"IT2FLC based Control Model 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. 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.

Keywords

Steam Turbine, Governing System Control, Interval Type-2 Fuzzy Logic Controller, Foot Print of Uncertainty, Internal Generator Angle, PID Controller.

1. 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 behavior 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 behavior 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. Here we present development of Interval Type-2 Fuzzy based Control Model of steam turbine Governing System of Power Plant which compensates their control inputs during faults. The speed (ω), accelerating speed $\Delta\omega$= (Pm- Pe) and the terminal voltage (Vt) of generator are observed to characterize the severeness of oscillation. In this paper, the design of Interval Type-2 Fuzzy based Control Model of steam turbine Governing System is presented. A 3-phase fault is used as an example of system disturbances. SIMULINK simulation model is built to study the dynamic behavior of synchronous, machine and the performance of proposed controller. 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.

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.

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 to be 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.

Modeling of the Steam Turbine and Its Governing

A simplified construction of the steam turbine and its governing system is proposed in the Fig.1. Using Matlab Simulink model, the simulink model of the speed governing system is indicated in the Fig. 2

To obtain the mathematical model of the process i.e. to identify the process parameters, the process is looked as a black box; a step input is applied to the process to obtain the open loop time response. From the time response, the transfer function of the open loop system can be approximated in the form of a third order transfer function. The identified model is approximated as a linear model, but exactly the closed loop is nonlinear due to the limitation in the control signal (Equa.1).

$$G_S = \frac{KK_g}{S(T_gS+1)(T_tS+1)} \approx \frac{1}{S(S+1)(S+5)} \quad (1)$$

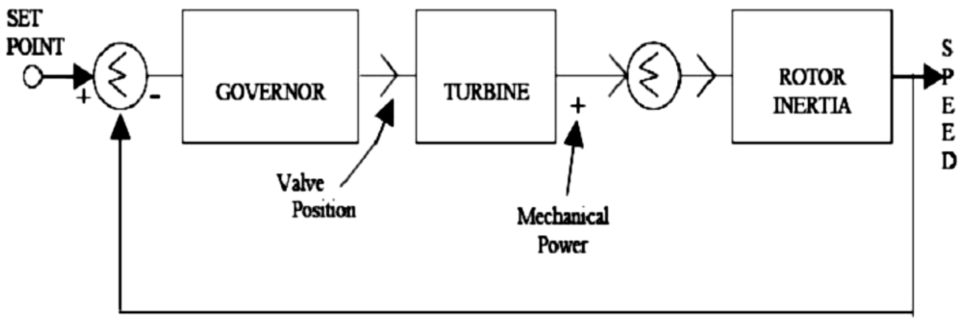


Fig.1 Basic Elements of a Governing System

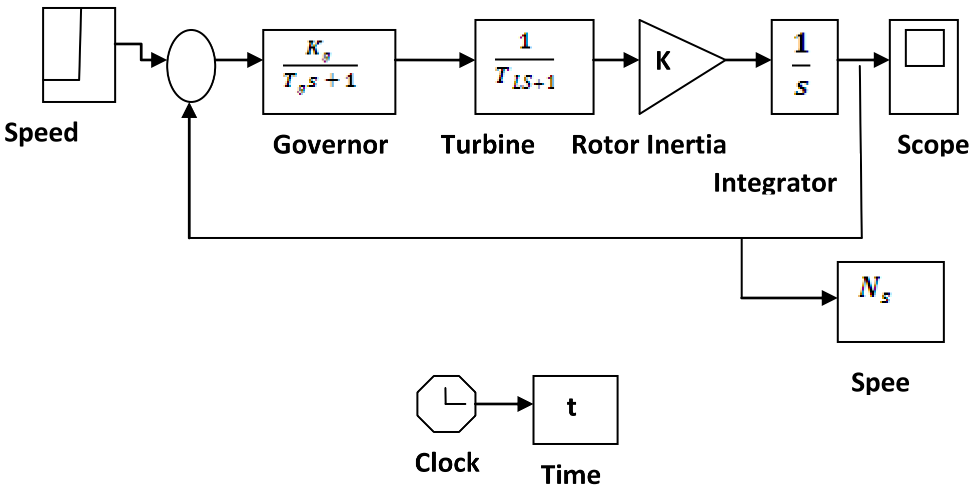


Fig.2 Simulink model of the speed governing system

Basic Governing Scheme: Need for governing system

The load on a turbine generating unit does not remain constant and can vary as per consumer requirement. The mismatch between load and generation results in the speed (or frequency) variation. When the load varies, the generation also has to vary to match it to keep the speed constant. This job is done by the governing system. Speed which is an indicator of the generation – load mismatch is used to increase or decrease the generation.

Basic scheme

Governing system controls the steam flow to the turbine in response to the control signals like speed error, power error. It can also be configured to respond to pressure error. It is a closed loop control system in which control action goes on till the power mismatch is reduced to zero.

