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Fuzzy Logic Controller for Power System Constancy Development & Control

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Abstract- Using speed and power output deviations as the controller input variables, a fuzzy logic based controller (FLC) has been developed to perform the function of a power system stabilizer and to provide a supplementary signal to the excitation system of a synchronous machine.

The complete range for the variation of each of the two controller inputs **is** represented by a 7 x 7 decision table, i.e. **49** rules. The FLC design steps and a procedure for tuning its parameters are described. Simulation studies for a variety of disturbances on the power system with the FLC based power system stabilizer demonstrate its effectiveness in improving system performance.

Key words: Fuzzy logic, simulation, MATLAB, Synchronous Machine

Introduction

The electrical energy has become the major form of energy for end use consumption in today's world. There is always a need of making electrical energy generation and transmission, both more economical reliable. The voltage throughout the system are also controlled to be within $\pm$ 5% of their rated values by automatic voltage regulators acting on the generator field exciters, and by the sources of reactive power in the network.

For proper operation, this large integrated system requires a stable operating condition. The power system is a dynamic system. It is constantly being subjected to small disturbances, which cause the generators relative angles to change. For the interconnected system to be able to supply the load power demand when the transient s caused by disturbance die out, a newer acceptable steady state operating condition is reached. That is, the power system must be stable. It is important that these disturbances do not drive the system to an unstable condition.

1. Power System Modeling

Park's Model

A great simplification in the mathematical description of the synchronous machine is obtained if a certain transformation of variable is performed.

The transformation used is usually called Park's transformation. It defines a new set of stator variables such as current, voltage, or flux linkages in terms of the actual winding variables on three axes. One along the direct axis of the rotor field winding, called the direct axis; a second along the neutral axis of the filed winding, called the quadrature axis; and the third on a secondary axis

The Park's transformation P is defined as

P =

$$\sqrt{2/3}\begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ \cos\theta & \cos(\theta-2\pi/3) & \cos(\theta+2\pi/3) \\ \sin\theta & \sin(\theta-2\pi/3) & \sin(\theta+2\pi/3) \end{bmatrix}$$

The inverse may be computed to be

$$P^{-1}=\begin{bmatrix} 1/\sqrt{2} & \cos\theta & \sin\theta \\ 1/\sqrt{2} & \cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) \\ 1/\sqrt{2} & \cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) \end{bmatrix}$$

Two – Axis Model

In this model the axis d and orthogonal axis q are represented only. Usually one machine is chosen to be the reference frame and a set of machine lineraized equation is used in simulation. The state variable may be chosen as $x^t = [\ \delta \quad \omega \quad E'_q \quad E'_d \ E_{fd}\ ]$. A linearized system network equations must be provided in the form i = f (E'q, E'd, δ).

Hiffron- Phillips Model

A detailed exploration of the Hiffron-Phillips model is presented as follow:

2.1 The Acceleration Equations

In the case of the classical generator model, the acceleration equations are

$$\Delta\omega_r = \frac{1}{2H}(Tm - Te - KD\Delta\omega r)$$

$$\Delta\delta = \omega_o \Delta\omega_r$$

Where $\omega_o = 2\pi f_o$ elect rad/s. In the case, the rotor angle δ is the angle (in elect rad) by which the q axis needs the references E_B. For the single machine connected to an infinite bus shown in fig (2.1.a) the rotor angle δ is the sum of the internal angle δi and the angle by which E_t leads E_B as in fig (2.1.b)

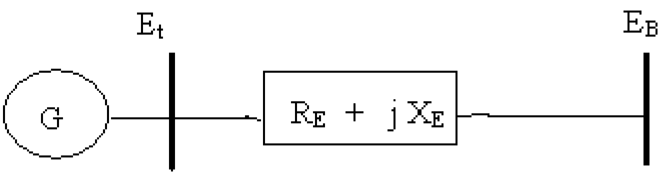


Fig (2.1.a) : Single machine connected to an infinite bus

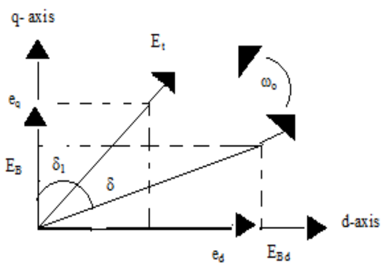


Fig. (2.1.b): Vector diagram of single machine connected to an infinite bus

3 Basic Concept

Unstable inter-area oscillations have been encountered in the last two decays by electrical power utilities throughout the world. In general, the unstable oscillations are involved in power systems, or areas within a power system, which are weakly interconnected. The following occurrence of the inter-area mode instability and their dates are documented in published papers.

These occurrences are summarized as follows:

- Mid –content Area Power Pool (MAPP) 1972
- Western U.S. (WSCC) 1978
- Western Australia 1982
- Taiwan 1984
- Southern Brazil 1985
- Ontario Hydra 1985

In this chapter the basic concept for analysis of the system state space model are explored with focusing on the information useful in design of controllers for damping modes of oscillations.

