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DEVELOPMENT OF INTERVAL TYPE-2 FUZZY BASED CONTROL MODEL AND SIMULATION OF STEAM TURBINE GOVERNING SYSTEM OF POWER PLANT

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ABSTRACT

The issue of power system stability is becoming more crucial. In deregulated power systems, competition could push the system near its security limit. The governing controls of generator play an important role in improving the dynamic and transient stability of power system. In this paper, we present an interval type-2 fuzzy logic based method for governing control including efficient terminal voltage regulation. Interval type-2 Fuzzy logic is applied to generate compensating signals to modify the controls during system disturbances. The oscillation of internal generator angles is observed to indicate the good performance of proposed control scheme, very over a wide range. In this work, development of Interval Type-2 Fuzzy based Model of steam turbine Governing System of Power Plant is proposed. The power system transient terminal voltage and frequency stability enhancement have been well investigated and studied through the following efforts.

Membership functions in interval type-2 fuzzy logic controllers are called footprint of uncertainty (FOU), which is limited by two membership functions of adaptive network based fuzzy inference systems; they were upper membership function (UMF) and lower membership function (LMF). The performances of the proposed controllers were evaluated and discussed on the basis of the simulation results. An experiment set up of power system governing system was built and used to verify the performance of IT-2FLC controller.
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KEYWORDS: Steam Turbine, Governing System Control, Interval Type-2 Fuzzy Logic Controller, Foot Print of Uncertainty, Internal Generator Angle, PID Controller.

INTRODUCTION

Governing system is an important control system in the power plant as it regulates the turbine speed, power and participates in the grid frequency regulation. For starting, loading governing system is the main operator interface. Steady state and dynamic performance of the power system depends on the power plant response capabilities in which governing system plays a key role. With the development of electro- hydraulic governors, processing capabilities have been enhanced but several adjustable parameters have been provided. A thorough understanding of the governing process is necessary for such adjustment. The role of governing system in frequency control is also discussed. Power system stability issue has been studied widely. Generator control is one of the most widely applied in the power industry. This typically includes governing and excitation control. Fuzzy set theory has been widely used in the control area with some application to power systems. A simple fuzzy control is built up by a group of rules based on the human knowledge of system behaviour in power engineering area, fuzzy set theory is applied in power system control, planning and some other aspects. Fuzzy logic has also been applied to design power system stabilizers. Governing system behaviour is neglected in the design of excitation control. Part of the reason is the slow response of governing systems compared with the exciting system. However proper control of governing system is helpful in damping system oscillation and improving the transient stability.

Power system stability can be defined as the tendency of power system to react to disturbances by developing restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium (synchronism). Stability problems are therefore concerned with the behavior of the Synchronous Generator (SG) after they have been perturbed.

Generally, there are three main categories of stability analysis. They are namely steady state stability, transient stability and dynamic stability. Steady state stability is defined as the capability of the power system to maintain synchronism after a gradual change in power caused by small disturbances. Transient state stability refers to as the capability of a power system to maintain synchronism when subjected to a severe and sudden disturbance. The third category of stability, which is the dynamic stability is an extension of steady state stability, it is concerned with the small disturbances lasting long period of time. The generators are usually connected to an infinite bus where the terminal voltages (Vt) are held at a constant value. The study of SG control systems can roughly be divided into two main parts: voltage regulation and speed governing. Both of these control elements contribute to the stability of the machine in the presence of per durations. There are various methods of controlling a SG and suitability will depend on the type of machine, its application and the operating conditions. The governing controls of the generator play an important role in improving the dynamic stability of the power system. The presence of poorly damped modes of oscillation, and continuous variation in power system operating conditions arises some limitations in the conventional controllers. These limitations have motivated research into so-called intelligent control systems. Artificial Neural Networks (ANNs) have been used in the design of nonlinear adaptive controllers with various control objectives in the field of electrical power engineering, especially for the synchronous generator excitation and governor control.

Here we present development of Interval Type-2 Fuzzy based Control Model of steam turbine Governing System and excitation system of Power Plant, which compensates their control, inputs during faults. Two separate Interval Type-2 Fuzzy controllers have been developed to address both the damping of frequency deviation and terminal voltage oscillation problems. To present complete comparative analysis of the proposed control strategy with conventional PID controller, two separate fluctuations scenario have been employed. SIMULINK simulation model is built to study the dynamic behavior of conventional PID controlled synchronous machine and the performance of proposed controller.

The Interval Type-2 Fuzzy Logic Controller (IT2FLC) is credited with being an adequate methodology for designing robust controllers that are able to deliver a satisfactory performance in applications where the inherent uncertainty makes it difficult to achieve good results using traditional methods. As a result the IT2FLC has become a popular approach to mobile robot control in recent years. There are many sources of uncertainty facing the IT2FLC for power system governing control; we list some of them as follows:

(a) Uncertainties in inputs to the IT2FLC which translate to uncertainties in the antecedent Membership Functions (MFs) as the sensor measurements are typically noisy and are affected by the conditions of observation (i.e. their characteristics are changed by the environmental conditions such as wind, sunshine, humidity, rain, etc.).

(b) Uncertainties in control outputs which translate to uncertainties in the consequent MFs of the IT2FLC. Such uncertainties can result from the change of the actuators characteristics which can be due to wear, tear, environmental changes, etc.

(c) Linguistic uncertainties as the meaning of words that are used in the antecedent and consequent linguistic labels can be uncertain - words mean different things to different people. In addition, experts do not always agree and they often provide different consequents for the same antecedents. A survey of experts will usually lead to a histogram of possibilities for the consequent of a rule; this histogram represents the uncertainty about the consequent of a rule.

(d) Uncertainties associated with the use of noisy training data that could be used to learn, tune or optimize the IT2FLC. While traditionally, type- 1 FLCs have been employed widely in governing system control, it has become apparent in recent years that the type-1 FLC cannot fully handle high levels of uncertainties as its MFs are in fact completely crisp. The linguistic and numerical uncertainties associated with dynamic unstructured environments cause problems in determining the exact and precise MFs during the governing control IT2FLC design. Consequently, research has started to focus on the possibilities of higher order FLCs, such as interval type-2 FLCs that use interval type-2 fuzzy sets.

A traditional, type-1 FLC is not completely fuzzy, as the boundaries of its membership functions are fixed. This implies that there may be unforeseen traffic scenarios for which the existing membership functions do not suffice to model the uncertainties in the governing system control task. An IT2FLC can address this problem by extending a Footprint-of-Uncertainty (FOU) on either side of an existing type-1 membership function. In IT2, fuzzy logic the variation is assumed constant across the FOU, Hence the designation ‘interval’. The firstIT2 controllers are now emerging, in which conversion or retyping from fuzzy IT2 to fuzzy type-1 takes place before output. Not only does such a controller bring confidence that re-tuning will not be needed for when arriving traffic displays un-anticipated or un-modeled behavior but the off-line training period required to form the membership functions can be reduced. This paper extends an existing FLC for governing system control to an IT2FLC and compares the performances in the presence of measurement noise, which is artificially injected to test the relative robustness. Encouragingly, the governing response is equivalent to the successful type-1 FLC when the measurement noise is limited and under test results in a considerable improvement when the perturbations are large. This research is focused mainly on voltage and frequency stability of SG in a typical power system using fourth order model of synchronous generator.

MODELING OF SYNCHRONOUS GENERATOR

The overall accuracy of the power system stability is primarily decided by how correctly the Synchronous Generators within the system are modeled. The proposed simulation model is developed as a fourth order machine time constants in order to improve the terminal voltage and frequency deviation responses [5]. With proper modeling of the synchronous machine in the power system, a better understanding of how the machine reacts under sudden large disturbances during transient conditions can be achieved and hence a better power system voltage regulator and governor controllers of the SG can be designed.

Some assumptions were taken into consideration and made prior to the design of the simulation model, these assumptions are:

- The SG turbine in this model produce a constant torque with a constant speed maintained during steady state operation.
- The SG output terminals are connected to infinite bus bar that has various load changes.
- Only basic and linear models of the power system components will be used.
- All the time constants of the SG which are used in this model of all components are assumed to be the optimum time constants extracted based on the values given in Walton [5].

The stability of a SG depends on the inertia constant and the angular momentum. The rotational inertia equations describe the effect of unbalance between electromagnetic torque and mechanical torque of individual machines. By having small perturbation and small deviation in speed, the swing equation becomes [1]:

$$\frac{d\Delta w}{dt} = \left(\frac{1}{2H}\right)\left(\Delta P_m - \Delta P_e\right) \qquad \ldots\ldots (1)$$

Then

$$\frac{d\Delta w}{dt} = \frac{d\delta}{dt}$$

Where H = inertia constant, P_m= change in mechanical power, P_e = change in electrical power, ω = change in speed (electrical rad/sec), δ = rotor angle (rad.)

Using Laplace Transformation, equation (1) becomes:

$$\delta(s) = \Delta w(s) = \left(\frac{1}{2Hs}\right)\left(\Delta P_m(s) - \Delta P_e(s)\right) \qquad \ldots\ldots (2)$$

A more appropriate way to describe the swing equation is to include a damping factor that is not accounted for in the calculation of electrical power *Pe*. Therefore, a term proportional to speed deviation should be included. The speed load characteristic of a composite load describing such issue is approximated by [6]:

$$\Delta P_e = \left(\Delta P_L + K_D \Delta w\right) \qquad \ldots\ldots (3)$$

Where K_D is the damping factor or coefficient in per unit power divided by per unit frequency. $K_D\ \Delta\omega$ is the frequency-sensitive load change and ΔP_L is the non frequency-sensitive load change. Fig.1 presents a block diagram representation of a load change derived from the swing equation with the aid of equation (3) or:

$$\Delta w(s) = \left(\frac{1}{(2Hs + K_D)}\right)\left(\Delta P_m(s) - \Delta P_L(s)\right) \qquad \text{......(4)}$$

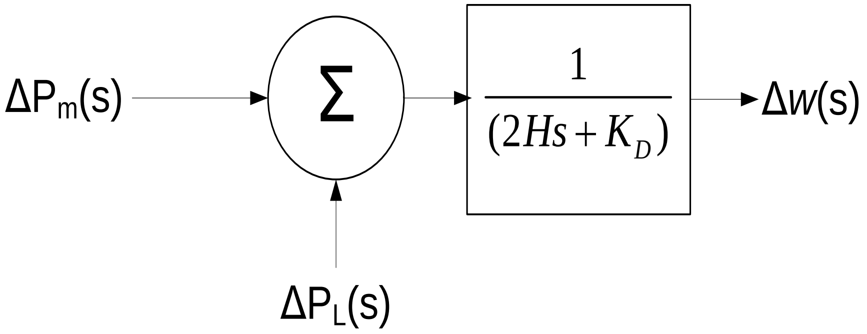


Fig.1 Block diagram of a load change model.