As shown in the basic scheme given in Fig. 3, then let steam flow is controlled by the control valve or the governor valve. It is a regulating valve. The stop valve shown in the figure ahead of control valve is used for protection. It is either closed or open. In emergencies steam flow is stopped by closing this valve by the protective devices. The governing process can be functionally expressed in the form of signal flow block diagram shown in Fig.1. The electronic part output is a voltage or current signal and is converted into a hydraulic pressure or a piston position signal by the electro- hydraulic converter (EHC).

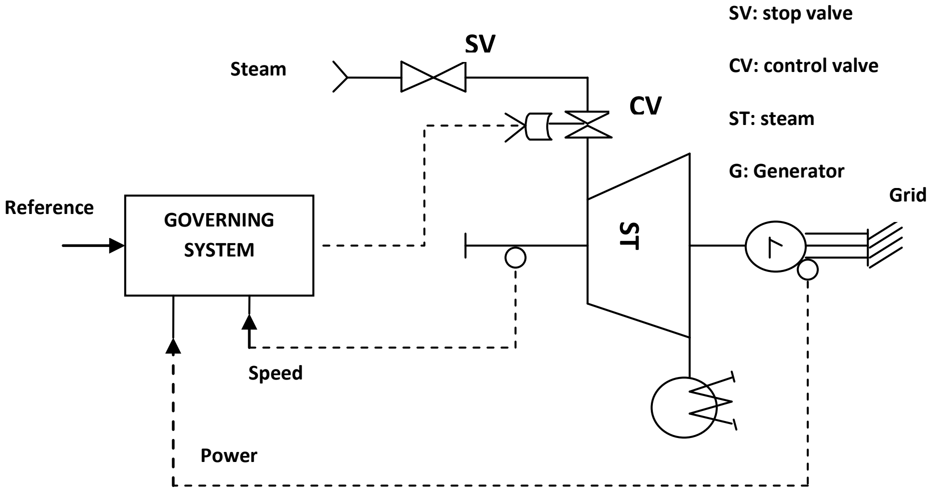
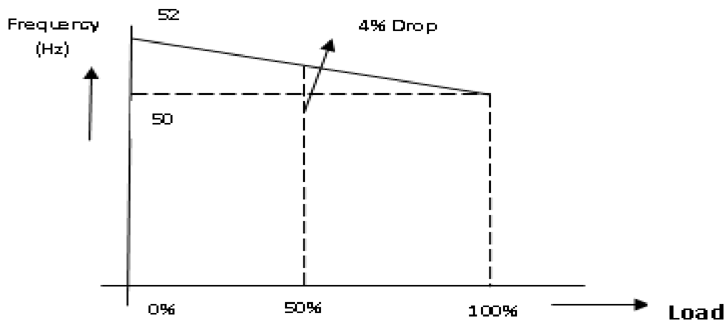


Fig. 3 Steam Turbine Governing Scheme

Some designs use high pressure servo valves. The control valves are finally operated by hydraulic control valve servo motors. Simulink Model of Speed governing system is shown in Fig.2. The steam flow through the control valve is proportional to the valve opening in the operating range. So when valve position changes, turbine steam flow changes and turbine power output also changes proportionally. Thus governing system changes the turbine mechanical power output. In no load unsynchronized condition, all the power is used to accelerate the rotor only (after meeting rotational losses) and hence the speed changes. The rate of speed change is governed by the inertia of the entire rotor system. In the grid connected condition, only power pumped in to the system changes when governing system changes the valve opening.

Performance Aspects: Regulation or droop characteristic

Whenever there is a mismatch in power, speed changes. As seen earlier, the governing system senses this speed change and adjusts valve opening which in turn changes power output. This action stops once the power mismatch is made zero. But the speed error remains. What should be the change in power output for a change in speed is decided by the 'regulation'. If 4% change in speed causes 100% change in power output, then the regulation is said to be 4% (or in per unit 0.04). The regulation can be expressed in the form of power – frequency characteristic as shown in Fig.4 (a & b). At 100% load the generation is also 100%, frequency (or speed) is also 100%. When load reduces frequency increases, as generation remains the same. When load reduces by 50%, frequency increases by 2%, in the characteristic shown. When load reduces by 100%, frequency increases by 4%. In other words 4% rise in frequency should reduce power generation by 100 %.



(a)

This 4% is called 'droop' of 4%. The characteristic is of 'drooping' type. Droop or regulation is an important parameter in the frequency regulation. In thermal power plants droop value is generally 4% or 5%. In terms of control system steady state gain it is expressed as inverse of droop: gain of 25 in per unit corresponds to 4% (or 0.04 p.u.) droop.