3.1 Eigen Values

A linear dynamic system can be modeled in state space in the form [19,20]

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

$$x = (sI-A)^{-1}[x(0) + Bu] = \frac{\text{Adj}(sI-A)[x(0)+Bu]}{\text{Det}(sI-A)}$$

3.2 Eigen Vectors

For each Eigen value λ_i, there is a column vector t_i which satisfies

$$At_i = \lambda_i t_i$$

The vector t_i is called the right Eigenvector of "A" associated with λ_i, Similarly, There exist a row vector v_i which satisfies

$$v_i A = \lambda_i v_i$$

This vector v_i is called the left Eigenvector of "A" associated with λ_i Also, if "A" is symmetric, then

$$v_i = t_i^T$$

3.3 Diagonalization of "A" Matrix

Diagonalization of the state matrix A is possible if it has a set of distinct Eigen values. Also the set of state variables can be transformed to another set of state variables via a linear transformation with the set of Eigen values being invariant. These are two useful properties of the state space model for the definition of modes and to compute the system response.

3.4 Mode Controllability

If the magnitude of a particular made of the system is completely unaffected by a particular input, this system is said to be uncontrollable. In the uncontrollable system at least one of the row vector b_i , i.e., at least one row of the matrix T^{-1} B is zero. This would imply for such modes $z_i(t) = e^{\lambda it} z_i(0)$

3.5 Mode Observability

In a similar way the measured output of a system may contain no contribution from a particular mode. The output is given by

$$y(t) = C\,x(t) + D\,u(t)$$

In terms of the modes, using the output is

$$y(t) = C\,T\,Z(t) + D\,u(t)$$

3.6 Participation Matrix

In controlling an unstable mode, it is essential to determine the states of the system, which strongly influence the mode to be controlled. Although Eigenvectors give the disturbance of a mode through the system, they depend on units and scaling of the state variable and cannot be used for comparison of states due to non-uniqueness and scaling problems.

4. METHOD OF DAMPING CONTROLLERS

4.1 Conventional Controllers

Lead-lag or PID controllers are the result of conventional control theory (i.e. phase and gain margins, root locus….). These controllers are used for the last three decades and still have the leading hand in the real world of PSSs. They can be designed off-line tuned after the installation.

4.2Modern Control Theory

Optimal, adaptive and pole placement controllers are the resultant controls from modern control theory. They give the desired stabilized response with the stability margin as required. Due to construction of power systems (i.e. the distances, the extensive numbers of variables…..) they always have problems in the real power system world, as they depend on extensive number of feedback signals.

4.3Optimal control Theory

The principle for optimal control is to minimize saturate cost function which is called the performance index. The design quadratic optimal controller based on such quadratic performance indexes boils down to the determination of the elements of the matrix feedback gain matrix "K"

4.4 Adaptive Controllers

The need of a controller with changes its parameters to give the desired performance while the operating condition change is a goal for several decades. This will avoid the need of investigation of the exact mathematical model. The self-tuning controller is used to evaluate the matrices and viability of such a controller. A self-tuning controller is a digital adaptive controller which can change the controller's parameters continuously the operating condition in real time and modified parameter accordingly

4.5 Pole Placement techniques

Let the system complex Eigen value λ is to be shifted to a new location in the s-plane λ_o. The new location is chosen to satisfy a specified damping ration. It also must satisfy the characteristic equation of the closed loop system, i.e.

$$H(\lambda_o) = \frac{-1}{G(\lambda o)}$$

$$|\,H(\lambda_o)\,| = \frac{-1}{G(\lambda o)}$$

4.6 Inter- Area Oscillations

The problem of Inter- Area is a result of power inters change between generating units in power system which are interconnected by a relatively weak transition links.

Inter- Area can be initiated by a small disturbance, such as a change in load or in generation. These types of disturbance occur continuously in power system i.e., a power system with an unstable in Inter- Area mode is impossible to operate.

5. FUZZY LOGIC CONTROLLER

5.1 Fuzzy logic Theory

Fuzzy logic is a kind of logic is using graded and quantified statement rather than once that are strictly true or false. The results of fuzzy reasoning are not definite as those derived by strict logic. The fuzzy sets allow objects to have grades of membership from 0 to 1. These sets are represented by linguistic variables, which are ordinary language terms. They are used to represent a particular fuzzy set in a given problem, such as “large” , “medium” and “small”.

5.2 Fuzzy Set Definition

Let U be a collection of objects denoted generically by{u}, which could be discrete or continuous. U is called the universe of discourse and u represents the generic elements of U.

A fuzzy set F in a universe of discourse U is characterized by a membership function μ_r which takes values in the interval [0,1]. A fuzzy set may be viewed as a generalization of the concept of an ordinary set that its membership function only takes two values {0,1}. Thus, a fuzzy set F is U may be represent as a set of ordered pairs of a generic elements u and its grade of membership function:

$$F = \sum_{i=1}^{n} \mu_F (u_i) / u_i$$

5.3 Fuzzification Operator

A Fuzzification Operator has the effect of transforming crisp data into fuzzy sets.

