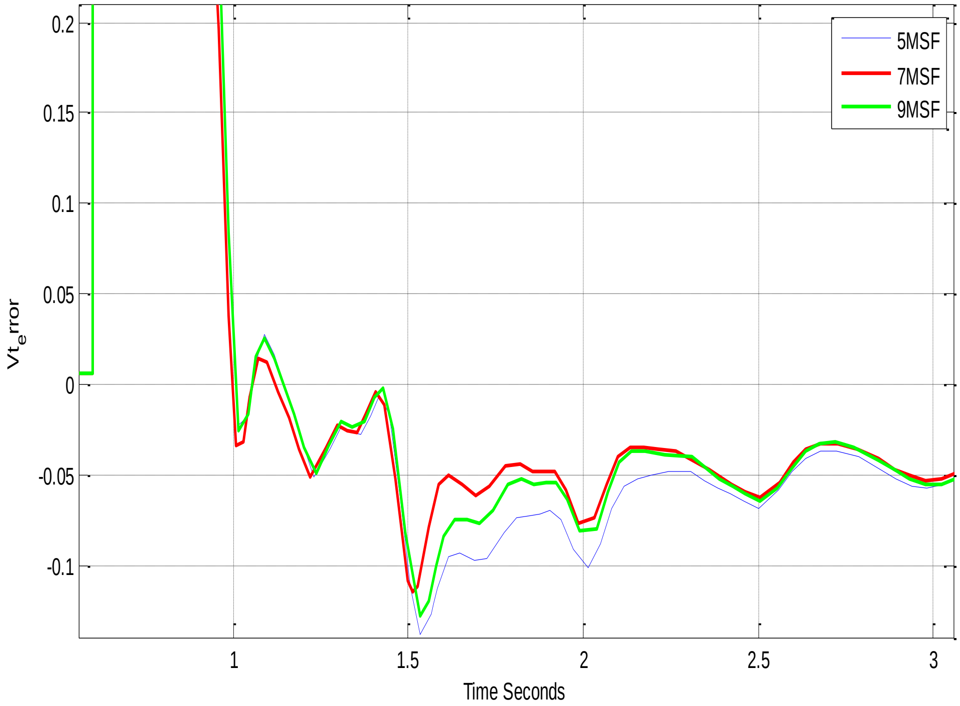


b) Voltage errors (between reference and actual voltages).

Figure (4.12) *Terminal and Error voltages Responses with different number of MFs at worst case of load condition* ($R_e = X_e = 0$) *and with time duration* (0.6) to (0.78) *seconds.*



a)Terminal voltage responses.



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

Figure (4.13) *Terminal and Error voltages Responses with different number of MFs at worst case of load condition* ($R_e = X_e = 0$) *and with time duration* (0.6) to (0.79) *seconds*

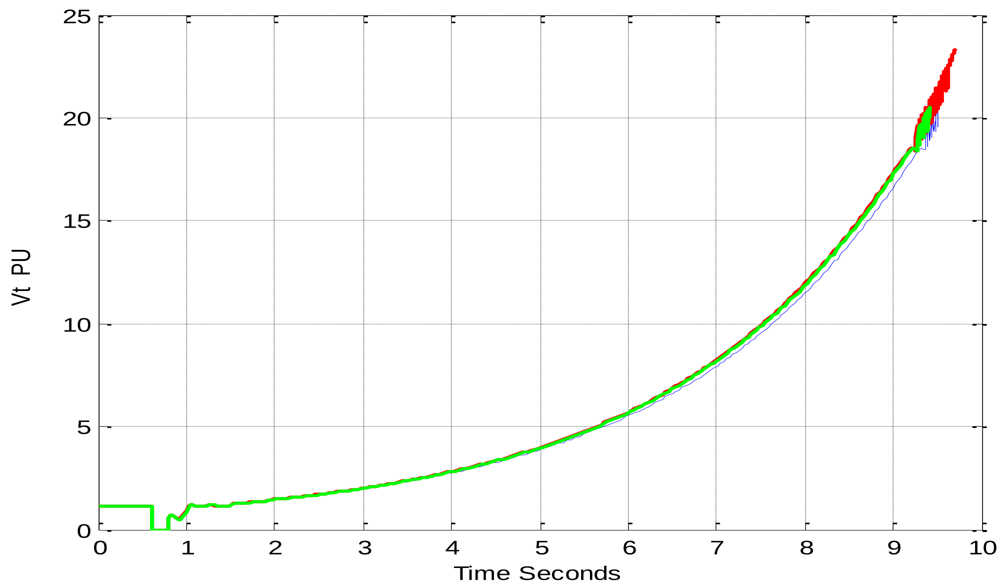


Figure (4.14) *Terminal Response with different number of MFs at worst case of load condition* ($R_e = X_e = 0$) *and with time duration* (0.6) to (0.8) *seconds.*