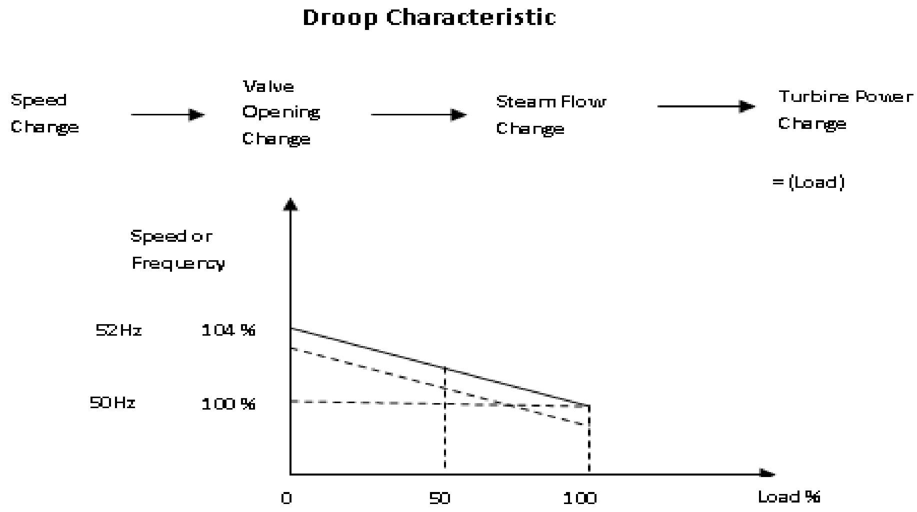


Fig 4(a,b) Regulation or droop characteristic

Modeling of Synchronous Generator

The overall accuracy of the power system stability is primarily decided by how correctly the Synchronous Generators (SGs) within the system are modeled. The proposed simulation model time constants in order to improve the terminal voltage and frequency deviation responses. 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 produces 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 Hiyama-T. 1995.

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 George K. Stefopoulos, at al. 2005.

$$d\Delta\omega / dt = (1/2H)\,(\Delta P_m - \Delta P_e) \qquad (2)$$

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Where $d\Delta\omega / dt = d^2\delta / dt^2$, H = inertia constant □, ΔPm = change in mechanical power, ΔPe = change in electrical power, $\Delta\omega$ = change in speed (elec. rad/sec), δ = rotor angle (rad.) Using Laplace Transformation, equa.2 becomes:

$$d\delta / dt = \Delta\omega(s) = (1/2Hs)\,[\Delta Pm(s) - \Delta Pe(s)] \quad (3)$$

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 Kundur P. at al.1994.

$$\Delta P_e = \Delta P_L + K_D \Delta\omega \quad (4)$$

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. Load change derived from the swing equation with the aid of equa.4 or:

$$\Delta\omega(s) = [\Delta Pm(s) - \Delta P_{\mathbf{L}}(s)]\,[1/(2Hs + K_{\mathbf{D}})] \quad (5)$$

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 ΔPm with the changes in steam valve position $\Delta €_V$ is given as:

$$G_T(s) = \Delta P_m(s) / \Delta €_V(s) = 1 / 1 + sT_T \quad (6)$$

Governor Model

The speed governor mechanism works as a comparator to determine the difference between the reference set power ΔP_{ref} and the power $(1/R)\,\Delta\omega$. The speed governor output ΔS_g is therefore

$$\Delta S_g(s) = \Delta P_{ref}(s) - (1/R)\Delta\omega(s) \quad (7)$$

Where R represents the drop. Speed governor output ΔS_g is being converted to steam valve position ΔVs through the hydraulic amplifier. Assuming a linearized model with a single time constant Tg:

$$\Delta Vs = (1 / (1 + sT_g))\,\Delta S_g(s) \quad (8)$$

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.

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3. Interval Type-2 Fuzzy Logic Controllers

The interval type-2 FLC uses interval type-2 fuzzy sets (such as those shown in Fig.5(a) to represent the inputs and/or outputs of the IT2FLC i.e.Fig.5(b) defines .Definition of 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.

