Chapter 1

Introduction

1.1 General

The electric power industries, throughout the world, have undergone unprecedented changes in its structure. In the restructured environment, the electric energy industries have changed from vertical integrated utilities into number of entities in each spectrum of power system. With the advent of an open market scenario, competition in the industries and restructuring in separate generation, transmission and distribution entities, new issues in power system operation and planning have to be anticipated. The reformulation of planning and operation in electric utility industry as per technical aspects are required. One of the major consequences of this new electrical utility environment has greater emphasis on reliability, security and stability of power system [59, 29]. Restructured market consists of generation companies (GENCOS), distribution companies (DISCOs), transmission companies (TRANCOS) and independent system operators (ISO). The ISO is independent and disassociated agent for market participation and performs the various ancillary services.

The small signal stability analysis and transient stability analysis have become essential ingredient of stable operation and secure operation of power system [15]. The power system stability is defined [50] as that property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance. The disturbances can be an intended one, such as an operator action, or a fault due to natural causes or maloperation of the protection system.

Stability is condition of equilibrium between opposing forces. The mechanism by which interconnected synchronous machines maintain synchronism with one another is through restoring forces, which act whenever there are forces tending to accelerate or decelerate one or more machines with respect to other machine. Under the steady-state conditions, there is balance between input mechanical torque and the output electrical torque of each machine and the speed remains constant. If the system is perturbed, this equilibrium is upset, resulting in acceleration and deceleration of rotors of machines. This tends to increase the speed difference and hence the angular separation. Beyond the certain limit, an increase in angular separation is accompanied by a decrease in power transfer. This increases angular separation further and leads to instability. With electric power systems, the change in electrical torque of a synchronous machine following a perturbation can be resolved into two components [15, 6]:

$$\Delta T_e = T_s \Delta\delta + T_D \Delta\omega \tag{1.1}$$

where $T_s\Delta\delta$ is the component of torque change in phase with rotor angle perturbation $\Delta\delta$ and is referred to as synchronising torque component; T_s is the synchronizing torque coefficient.

$T_D\Delta\omega$ is the components of torque in phase with speed deviation $\Delta\omega$ and is referred to as the damping torque component; $T_D$is the damping torque coefficient.

System stability depends in the existence of the both components of torque for every synchronous machine. The Lack of sufficient synchronizing torque results in instability through an aperiodic drift in rotor angle and the lack of sufficient damping torque results in oscillatory instability.

The power system stabilizer (PSS) has been recognized as an ancillary service in restructured electrical market [54], and important control device that is essential for enhancing system stability. The PSS is used to add damping to the generator rotor oscillations by controlling its excitation using auxiliary stabilizing signal. To provide damping, the stabilizer produces a component of electrical torque in phase with the rotor speed deviation. The control action provided by PSS to enhance system stability is considered as one of the system ancillary services.

Flexible Alternating Current Transmission System (FACTS) controllers are another ancillary service in deregulated electric market. The FACTS controller plays very important role in deregulated electric market to enhance the stability of the power system [55, 26]. FACTS devices can be effectively used for load flow control, loop power flow control, load dispatched, voltage regulation, enhancement of transient stability and mitigation of system oscillation [55, 25, 26, 44]. The Thyristor Control Series Capacitor (TCSC) is the versatile FACTS device which can nullify many problems of power system operation due to its faster control action and adaptive capabilities [44].

For achievement of desired performance of power system under contingencies, the intelligent techniques based adaptive PSS and TCSC damping controllers are required to be designed. The controllers accompany load frequency control (LFC) in multiple area generation (AGC) system in deregulated environment have been an attraction in ongoing research work.

1.2 State-of-the Art

The worldwide electric energy industries have undergone the changes from vertical integrated utilities to restructured electric market. The restructured market provides platform to sell the electric energy to various customer at competitive price. In restructured market, reformulation of planning and operation in electric industry as per technical aspects have required [21, 59, 29]. However, the essential ideas remain the unchanged. The open market consists of generation companies (GENCOs), distribution companies (DISCOs), transmission companies (TRANCOs) and independent system operators (ISO).