4.4 <u>Effect of change rules as in the two figures:</u>

In what follow, the elements of knowledge base are selected as the next design parameters. The zero diagonal is assumed fixed, while the elements on both sides are changed. Again, the fault exertion time interval will be varied and the robustness of the FL controller (with every setting of knowledge base entries) will be examined. The best set of knowledge base is those which enable its corresponding FL controller to withstand longer fault exertion time interval. Table (4.4) and (4.5) shows two pairs of knowledge bases. The elements of Table (4.5) are the same as those of Table (4.4), but their positions are reversed around the zero diagonal.

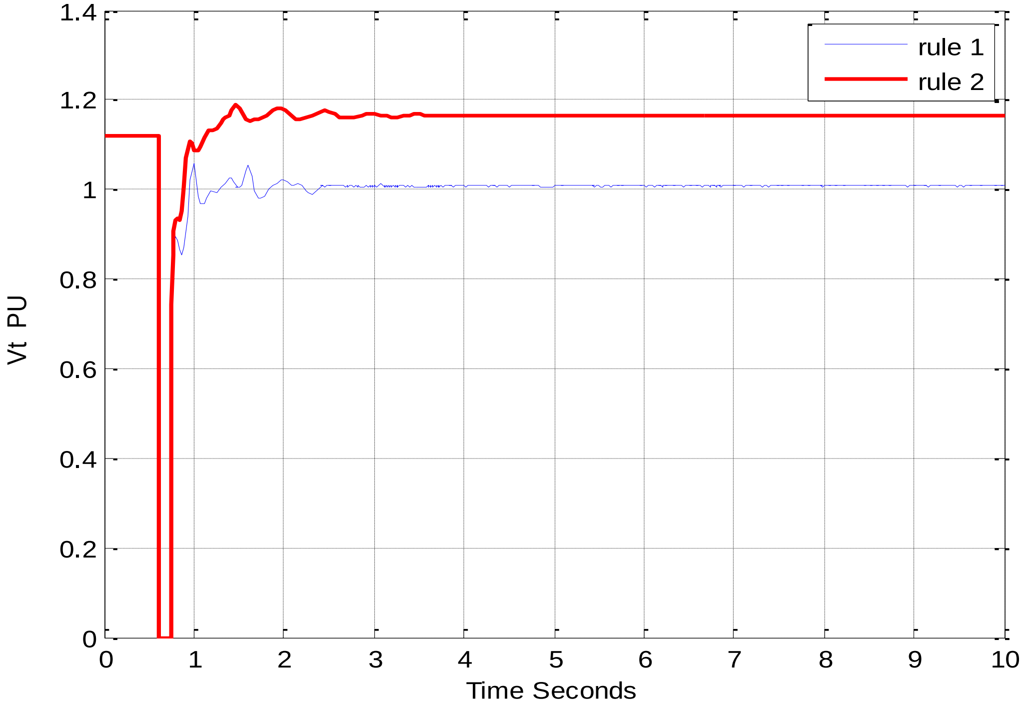
Table (4.4) *knowledge base of the second FL controller(rule2)*

ΔE								
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NM	NM	NS	Z	PS
	NS	NL	NM	NM	NS	Z	PS	PM
	Z	NM	NM	NS	Z	PS	PM	PM
	PS	NM	NS	Z	PS	PM	PM	PL
	PM	NS	Z	PS	PM	PM	PL	PL
	PL	Z	PS	PM	PL	PL	PL	PL