Figure (2) represents a simplified block diagram of the Governor and automatic voltage regulator (AVR) of the synchronous generator with the two feedback quantities (voltage and frequency).

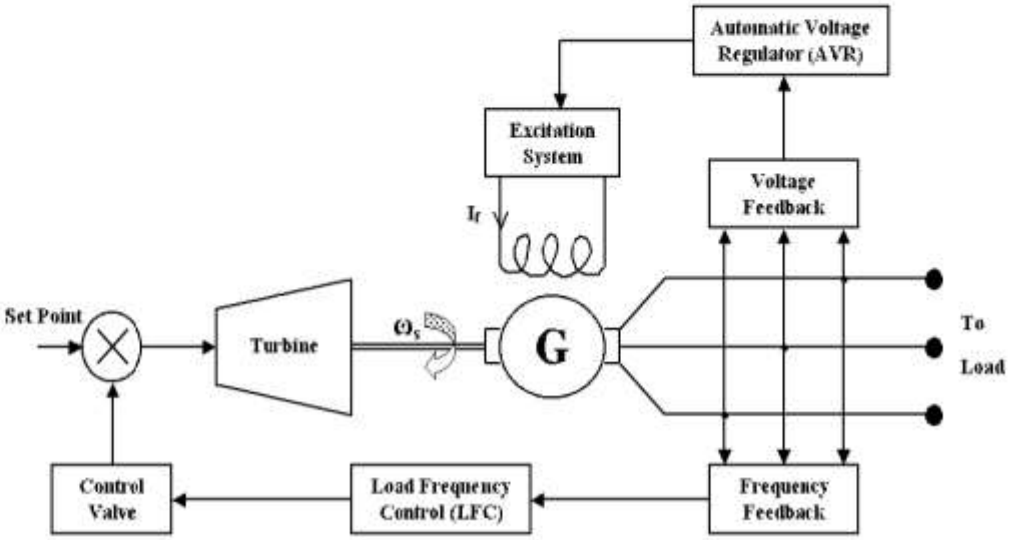


Fig.2 Block Diagram of Governor and AVR of the SG

The main control function of the excitation system is to regulate the generator terminal voltage Vt which is accomplished by adjusting the field voltage with respect to the variation of Vt**.**

The following proposed models are needed to study the effect of using the PID controllers and the Interval Type-2 fuzzy controller which represent on the fourth order model of synchronous generator for terminal voltage and frequency deviation stability control and how this stability have been enhanced.

Generator Model

A fourth order model of the SG consists of a generator gain plus four pairs of pole-zero time constants can be modeled. In terms of expressing this as a transfer function, then the following equation is given:

$$V_t(s)/V_F(s)=K_G\frac{(1+sT_{Z1})\,(1+sT_{Z2})\,(1+sT_{Z3})\,(1+sT_{Z4})}{(1+sT_{P1})\,(1+sT_{P2})\,(1+sT_{P3})\,(1+sT_{P4})} \quad ......(5)$$

There are two ways in MATLAB Simulink to design the machine model, these are:

1. Using power system block set which is a set of ready-made [4].
2. Using blocks of transfer functions of the machine to manipulate the design model.

However, using blocks of the transfer function to represent the components in the power system is capable of having higher order machine time constants as inputs. This can be achieved by the illustration shown in Figure (6.3) [8, 9].

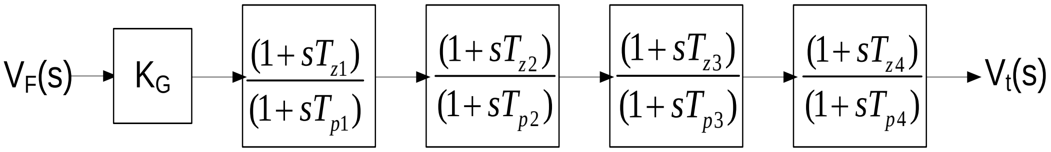


Fig.3 Block diagram representing a 4th order SG time constants model

Where: KG = Gain of the generator, Tz = Time constant of the zero, Tp = Time constant of the pole, VF = Field voltage of the SG, Vt = Terminal voltage of the SG.

Exciter model

The most basic form of expressing the exciter model can be represented by a gain KE and a single time constant TE :

VF(s) / VR(s) = KE / (1 + sTE) ….. (6)

VR = the output voltage of the regulator (AVR), VF = field voltage

The excitation system amplifier is represented similarly by a gain KA and a time constant TA. The transfer function of the amplifier is:

$VR(s)/\Delta Ve(s)= KA/(1+ sTA)$ ……(7)

Where: ΔVe = Voltage error = reference voltage (Vref) - output voltage of the sensor(VS).

Sensor Model

The terminal voltage of the SG is being fed back by using a potential transformer that is connected to the bridge rectifiers. The sensor is also being modeled, likewise as the exciter:

VS(s) / Vt(s) = KR / (1 + sTR) ...... (8)

VS = output voltage of the sensor, KR and TR are the gain and time constant of the sensor.

Automatic Voltage Regulator

In most modern systems, the AVR is a controller that senses the generator output voltage then initiates corrective action by changing the exciter control in the desired direction [10]. A simple AVR is created with a 1st order model of SG as shown in the Fig.4.

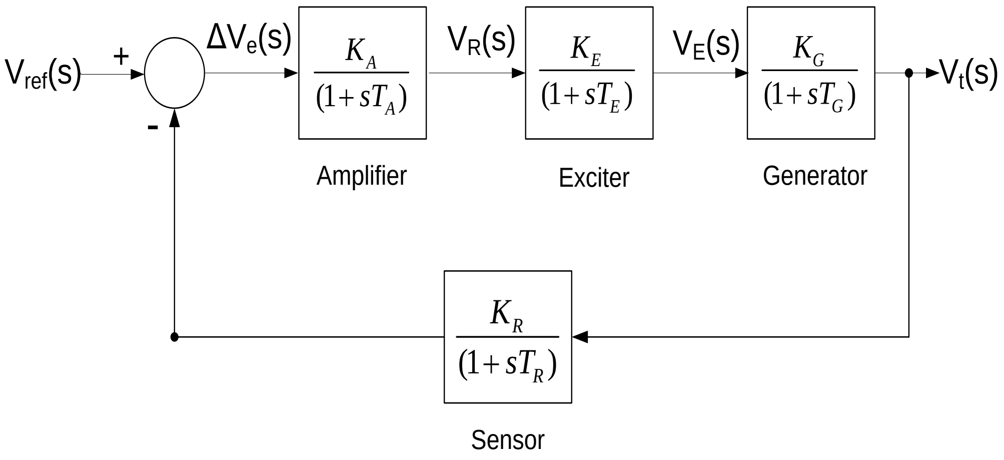


Fig.6.4 Block diagram of a simple AVR

From this block diagram, the closed loop transfer function of a 1st order relating the generator terminal voltage *V*t(s) to the reference voltage *V*ref(s) can be written as follow:

$$V_t(s) / V_{ref}(s) = \frac{K_A K_E K_G (1+sT_R)}{(1+sT_A)(1+sT_E)(1+sT_G)(1+sT_R)+K_A K_E K_G} \quad \text{...... (9)}$$

Turbine Model

The simplest form of model for a non-reheat steam turbine can be approximated by using a single time constant T_T. The model for turbine associates the changes in mechanical power *P*m with the changes in steam valve position □€V is given as:

*G*T(s) = □*P*m(s) □□□€V(s) = 1 / 1 + s*T*T .....(10)

Governor Model

The speed governor mechanism works as a comparator to determine the difference between the reference set power □*P*ref and the power (1/*R*)□□□□as□shown in Figure (5). The speed governor output □*S*g is therefore:

□*S*g(s) = □*P*ref(s) – (1/ *R*)□□(s) ….. (11)

Where R represents the drop. Speed governor output □*S*g is being converted to steam valve position □€V through the hydraulic amplifier. Assuming a linearized model with a single time constant *T*g:

□€V(s) = (1 / (1 + s*T*g)) □*S*g(s) ….. (12)

The final simulation model for a 4th order SG can be developed in "Matlab" as shown in Fig.5.

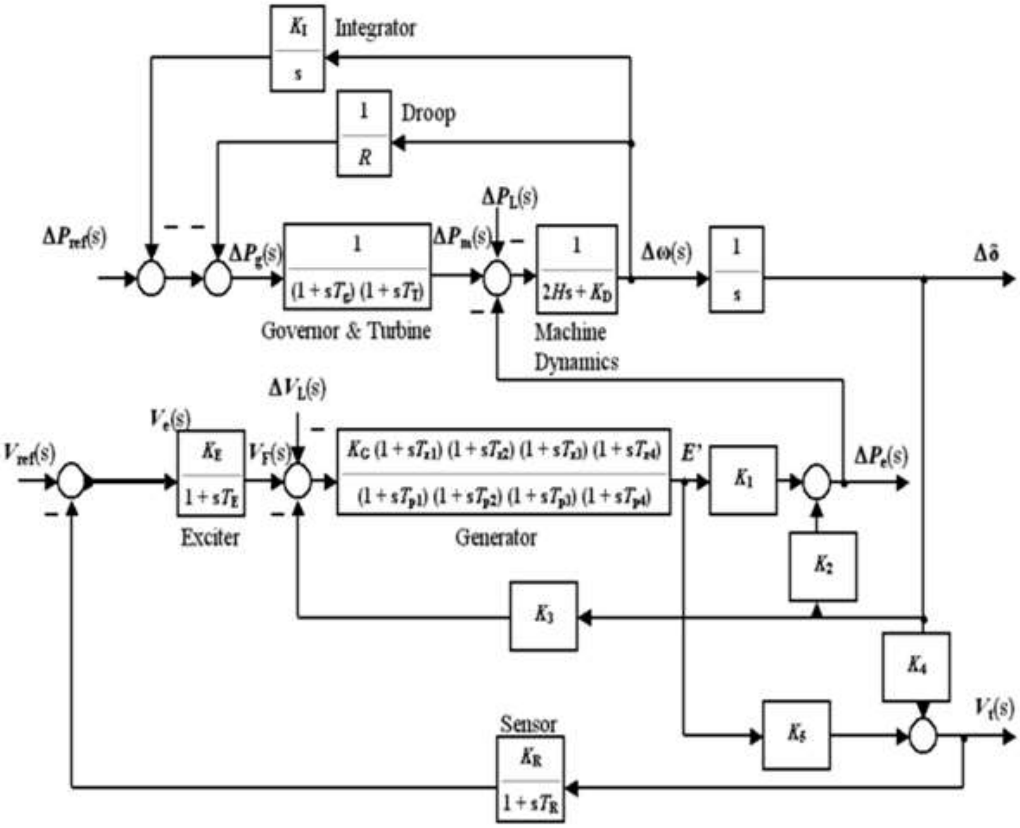


Fig.5 Simulation model for the 4th order synchronous generator time constants

Typically the excitation control and governing control are designed independently since there is a weak coupling between them, then the voltage and frequency controls are regulated separately. The suggested conventional PID controller and proposed interval type-2 fuzzy controller that can be used to enhance the output response of the AVR in the excitation system is differing from the conventional PID controller and proposed interval type-2 fuzzy controller that can be used to enhance the frequency deviation in the governing system.