Symbolically,

$$x = \text{fuzzifier}\ (x_o)$$

where x_o is a crisp input value from a process, x is a fuzzy set, and fuzzifier represent a fuzzification operator.

5.4 Compositional Operator

To infer the output z from the given process states x,y and the fuzzy relation R. The sup-star compositional rule of inference is applied

$$z = y \circ (x \circ R)$$

Where o is the sup-star composition

5.5 Defuzzification Operator

The output of the inference process so far is a fuzzy set, specifying a possibility distribution of control action. In the in-line control, a non-fuzzy (crisp) control action is usually required. Consequently, one most defuzzify the fuzzy control action (output) inferred from the

$$\mathbf{z_o = defuzzifier\ (z)}$$

Where z_o is the non-fuzzy control output and defuzzifier is the defuzzification operator.

6. PROPOSED CONTROLLER

A simple fuzzy controller based on the experience can damp only local modes. To damp both local and inter-area modes of oscillation, the experience is difficult to be obtained. So, the design process needs a systematic method for obtaining the rule base and the domain ranges. The proposed solution of this problem is that is a fuzzy controller is to be developed based on the optimal control theory. This is capable to obtain a near optimal fuzzy controller that is characterized by its systematic nature in design.

6.1 Choice of Process State and Control Output

A first step is to choose the correct input signals to the fuzzy logic control stabilizer. For this controller a choice of state variables representing the contents of the rule-antecedent (If-part of a rule) is selected amongst

1.Generator speed deviation signal.
2.Generator speed deviation change signal.

The control output signal (process input) variable represent the contents of the rule-consequent (then-part of the rule) Fig. (6.2). This control output is denoted by U_{pss} (The damping signal which is fed into the reference voltage summing point).

Normalization

Normalization performs a scale transformation and its also called input normalization. It maps the physical values of the current process state variables into a normalized universe of discourse (normalized domain). It also maps the normalized value of control output variable onto its physical domain (output demoralization). For this controller a normalization is got by dividing each crisp input on the upper boundary value for the associated universe.

Fuzzification

Fuzzification is related to the vagueness and imprecision in a natural language. It is a subjective valuation, which transforms a measurement into a valuation of a subjective value. Hence, It could be defined as a mapping from an observed input space to fuzzy sets in creation input universe of discourse. Fuzzification plays an important role in dealing, with uncertain information, which might be objective or subjective in nature.

6.2 The generator speed deviation is classified into:

{negative big (w_nb); negative medium (w_nm); negative small (w_ns); zero (w_z);

Positive small (w_ps); positive medium (w_pm); positive big (w_pb)}.

The generator speed deviation change is classified into:

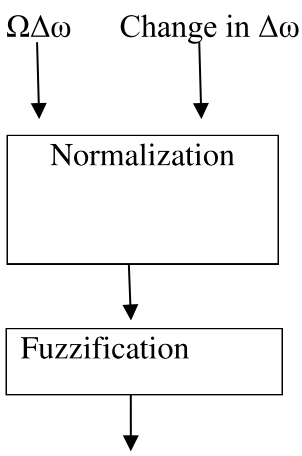
{negative big (dw_nb); negative medium (dw_nm); negative small (dw_ns); zero (dw_z);

Positive small (dw_ps); positive medium (dw_pm); positive big (dw_pb)}.

6.3 The output of fuzzy controller is classified into:

{negative big (u_nb); negative medium (u_nm); negative small (u_ns); zero (u_z);

Positive small (u_ps); positive medium (u_pm); positive big (u_pb)}.