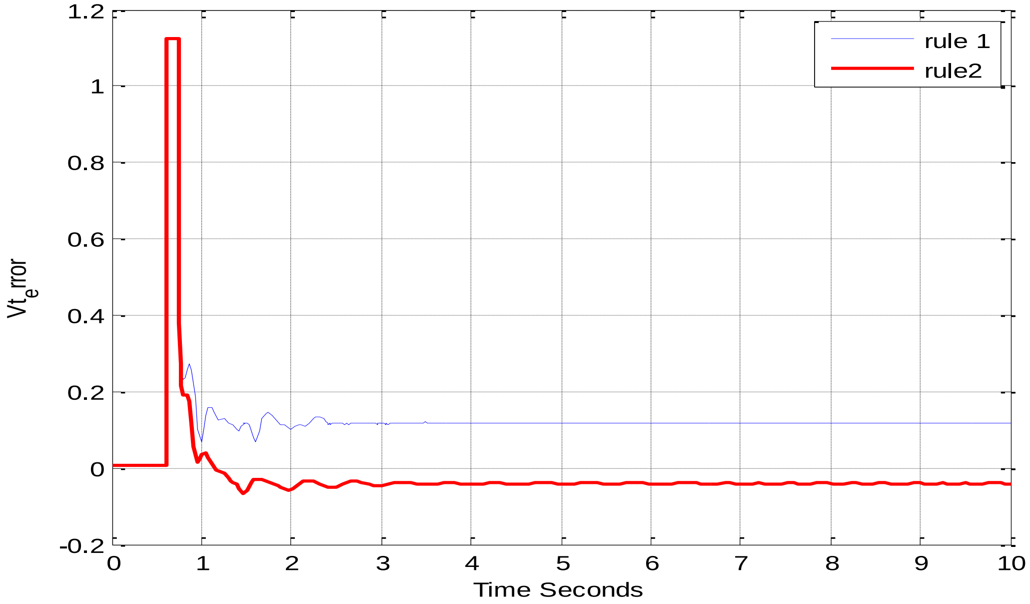
Table (4.5) *knowledge base of the first FL controller(rule 1)*

		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	PL	PL	PL	PL	PM	PS	Z
	NM	PL	PL	PM	PM	PS	Z	NS
	NS	PL	PM	PM	PS	Z	NS	NM
	Z	PM	PM	PS	Z	NS	NM	NM
	PS	PM	PS	Z	NS	NM	NM	NL
	PM	PS	Z	NS	NM	NM	NL	NL
	PL	Z	NS	NM	NL	NL	NL	NL

Figures (4.15) shows the terminal voltage responses due to FL controllers having Table (4.4) and (4.5) as their knowledge base, respectively. The fault exertion time interval is selected to be (0.6-0.75) and the worst short circuit condition is considered. One can easily see from the figure that FL controller based on knowledge base given by Table (4.4) has less ISE value (ISE= 0.2105) than that based on Table (4.5) (ISE= 0.3262).



a)Terminal voltage responses.



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

Figure (4.15) *Terminal and Error voltages Responses with knowledge Base given by Table (4.4) and (4.5) at worst case of load condition* (R_e = X_e=0) *and with time duration* (0.6) to (0.75) *seconds.*

Table (4.6) *knowledge base of the first FL controller (rule 3)*

		ΔE						
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NM	NM	Z
	NM	NL	NL	NL	NM	NM	Z	PM
	NS	NL	NL	NM	NM	Z	PM	PM
	Z	NL	NM	NM	Z	PM	PM	PL
	PS	NM	NM	Z	PM	PM	PL	PL
	PM	NM	Z	PM	PM	PL	PL	PL
	PL	Z	PM	PM	PL	PL	PL	PL

Table (4.7) *knowledge base of the first FL controller (rule 4)*

		ΔE						
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NL	NM	NS	Z	PS
	NS	NL	NL	NM	NS	Z	PS	PM
	Z	NL	NM	NS	Z	PS	PM	PL
	PS	NM	NS	Z	PS	PM	PL	PL
	PM	NS	Z	PS	PM	PL	PL	PL
	PL	Z	PS	PM	PL	PL	PL	PL

Table (4.8) *knowledge base of the first FL controller (rule 5)*

ΔE								
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NL	NM	NS	Z	PS
	NS	NL	NL	NM	NS	Z	PS	PS
	Z	NL	NM	NS	Z	PS	PS	PM
	PS	NM	NS	Z	PS	PS	PM	PM
	PM	NS	Z	PS	PS	PM	PM	PL
	PL	Z	PS	PS	PM	PM	PL	PL