PID Controller

The PID is a common sense approach to control based on the nature of error. It can be applied to wide varieties of systems. The most applications of the PID controllers in power system control are in the control circuits of power generation control the load angle variation and stability of the power system, or as an auxiliary regulating controller inserting in the Excitation Control System together with the AVR to control and enhance the terminal voltage transient stability response.

The three parameters that must be determined (some times, must be optimized) for the given process, to give the desirable output responses for the plant are: proportional gain, integral gain and derivative gain. The transfer function of the PID controller looks like the following :

$$C(s) = Kp + Ki / s + Kd\, s = (Kd\, s2 + Kp\, s + Ki) / s \qquad \text{….(13)}$$

Kp = Proportional gain, □Ki = Integral gain, and □Kd = Derivative gain. The error signal (e) will be sent to the PID controller, and the controller computes both the derivative and the integral of this error signal. The signal (u) just past the controller is given as:

$$u = K_p.e + K_i \int e.dt + K_d\, de/dt \qquad \text{….. (14)}$$

This signal will be sent to the plant, and the new output (y) will be obtained. This new output (y) will be sent back to the sensor again to find the new error signal (e). The controller takes this new error signal and computes its derivative and its integral again. This process will continuous until the desired output achieved.

A proportional controller (Kp) will have the effect of reducing the rise time and will reduce, but never eliminate, the steady –state error. An integral control (Ki) will have the effect of eliminating the steady – state error, but it may make the transient response worse.

A derivative control (Kd) will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response.

Two PID controllers are introduced in this research; one of them is introduced in the excitation system and the other PID controller is introduced in the governing system. These PID controllers are developed to improve the dynamic response and also reduce the steady state error.

However, the use of a high derivative gain will result in excessive oscillation and instability when the generators are strongly connected to an interconnected system. Therefore, an appropriate control of derivative gain is required. The proportional and integral gains can be chosen to result in the desired temporary droop and reset time. The proposed AVR and governor system block diagram for simulating a 4th order model of synchronous generator with PID controllers is shown in Fig.6 (a).

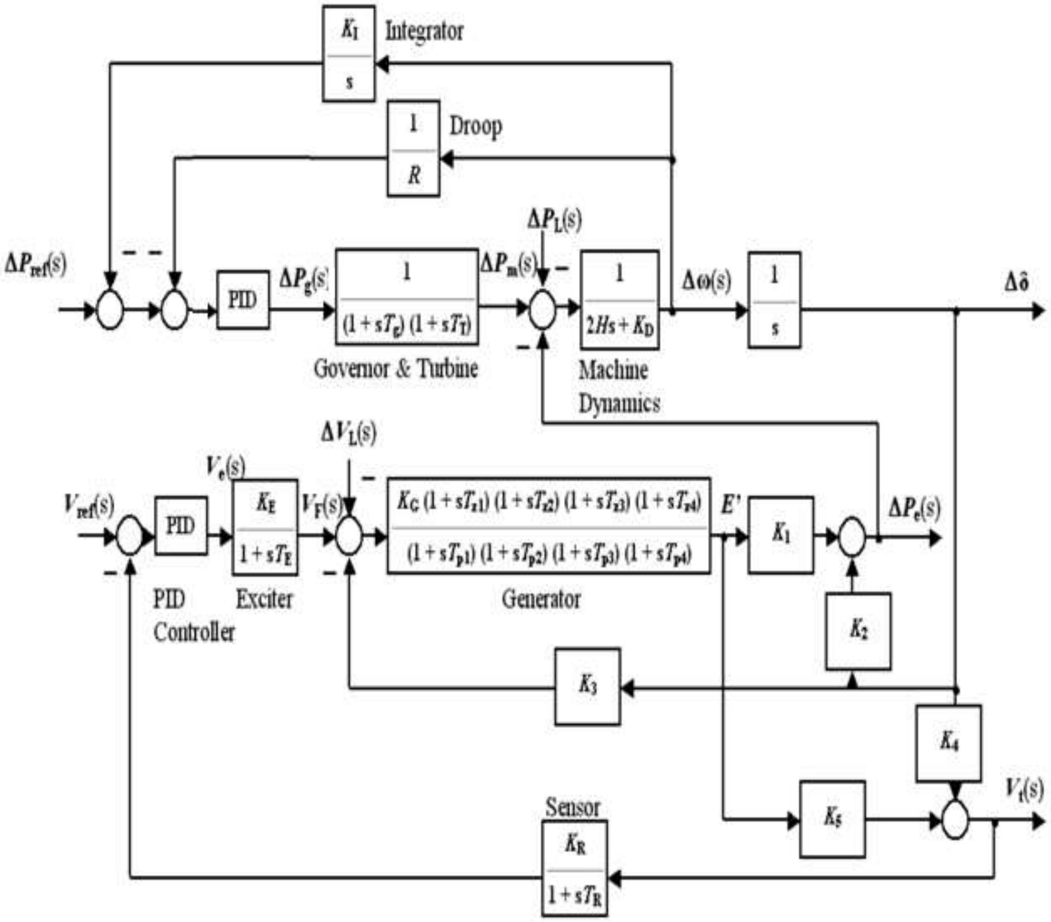


Fig.6 (a) Block diagram of the AVR and governor system with PID Controller

The proposed design scheme is implemented in SIMULINK. The test system parameters are given in Table 1.Here the symbols follow the standard representation.

Table-1 the test system parameters

Block	Variable with its value
PID	Kp = 1, K_i = 2 and K_d = 0.05.
Exciter	KE =200, T_E=0.05.
Generator	KG =1, Tp_1=3.9517, Tp_2=0.1481, Tp_3=8.38e-3, Tp_4=9.37e-4, Tz_1=0.9087 Tz_2=0.1257, Tz_3=6.88e-3, Tz_4=7.75e-4
Sensor	KR =1, T_R=0.05
Governor and Turbine	Tg=0.2, TT=0.5
Machine	H= 10
Dynamics	KD =0.8
Integrator	KI = adjusting according in order to satisfy the transient response of the machine.

Finally the actual Simulation model developed for the AVR and governor system with PID controller is shown in fig.6 (b).

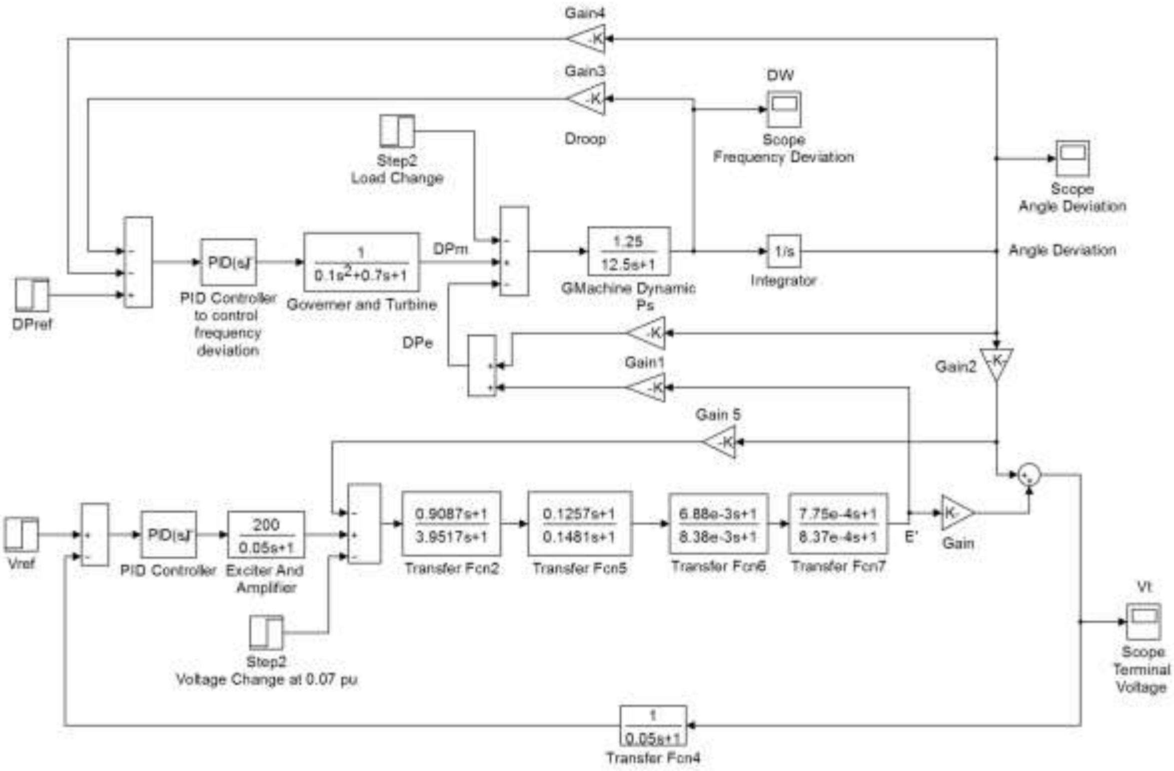


Fig.6 (b) Actual Simulation model developed for the AVR and governor system with PID controller.

Interval Type-2 Fuzzy Logic Controllers

The interval type-2 FLC uses interval type-2 fuzzy sets (such as those shown in Fig. 7(a) to represent the inputs and/or outputs of the IT2FLC i.e. Fig. 7(b), defines membership functions of interval type-2 fuzzy logic inference system. In the interval type-2 fuzzy sets all the third dimension values equal to one.