GENCOs generate electricity and have the opportunity to sell the electricity to entities with which they have negotiated sales contracts. Generally GENCOs consist of a group of generating units within a single company ownership structure with the sole objective of producing electrical power. In addition to active power, they may sell reactive power (ancillary services) and operating reserves.

TRANCOSs transport electricity using a high voltage, bulk transmission system from GENCOs to Distribution Companies (DISCOs)/retailers for delivering power to customers. A TRANCOs has role of building, owning, maintaining and operating the transmission system in a certain geographical region to provide services for maintaining the overall reliability of the electrical power systems and provides open access of transmission wires to all market entities in the system. The investment and operating costs of transmission facilities are recovered using access charges, which are usually paid by every user within the area/region, and transmission usage charges based on line flows contributed by each user.

A distribution company (DISCO) distributes the electricity, through its facilities, to customers in a certain geographical region. They buy wholesale electricity either through the spot markets or through direct contracts with GENCOs and supply electricity to the enduser customers. A DISCO is a regulated utility that constructs and maintains distribution wires connecting the transmission grid to the end user customers. A DISCO is responsible for building and operating its electric system to maintain a desired degree of reliability and availability.

Several market structure and transactions exist to achieve a competitive electricity environment. Three basic models exist based on the types of transactions [22]. First is a PoolCo, which is defined as a centralized market place that clears the market for the buyers and sellers. Electric power sellers/buyers submit bids to the pool for the amount of power that they are willing to trade in the market. Second is Bilateral Contract model, a bilateral transaction is an exchange of power between buying and selling entities [21]. These transactions can be defined for a particular time interval of the day and its value may be time varying. It may be either firm or non-firm and can be a short term and long term transaction. Third model is the hybrid model, which combines various features of the previous two models. In the hybrid model, the utilization of the PoolCo is not obligatory, and any customer would be allowed to negotiate a power supply agreement directly with the suppliers or choose to accept power at the pool market price.

A competitive market would necessitate an independent operation and control of the grid. Due to this reason, most of the utilities have established an entity called Independent System Operator. It is entrusted with responsibility of ensuring the reliability, security and efficient operation of an open access transmission system. It is an independent authority and does not participate in trading of electricity. The ISO has the authority to commit and redispatch the system resources and to curtail loads for maintaining the system security.

An ancillary service is an interconnected operation service that is necessary to support a transfer of electricity between purchasing and selling entities. Ancillary services are needed to ensure that the system operators are able to meet their responsibilities, although also aim at enhancing system reliability and maintaining adequate quality standards. In the deregulated market, the ancillary services are mandated to be unbundled from the energy services. Ancillary services are procured through the market competitively. The ISO uses ancillary services for the following tasks [54, 55]:

- Keeping the frequency of the system within certain bounds
- Controlling the voltage profile of the system
- Maintaining the stability of the system
- Preventing the overloads in the transmission system
- Restoring the system after the black out.

The instability in a power system can occur in a variety of ways depending on the system configuration and operating conditions. Traditionally, the stability problem has been associated with maintaining synchronous operation. In the evaluation of stability, the concern is the behavior of the power system when subjected to a disturbance. The disturbance may be small or large. This aspect of stability is influenced by the dynamics of the generator rotor angles and the power-angle relationships and is referred to as rotor angle stability. The details of rotor angle stability analysis can be found in [33, 15, 43, 31, 6]. This stability problem deals with the study of the electromechanical oscillations inherent in power systems. The fundamental factor in this analysis is the characterization of the variation of the power or torque outputs of synchronous machines as their rotors oscillate. In general, the components of the power system that influence the electrical and mechanical torques of the synchronous machines are included in the model. These components are listed below.

- The transmission network before, during, and after the disturbance.
- The loads and their characteristics.
- The parameters of the synchronous machines.
- The control components of the synchronous machines (excitation systems, power system stabilizers).
- The mechanical turbine and the speed governor.
- Other power plant components that influence the mechanical torque.
- Other control devices, such as supplementary controls, special protection schemes and FACTS (Flexible AC Transmission System) devices that are deemed necessary in the mathematical description of the system.