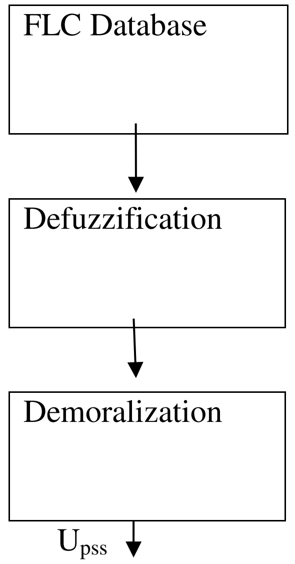


Fig.(6.1): The stages of the proposed FLC

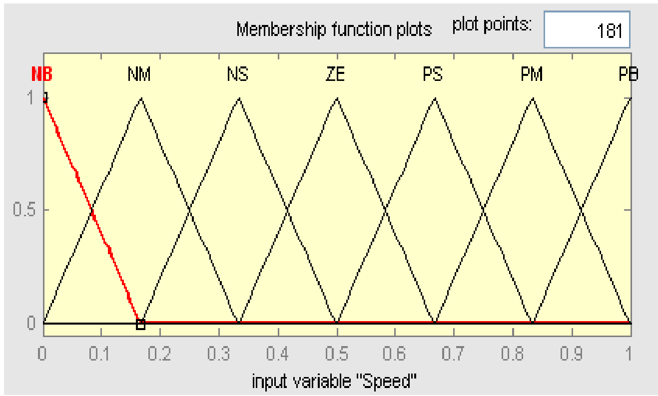


Fig.(6.2): Blocker diagram shows the exciter and the proposed FLC

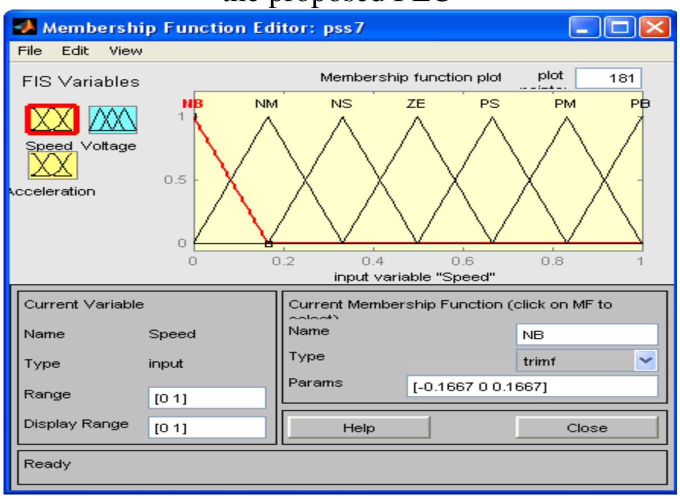


Fig.(6.3): Membership functions normalized in one common universe (nb: negative big, nm: negative medium, ns: negative small, z: zero, ps: positive small, pm: positive medium, pb: positive big)

After this classification, the fuzzification module can be applied. By conversion of a point-wise (crisp) and current value of a process state variable (generator speed deviation signal and generator speed deviation change signal) into their associated fuzzy sets, this will make it compatible with the fuzzy set representation of the process state variable in the rule-antecedents. Each crisp input (either generator speed deviation signal or generator or speed deviation change signal) has seven tuples denoted by : {classed fuzzy set and its membership function value.}

For example if normalized generator speed deviation = -0.2 then it has seven tuples as follows:

(w_nb,0)

(w_nm,0)

(w_ns,0.8)

(w_z,0.2)

(w_ps,0)

(w_pm,0)

(w_pb,0)

Then each crisp input can be fuzzified to obtain its membership values through the associated seven classes in the normalized universe of discourse.

6.4 Fuzzy Controller Simulation

In this section the simulation algorithm of the proposed fuzzy controller is discussed. For each time step in the system main simulation, a calculation of the generator speed deviation signal and generator speed deviation change in signal is made. This is achieved by getting the value of the state variable in the state matrix "A" which equal to the generator speed deviation. The value of generator speed deviation signal from the previous generator speed deviation signal. The associated membership values for each normalization input are calculated. Then applying the max-min method inference method to get the control output in fuzzy values. These fuzzy values can be converted to a crisp value by COG method. The signal of the controller is the damping signal that is fed into the reference voltage summing point to get the next state values.

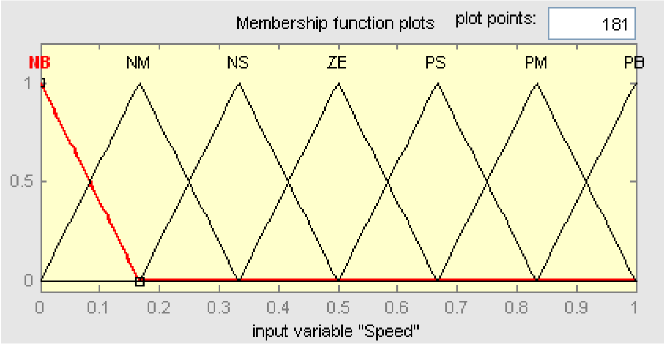


Fig.(6.5): Calculation of the membership values due to a certain input

7.BASE STUDY

For the integrated system both local modes and inter-area modes appear. Then, a simple fuzzy controller based on the experience can only damp local modes. Therefore, the solution of this problem is that a fuzzy controller is to be developed based on the optimal control theory. The optimal controller depends on feeding back signals from all states of the system, to damp both local and inter-area modes. The resultant fuzzy controller should approach the optimal as compared with the optimal controller results for damping small disturbance through many operating conditions. So a near-optimal fuzzy stabilizer for damping both local modes and inter-area modes is developed.

6.5 Fuzzy Logic Controller for Damping Oscillation in a Simple Power System

In this section, it is decided to apply a fuzzy logic controller for a synchronous machine to an infinite bus system. The synchronous machine as represented in[1] is assumed to have a thyristor-type excitation system and connected through a transformer and a transmission line to an infinite bus. The system data is found in [1] and Appendix (B). To discuss the small signal stability problem, the nonlinear equations representing the system must be linearized.