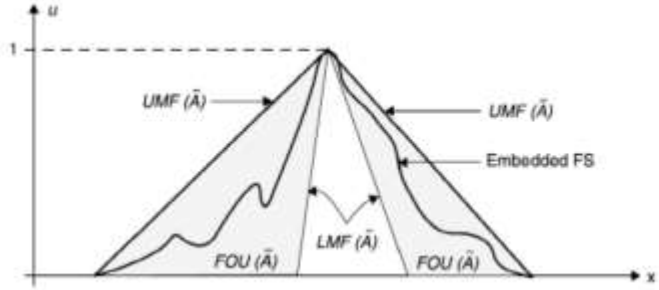


Fig.7 (a) an interval type-2 fuzzy set

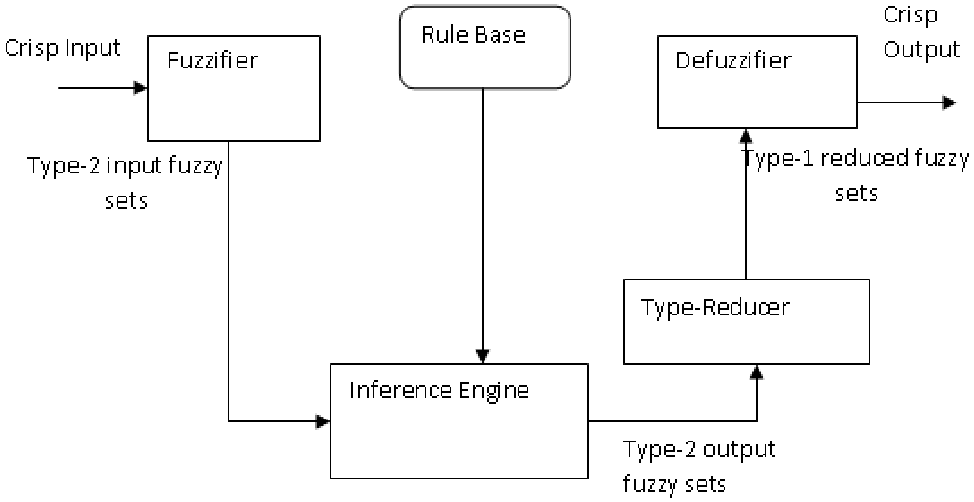


Fig.7 (b) Structure of the interval type-2 FLC

The use of interval type-2 FLC helps to simplify the computation (as opposed to the general type-2 FLC which is computationally intensive) which will enable the design of aIT2 FLC that operates in real time. The structure of an interval type-2 FLC is depicted in Fig.7 (b), it consists of a Fuzzifier, Inference Engine, Rule Base, Type-Reducer and a Defuzzifier. It has been argued that using interval type-2 fuzzy sets to represent the inputs and/or outputs of FLCs has many advantages when compared to type-1 fuzzy sets; we summarize some of these advantages as follows:

(a) As the type-2 fuzzy set membership functions are themselves fuzzy and contain a footprint of uncertainty, they can model and handle the linguistic and numerical uncertainties associated with the inputs and outputs of the FLC. Therefore, FLCs that are based on interval type-2 fuzzy sets will have the potential to produce a better performance than type-1 FLCs when dealing with uncertainties.

(b) Using interval type-2 fuzzy sets to represent the FLC inputs and outputs will result in the reduction of the FLC rule base when compared to using type-1 fuzzy sets as the uncertainty represented in the footprint of uncertainty in interval type-2 fuzzy sets lets us cover the same range as type-1 fuzzy sets with a smaller number of labels. The rule reduction will be greater as the number of the FLC inputs increases.

(c) Each input and output will be represented by a large number of type-1 fuzzy sets which are embedded in the type-2 fuzzy sets. The use of such a large number of type-1 fuzzy sets to describe the input and output variables allows for a detailed description of the analytical control surface as the addition of the extra levels of classification gives a much smoother control surface and response. According to Karnik and Mendel, the type-2 FLC can be thought of as a collection of many different embedded type-1 FLCs.

(d) It can be seen that the extra degrees of freedom provided by the footprint of uncertainty enables a type-2 FLC to produce outputs that cannot be achieved by type-1 FLCs with the same number of membership functions. It has also been shown that a type-2 fuzzy set may give rise to an equivalent type-1 membership grade that is negative or larger than unity.

Thus a type-2 FLC is able to model more complex input-output relationships than its type-1 counterpart and thus can give a better control response. Assuming the usual singleton input of error (e) and change in error (de) (or, an interval set requires just an upper and lower value to be resolved to form the resulting FOU in the corresponding output set. For example, Fig.7 shows two IT2 membership functions for input sets A and B, each with an FOU. Singleton input X is a member of each with different degrees of membership. Strictly, an infinite number of membership functions (not all necessarily triangular) can exist within the FOUs of sets A and B, but IT2 sets allow the upper and outer firing levels to be taken, as shown in Fig.8. The minimum operator (min) acts as a t-norm on the upper and lower firing levels to produce a firing interval.

The firing interval serves to bind the FOU in the output triangular membership function shown to the right in Fig.8. The lower trapezium outlines the FOU, which itself consists of an inner trapezoidal region that is fixed in extent. The minimum operator, also used by us as a t-norm, has the advantage that it requires less hardware circuitry than product t-norm. Once the FOU firing interval is established, Center-of-Sets type reduction was applied by means of the Karnik-Mendel algorithm. Type reduction involves mapping the IT2 output set to a type-1 set.

In practice, defuzzification of this type-1 output fuzzy set simply consists of averaging maximum and minimum values. The result of defuzzification is a crisp value that determines the change in the video rate.

IT2 FLS Inference for One Rule:
Rule: IF x_1 is $F1$ and x_2 is F_2, THEN y is G Firing interval Calculation

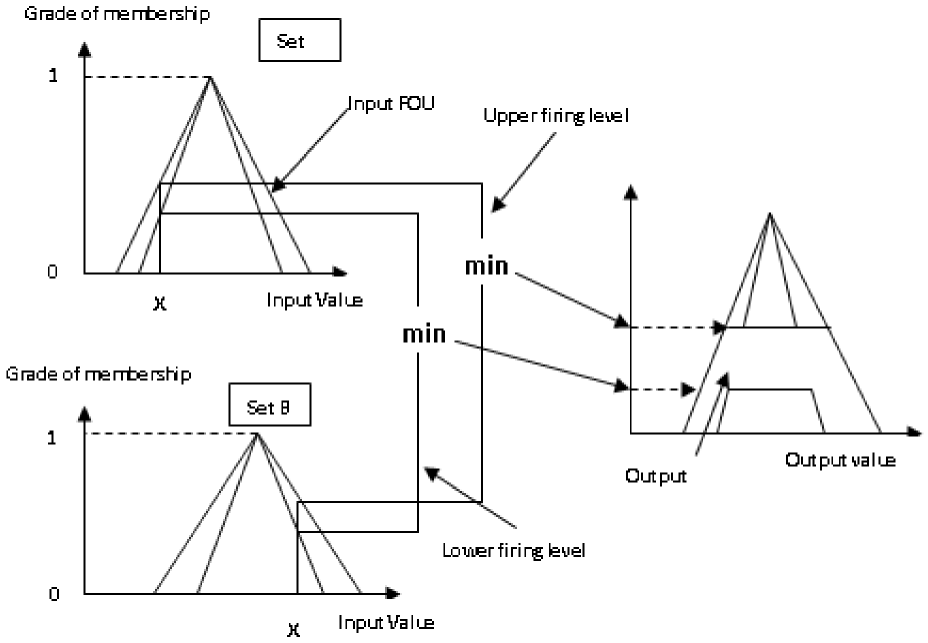


Fig.8 IT2 FL calculation of output FOU

Development of Interval Type-2 Fuzzy Controller for Controlling Frequency Deviation and Voltage regulation
This subsection deals with the development of the Interval Type-2 Fuzzy Controller (IT2FLC) for the efficient frequency deviation control and voltage regulation. Two separate Interval Type-2 Fuzzy Controller (IT2FLC) have been developed for these tasks. Interval Type-2 Fuzzy Controller (IT2FLC) named as RT2.fis is designed for the frequency deviation control, while RT1.fis is designed for the efficient voltage regulation.

Development of Interval Type-2 Fuzzy Controller RT2.fis for Controlling Frequency Deviation

This subsection presents the development of proposed IT2FLC (VST2.fis) designed to efficiently control the deviations in the frequency (Δ*w*(s)). Fig. 8, shows Block Diagram of Interval Type-2 Fuzzy Logic controller (RT2.fis) Module.

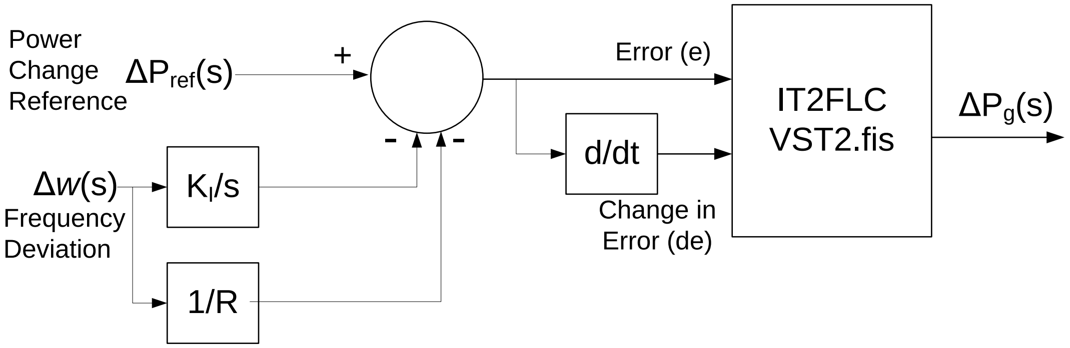


Fig.6.9 Block Diagram of Interval Type-2 Fuzzy Logic control (RT2.fis) Module

Fig.10 to Fig.11 show the fuzzifide interval type-2 membership functions of antecedent and consequent parameters.

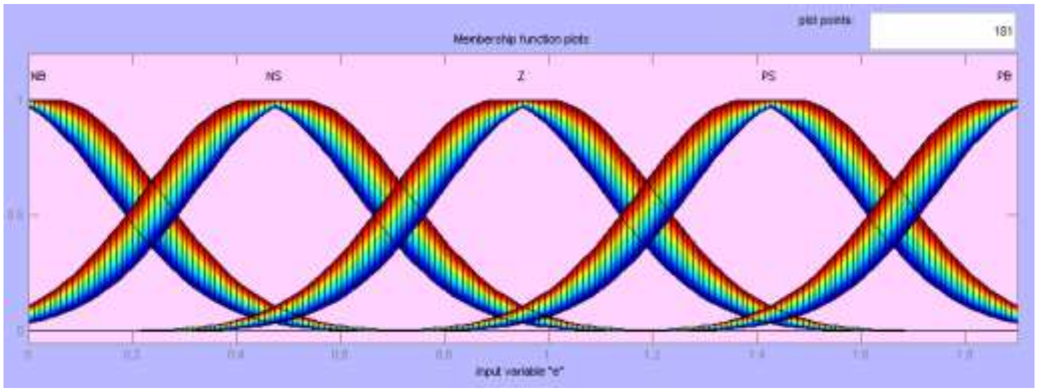


Fig.10 Fuzzification of first input error (e)

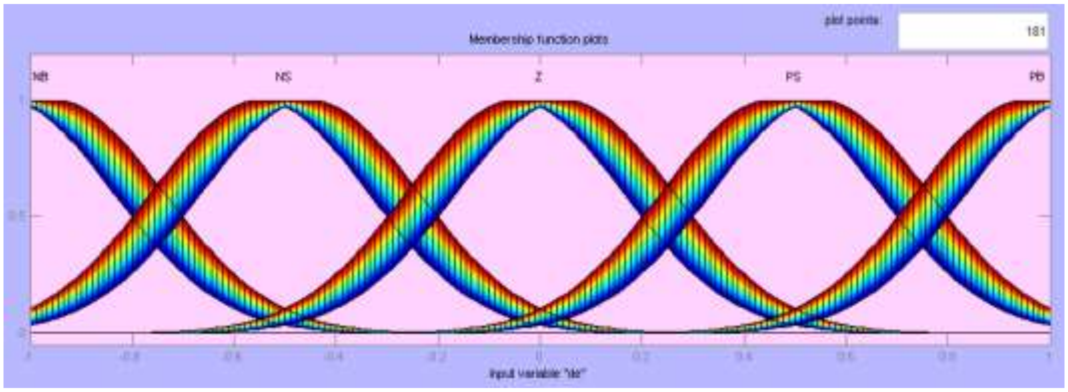


Fig.11 Fuzzification of second input change in error (de)

Similarly the membership function plot for the output variable controlled change in dpg is shown in fig.12.