Table (4.9) *knowledge base of the first FL controller (rule 6)*

ΔE								
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NS	NS	Z
	NM	NL	NL	NM	NM	NS	Z	PS
	NS	NL	NM	NM	NS	Z	PS	PS
	Z	NM	NM	NS	Z	PS	PS	PM
	PS	NS	NS	Z	PS	PS	PM	PL
	PM	NS	Z	PS	PS	PM	PL	PL
	PL	Z	PS	PS	PM	PL	PL	PL

Table (4.10) *knowledge base of the first FL controller (rule7)*

ΔE								
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NM	NS	Z
	NM	NL	NL	NL	NM	NS	Z	PS
	NS	NL	NL	NM	NS	Z	PS	PS
	Z	NL	NM	NS	Z	PS	PS	PM
	PS	NM	NS	Z	PS	PS	PM	PM
	PM	NS	Z	PS	PS	PM	PM	PM
	PL	Z	PS	PS	PM	PM	PM	PL

Table (4.11) *knowledge base of the first FL controller (rule 8)*

ΔE								
		NL	***NM***	***NS***	***Z***	***PS***	***PM***	***PL***
E	***NL***	NL	NL	NL	NL	NL	NM	Z
	NM	NL	NL	NL	NL	NM	Z	PS
	NS	NL	NL	NL	NM	Z	PS	PS
	Z	NL	NL	NM	Z	PS	PS	PM
	PS	NL	NM	Z	PS	PS	PM	PL
	PM	NM	Z	PS	PS	PM	PL	PL
	PL	Z	PS	PS	PM	PL	PL	PL

Eight different knowledge bases have been considered and the performances of the corresponding FL controllers are assessed based on ISE measure. Table (4.12) gives the details of ISE values for those various FL controllers with two period of load application. One can see from the table that the accumulated square errors for FL controllers based on Tables (4.7), (4.8) and (4.10) are the same. Also, this is the case with Table (4.4) and (4.9). However, Table (4.12) shows that the minimum ISE has been reported for the knowledge base corresponding to Table (4.6).

Table (4.12) *Different Knowledge Bases for Two Selected Time Intervals o f Fault Application*

Knowledge Base	***ISE***	***Time interval of Fault Exertion***
Table (4.4)	0.2592	(0.6 to 0.78) *sec.*
Table (4.5)	unstable	
Table (4.6)	0.2432	
Table (4.7)	0.2591	
Table (4.8)	0.2591	
Table (4.9)	0.2592	
Table (4.10)	0.2591	
Table (4.11)	0.2482	
Table (4.4)	*unstable*	(0.6 to 0.8) *sec.*
Table (4.5)	*unstable*	
Table (4.6)	*unstable*	
Table (4.7)	*unstable*	
Table (4.8)	*unstable*	
Table (4.9)	*unstable*	
Table (4.10)	*unstable*	
Table (4.11)	0.31	

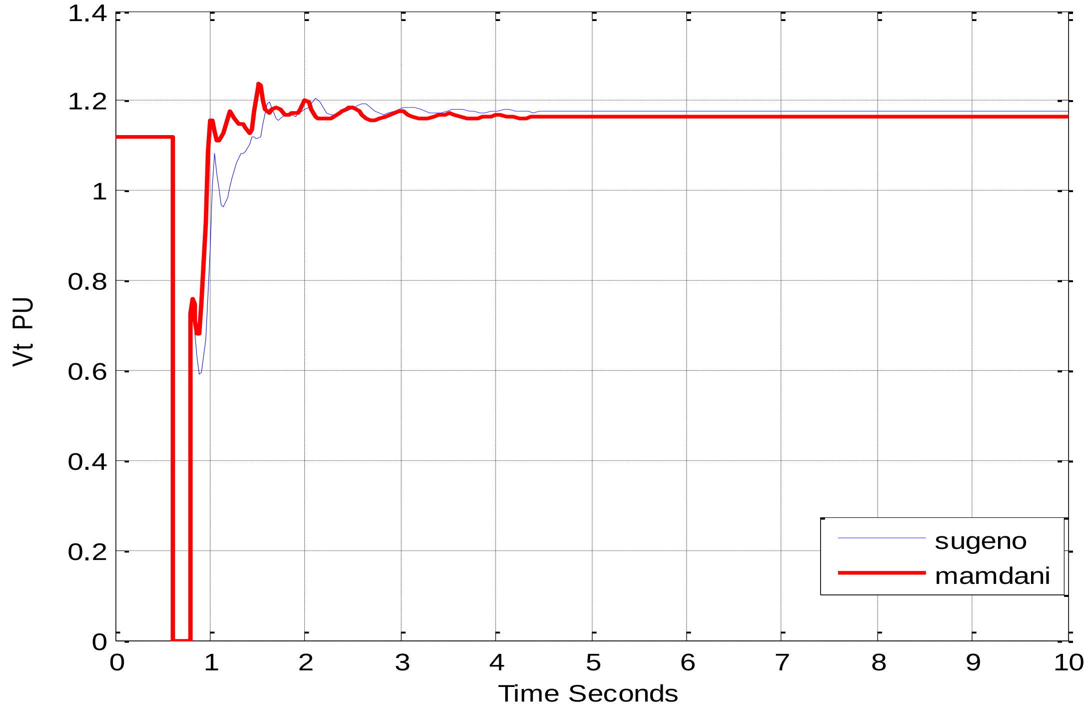
If the duration time is extended to range of (0.6-0.8) second, all FL controllers would fail except that one whose knowledge base is equivalent to Table (4.11). However, no FL controller would succeed to give stable responses or characteristics if further extension of time interval (0.6-0.81) would occur. All the above results are based on the fuzzification method of Mamdani. Another fuzzification method which is also famous in most fuzzy logic applications is called Sugeno method. Let us now compare the performance of two FL controllers; one is based on Mamdani fuzzification method and the other relies on Sugeno method. The load condition change is still the short circuit case and the load exertion interval is the design parameter by which one can decide the validity of certain controller.