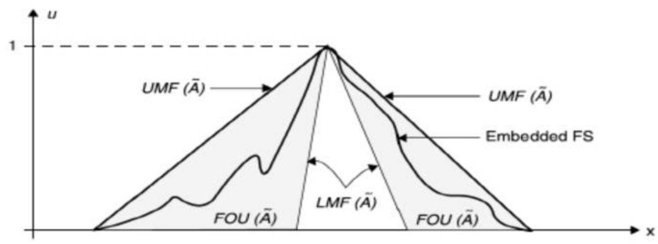


Fig.5. (a) an interval type-2 fuzzy set

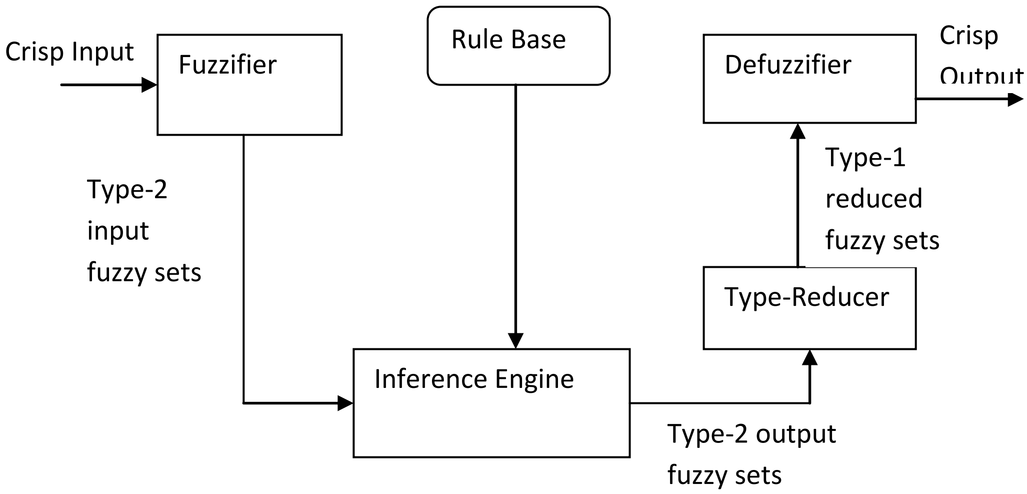


Fig.5(b) Structure of the interval type-2 FLC.

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.5(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.

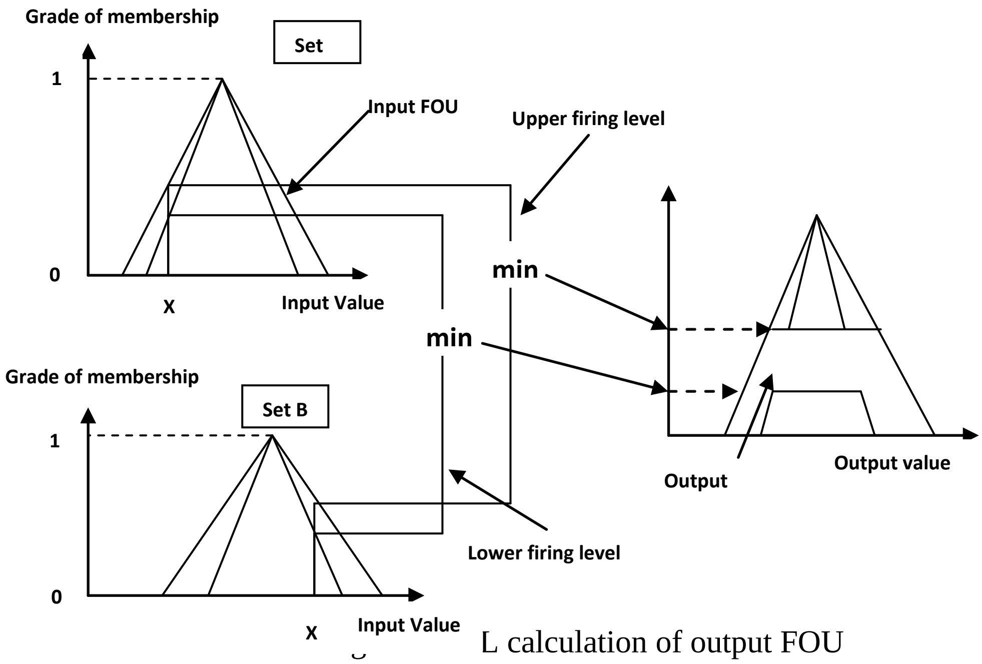
(b) Using interval type-2 fuzzy sets to represent the FLC inputs and outputs will result in the reduction of the FLC rule base when compared to using type-1 fuzzy sets as the uncertainty represented in the footprint of uncertainty in interval type-2 fuzzy sets lets us cover the same range as type-1 fuzzy 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 V_t & $\Delta\omega$ (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.6 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.6. 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. 6. 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 thana 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