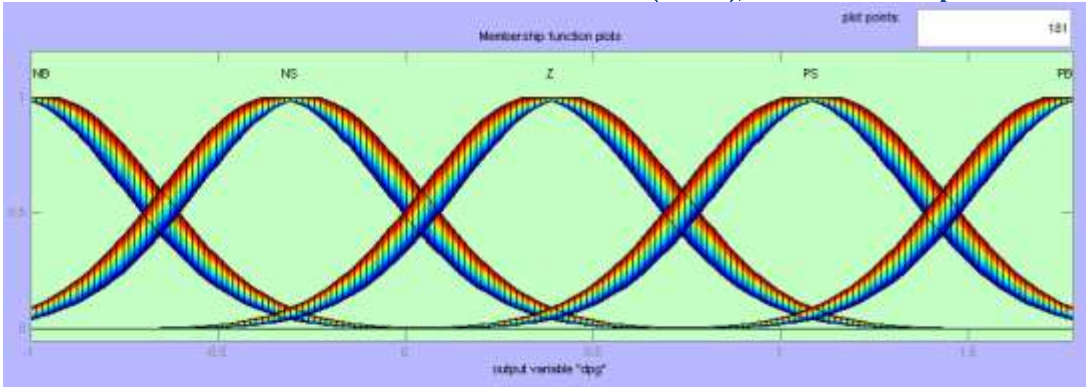
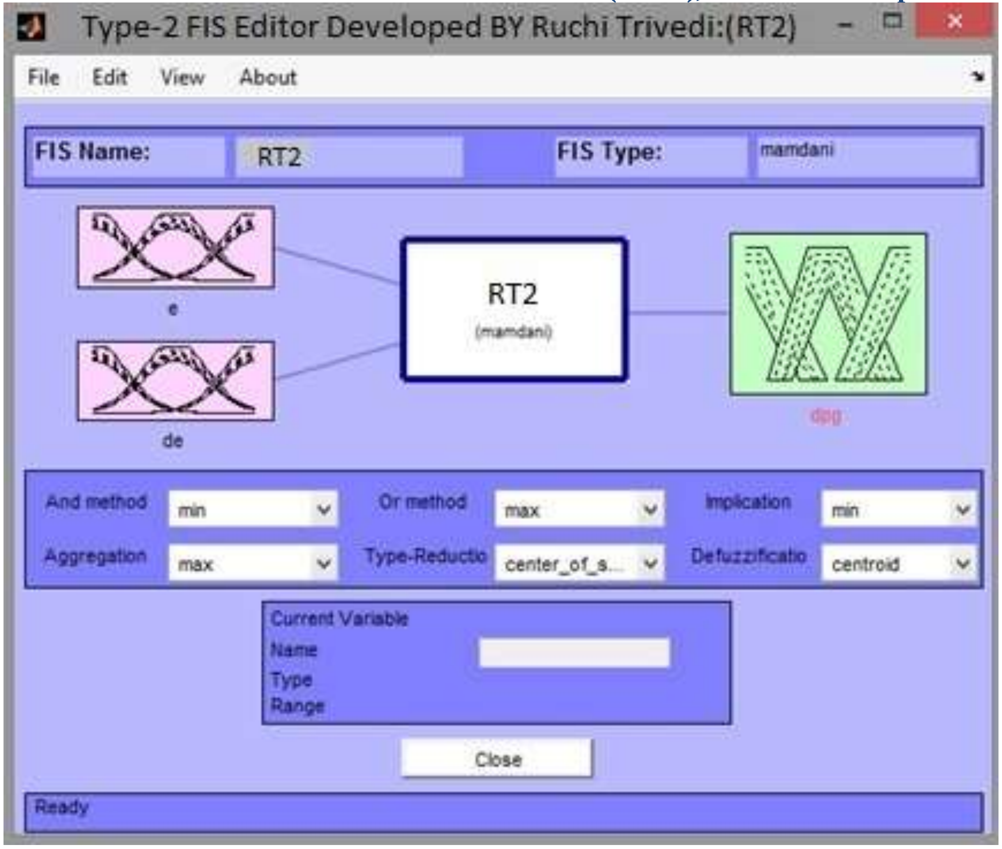


Fig.12 Membership function plot of the output variable dpg.

The rule base designed for the Interval Type-2 Fuzzy Logic controller (RT2.fis) Module is:
1. If (e is NB) and (de is NB) then (dpg is NB) (1)
2. If (e is NB) and (de is NS) then (dpg is NB) (1)
3. If (e is NB) and (de is Z) then (dpg is NB) (1)
4. If (e is NB) and (de is PS) then (dpg is PS) (1)
5. If (e is NB) and (de is PB) then (dpg is Z) (1)
6. If (e is NS) and (de is NB) then (dpg is NB) (1)
7. If (e is NS) and (de is NS) then (dpg is NB) (1)
8. If (e is NS) and (de is Z) then (dpg is NS) (1)
9. If (e is NS) and (de is PS) then (dpg is Z) (1)
10. If (e is NS) and (de is PB) then (dpg is PS) (1)
11. If (e is Z) and (de is NB) then (dpg is NB) (1)
12. If (e is Z) and (de is NS) then (dpg is NS) (1)
13. If (e is Z) and (de is Z) then (dpg is Z) (1)
14. If (e is Z) and (de is PS) then (dpg is PS) (1)
15. If (e is Z) and (de is PB) then (dpg is PB) (1)
16. If (e is PS) and (de is NB) then (dpg is NS) (1)
17. If (e is PS) and (de is NS) then (dpg is Z) (1)
18. If (e is PS) and (de is Z) then (dpg is PS) (1)
19. If (e is PS) and (de is PS) then (dpg is PB) (1)
20. If (e is PS) and (de is PB) then (dpg is PB) (1)
21. If (e is PB) and (de is NB) then (dpg is Z) (1)
22. If (e is PB) and (de is NS) then (dpg is NB) (1)
23. If (e is PB) and (de is Z) then (dpg is Z) (1)
24. If (e is PB) and (de is PS) then (dpg is Z) (1)
25. If (e is PB) and (de is PB) then (dpg is PS) (1)

During rule base and membership function designing the short terms stands as: NB = Negative Big, NS = Negative Small, Z = Zero Error, PS = Positive Small and PB = Positive Big. Finally the layout of the developed Interval Type-2 Fuzzy Logic controller (RT2.fis), for controlling deviation in frequency is shown in fig.13.



FIS Name: RT2

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Type-Reductio: center_of_s...

Defuzzificatio: centroid

Current Variable
Name
Type
Range

Ready

Fig.13 The layout of the developed Interval Type-2 Fuzzy Logic controller (RT2.fis)

Development of Interval Type-2 Fuzzy Controller RT1.fis Terminal Voltage Regulation

This subsection presents the development of proposed IT2FLC (RT1.fis) designed to efficiently regulates the terminal voltage Vt. Fig.14, shows Block Diagram of Interval Type-2 Fuzzy Logic controller (RT1.fis) Module.

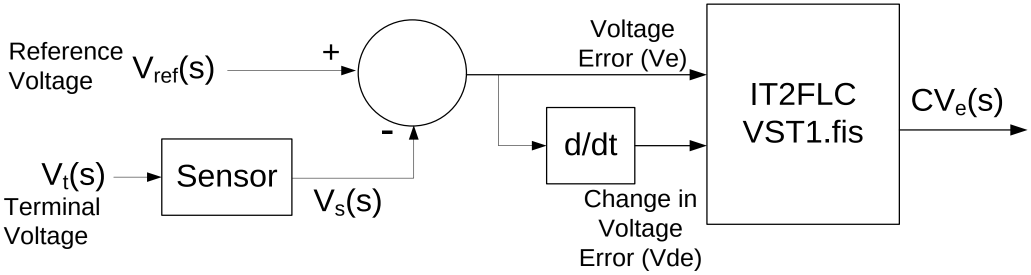


Fig.14 Block Diagram of Interval Type-2 Fuzzy Logic control (RT1.fis) Module

Now Fig.15 and Fig.16 shows membership functions of developed Interval Type-2 Fuzzy Logic controller (RT1.fis).

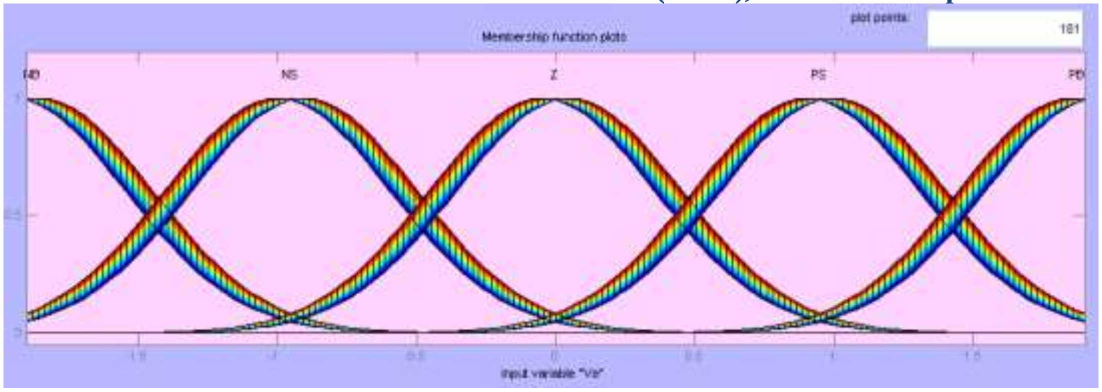


Fig. 15 Fuzzification of first input Voltage error (Ve)

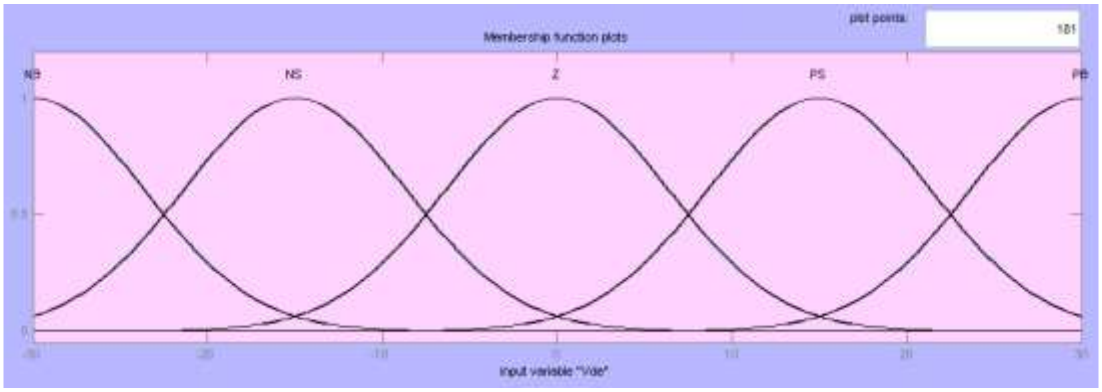


Fig.16 Fuzzification of second input change in Voltage error (Vde)

Similarly the membership function plot for the output variable controlled error voltage (CVe) is shown in figure 17.