7. RESULT AND DISCUSSION

7.1 Introduction

The performance of single machine infinite bus system with lead-lag PSS and fuzzy PSS has been studied in SIMULINK environment. The fuzzy stabilizer has been modeled in *fis* editor of *matlab*. The SIMULINK model of the system with fuzzy PSS is shown in Fig. 8.1. Corresponding to the system data specified in Appendix, the K-coefficients are calculated as K1=0.7636, K2=0.8644, K3=0.3231, K4=1.4189, K5 =-0.1463, K6=0.4167. The scaling factors associated with input and output variables are tuned and taken as Kin1=1.8, Kin2=29.58, Kout=1.05. For such constants, which are in Fig. 8.1, the performance has been studied under different conditions. Although the stability problem in practical power system is mainly due to poor damping, the constant K5 has important bearing on system performance. Its value normally found to be negative for high reactance and high power output, a practical situation. The K5 can have positive value for low reactance and low power output. Therefore, the performance is studied for small 0.05 p.u. change in input for both K5 negative (-0.1463) and K5 positive (0.1463) and response characteristics are shown below.

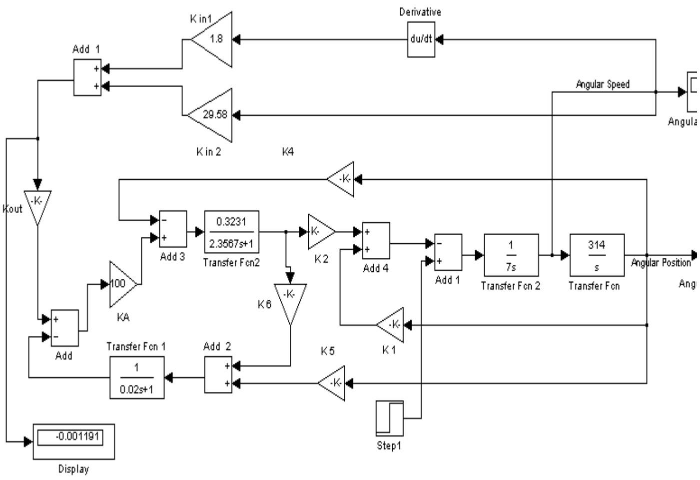


Fig. 7.1: SIMULINK model with Lead lag PSS

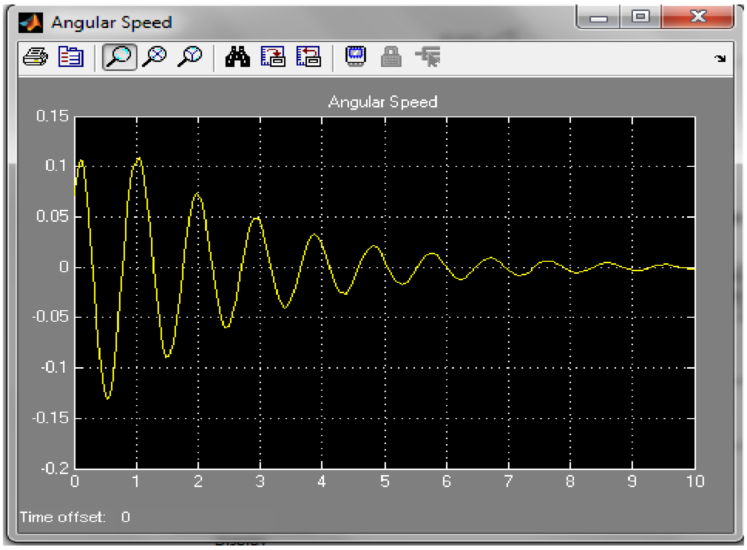


Fig. 7.2: Angular speed for change in mechanical input with K5 Positive (PSS)

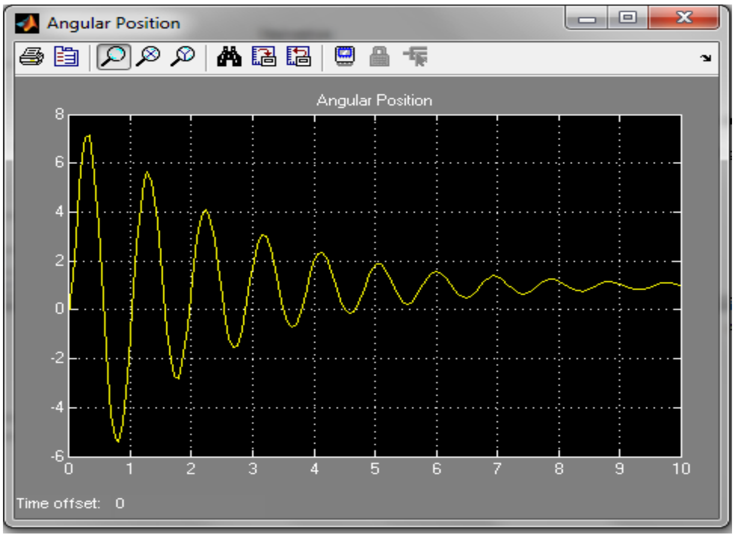


Fig. 7.3: Angular position for change in mechanical input with K5 Positive (PSS)