L calculation of output FOU

One objective of governing control is to keep the generator operating after some unexpected system faults. Two performance indices are concerned. One is the oscillating time, or the system damping. The other is the system transfer capability. The more power transferred the better. To demonstrate this objective, we are using the simplest system. In a single machine to infinite bus system, the power output of generator can be expressed as

$$P_e = \frac{E_q V_s}{X_{d\Sigma}} \sin \delta \qquad (9)$$

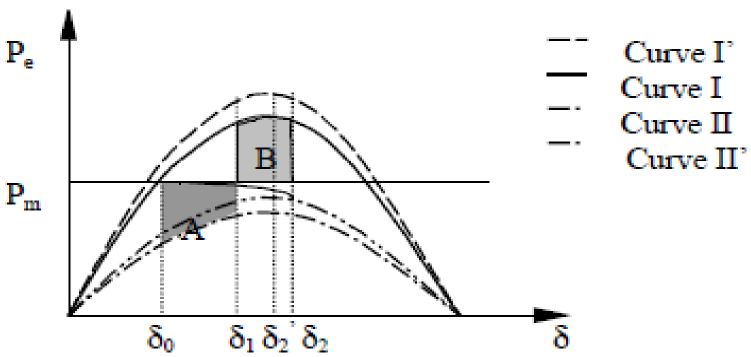


Fig.7 Equal Area Rule of Generator Oscillation in First Swing

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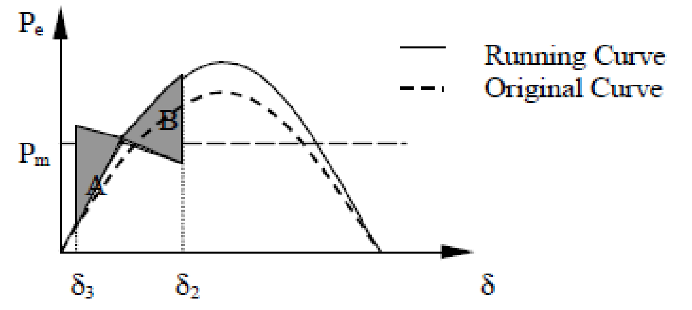

Fig.8 Expected Dynamic Behavior when increases

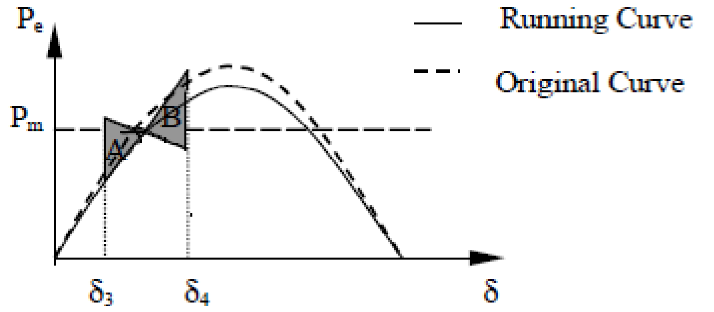

Fig.9 Expected Dynamic Behavior when decreases

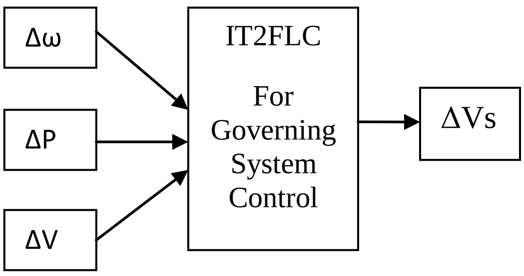

Fig.10 Block Diagram of Interval Type-2 Fuzzy Logic Module

The machine will run along the curve II during the fault period. When the fault disappears, the machine will run along curve I. Area A is the accelerating energy and Area B is the decelerating energy. To damp system as soon as possible, Area A and B must become smaller. Two possible measures will be taken. One is reducing the mechanic power Pm input; the other is increase the electric power Pe output.

The expected running curve is Curve II during the fault period and Curve I after fault. Then the maximum internal angle is decreased from δ_2 to δ_2. This operation can be achieved by increase the voltage and decrease Pm. The behavior after the first swing (Fig.7) will follow same argument;

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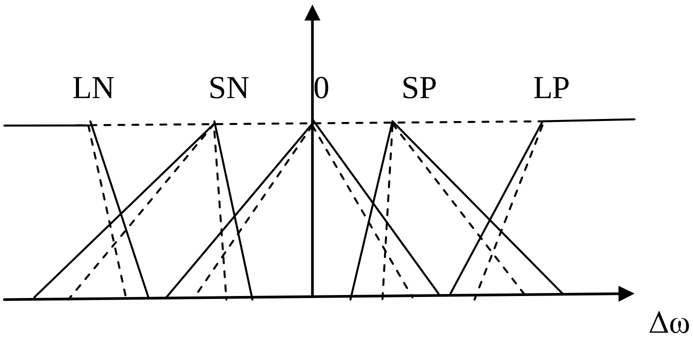
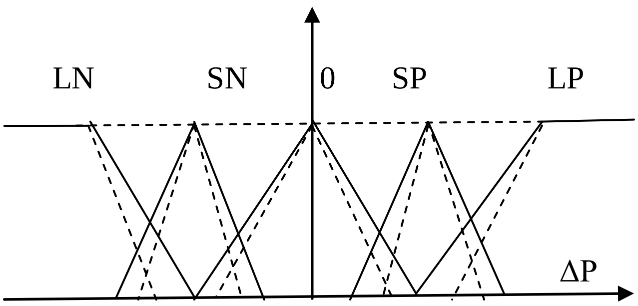
increasing the voltage and decreasing the mechanic power when machine is in acceleration, decreasing the voltage and increasing the mechanic power when machine is in deceleration. Simply the argument can be shown in diagram in Fig.8 and 9. Fig.10 shows the block diagram of interval type-2 fuzzy logic module.Fig.11 to Fig.15 show the fuzzifide interval type-2 membership functions of antecedent and consequent parameters.