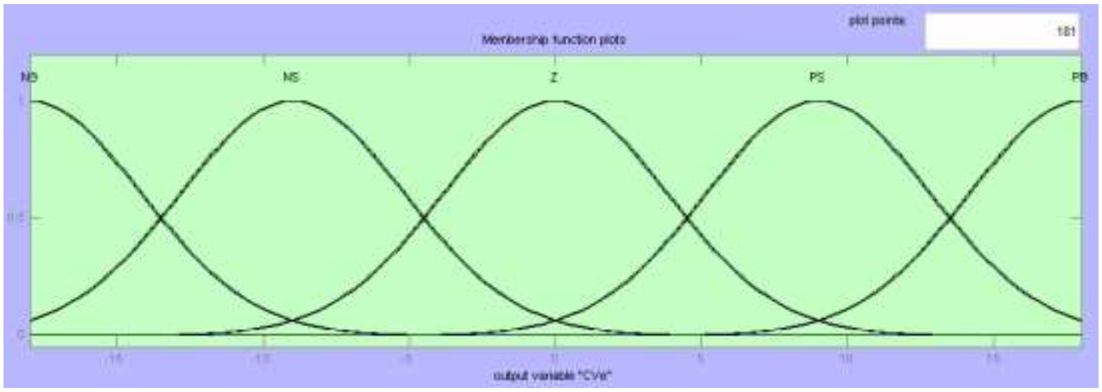


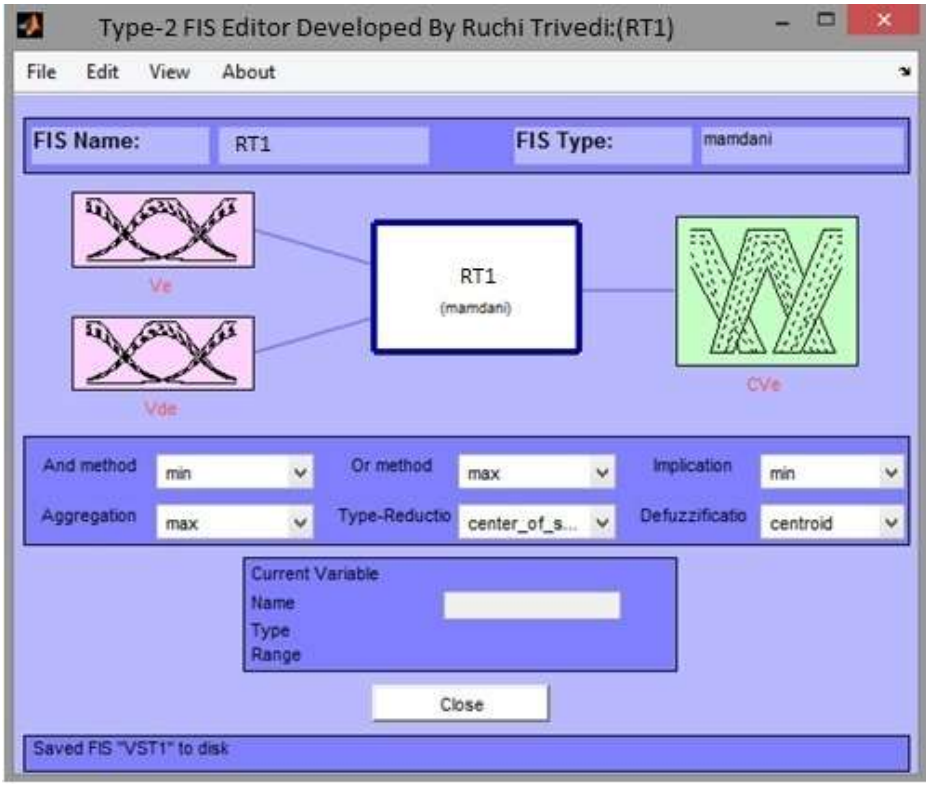
Fig. 17 Membership function plot of the output variable controlled error voltage (CVe).

The rule base designed for the Interval Type-2 Fuzzy Logic controller (RT1.fis) Module is:
1. If (Ve is NB) and (Vde is NB) then (CVe is NB) (1)
2. If (Ve is NB) and (Vde is NS) then (CVe is NB) (1)
3. If (Ve is NB) and (Vde is Z) then (CVe is NB) (1)
4. If (Ve is NB) and (Vde is PS) then (CVe is PS) (1)
5. If (Ve is NB) and (Vde is PB) then (CVe is Z) (1)
6. If (Ve is NS) and (Vde is NB) then (CVe is NB) (1)

7. If (Ve is NS) and (Vde is NS) then (CVe is NB) (1)
8. If (Ve is NS) and (Vde is Z) then (CVe is NS) (1)
9. If (Ve is NS) and (Vde is PS) then (CVe is Z) (1)
10. If (Ve is NS) and (Vde is PB) then (CVe is PS) (1)
11. If (Ve is Z) and (Vde is NB) then (CVe is NB) (1)
12. If (Ve is Z) and (Vde is NS) then (CVe is NS) (1)
13. If (Ve is Z) and (Vde is Z) then (CVe is Z) (1)
14. If (Ve is Z) and (Vde is PS) then (CVe is PS) (1)
15. If (Ve is Z) and (Vde is PB) then (CVe is PB) (1)
16. If (Ve is PS) and (Vde is NB) then (CVe is NS) (1)
17. If (Ve is PS) and (Vde is NS) then (CVe is Z) (1)
18. If (Ve is PS) and (Vde is Z) then (CVe is PS) (1)
19. If (Ve is PS) and (Vde is PS) then (CVe is PB) (1)
20. If (Ve is PS) and (Vde is PB) then (CVe is PB) (1)
21. If (Ve is PB) and (Vde is NB) then (CVe is Z) (1)
22. If (Ve is PB) and (Vde is NS) then (CVe is PS) (1)
23. If (Ve is PB) and (Vde is Z) then (CVe is PB) (1)
24. If (Ve is PB) and (Vde is PS) then (CVe is PB) (1)
25. If (Ve is PB) and (Vde is PB) then (CVe is PB) (1)

Similar to previous proposed controller Interval Type-2 Fuzzy Logic controller VST2.fis, during designing of rule base and membership functions for second proposed Type-2 Fuzzy Logic controller VST1.fis short terms stands as:NB = Negative Big, NS = Negative Small, Z = Zero Error, PS = Positive Small and PB = Positive Big.

Finally the layout of the second developed Interval Type-2 Fuzzy Logic controller (RT1.fis), for efficient regulation of the terminal voltage Vt is shown in fig.18.


Type-2 FIS Editor Developed By Ruchi Trivedi:(RT1)

FIS Name: RT1
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Type-Reductio: center_of_s...
Defuzzificatio: centroid

Saved FIS "VST1" to disk

Fig. 18 The layout of the developed Interval Type-2 Fuzzy Logic controller (RT1.fis)

Now the actual Simulation model developed for the AVR and governor system with proposed interval type-2 fuzzy logic controllers is shown in Fig.19.

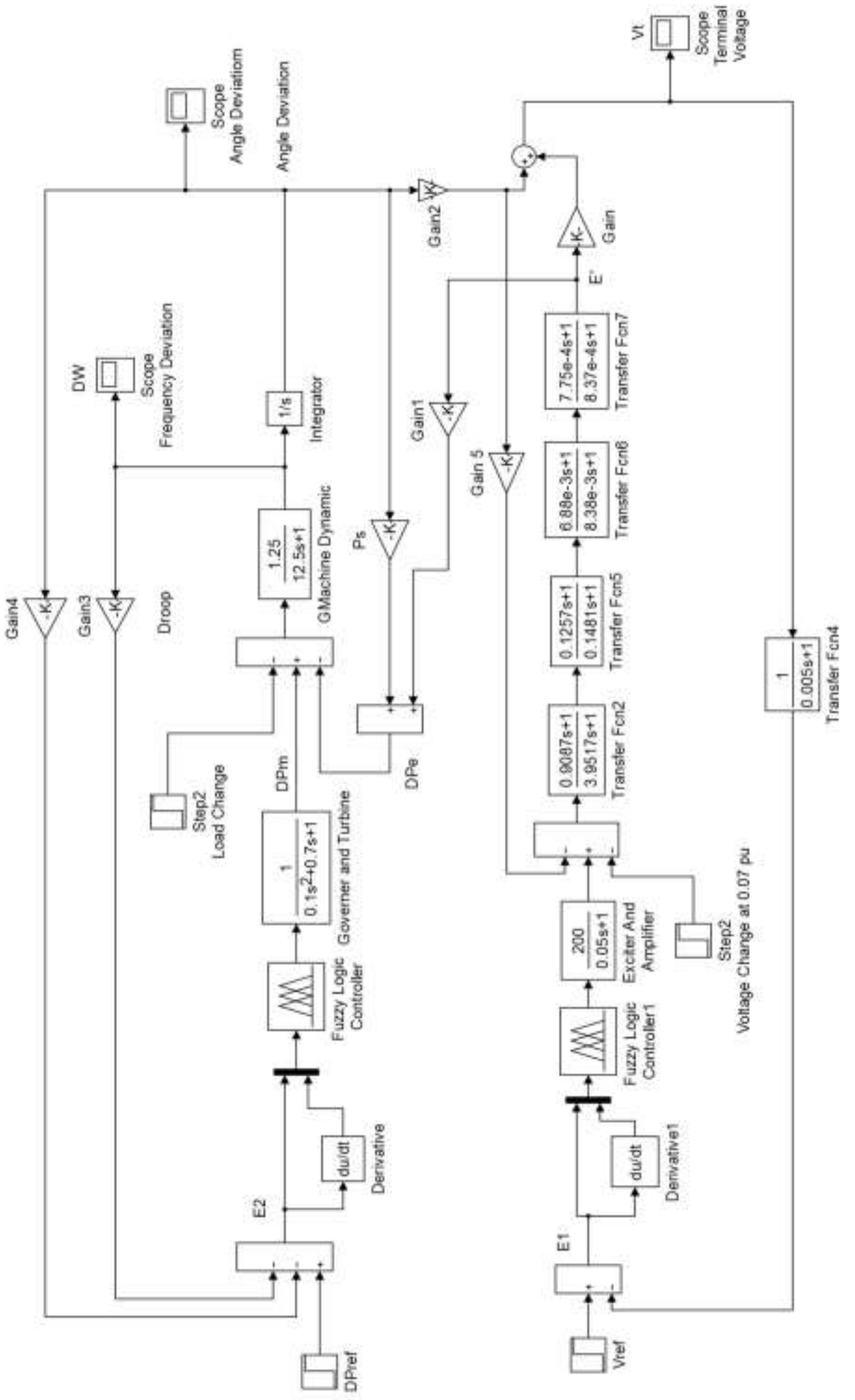


Fig.19 Actual Simulation model developed for the AVR and governor system with proposed interval type-2 fuzzy logic controllers

The generator and system parameters used here also same as given in Table 1.