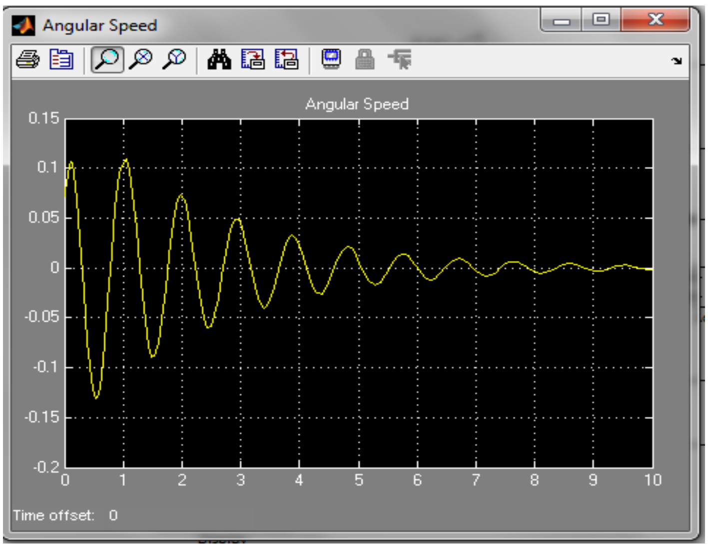


Fig. 7.4: Angular speed for a 0.05pu change in mechanical input with K5 Negative (PSS)

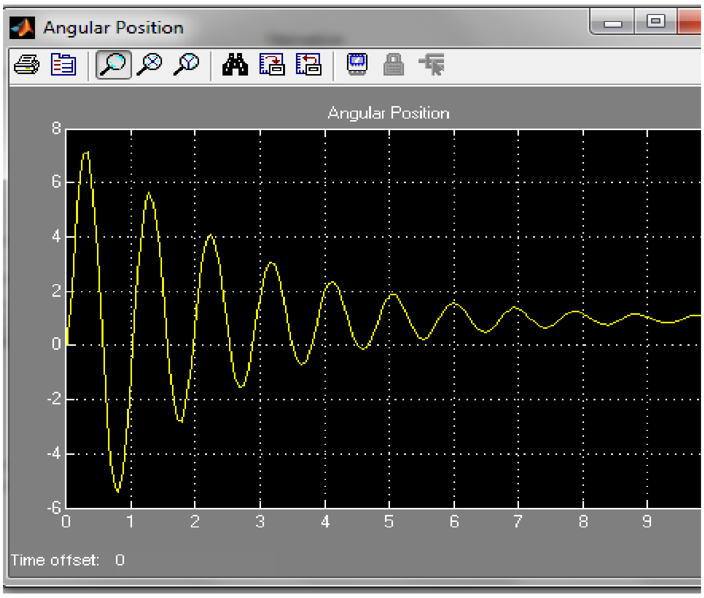


Fig. 7.5: Angular position for a 0.05pu change in mechanical input with K5 Negative (PSS)

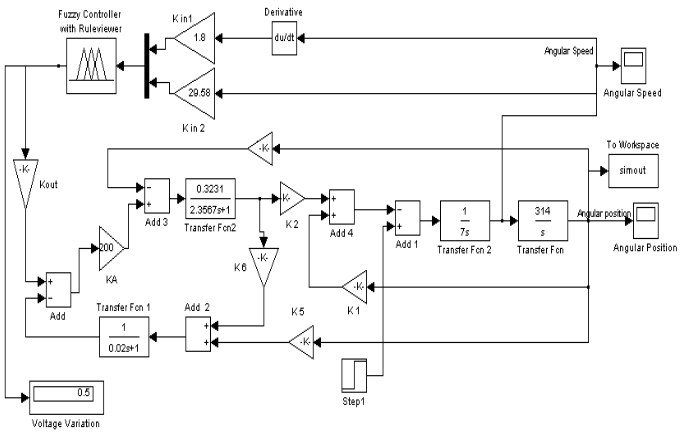


Fig. 7.6: SIMULINK model with fuzzy logic based PSS

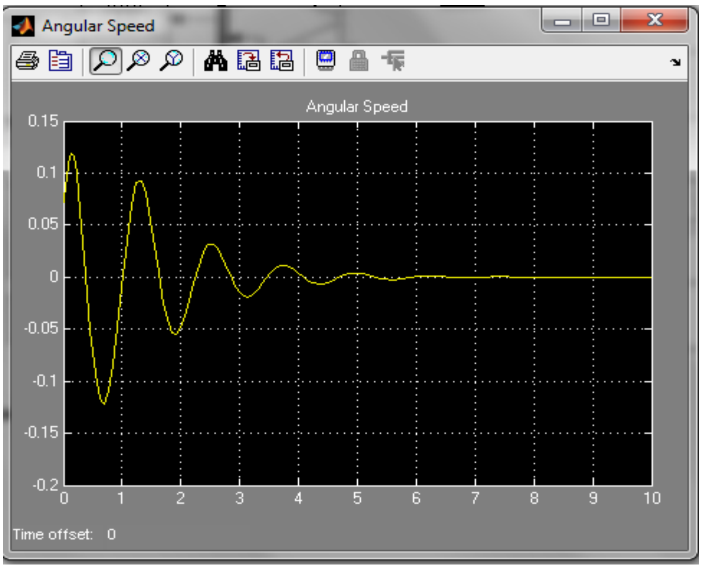


Fig. 7.7: Angular speed for a 0.05pu change in mechanical input with K5 Positive (FPSS)

