STABILITY ENHANCEMENT USING POWER SYSTEM STABILIZER

ABSTRACT: A power system stabilizer (PSS) installed in the excitation system of the synchronous generator improves the small-signal power system stability by damping out low frequency oscillations in the power system. It does that by providing supplementary perturbation signals in a feedback path to the alternator excitation system. There are different conventional PSS design (CPSS) techniques along with modern adaptive fuzzy design techniques. By using linearized single-machine infinite bus model for design and simulation of the CPSS and the voltage regulator (AVR). By using different input signals in the feedback (PSS) path namely, speed variation (w), Electrical Power (Pe), and integral of accelerating power (Pexw), and find the results in each case. For simulations, By using different linear design techniques, namely, (root-locus design, frequency-response design, and pole placement design) and the preferred non-linear design technique is the adaptive fuzzy based controller design. The MATLAB package with Control System Toolbox and SIMULINK is used for the design and simulations.

I. POWER SYSTEM STABILITY

"Power system stability is the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact." Fig 1.1 gives the overall picture of the power system stability problem, identifying categories and subcategories.

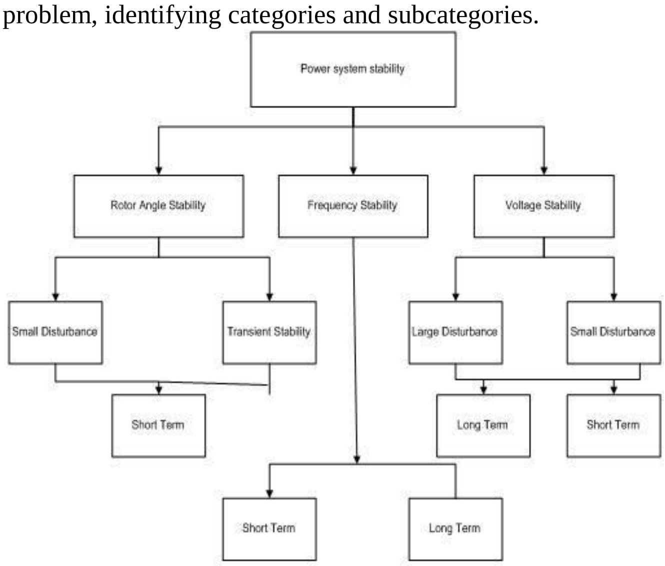

Fig 1 Power System Stability Classifications

The brief descriptions of all this power system stability is given below.

ROTOR ANGLE STABILITY- It refers to the ability of synchronous machines of an interconnected power system to remain in synchronism after being subjected to a disturbance.

- Small-disturbance or small-signal rotor angle stability- It is concerned with the ability of the power system to maintain synchronism under small disturbances.
- Large-disturbance rotor angle stability or transient stability- It is concerned with the ability of the power system to maintain synchronism when subjected to a severe disturbance, such as a short circuit on a transmission line.

VOLTAGE STABILITY- It refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain equilibrium between load demand and load supply from the power system.

- Large-disturbance voltage stability- It refers to the system's ability to maintain steady voltages when subjected to large disturbances such as system faults, loss of generation etc.
- Small-disturbance voltage stability- It refers to the system's ability to maintain steady voltages when subjected to small perturbations such as incremental changes in system load.

The time frame of interest for voltage stability problems vary from a few seconds to tens of minutes. Therefore, voltage stability may be either a short term or long term phenomena as identified in fig.1.1

FREQUENCY STABILITY- It refers to the ability of a power system to maintain steady frequency resulting in a significant imbalance between generations and loads it depends on the ability to maintain equilibrium between system generation and load. An example of short-term frequency instability is the blackout of the island within a few seconds. On the other hand, more complex situations in which frequency instability is caused by steam turbine over-speed controls or boiler protection and controls are long-term phenomena with the time frame of interest ranging from tens of seconds to several minutes.

II. POWER SYSTEM STABILITY

A PROBLEM Power system stability is best defined as the ability of an electric power system to regain a state of operating equilibrium after being subjected to a physical disturbance,

when variables are bounded so that practically the entire system remains intact .Stability of power system is related to stability of synchronous generator. The mechanical angle between rotor magnetic field and armature magnetic flux of a generator is known as the load angle or power angle.

Basically power system stability is a synchronism between rotating field flux and circulating armature flux. Power system stability is classified into different classes based on the variables involved, magnitude of disturbance and time duration of disturbance, as illustrated in Figure-3.1.