Simulation Results

This section is focusing on the simulation results of the SG model under transient response with various load change. MATLAB program simulation method is adopted to simulate different cases related to terminal voltage and frequency responses of a fourth order model of SG. The model is inserted in the Simulink diagram and run firstly for the case without controller to calculate values of overshooting and settling time from the output response. To improve this response then a PID controller is introduced and then the proposed Interval type-2 fuzzy logic controller (IT2FLC) is examined.

Results for 0.6 p.u. load change without controller

Using the simulation model governing system of the 4th order SG for 0.6 p.u. load change without controller then, the simulation results for terminal voltage (Vt), frequency deviation (Δω) are illustrated in Fig.19 and Fig.20 respectively .The period of simulation in the frequency deviation step response (Δω)) and the terminal voltage (Vt) is set as 30 seconds, and 1.2 second respectively so as to verify that there are no further oscillations. In Fig.21 the response for (Δω) oscillates for a period of 14.8 seconds before settling down to zero deviation. There is an overshoot error occurring at 2 seconds. The ideal response is to keep the deviation (oscillation) as close to zero as possible at the minimum period of time.

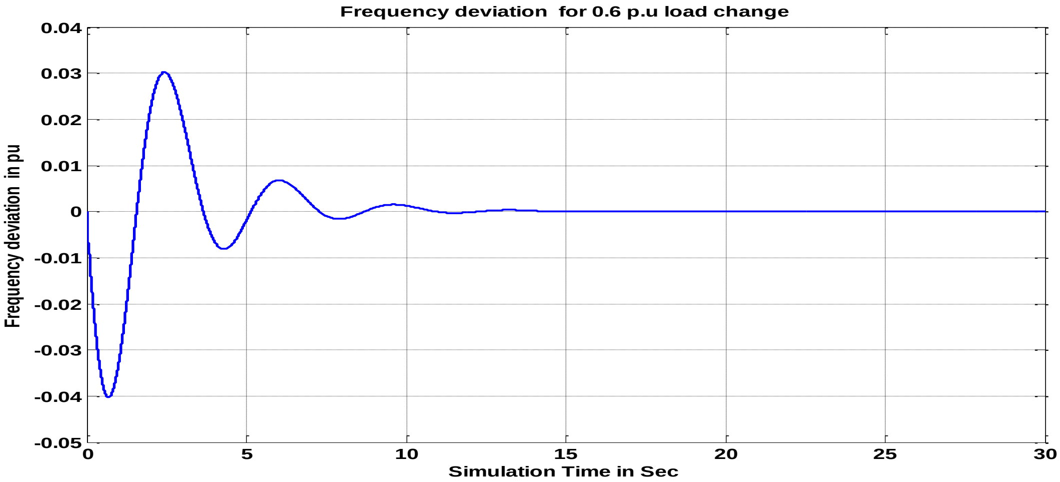


Fig. 20 Frequency deviation (Δω) for 0.6 p.u load change without controller

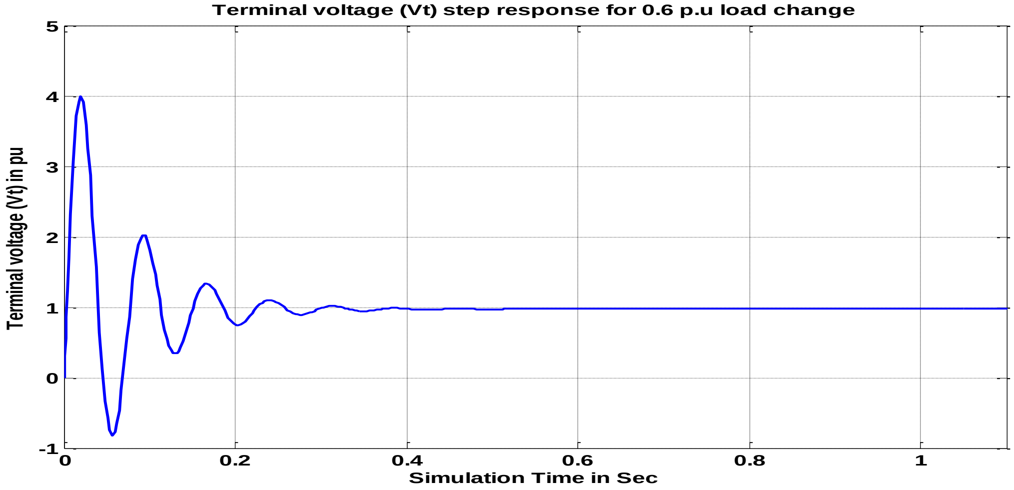


Fig.21 Terminal voltage (Vt) step response for 0.6p.u load change without controller

Simulation Results With Pid Controller

In this section two PID controllers are added to the plant, one unit of PID is in the governor part and the other in the excitation part. It is very interesting to investigate the effects of each of PID controller's parameters Kp, Ki and Kd on the terminal voltage response that exist in the excitation system only**.**

Tuning the PID controller by setting the gains Kp, Ki and Kd, the best values of the PID controller parameters for the governing systems are selected as: Kp = 0.8, Ki = 0, Kd = 0.6 respectively. The new simulation result for frequency deviation (Δω) response with PID controller is illustrated in Fig.21.

While in a similar way, the best values of Kp, Ki, and Kd of the PID controller in the excitation system are set to be: 0.5, 2, 0.005. Then the new response for terminal voltage (Vt) with PID controller is illustrated in Fig.22 for load change of 0.6 (p.u.).

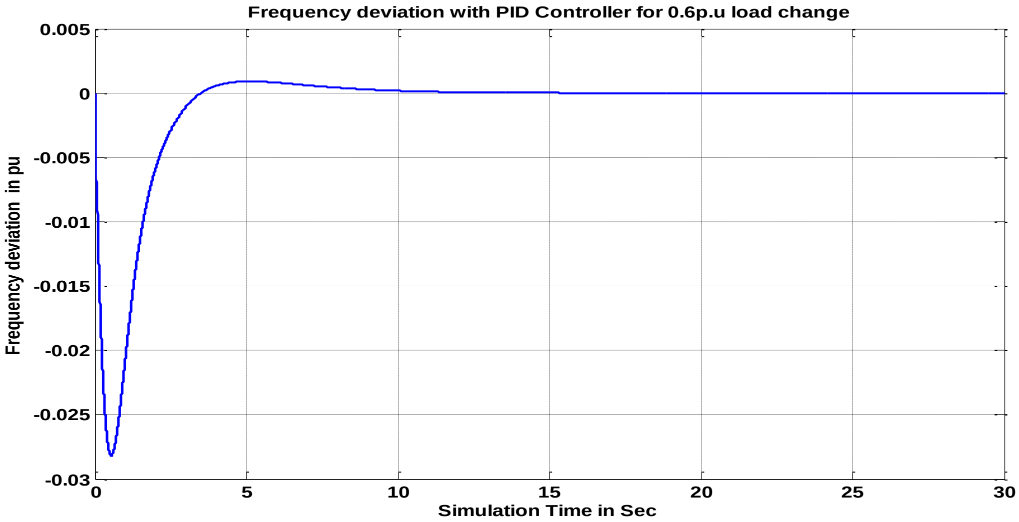


Fig. 22 Frequency deviation (Δω) with PID Controller for 0.6p.u load change

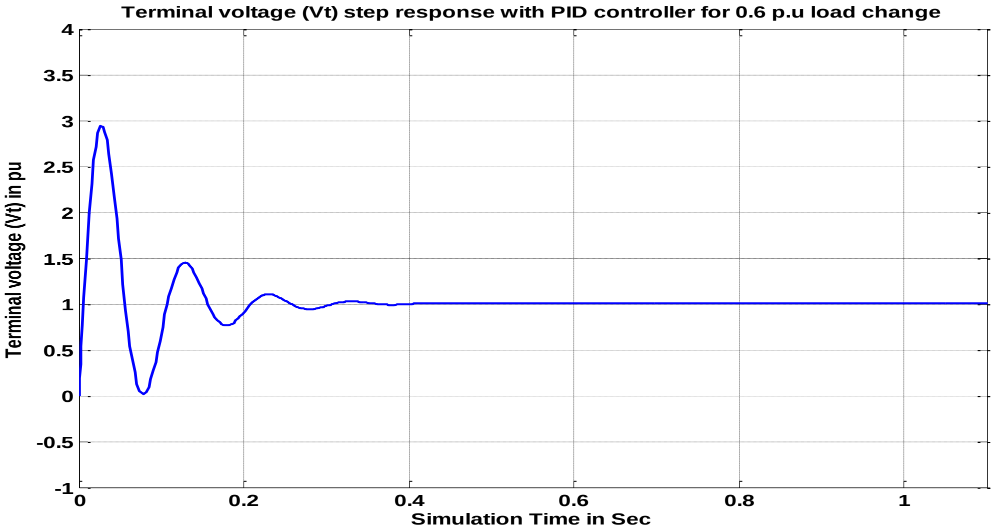


Fig. 23 Terminal voltage (Vt) step response with PID controller for 0.6 p.u load change

Simulation results with IT2FLC

In this case, the IT2FLC controller for prediction and control the SG to enhance terminal voltage response in the excitation system is examined. The controlling steps and output response is discussed in the following section. Return to the Simulink model and start the simulation by choosing the start command from the Simulation menu. As the simulation runs, the plant output and the reference signal are displayed. Fig.24 shows the terminal voltage response for the 4th order SG model using proposed IT2FLC controller RT1.fis. The frequency deviation control response with proposed IT2FLC controller RT2.fis is shown in fig.25 for load change of 0.6 pu.