Figures (4.16), (4.17) show the responses due to the two FL controllers based on two different fuzzification methods and for two different time intervals. Also, Table (4.13) lists the performances of these controllers.

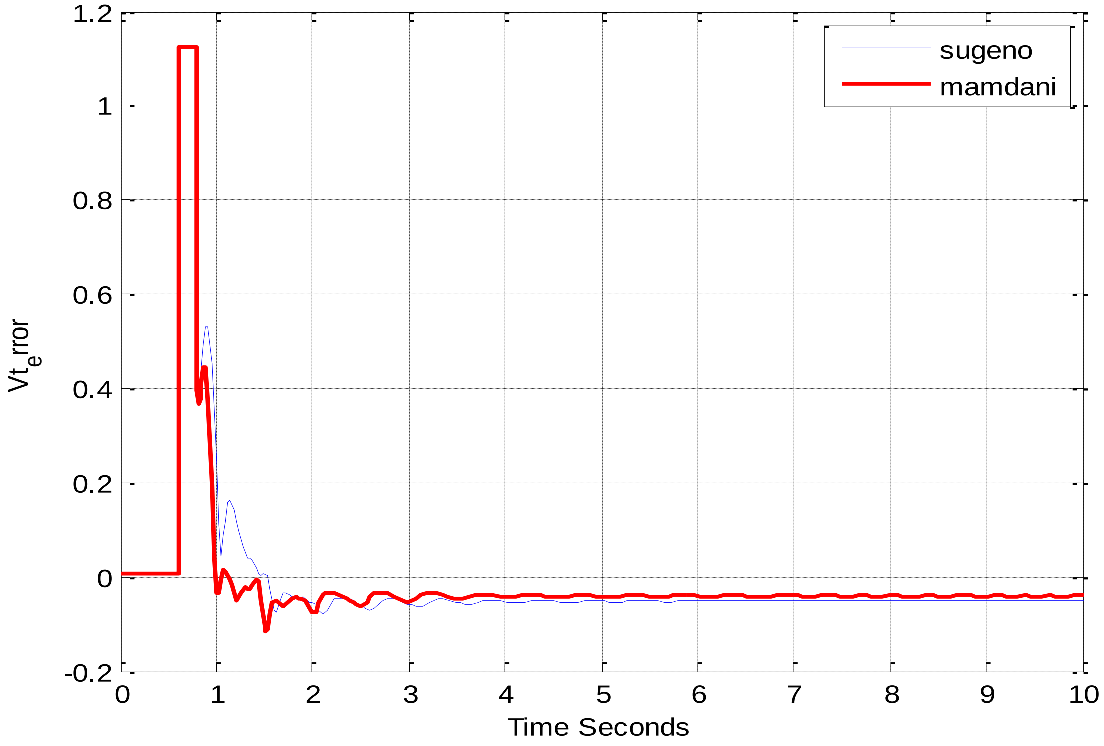
Table (4.13) *Performance of two FL controllers based on Different fuzzification methods.*