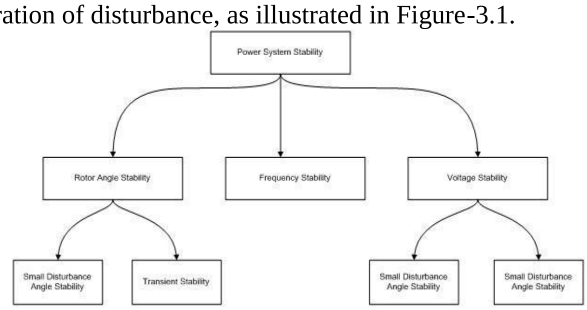

Fig-2.Classification of Power System Stability

Angle stability is the balance between electromagnetic torque and mechanical torque, whereas voltage stability is to match between reactive power generation and consumption. It is hard to draw a clear line of demarcation between these two types of instabilities, since one leads to another. However, it is well-established that voltage instability is caused by load characteristics, whereas angular instability is generator-rotor-dynamics phenomenon. Alternatively, for voltage stability, the vulnerable points of the power systems are generally among load buses, also referred as P-Q bus. Whereas, for angle stability vulnerable points of a system lie within generator buses, also known as P-V bus. Ability of power system to maintain steady state frequency following a severe upset is known as frequency stability. The focus of this project is transient stability, which is an important subset of angle stability of power system. Transient stability is the ability of a system to remain intact following major disturbances. The time period of interest in transient stability studies generally varies within 3 to 5 seconds and may extend to 10-20 seconds for very large systems, following any disturbance. In addition, transient stability behaviour of power system is best characterized by generator angle and velocity. The problem of transient stability is divided into two main categories; evaluation and prediction. Transient stability evaluation focuses on the time required to isolate faulty section before system becomes instable and it is called critical clearing time. On the contrary, in transient stability prediction the focus shifts to whether transient swings will manually converge or otherwise.

Power system transient stability can best be explained by equal area criterion illustrated in Figure-3.2

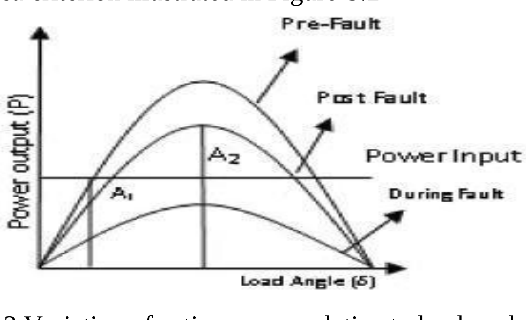

Fig.3 Variation of active power relative to load angle

The difference of input mechanical torque and electrical torque output acting on the rotor of synchronous generator is given by,

$$T_A = T_M - TE_M \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where T_A is the accelerating torque, T_M is the mechanical input torque; TE_M is the induced electromagnetic torque. Area A_1 in Figure 2 is the accelerating area because resultant of Equation (1) is positive in this case. Whereas A_2 is called the decelerating area as accelerating torque is negative in this case. As stated by the definition of stability, rotor must remain in a state of dynamic equilibrium for a stable operation. To meet the condition, the magnitude of A1 must be either equal to or lesser than A2 during any contingency. This can be ensured by either increasing during-fault-curve or post-fault-curve or isolating faulty section in a very short time. Isolation of fault comes under the category of power engineering branch known as power system protection. The former is associated with effective controlling of generators and/or power flow controllers installed at transmission end. The primary control of a power system is carried out at generator end, whereas secondary control is through power flow control at transmission end. Power system stability can be improved by using dynamic controllers as excitation systems, power system stabilizers and FACTS devices, controlled islanding and HVDC.

III. POWER SYSTEM STABILITY ENHANCEMENT

Flexible AC Transmission System (FACTS) devices are example of enhancing power systems stability by controlling power flow at transmission end. They are divided into series, shunt and series-shunt categories according to the manner of device connection with the system. The concept behind enhancing power system stability by series FACTS devices such as Static Series Synchronous Compensator (SSSC) is to increase active power flow during faulty condition consequently decreasing area A1 and increasing area A2. On the other hand, shunt devices as Static Synchronous Compensator (STATCOM) boost power system transient stability by injecting reactive power into system to support the system voltage during disturbance and ultimately leading to decrease of area A1 and increasing area A2. The most commonly used FACTS controller is Unified Power Flow Controller (UPFC). It consists of two branches; one is connected in series and the other is in shunt with the system. UPFC controller uses notion of both series and shunt FACTS controllers for increasing power system stability effectively than any other FACTS controllers .Controlled Islanding is a technique in which whole power system is divided into sections, without having any interconnection, to avert major blackouts. Controlled islanding is the last line of defence in strategy to keep power system stable. Additionally, it is not proposed as the answer to all instability problems in the system. High Voltage DC (HVDC) transmission system is potentially a shield against synchronism loss. Nonetheless, it poses problem of voltage instability following disturbance, if the system depletes reactive power reserves .The control actions at generator end to thwart the system instability are either in terms of excitation system or power system stabilizers or at mechanical end of power plants. The main cause of transient instability of generator is inability of mechanical torque to quickly balance out changes in electrical torque and also generator rotor inertia plays major role. After disturbance the electrical torque can be resolved into two components, one is synchronizing torque and other is called damping torque given by,