Small signal stability is ability of the power system to maintain synchronism under small disturbances. Such disturbances occur continually on the system because of small variations in loads and generation. The disturbances are considered sufficiently small for linearization of system equations to be permissible for purpose of analysis. Instability that may result can be of two forms: (i) steady increase in rotor angle due to lack of sufficient synchronising torque, or(ii) rotor oscillations of increasing amplitude due to lack of sufficient damping torque. The nature of the system response to small disturbances depends on a number of factors including the initial operating, the transmission strength, and the type of generator excitation control used. For a generator connected radially to power system, in the absence of automatic voltage regulators (i.e.with constant field voltage) the instability is due to lack of sufficient synchronising torque. With continuously acting voltage regulators, the small disturbance stability problem is one of ensuring sufficient damping of system oscillation. Instability is normally through oscillations of increasing amplitude. The small signal stability is largely a problem of insufficient damping of oscillations.

Transient stability is the ability of the power system to maintain synchronism when subjected to a severe transient disturbance. The resulting system response involves large excursion of generator rotor angles and is influenced by the non linear power angle relationship. The non linear algebraic differential equations are used for analysis of transient stability. The numerical solutions of the non linear algebraic differential equations are obtained.

The Power system stabilizer (PSS) generates the supplementary control signal for the excitation system to damp the low frequency oscillations and to improve power system stability. The power system stabilizers have been designed very extensively using phase compensation techniques and parameters of PSS have been calculated based on linearized Philips–Heffron model of the power system for the small signal stability analysis [2, 43, 15, 33]. The small signal stability and transient stability with concepts of synchronizing and damping torques has been explained by [74]. Different types of arrangement of phase compensator based PSSs have been used for detail analysis of the power system [56, 33, 43, 15]. The coordinated design of PSS and automatic voltage regulator (AVR) [84] can handle power system stability problem under certain operating conditions. The paper [80] presents artificial neural network (ANN) based controller model to simulate the automatic voltage regulator (AVR) response for the transient stability analysis.

Modulation of generation excitation can produce transient change in the generator's electrical output power. Fast responding exciters equipped with high gain AVR's use their speed and forcing to increase a generator's synchronizing torque coefficient T_s, result in improved steady-state and transient stability limits. Improvements in synchronizing torque are often achieved at the expense of damping torque, hence in reduced levels of oscillatory or small signal stability. To counteract this effect, many units that utilize high-gain AVRs are also equipped with PSSs to increase the damping coefficient T_D and to improve oscillatory stability.

The modern and conventional control techniques based PSS can provide optimal performance for the normal operating conditions and normal system parameters. However, a modern power system has become large, tight and highly dynamic, hence too difficult to solve low frequency oscillations problem through conventional and linear optimal control approaches. For the different loading conditions and configuration of power network, the parameters of PSS needed to be modify.

The proportional integral improved adaptive control law [81], H-infinity control technique [35] and robust control based [46] power system stabilizer can overcome the time consuming and non optimal damping. However, it required complex computation for implementation in the dynamic power system. To overcome these limitations, computational intelligent techniques such as Fuzzy Logic (FL), Artificial Neural Network (ANN), Genetic Algorithm (GA), Particle Swarm Optimization (PSO) etc. based PSS have been proposed in the literature.

Fuzzy logic is very attractive technique for model free design of the plant. Fuzzy logic based power system stabilizer [28, 51], adaptive fuzzy logic base power system stabilizer [61] for maintaining the stability of the power system cover a wide range of operating conditions. But the linguistic or user defined variables are needed to design the rule based of fuzzy inference system. The gain and time constants of conventional PSS are optimized under the different operating conditions through different computational optimization techniques like: Genetic algorithm, particle swarm optimization and bacterial foraging and simulated annealing have been explained by [83, 24, 108]. For each and individual operating condition, the individual PSS parameters are needed to be tune. The parameters of PSS have to be calculated and evaluated through Artificial Neural Network [52] under the different operating conditions of the power system. The adaptive neural network based power system stabilizer has been proposed by [45]. By combining the generalized neuron predictor and a fuzzy logic controller based adaptive fuzzy logic power system stabilizer [68] and the two level fuzzy and adaptive neurofuzzy inference systems based power system stabilizer [106] have been applied to the power system dynamics.