Figure No.	***Fuzzification Method***	***ISE value***	***Time interval of Fault Exertion***
Figure (4.16)	*Mamdani*	0.3113	(0.6) to (0.76)
	Surgeno	0.2827	
Figure (4.17)	*Mamdani*	*unstable*	(0.6) to (0.8)
	Surgeno	0.3858	

One can conclude from Figures (4.16) and (4.17) and Table (4.13) that for the time interval (0.6-0.76), the FL controller based on Sugeno method has less ISE value than that based on Mamdani. On the other hand, if the time interval is increased to include the critical end time of 0.8 second, the responses based on Mamdani will breakdown and would increase without bound; while those relied on Sugeno method would keep the responses with satisfactory performance.

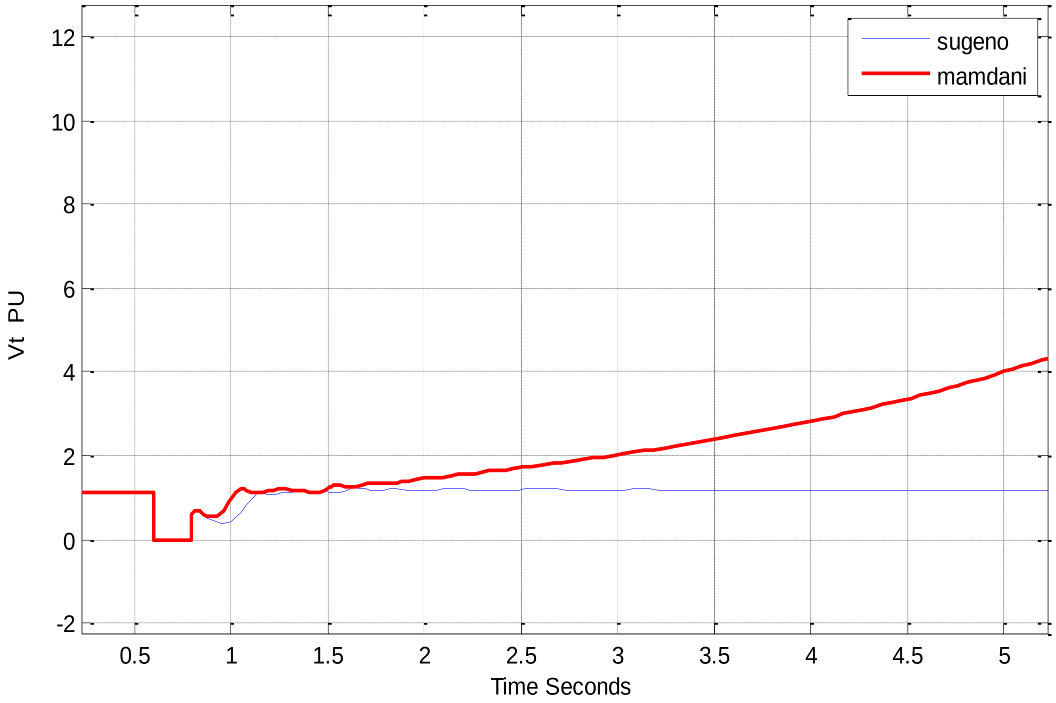


a)Terminal voltage responses.