$$\Delta TE = \quad \Delta \ + KD\Delta\omega \ldots\ldots\ldots\ldots.. (2)$$

Where δT_E is load angle also known as torque angle, ω is angular speed and *K* is constant. The first term of Equation is synchronizing torque. This torque is dependent on air gap magnetic flux and magnetic coupling between rotor and armature of synchronous generator. This component of torque can be enhanced by high initial response Automatic Voltage Regulator (AVR) and negative field forcing capability of Exciter as well. Excitation system comprises of AVR and Exciter. The second component of Equation (2) is damping torque. It has very profound impact on small signal stability and generator dynamics during transient state following short circuit fault. Damping torque results from the phase lag or lead of excitation current. The first swing transient instability is due to lack of sufficient synchronizing torque. Power system can diverge after convergence of first swing mainly because of insufficient damping torque. Currently, installed excitation systems are very fast responding systems and can immediately take corrective measures following very small oscillations. Nevertheless, from the time of recognition of desired excitation action to its real fulfilment, there is inevitable time delay owing to high time constant of field and armature windings. During this time period, position of oscillating system is bound to change and thus resulting in need of new excitation adjustment. The overall outcome of this time lag is induction of oscillations at the generator end. Power System Stabilizers (PSS) can effectively be used to damp out generator electromechanical oscillations by minimizing the phase lead and lag between synchronously rotating armature flux and rotor. AVR along with PSS are used to enhance power system stability .The focus of this research is transient stability enhancement by using efficient controlling at generator end, as it is a primary control.

IV. DIFFERENT METHODS FOR PSS DESIGN

In this chapter we shall design and review different aspects and methods of PSS design, its advantages, disadvantages and uses in field. We will discuss only linear methods which are necessary for the design of PSS.
The schematic of different methods for PSS design is given below.

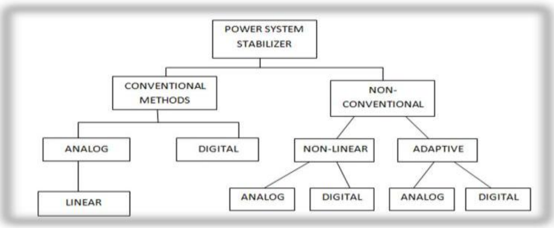

Fig.4. Different methods of PSS

The different linear methods are discussed below.

4.1.1 THE LINEAR METHODS:

ROOT LOCUS METHOD-The root locus technique can be utilized after designing gains separately to adjust the gains by which only valid modes are selected. It is old technique but easy to design compare to other method.

POLE-PLACEMENT METHOD- Controllers designed using simultaneous stabilization design has fixed gain constant to adaptive controllers. The root locus technique can be utilized after designing gains separately to adjust the gains by which only dominant modes are selected. In a more efficient manner the pole-placement design was proposed in which participation factor were used to determine size and number of stabilizers in a multi machine system.

POLE-SHIFTING METHOD- In this method system input-output relationship are continuously estimated form the measured inputs and outputs and the gain setting of the self-tuning PID stabilizer was adjusted in addition this the real part of the complex open loop poles can be shifted to any desired location.

FREQUENCY RESPONSE METHOD-The frequency response design method involves the use of bode-diagrams to measure the phase and gain margin of the system and compensating the phase by using lead controller for PSS.As in case of the previous design method, we find that the introduction of the voltage regulator eliminates the steady state error and makes the system much faster. But it also introduces low frequency oscillations in the system. Hence we have to design the PSS loop taking input as the perturbation in rotor angular speed (Δw).

STATE-SPACE METHOD-The state space design involves designing full state observers using pole placement to measure the states and then designing the controller such that the closed loop poles lie in the desired place. As before, we first design the voltage controller AVR such that the dominant pole is made faster by placing it away from the jw axis. Then, we design the PSS to stabilize the oscillations due to the VR loop by manipulating the swing mode (dominant poles).

LINEAR QUADRATIC REGULATION-This is proposed using differential geometric linearization approach. This stabilizer used in formation at the secondary bus of the step-up transformer as the input signal to the internal generator bus and the secondary bus is defined as the reference bus in place of an infinite bus.

QUANTITATIVE FEEDBACK THEORY-By simply retuning the PSS the conventional stabilizer performance can be extended to wide range of operating and system conditions. The parametric uncertainty can be handled using the Quantitative feedback Theory for the global control of power system.

4.1.2 THE NON-LINEAR METHODS:

1. ADAPTIVE CONTROL: - Several adaptive methods have been suggested like Adaptive Automatic Method, Heuristic Dynamic programming. In adaptive automatic method the lack of adaptability of the PSS to the system operating changes can be overcome. Heuristic Dynamic programming

combines the concepts of dynamic programming and re enforcement learning in the design of non-linear optimal PSS.

2. GENETIC ALGORITHM: -Genetic algorithm is independent of complexity of performance indices and suffices to specify the objective function and to place the finite bounds on the optimized parameters. As a result it has been used either to simultaneously tune multiple controllers in different operating conditions or to enhance the power system stability via PSS and SVC based stabilizer when used in dependently and through coordinated applications.

3. PARTICLE SWARM OPTIMIZATION:-Unlike other heuristic techniques, PSO has characteristics of simple concept, easy implementation, computationally efficient, and has a flexible and well balanced mechanism to enhance the local and global exploration abilities.

4. FUZZY LOGIC: -The second controllers are model- free controllers. They do not require an exact mathematical model of the control system. Several papers have been suggested for the systematic development of the PSS using this method.

5. NEURAL NETWORK: Extremely fast processing facility and the ability to realize complicated nonlinear mapping from the input space to the outer space has put forward the Neural Network. The work on the application of neural networks to the PSS design includes online tuning of conventional PSS parameters, the implementation of inverse mode control, direct control, and indirect adaptive control.