Lower -0.015 -0.01 -0.005 -0.0045 0 0.0045 0.005 0.01 0.015

Upper-0.025 -0.02 -0.015 -0.01 0 0.01 0.015 0.02 0.025

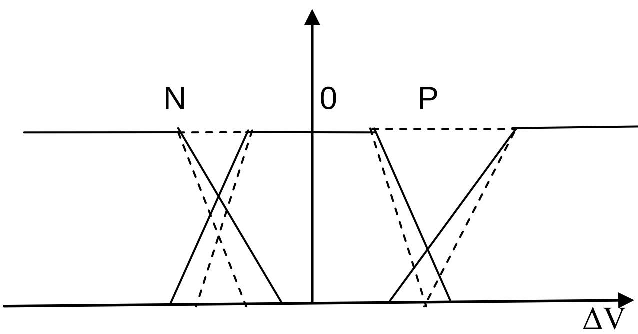
Fig.11 Fuzzification of Δω



Lower-0.55 -0.35 -0.15 -0.05 0 0.05 0.15 0.35 0.55

Upper-0.65 -0.45 -0.25 -0.15 0 0.15 0.25 0.45 0.65

Fig.12 Fuzzification of ΔP



Lower -0.15 -0.1 -0.05 0 0.05 0.1 0.15

Upper -0.25 -0.2 -0.15 0 0.15 0.2 0.25

Fig.13 Fuzzificationof ΔV

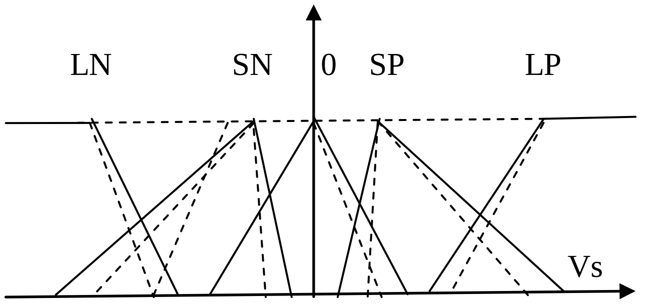


Fig.14 Defuzzification of Vs

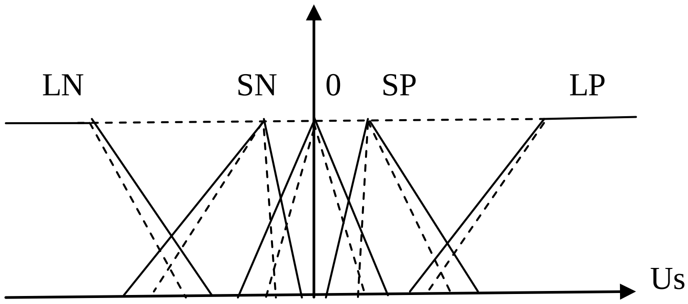


Fig.15 Defuzzification of Us

When $\Delta V=V_0 - V_t$ is P, then Us is always LN and Vs is always LP except when dω and dP are 0s. Here dω is denoted as ω-ω_0, and dP is denoted as Pm-Pe. The proposed design scheme is implemented in SIMULINK. We tested the design in the single machine to infinite bus through a double lines system. The generator and system parameters are given in Table 1.Here the symbols follow the standard representation. The voltage of infinite bus is set as V = 1.0.

Table 1 Parameters of Model System

X_d	x_q	X_d	x_q	X_2	T_{do}
1.2	1.2	0.2	0.2	0.2	6.0
T_{qo}	H	D	X_T	X_L	P_N
0.6	10	2	0.2	1.6	1.0

4. The 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 NARMA-L2 controller is examined.

A. Results for 0.6 p.u. load change without controller

Using the simulation model governing system of the 4th order SG Fig .2 for 0.6 p.u. load change without controller then, the simulation results for terminal voltage (Vt) ,frequency deviation ($\Delta\omega$) are illustrated in Fig.16 and Fig.17 respectively .The period of simulation in the frequency deviation step response ($\Delta\omega$)) and the terminal voltage (Vt) is set as 30seconds, and 1.14 second respectively so as to verify that there are no further oscillations. In Fig.17 the response for ($\Delta\omega$) oscillates for a period of 14.03 seconds before settling down to zero deviation. There is an overshoot error occurring at 1.6 seconds. The ideal response is to keep the deviation (oscillation) as close to zero as possible at the minimum period of time.