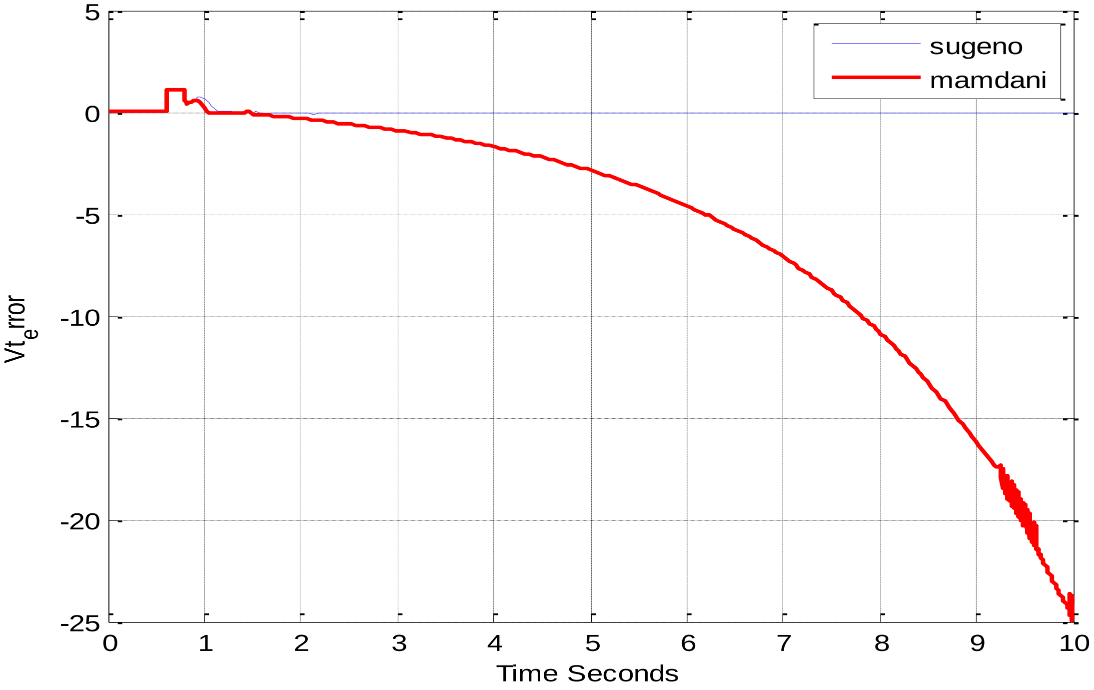


b) Voltage errors (between reference and actual voltages).

Figure (4.16) *Terminal and Error voltages Responses with two different fuzziffication methods, with worst case of load condition* $(R_e = X_e = 0)$ *at time range* (0.6-0.76) *seconds*



a)Terminal voltage responses.



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

Figure (4.17) *Terminal and Error voltages Responses with two different fuzziffication methods, with worst case of load condition* (R_e= X_e=0)*at time range* (0.6-0.8) *seconds*

Chapter-5

Conclusion and Future Work

5.1 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 evaluated and compared at different machine loading conditions. Also, the 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 outperform the conventional controller.
2. If the fault duration time is 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, the FL controller shows better characteristics than DC1 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 show that for certain time duration, the DC1 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 controller.
4. It is interesting to consider the effect of changing the FL parameters on the performance FL controller itself. The type of MF, number of MFs and knowledgebase elements will be considered as the design parameters for this assessment. For specified knowledge-base elements and fixed number of MFs, the performance of intelligent controller has been evaluated based on type of MF and the duration length of load exertion. In this case, three types has been considered; triangular, trapezoidal and Gaussian function. The results showed that the FL controller with triangular MFs could withstand shorter fault duration than with other types. However, the FL controller with trapezoidal and Gaussian function types lacks

the ability to keep stable characteristic with extended time duration; as the response would increase without bound at specified extended time limit.

5. The next test on FL-controller is to show the effectiveness of the controller when the number of MFs is changed for specified fault exertion duration and type of MFs. The triangular function is selected to be the function type of FL controller and the short-circuit fault condition is still considered here. One can conclude from the simulated results that no significance difference is found in the voltage responses when the number of MFs is changed. Moreover, extension of fault exertion duration length would lead to instability problems irrespective with number of MFs.
6. The effectiveness of FL controller will be examined against length variation of fault period with different knowledge bases. Eight different knowledge-bases have been considered, and one can conclude that the knowledge-base of Table (4.11) could enable the FL controller to withstand longer time duration without loss its stability characteristics.
7. For the purpose of comparison, the Sugeno method is included as another fuzzification candidate. The performances of FL controller with two different fuzzification methods have been examined. The simulation is started with knowledge-base of Table (4.4). The results show that the FL controller based on sugeneo method could withstand longer fault duration and gives less ISE compared to that one based on Mamdani fuzzification method.

5.2 Suggestion for Future Work:

It is interesting to suggest the following modern techniques to enhance the present work:

1. The FL controller can be replaced by Fuzzy model Reference Logic controller for on-line compensation of machine parameter. The tuning can be performed on output and input scaling gains of FL controller or to continuously change the position of MFs to reach the requirements.
2. Applying the direct or adaptive FL controller to improve the synchronous generator stability in terms of voltage and frequency.
3. Modern optimization methods based on Artificial Neural Networks, Genetic Algorithm, Particle Swarm Optimization, Ecoli optimization technique can be employed to on-line tune the parameters of FL controller.