6. TABU SEARCH: -By using Tabu Search the computation of sensitivity factors and Eigen vectors can be avoided to design PSS formula machine systems.

7. SIMULATED ANNEALING:-It is derivative free optimization algorithm and to evaluate objective function no sensitivity analysis is required.

8. LYAPUNOV METHOD:-With the properly chosen control gains the Lyapunov Method shows that the system is exponentially stable.

9. DISSIPATIVE METHOD:-A frame work based on the dissipative method concept can be used to design PSS which is based on the concept of viewing the role of PSS as one of dissipating rotor energy and to quantify energy dissipation using the system theory notation of passivity.

10. GAIN SCHEDULING METHOD: -Due to the difficulty of obtaining a fixed set of feedback gains design of optimum gain scheduling PSS is proposed to give satisfactory performance over wide range of operation. As time delay can make a control system have less damping and eventually result in loss of synchronism, a centralized wide area control design using system wide has been investigated to enhance large inter connected power system dynamic performance. Again scheduling model was proposed to accommodate the time delay.

PHASOR MEASUREMENT:-An architectures in multi-site power system control using wide area information provided by GPS based phasor measurement units can give a step wise development path for the global control of power system.

V. SIMULATION AND RESULTS

The simulation model for system stability issues are as given below.

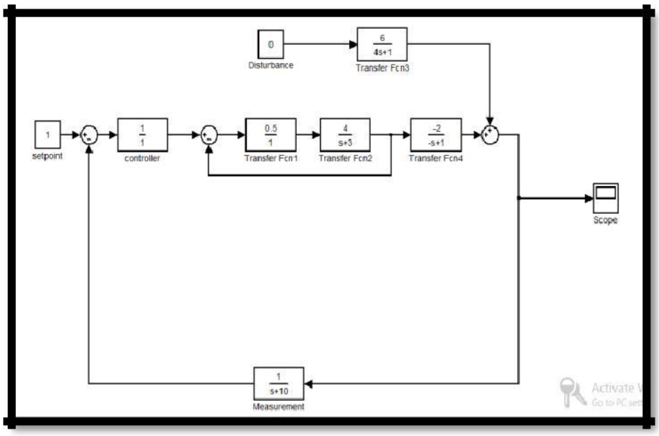

Fig 5. Simulation model for system stability issue

The stability problems regarding this system are given below in the results-