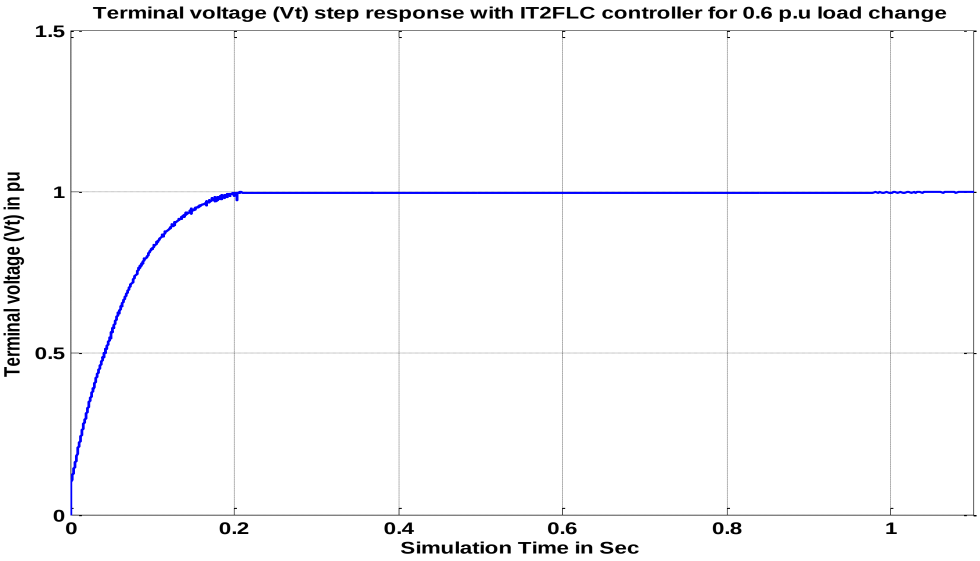


Fig.23 Terminal voltage step response with IT2FLC controller for 0.6 p.u load change

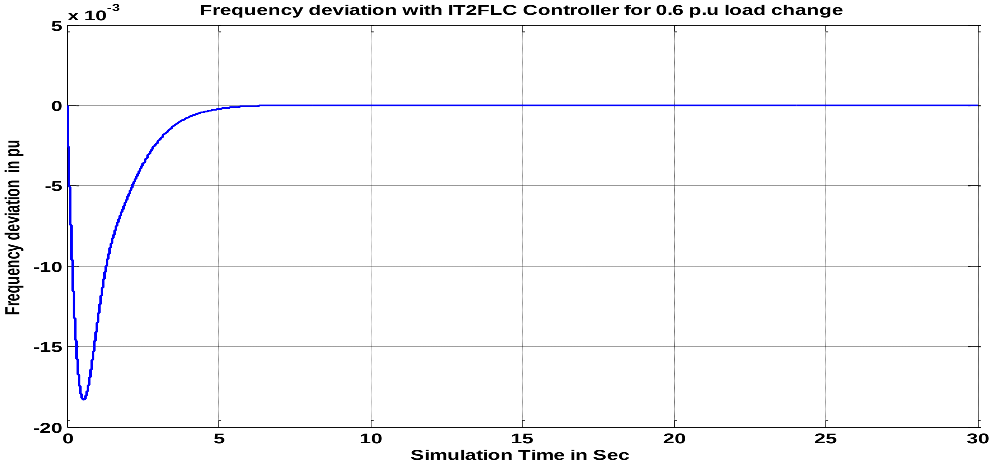


Fig.24 Frequency deviation (Δω) with IT2FLC Controller for 0.6 p.u load change

Comparison Results

It is interesting to display a comparison response for 0.6 p.u. load change with different types of controllers; it can be summarized as follows:

- The enhancements of the transient responses of Vt are very clear as shown in Fig.27. From which, one can deduce that, the proposed interval type-2 fuzzy logic controller (IT2FLC), type has the best transient response than others.
- In addition to this, Fig.28 shows the efficient capability of the proposed IT2FLC controller to keep frequency deviation to its minimum level as compare to others.

The overall enhancements results of the settling time and overshoot which being a measures for the Vt transient stability enhancements and frequency deviation control are illustrated in Table 2 and Table 3 respectively.

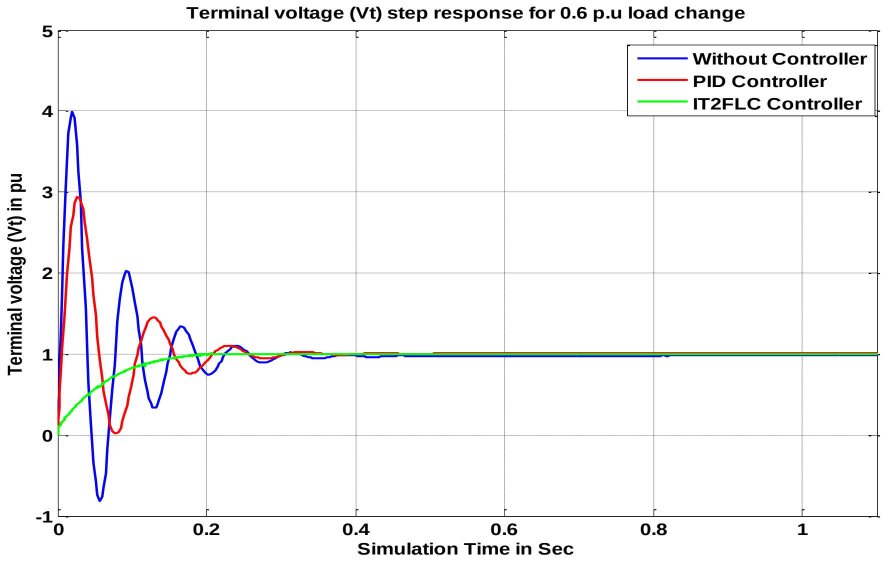


Fig.25 Vt transient responses of the SG model for 0.6 p.u. load change with different types of controllers

Table 2 Terminal voltage response for 0.6 p.u. load change

Parameter	**Type of controller**	**Settling time (ts) (sec.)**	**Overshoot (p.u)**
Terminal voltage (Vt) response of a 4th order model SG for 0.6 p.u. load change	Without	0.4	+4 -0.82
	PID	0.4	+2.9 -0.35
	Proposed IT2FLC	0.2	0 0

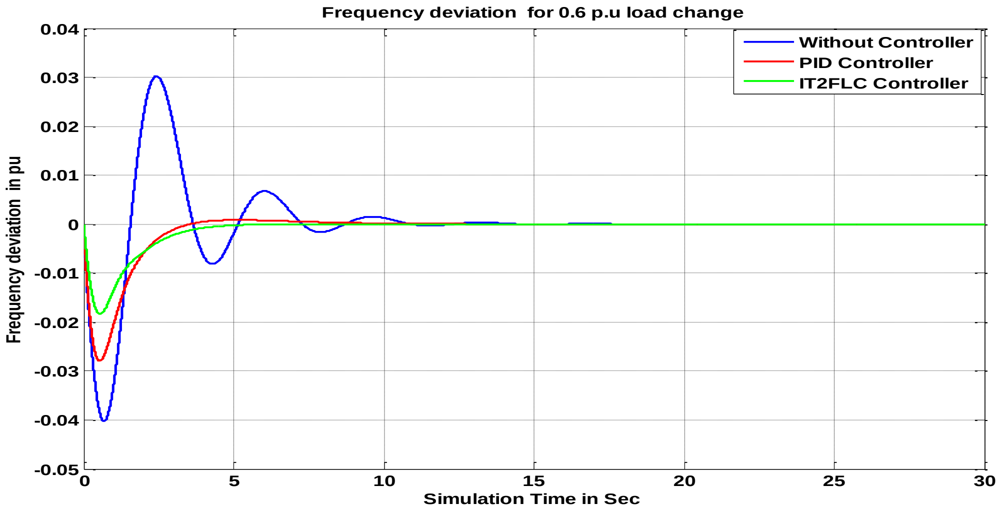


Fig.26 Comparison of Frequency deviation (Δω) control ability for 0.6 p.u load change

Table 3 Frequency deviation response for 0.6 p.u. load change

Parameter	**Type of controller**	**Settling time (ts) (sec.)**	**Overshoot (p.u)**
Freq. Deviation response of a 4th order model SG for 0.6 p.u. load change	Without	14.8	0.03 -0.04
	PID	10	0.01 -0.028
	Proposed IT2FLC	5	0 -0.018

Results for different load changes

The overall enhancements results of the settling time and overshoot for different load changes are well investigated for the previous cases. It has been noticed that the load change has no effect on the terminal voltage response but it has affecting the frequency deviation stability as illustrated in Table 4.

Table 4 Freq. Dev. response for various load changes

Load Condition	**Type of controller**	**Settling time (ts) (sec.)**	**Overshoot (p.u)**

Freq. Deviation response of a 4th order model SG for 0.6 p.u. load change	Without	14.8	0.03 - 0.04
	PID	10	0 - 0.028
	Proposed IT2FLC	5	0 - 0.018
Freq. Deviation response of a 4th order model SG for 0.3 p.u. load change	Without	14.7	0.035 - 0.024
	PID	11	0.08 - 0.017
	Proposed IT2FLC	5	0 - 0.007

CONCLUSIONS

This work has put forward a new scenario in the steam turbine control structure, by development of Interval Type-2 Fuzzy based Control Model of steam turbine Governing System and excitation system of Power Plant, which compensates their control, inputs during faults. Two separate Interval Type-2 Fuzzy controllers have been developed to address both the damping of frequency deviation and terminal voltage oscillation problems. To present complete comparative analysis of the proposed control strategy with conventional PID controller, two separate fluctuations scenario have been employed. SIMULINK simulation model is built to study the dynamic behaviour of conventional PID controlled synchronous machine and the performance of proposed IT2FLC controller.

The main conclusions of this work can be summarized as follows:

1. Building of fourth order simulation model for SG, speed governor and exciter voltage regulator for SMIB system under study enables to treat the problem (transient state power system stability) with much ease and comfort.
2. Due to the weak coupling relationship between the AVR and AGC of the synchronous generator controls systems, the voltage and frequency controls are regulated separately that mean any controller in the excitation system will not affect governing system and vice versa.
3. The conventional PID controller used, suffers from the high settling time and overshoot values, for the transient responses of both the obtained terminal voltage and frequency deviation.
4. The proposed IT2FLC Controller gives excellent results. It shows the high efficiency in controlling the overshoot and undershoots in the transient part, as well as keeps efficient control on the output during steady state part. Moreover the terminal voltage transient stability response enhancements through the obtained results are outstanding with respect to the conventional PID controller. By this controller, the generator terminal voltage profile and the generator transient stability response are improved.

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