Many applications of computational intelligent techniques in power system engineering have been mentioned by literature. The voltage stability [17, 104, 91], load flow analysis [67], power system security [70], load and price forecasting [60, 101, 109], reactive power compensation [73], transmission loss allocation [95], harmonic estimation [98], fault detection in distribution network [82], induction generator and wind power forecasting [64, 69, 86, 72], and state estimation [18] have been discussed.

During the last decade, a number of the Flexible Alternating Current Transmission System (FACTS) control devices have been proposed and implemented in real power system [25, 44]. An Adaptive Neuro-Fuzzy Inference System (ANFIS) method based on the Artificial Neural Network (ANN) to design a Static Synchronous Series Compensator (SSSC)-based controller for the improvement of transient stability has been suggested in paper [107] . The proposed ANFIS controller combines the advantages of a fuzzy controller as well as the quick response and adaptability nature of an ANN. The ANFIS structures were trained using the generated database by the fuzzy controller of the SSSC. It is observed that the proposed SSSC controller improves greatly the voltage profile of the system under severe disturbances. The results prove that the proposed SSSC-based ANFIS controller is found to be robust to fault location and changes in operating conditions.

The laboratory implementation and test results of an advanced TCSC ANN-based inverse control system to enhance power system transient stability has been presented by [47]. Satisfactory performance and robustness of the TCSC control are demonstrated by the test results on a laboratory power system subject to different disturbances under various operating conditions

A supplementary damping controller for a unified power flow controller (UPFC) is designed for power system dynamic performance enhancement has been discussed in paper [39].

The paper [93] presents a new control method based on Neural Network technique to damp out the power system low frequency oscillations using STATCOM controller. The main objective of this paper is to investigate the power system dynamic stability enhancement by using neural network based FACTS (STATCOM) Controller.

An integrated approach of radial basis function neural network (RBFNN) and Takagi-Sugeno (TS) fuzzy scheme with a genetic optimization of their parameters has been developed to design intelligent adaptive controllers for improving the transient stability performance of power systems has been presented by [36].

Nowadays the FACTS controller plays very important role in deregulated electric market, which has been explained in literature [55, 26, 62].

In general, FACTS controllers can be divided into four categories:

Series controller

Shunt controller

Combined series-series controller

Combined series-shunt controller

One of the most important devices of series FACTS controller is thyristor controlled series capacitor (TCSC) [38] in order to enhance the stability and loadability of the transmission network. The nonlinear H∞ controller and LQR/LTR controllers based TCSC have been presented by [63, 30]. The various computational intelligent algorithms based TCSC [102, 75, 99, 47] are being designed to cope up the stability of the power system under the different system configuration as well as load variation. The self tuning fuzzy-PI controller and type-2 fuzzy controller for TCSC has been proposed by [75, 99]. The artificial neural network and search algorithms based TCSC have been presented by [102, 47]. For the performance enhancement of the dynamical power system, the new area of the research is build up on coordinated design of PSS and TCSC. The different computational intelligent techniques based coordinated design of PSS and TCSC have been mentioned in literature [103, 66].

The power system stability in deregulated electric market has been addressed [37]. The ancillary services such as power system stabilizer (PSS) [54] and Flexible Alternating Current Transmission System (FACTS) controllers [55, 26] in deregulated electric market have been addressed. Nowadays, by increasing complexity in power system, it is important to provide stable, secure, controlled, monetary and high quality electric power in restructured environment. The FACTS controller plays very important role in deregulated electric market to enhance the stability of the power system with their fast control characteristics and continuous compensating capability. FACTS devices can be effectively used for load flow control, loop power flow control, load dispatched, voltage regulation, enhancement of transient stability and mitigation of system oscillation [55, 26, 25, 44].

Large scale power systems are composed of control areas or regions representing coherent groups of generators. In large power system abnormal phenomena have been frequently observed such as tie-line power deviation, rotor speed deviation and outage of generators under various loading conditions. Automatic generation control (AGC) is an essential control loop in electric power system which maintains balance between generated power and demand power in each control area. For the conventional Load Frequency controller, the integral of area control error (ACE) is utilized as the control signal for conventional control strategy. Literature [3, 92, 41, 57, 5] has addressed the area generation control with ACE in conventional LFC loop. An integral controller provides zero steady state deviation, but it produces poor dynamic performance. Therefore advanced control techniques are needed to cope up with abnormal situation in power system. Nowadays, smart controllers have been introduced and are replacing conventional controller. They have fast, adaptive and good dynamic characteristics for load frequency control issue. Genetic algorithm, bacteria foraging, [40, 79], fuzzy logic [53], neural network [23, 100], adaptive neuro fuzzy inference system [76, 105] based LFC have been developed.