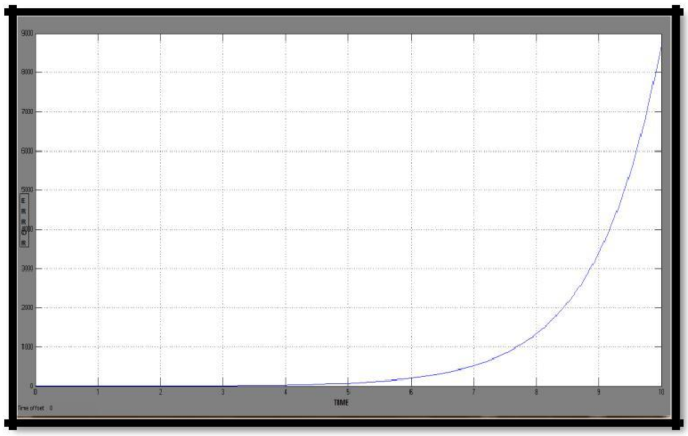

Fig 5.1.2 unstable system

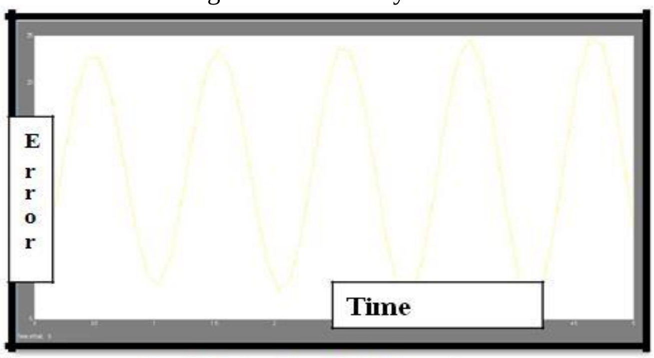

Fig 5.1.3 Another Unstable system

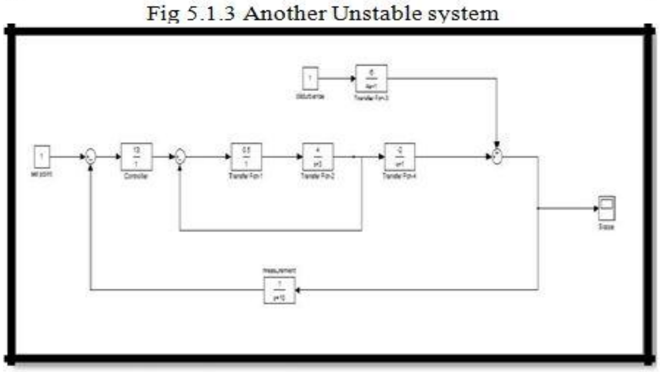

Fig 5.1.4 Simulation model for system stability issue

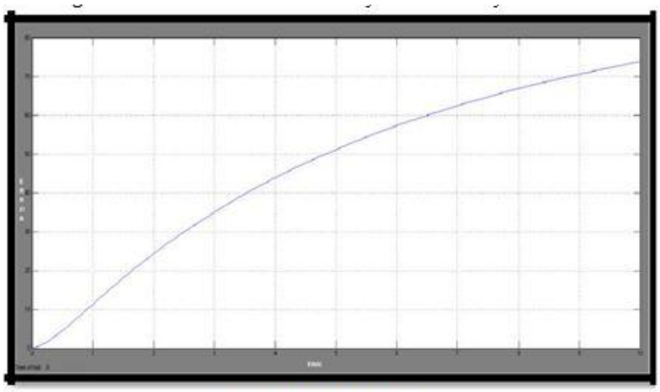

Fig 5.1.5 Stable system

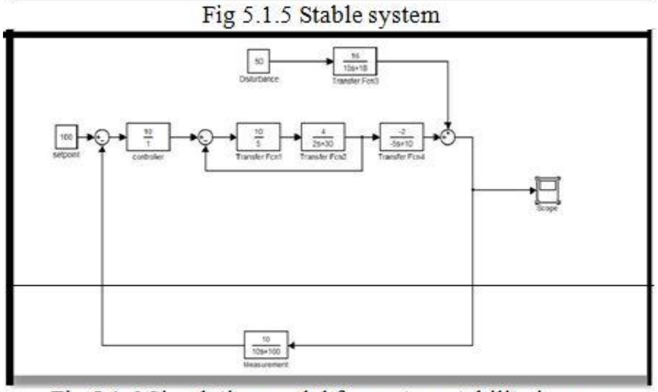

Fig 5.1.6 Simulation model for system stability issue

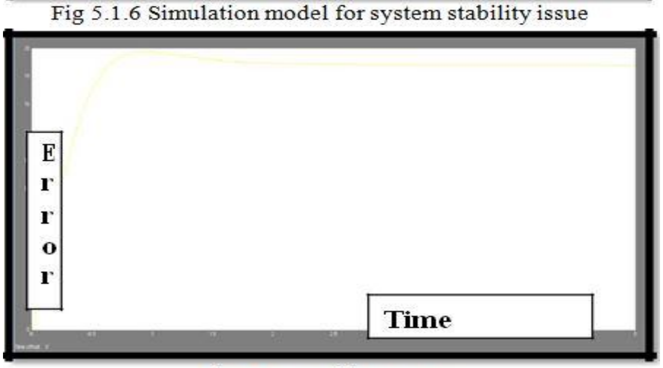

Fig 5.1.7 Stable system

ROOT LOCUS METHOD:

- We close the VR loop with the Kp and Ki and simulate the system response for a step input. To reduce the oscillations, we have to introduce a feedback loop involving the swing in rotor angular speed (Δω) as input to the PSS loop. First we analyse the root locus of the PSS loop from u to wf imaginary axis.
- After the design we find that: z= 3.5, p= 24, Kα= 13.8, K= 0.4

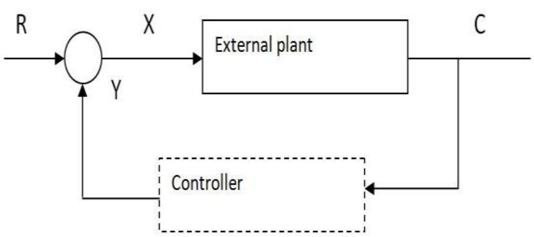

Fig-5.2.1 general block diagram of feedback system External plant transfer function is given as below:-
(+)G(s) = Ke(+)
Controller transfer function is given as below:-

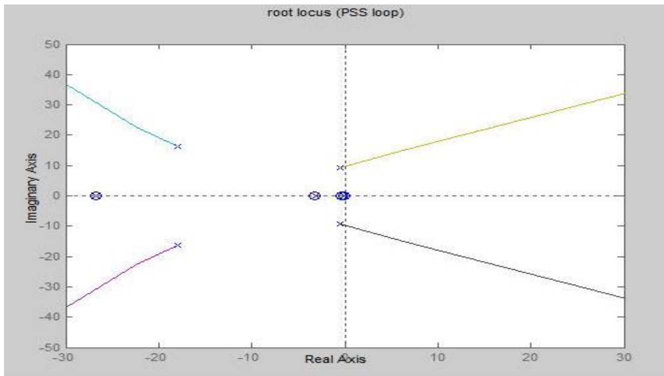

Fig.5.2.2 Root locus of PSS loop

5.2.2 FREQUENCY RESPONSE METHOD

- The frequency response design method involves the use of bode-diagrams to measure the phase and gain margin of the system and compensating the phase by using lead controller for PSS.
- As in case of the previous design method, we find that the introduction of the voltage regulator eliminates the steady state error and makes the system much faster. But it also introduces low frequency oscillations in the system. Hence we have to design the PSS loop taking input as the perturbation in rotor angular speed (Δω).