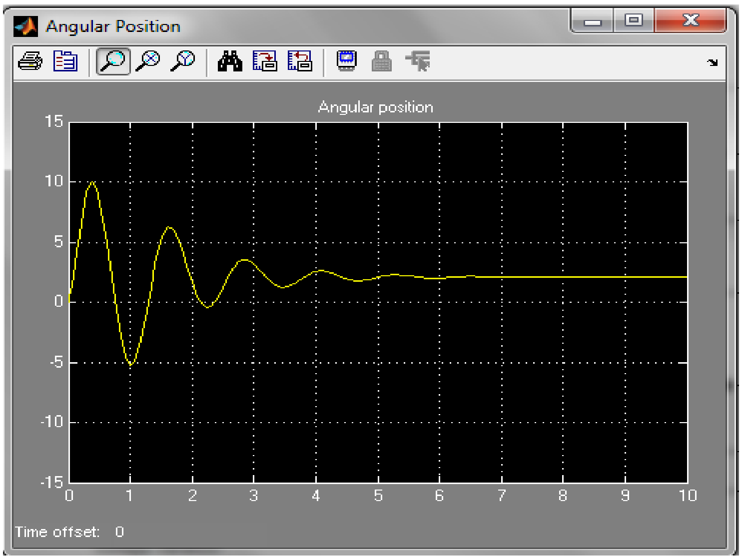


Fig. 7.8: Angular position for a 0.05pu change in mechanical input with K5 Positive (FPSS)

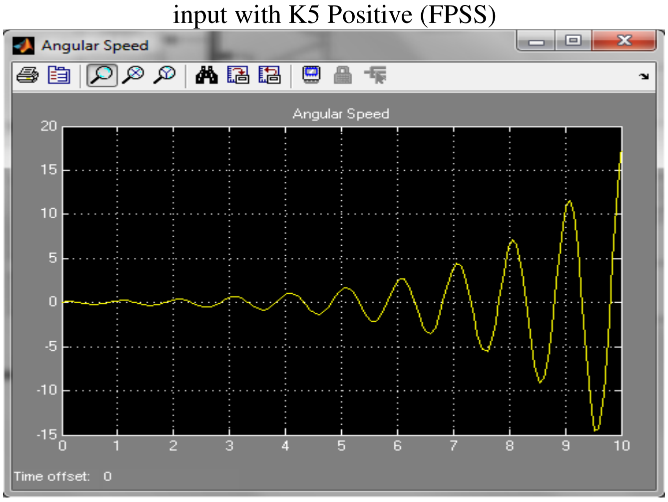


Fig. 7.9: Angular speed for a 0.05pu change in mechanical input with K5 Negative (FPSS)

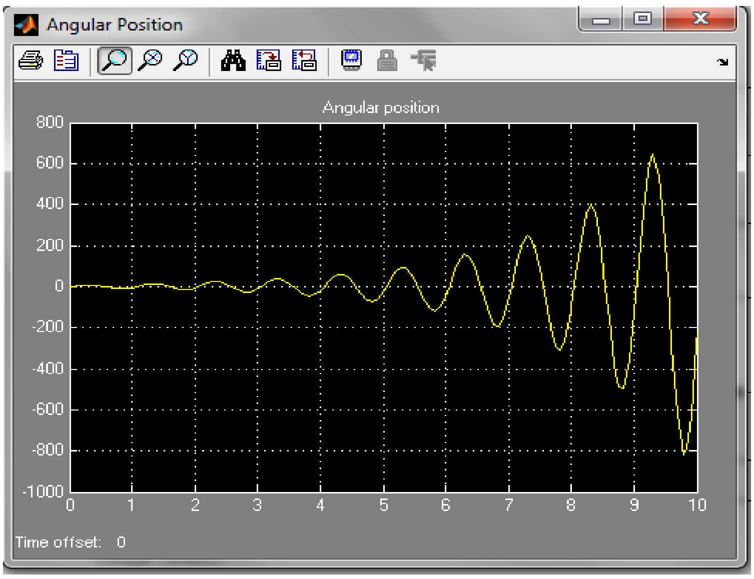


Fig. 7.10: Angular position for a 0.05pu change in mechanical input with K5 Negative (FPSS)

As shown in Fig. 8.2 and Fig. 8.3 the oscillations are more pronounced in case of inputs and outputs having trapezoidal membership functions for K5 positive and the system become stable after a long time of 9 seconds approximately. With K5 negative, generally the practical case, the performance characteristics are shown in Fig. 8.4 and Fig. 8.5 The unstable behavior is resulted if the trapezoidal membership function is used with negative value of K5. As evident from Fig. 8.2 and Fig. 8.3, the performance with trapezoidal membership functions is unsatisfactory and thus this membership function is not suited for the PSS design. The performance of lead-lag PSS and FPSS using Gaussian and triangular membership functions is comparable and the system becomes stable after in nearly 5 seconds.