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APPENDIX –A

FUZZY CONTROLLER PROGRAM BY M.FILE MATLAB CODE

```
%Define function name
function [Efd]=SGFC3(E,DE)

 %%%to add 1st input parameter of E into FIS
FLCEfd =addvar(FLCEfd,'input','E',[-1 1]);
FLCEfd =addmf(FLCEfd,'input',1,'NL','trimf',[-1 -1 -0.6667]);
FLCEfd =addmf(FLCEfd,'input',1,'NM','trimf',[-1 -0.6667 -0.3333]);
FLCEfd =addmf(FLCEfd,'input',1,'NS','trimf',[-0.6667 -0.3333 0]);
FLCEfd =addmf(FLCEfd,'input',1,'Z','trimf',[-0.3333 0 0.3334]);
FLCEfd =addmf(FLCVF,'input',1,'PS','trimf',[0 0.3333 0.6667]);
FLCEfd =addmf(FLCEfd,'input',1,'PM','trimf',[0.3333 0.6667 1]);
FLCEfd =addmf(FLCEfd,'input',1,'PL','trimf',[0.6666 1 1]);

%%%to add 2nd input parameter of DE into FIS
FLCEfd =addvar(FLCEfd,'input','DE',[-3 3]);
FLCEfd =addmf(FLCEfd,'input',2,'NL','trimf',[-3 -3 -2]);
FLCEfd =addmf(FLCEfd,'input',2,'NM','trimf',[-3 -2 -1]);
FLCEfd =addmf(FLCEfd,'input',2,'NS','trimf',[-2 -1 0]);
FLCEfd =addmf(FLCEfd,'input',2,'Z','trimf',[-1 0 1]);
FLCEfd =addmf(FLCEfd,'input',2,'PS','trimf',[0 1 2]);
FLCEfd =addmf(FLCEfd,'input',2,'PM','trimf',[1 2 3]);
FLCEfd =addmf(FLCEfd,'input',2,'PL','trimf',[2 3 3]);

%define the output name, range ,and number
FLCEfd =addvar(FLCEfd,'output','VF',[-5.282 10.564]);
FLCEfd =addmf(FLCEfd,'output',1,'NL','trimf', [-5.282 -5.282 -2.641]);
FLCEfd =addmf(FLCEfd,'output',1,'NM','trimf', [-5.282 -2.641 0]);
FLCEfd =addmf(FLCEfd,'output',1,'NS','trimf', [-2.641 0 2.641]);
FLCEfd =addmf(FLCEfd,'output',1,'Z','trimf',  [0 2.641 5.282]);
FLCEfd =addmf(FLCEfd,'output',1,'PS','trimf', [2.641 5.282 7.923]);
FLCEfd =addmf(FLCEfd,'output',1,'PM','trimf', [5.282 7.923 10.564]);
FLCEfd =addmf(FLCEfd,'output',1,'PL','trimf', [7.923 10.564 10.564]);

%%% add Rule_base 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 ];

FLCVF=addrule(FLCEfd,Rule1);
ruleedit(FLCVF)

%%%%%showrule(FLCEfd)
showrule(FLCEfd);

%Show rule surface of controller
gensurf(FLCEfd);

% FLCEfd _input=[E DE];
Efd=evalfis([E DE], FLCEfd);
```

APPENDIX B

The machine parameters and coefficients

GENERATOR	
Type	Synchronous Generator
Rated power	160 MVA
Rated voltage	15 KV
Rated Frequency	60 HZ
P_O	0.8
Q_O	0.496
V_O	1
$T_{do}^{'}$	5.9 s
$T_{qo}^{'}$	0.075s
Reactances and Resistances	
R_a	0.001096
R_e	0.01
X_d	1.7
X_q	1.64
$X_d^{'}$	0.245
x_e	0.2
Turbine and Governor Coefficient	
K_{RH}	0.3
M	4.74
D	0
T_{RH}	8s
T_{CH}	0.05 s
$\mathbf{T_{SR}}$	0.1 s
K_{G}	3.5
T_{SM}	0.2 s
ω_{r}	1
$\omega_{\boldsymbol{o}}$	1
Exciter	
K_E	400
T_E	0.052 s
T_F	1s
K_F	0.025
K_{A}	50

$\boldsymbol{T_A}$	0.06
AEx	0.0012
BEx	1.264
VRmax	1
VRmin	-1