The Load frequency controller (LFC) is recognized as an ancillary service in deregulated electric market. The extensive details and modified block diagram of two area AGC under the restructured market has been discussed by [32, 85].

The adaptive neurofuzzy inference system based automatic generation control [76], genetic algorithms and linear matix inequality [40], gradient Newton algorithm [32] are some published researches on minimization of ACE in deregulated LFC. The application of different FACTS controllers in deregulated market in multi area AGC system has been reported [77, 49, 78, 96] by recent research paper. The fuzzy logic based tie line power controller TCPS has been designed for the hydrothermal system [77], decentralized control law of SSSC devices [49] and particle swarm optimization based TCPS [78] have been designed. The super conducting energy devices with TCPS and SSSC using evolutionary algorithms for two area hydro system have been extensively designed in literature [96].

Intelligent computing consists of several computing paradigms [87, 89, 90], including neural networks [7, 12, 11, 10], fuzzy set theory [1], approximate reasoning, and derivative free optimization methods such as genetic algorithm [8], swam optimization [27, 16], ant colony optimization [58], bacterial foraging [34], simulated annealing [87, 90] etc. have been reported. Each of these constituent methodologies has it own strengths. The integration of these methodologies have been formed the core of soft computing. The synergisms allow soft computing to incorporate human knowledge effectively, deal with imprecision and uncertainty and learn to adapt to unknown or changing environment. Main characteristic is its inherent capability to create hybrid systems that are based on an integration of the techniques. They have provided complementary learning, reasoning and searching methods to combine domain knowledge and empirical data to develop flexible computing tools and to solve complex problems. In confronting real world computing problems, it is frequently advantageous to use several intelligent computing techniques synergistically rather than exclusively, resulting in construction of hybrid intelligent system.

1.3 Motivation

The extensive survey of literature could give the information regarding to the application of the computational intelligent methods in field of power system stability but it could also divulge the growing interest of the researchers on the relatively new field of intelligent computing in restructured power industries.

The Third –order dynamic model and Philips-Heffron linear model of the synchronous machine is most preferable for a researcher for stability analysis of power system. The power system model only takes into account the generator main field winding. However, for the effective analysis of single machine infinite bus system, linear and non linear higher order power system model accompany of automatic voltage regulator are to be required for small signal stability and transient stability analysis. Computational intelligent method based Power system stabilizer [83, 24, 108] has been developed, but comparison between evolutionary algorithm based conventional power system stabilizer and proportional integral derivative power system stabilizer, and their application to linear and non linear with fourth order power system model have not been discussed. The eigen values analysis with power system stabilizer and TCSC controller are required for effective analysis of closed loop stability. Mathematical modeling of individual power system, model of power system with PSS and model of power system with simultaneous PSS and TCSC are to be required for identification of power system stability. The paper [103, 66] shows the non linear simulation of power system with PSS and TCSC, but the closed loop system stability with controllers have not been discussed.

Artificial neural network based power system stabilizer [52, 45] has been discussed. The feed forward multilayer neural networks are the most common neural network architecture for solution of control problem. A widely used training method for feed forward multilayer neural network is the back propagation algorithm. The standard back propagation learning algorithm has several limitations. Most of all, a long and slow training process, when plant is non-linear and parameters of the plant are dynamic. The rate of convergence is seriously affected by the initial weights and the learning rate of parameters. So fast and adaptive algorithm has to be required to cope up with dynamical situation in power system.

The literature survey motivates to develop other intelligent techniques based power system stabilizer and Thyristor control series capacitor for single machine infinite bus system extensively. Literature survey reveals that no research work has been carried out for designing of PSS using hybrid genetic algorithm based neural network and neural network identification technique. Literature survey reveals that no any research work has been discussed the comparison between different intelligent methods for designing of PSS and TCSC and their simultaneously application in dynamical power system.