B. 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 controllers parameters Kp, Ki and Kd on the terminal voltage response that exist in the excitation system only **.**Tuning the PID controller by setting the proportional gain Kp to 1, Ki to 0.5, and Kd to 0.005, then the frequency deviation step response ($\Delta\omega$) has similar response to that for Fig.17. The response for terminal voltage is improved as illustrated in Fig.18 for 0.6 p.u. load change. The overshoot is decreased to 3.1 p.u.. Also, the time taken for the terminal voltage to reach the value of 1 p.u. is now 0.8 seconds. It's found that these settings of Kp, Ki, and Kd don't produce a good overall response. From these responses and refer to tuning method, the best values of the PID controller parameters for the excitation and governing systems are selected as: Kp=1, Ki=2, Kd=0.005.Then the new response for terminal voltage (Vt) with PID controller is illustrated in Fig.19 for load change of 0.6 (p.u.).While in a similar way, the best values of Kp, Ki, and Kd of the PID controller in the governing system are set to be: 0.8, 0, 0.6 respectively. The new simulation results for frequency deviation ($\Delta\omega$) response with PID controller are illustrated in Fig.20.

C. 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.21 shows the terminal voltage response for the 4th order SG model using NN. The frequency response is similar to that response with PID controller because this NNC is exactly exist in the excitation system and we know that the excitation and governing control are designed independently that mean there is a weak coupling between them.

D. 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.22. From which one can deduced that, the artificial intelligent controller, type NARMA-L2 has the best transient response than others.

• Also, the enhancements of the transient responses are obviously appeared in Fig.17 which illustrates the frequency deviation responses of the 4th order SG model for 0.6 p.u. load change without controller and with PIDC.

It's seen from Fig.23 that the PID controller is highly improved the frequency deviation step response. The overall enhancements results of the settling time and overshoot which being a measures for the Vt transient stability enhancements are illustrated in Table (2).

E. 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 (3).

Table (2) Terminal voltage response for 0.6 p.u. load change without controller

	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	14.03	+0.03 -0.04
	PID	10	+0 -0.03

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Freq. Deviation response of a 4th order model SG for 0.3 p.u. load change	Without	14	+0.0342 -0.024
	PID	11	+0.0155 -0.0182
Freq. Deviation response of a 4th order model SG for 0.8 p.u. load change	Without	14.25	+0.029 -0.051
	PID	10	0 -0.025

Table(3) Freq.Dev. response for various load changes with PID controller, and with NNC

	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	1.14	+4 -0.82
	PID	0.2	+3.2 -0.35
	NNC	0.028	+2.4 0

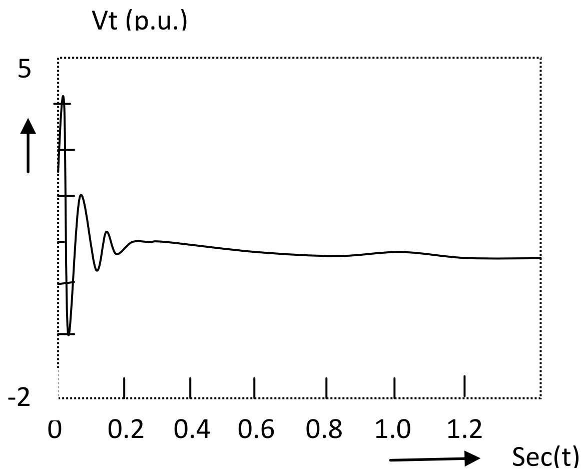


Fig.16 Terminal voltage (Vt) step response for 0.6p.u load change.

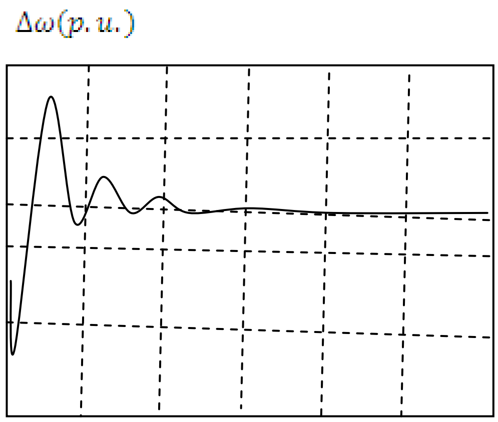
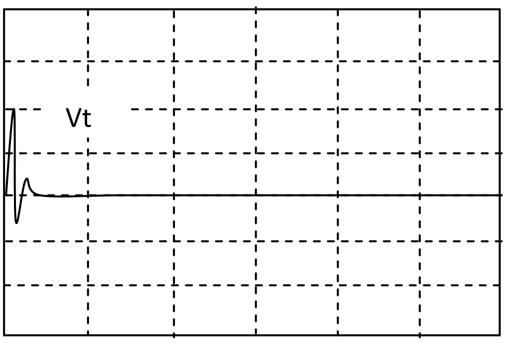


Fig.17 Frequency deviation (Δω) for 0.6p.u. load Change.