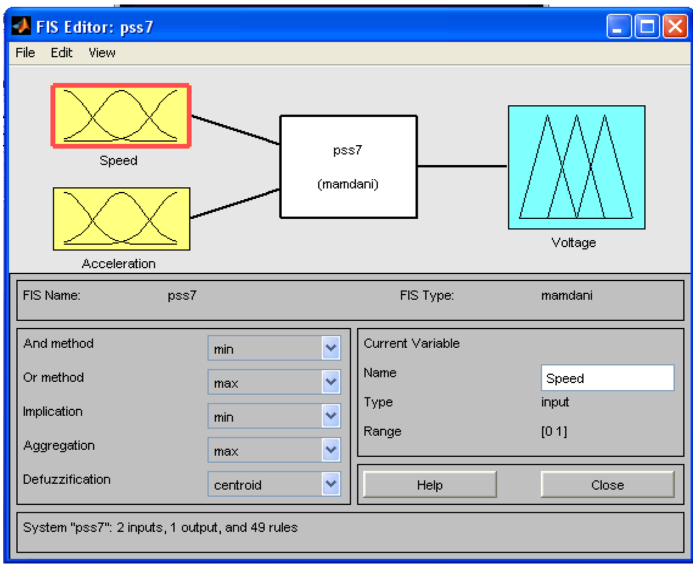


Fig 7.11: FIS Editor

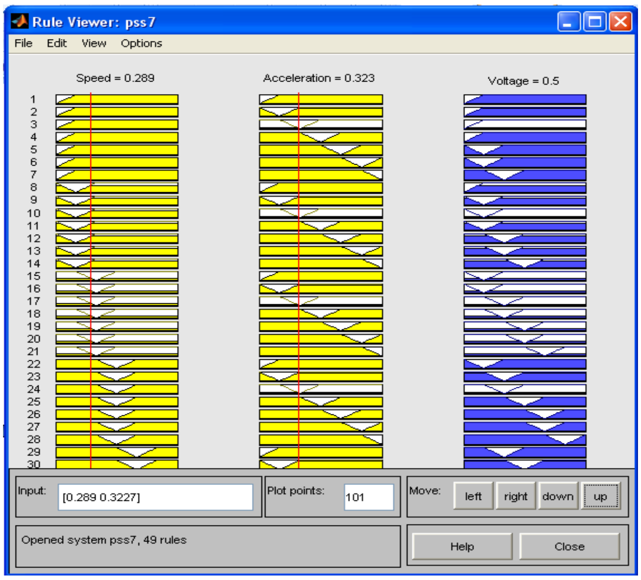


Fig 7.12: Rule Viewer

8. CONCLUSION

8.1 Summary of Results

The target of the developed work is the damping of oscillations related to power system using a controller based on fuzzy logic theory. On two systems, single machine to infinite bus system and 4-machine test system, the purposed controller provide a more robust control over a large excursion of the operating points various and optimal controller and lead lag stabilizer most of the previous control method either are not working sufficiently under whole range of operating condition or they need complicated calculation as they require the exact model methodology to site the proposed controller doesn't depend on the Eigen analysis approach model analysis approach is the usually used techniques for getting the controller result the methodology here is from the time response of the system due to various operating condition are proposed and tested. The resulting of the proposed controller is the increased damping and stability of both local and inter-area modes. The proposed controller showed its effectiveness through-out a board range of the test system operating conditions.

8.2 Conclusion

1) An effective controller based on fuzzy logic theory for the damping both local inter-area modes is developed.

2) A systematic generation of fuzzy logic controller rule base and I/O domain range is investigated and tested.
3) No need to transfer measurements between areas as each controller has its input from its area.
4) Fuzzy logic controllers can be effective in large-scales systems.

8.3 Future Work

The future of this particular research topic has many different facts this include, using of different input signal for a fuzzy logic controller and investigation about non-linear loading.

8.3.1 Other PSS Input Signals

Current resource has focused on rotor speed as a control variable; a frequency-input controller (Δf) must be investigated as-well. However, it has been found that frequency is highly sensitive to the strength of the transmission system, that is, more sensitive when the system is weaker which may off-set the controller action of the electrical torque of the machine other limitation include the presence of sudden phase shift following rapid transient and large noise include by industrial loads. On the other hand, the frequency signal is more sensitive to inter-area oscillations then the speed signal. Also, using of power-input signal (ΔP) as the input to the fuzzy controller as well. However this signal was prove to be more effective for damping the inter-area mode efficiently but the local modes the rotor speed is efficient, so trade off may be appeared [2].

8.3.2 Non-linear Loading

In this research, the simulations for the two systems are done by an assumption that is the loads are static. Then each load can be represented by constant shunt impedance. However the future work may study the effect of non-linear loading upon the power system modes and the controller.

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