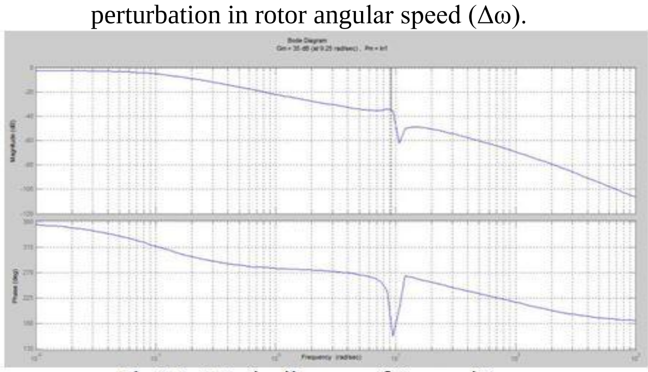

Fig.5.2.3 Bode diagram of Gm and Pm

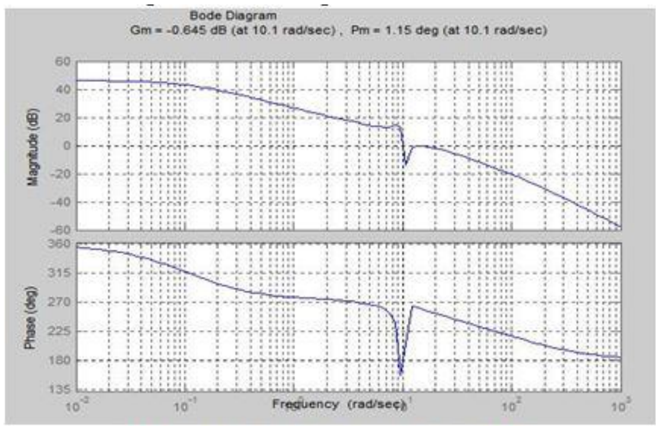

Fig.5.2.4 Bode diagram of Gm and Pm

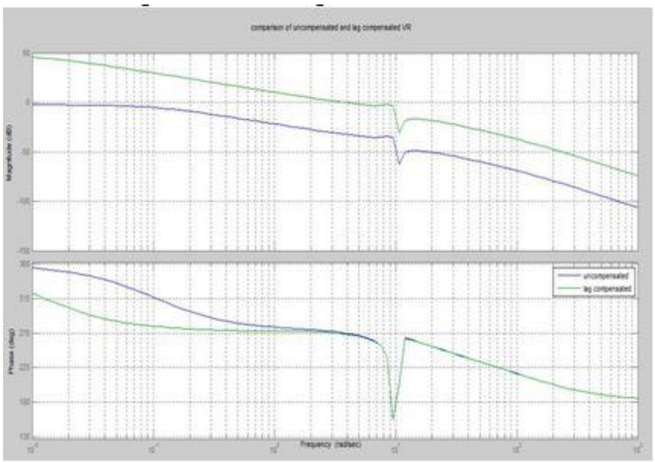

Fig.5.2.5 Comparison of uncompensated and lag compensated VR

5.2.3 STATE SPACE METHOD

- The state space design involves designing full state observers using pole placement to measure the states and then designing the controller such that the closed loop poles lie in the desired place. As before, we first design the voltage controller AVR such that the dominant pole is made faster by placing it away from the jω axis. Then, we design the PSS to stabilize the oscillations due to the VR loop by manipulating the swing mode (dominant poles). The details are given below:

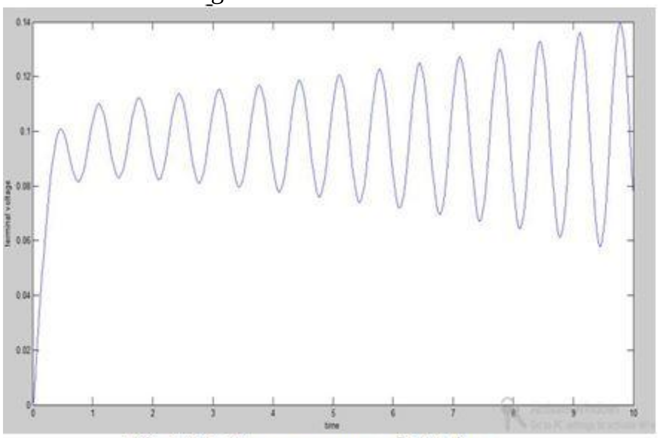

Fig.5.2.6 Step response of PSS loop

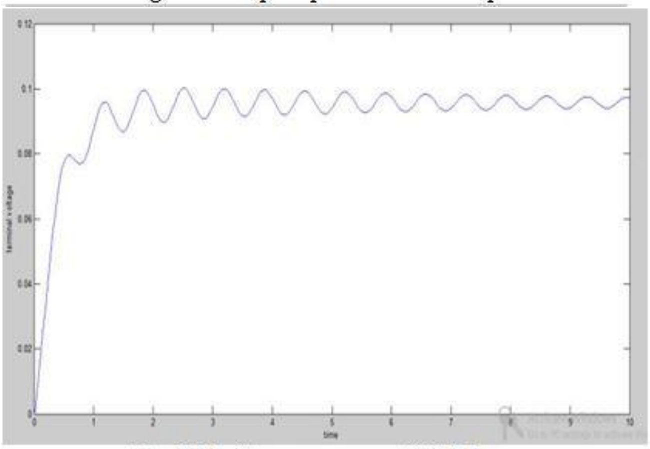

Fig.5.2.7 Step response of PSS loop

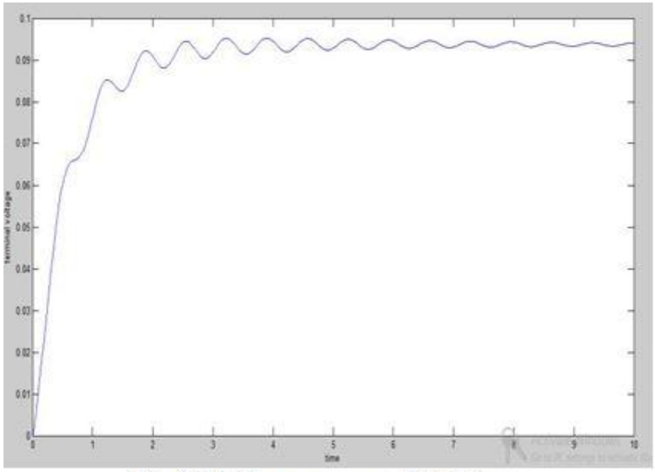

Fig.5.2.8 Step response of PSS loop

VI. COMPARISON OF DIFFERENT METHODS ERROR TIME FOR STATE SPACE

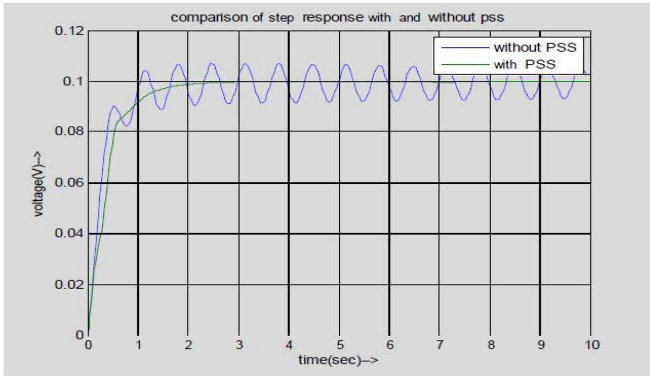

Fig 5.8.1 Step response of the final system with and without PSS loop

STEP RESPONSE ERROR-TIME

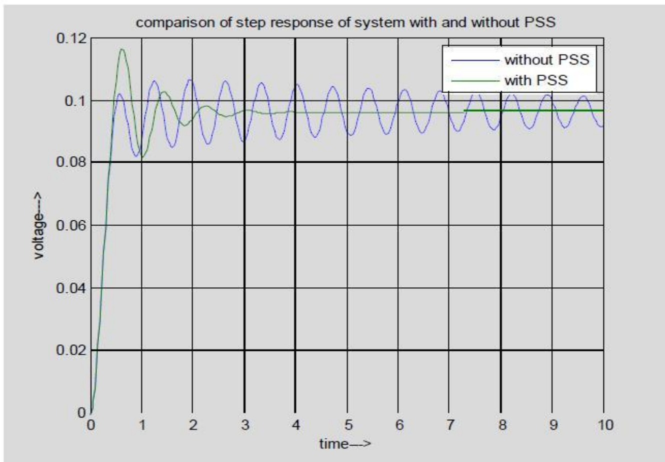

Fig 5.8.2. Comparison of the step response of system with and without PSS

FUZZY ERROR TIME

Now, the training is started using the back-propagation method and the model is trained for 100 epochs for greater reliability. The error is given as below:

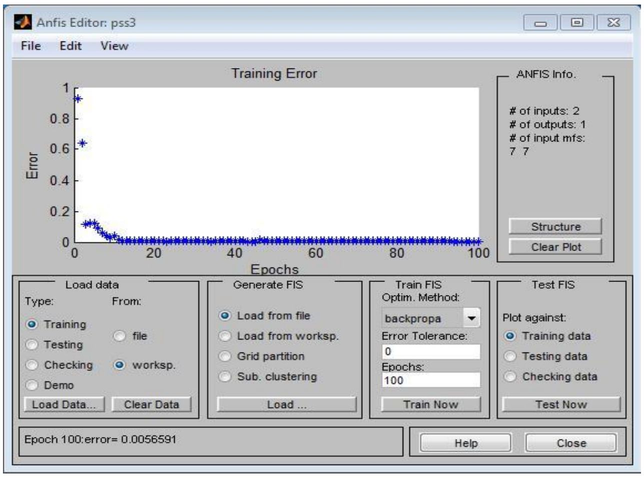

Fig.5.8.3 The training of ANFIS showing the training error

Finally the trained model is tested against the output data as below:

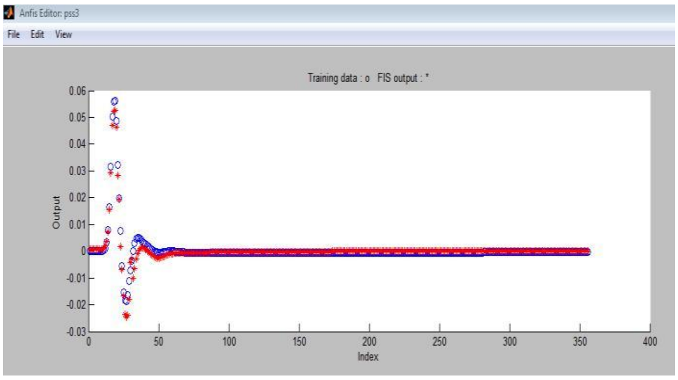

Fig.5.8.4 Comparison between trained and test data

The output responses as seen from the simulation results are crisp and have good design Specifications such as rise time, overshoot and settling time.