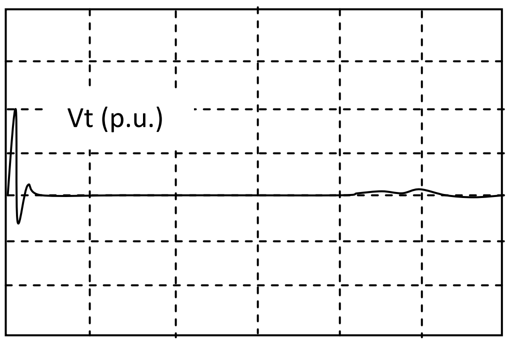


Fig.18 Terminal voltage when Kp = 1, Ki=0.5 and Kd=0.005

Fig.19 Vt step response for 4th order model with PID controller

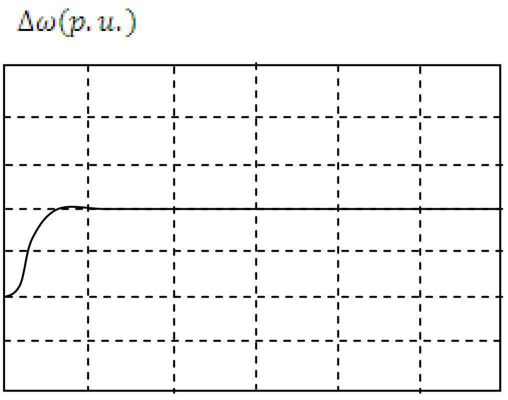


Fig.20 Frequency deviation (Δω) step response for with PID controller

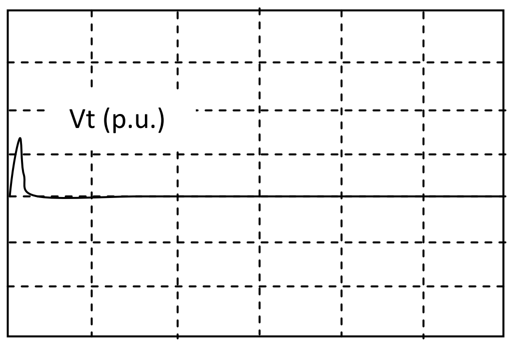


Fig.21 Terminal voltage (Vt) step response for 4th order model with IT2FLC

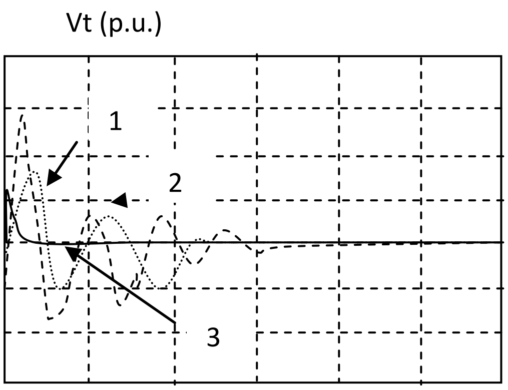


Fig.22 Vt transient responses of the SG model for 0.6 p.u. load change with different types of controllers change

Where:1- Terminal voltage response without controller.

2- Terminal voltage response with PID controller.

3- Terminal voltage response with IT2FLC.

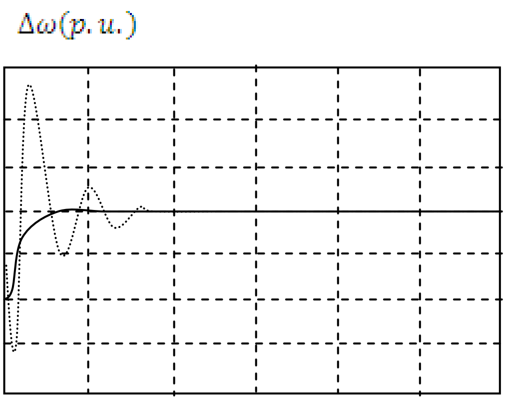


Fig.23 Freq. Dev.(Δω) step response of the SG Model for 0.6 p.u. load

where:1-Freq. Dev. Step response Without Controller.

2. Frequency Deviation step response with PID controller

5. Conclusions

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

1. When excitation and governing systems are tested for various load changes, these changes in the load did not affect the output response of the excitation system that mean excitation system is always the same as at no load but it has an effect on frequency response.
2. The proposed IT2FLC Controller gives excellent results. The terminal voltage transient stability response enhancements through the obtained results are remarkable and comparable with respect to others. By this controller, the generator terminal voltage profile and the generator transient stability response are improved.

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