Literature survey shows linear single order transfer function of the synchronous generator used in Load frequency control loop for area generation control in convention and deregulated electric market. TCPS and SSSC have been used as tie line power controller [77, 78, 76, 96], which are designed using computational intelligent methods. But effect of FACTS controllers on frequency deviation with higher order power system model with automatic voltage regulator in multiarea control loop have not been discussed. Literature survey reveals that no research work has been carried out on the smart control techniques based TCSC as tie line power controller in conventional and deregulated electric market. Literature survey reveals that no research work has discussed the effect of individual and simultaneous application of ancillary controllers such as PSS and TCSC on closed loop stability and transient stability of multiarea power system using intelligent methods under restructured electric market, with different correlative conditions between GENCOs and DISCOs and load variation in various control area. Mathematically justification for application of ancillary controllers in two area deregulated electric market with load frequency control loop has not been addressed in literature survey.

Hence, the main objectives behind the present work are as follows:

1. To develop the linearized model of fifth order synchronous machine from non linear model and to derive the different constants followed by block diagram of the synchronous machine connected to single machine infinite system.

2. To develop the mathematical model of the machine in state space form with conventional power system stabilizer (CPSS), proportional integral derivative PSS and TCSC individually and simultaneously.

3. To design the PSS using different intelligent techniques such as Genetic Algorithm, Levenberg Marquardt neural network (LMNN), adaptive neuro fuzzy inference system (ANFIS), genetic algorithm based artificial neural network hybrid algorithm (GA-ANN), Neural Netwrok based non linear auto regressive moving average (NARMA) -L2 controller.

4. To design the stability control loop of TCSC using GA, ANN and ANFIS techniques. To analyze the simultaneous and individual application of PSS and TCSC using programming and to carry out non linear simulations under different operating conditions and disturbances in power system .

5. To develop linear model and block diagram of the two area automatic generation control system with the first order and fifth order power system model under the restructured electric environment.

6. To build the model of two area power system with multiple PSS, individual tie-line TCSC and combining PSSs and TCSC.

7. To study the effectiveness of ancillary controllers such as multiple PSSs and TCSC in restructured electric market.

8. To evaluate the performance of smart control techniques based ancillary controller using linear analysis and non linear simulation.

1.4 Thesis Organization

The present Chapter 1 introduces the restructured electric market, stability issue and application of ancillary controllers in restructured market. It represents the relevant state-of-the-art survey and sets the motivation behind the research work carried out in this thesis.

Chapter 2 presents, detail modeling of the system components and linerization of non linear equations using Taylor's series method. The state space form of power system with conventional power system stabilizer and PID- power system stabilizer have been described. The linearized state space form of power system with individual TCSC and simultaneous CPSS and TCSC have also been derived.

Chapter 3 presents, Genetics Algorithm based control strategies for designing of CPSS, PID-PSS and TCSC damping controller. The individual PSSs and simultaneous designed TCSC and PSS have been applied to the dynamic power system. The small signal stability analysis and non-linear simulation for the transient stability analysis have been carried out for detailed investigation of the power system stability issue.

Chapter 4 discusses Adaptive Neuro-Fuzzy Inference System and Levenberg-Marquardt Artificial Neural Network algorithm for development of the control strategy for thyristor control series capacitor based damping controller and power system stabilizer. The non-linear simulations of single machine infinite bus system have been carried out using individual and simultaneous application of PSS and TCSC. The comparisons between intelligent control strategies based damping controllers have also been carried out.

Chapter 5 discusses Non Linear Auto regressive Moving Average-L2 controller and hybrid Genetic Algorithm based Network Network for development of the control strategy for power system stabilizer. In order to achieve appreciable damping, developed ANFIS based Thyristor control series capacitor has been suggested in addition to power system stabilizer. The non-linear simulations of single machine infinite bus system have been carried out using individual and simultaneous application of PSS and TCSC.

Chapter 6 presents, performance and role of ancillary controllers such as PSS and TCSC in two area control system under restructured electric market. Low order power system model and higher order power system model have been considered for in depth analysis of two area system with ancillary controllers. The stability analysis and non-linear simulation for the transient stability analysis are carried out for investigation of the power system stability issue.

Chapter 7 summarizes the main finding and significant contribution of the thesis and provides a few suggestion for future scope of research work in this area.