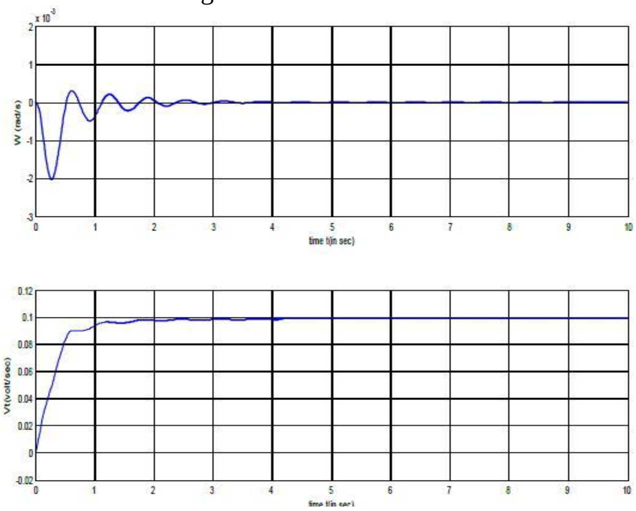

Fig5.8.5 w and Vt outputs using the fuzzy controller

VII. COMPARISON OF THE ANFIS PSS CONTROLLER WITH CPSS

Finally, we are in a position to compare the conventional PSS or CPSS with the PSS developed using Fuzzy inference system. As seen in Figure 28, the fuzzy PSS has the best output response (Vt), the least overshoot and settling time. Also, it produces the best damping which is manifested in the plot showing the rotor speed perturbation (w). Thus, by proper training algorithms, the fuzzy PSS can surpass the performance of the CPSS.

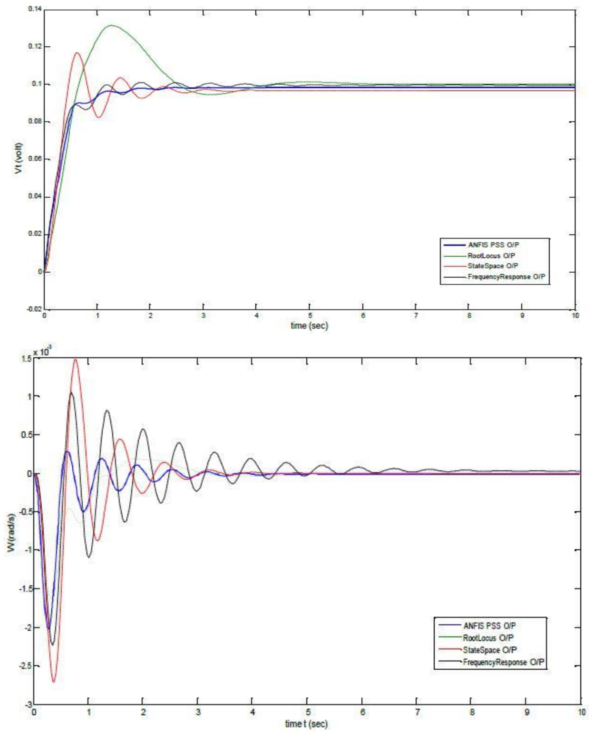

Fig.5.8.6 Comparison of Vt and w between CPSS and ANFIS PSS

Parameter	Conventional/linear method	Non linear method
Frequency	50Hz	60Hz
Xd & Xq	NA	1.305,0.474
Tf-1	0.5/1	1/0.2s+1
Tf-2	4/s+3	1/0.6s+1
Derivative & Integer	1/5	1/2
Supply source	NA	10000MVA,230kv
Frequency response	Initial unstable then stable. take more time for stability	Initial unstable then stable. take less time for stability
Gain margin	Large	NA
Bode plot	Yes	No
Anfis model	No	Yes
Surface model	No	Yes

Table-Comparison between conventional and non conventional method for PSS Design

VIII. CONCLUSION

The optimal design of Power System Stabilizer (PSS) involves a deep understanding of the dynamics of the single machine infinite bus system. In this project, we have tried to design the PSS using control system principles and hence view the problem as a feedback control problem. Both conventional control design methods like root-locus method, frequency response method and pole placement method as well as more modern adaptive methods like neural networks and fuzzy logic are used to design the PSS. By comparison of these methods, it is found that each method has its advantages and disadvantages. The actual design method should be chosen based on real time application and dynamic performance characteristics. In general, it is found from our simulations that the ANFIS based adaptive PSS provides good performance if the training data and algorithms are selected properly. However, adaptive control involves updating controller parameters in real-time using a system identifier which can be complicated and expensive. Hence, the economics of the process is also a constraint. Although the first power system stabilizers were developed and installed during the1960s and a lot of work has been done to improve its performance, modern control design algorithms can further enhance the performance of the PSS. In particular, adaptive control of PSS is still an active area. Digital design of the PSS is also possible. Hence, the design of the Power System Stabilizer has a lot of scope for future research.

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