CHAPTER 1

PROLOGUE

1.1 INTRODUCTION

The operational complexity of large interconnected power system is increasing day by day due to various factors such as load demand growth, transmission line expansion and Renewable Energy Sources (RES) integration in existing power network along with evolving energy market mechanism. Under such situations, even a moderate change in the system may result in power oscillations, which may be detrimental to system operation, especially inter-area oscillations. At present, power grids are forced to operate near to their thermal limits in order to utilize the full capacity of existing network so as to match the ever increasing load demand and upcoming generation injection, especially those connected to the heavy load areas. For this reason, there is a general consensus that system should have the features with smart functionality in order to have quick control under dynamical conditions leading to secure operations. This framework can be viewed as self-healing network architecture. The network reinforcement, in order to achieve self-healing features, may be in the form of new transmission lines for evacuating power flow from one point to another point, Distributed Generation (DG) suitably integrated and control devices such as tuned Power System Stabilizers (PSS), Flexible AC Transmission System (FACTS) and HVDC [1-3]. However, construction of new transmission lines is difficult due to cost, right of way (RoW) and time.

The operational performance of power system can be improved by proper tuning of existing controllers under dynamical conditions along with hierarchical control structure. It is well known that an improperly designed/tuned controller would not only degrade the system performance but also aggravate adverse dynamic interactions under varying system conditions. Therefore, an adequate controller design/tuning is of utmost importance for damping inter-area oscillations with improved system reliability and stability for interconnected large power network. Power System Stabilizer (PSS) has been used widely as local supplementary excitation control to enhance the damping of the electromechanical mode of oscillations in power system by individual generator regulated participation. It has been realized that FACTS controllers, due to fast power flow control, not only enhance the steady-state stability but also improve transient stability along with damping of low-frequency oscillations and thus ensure better network availability along with operational efficiency. The FACTS devices such as Static Synchronous Compensator (STATCOM), Static Synchronous Series Compensation (SSSC) and Unified Power Flow Controller (UPFC) etc. connected in series or shunt (or both) depending upon the system requirement can result in control of real and reactive power flow along with voltage regulation [4-5]. However, the current challenge in utilities has been to ensure satisfactory performance of existing controllers under operational shifts due to changing operating conditions. Power oscillations damping for local and inter-area oscillation modes have been an essential requirement of the controller with operational shift for system stability and security as well. The proposed novel Knowledge Domain States Mapping Concept with intelligent dynamical tuning/ control shifting/sharing may be more effective for damping oscillations arising due to dynamical changes in the power network.

1.2 LITERATURE SURVEY

The power oscillations are experienced in weak transmission corridor and related generating units. The transmission system up-gradation classically may include appropriate expansion of existing systems in order to evacuate more power depending on the generation injection/loading patterns or embedding strategic controllers in existing network based on system studies. This not only improves the operational performance of transmission corridor leading to quick power oscillation damping but also parallelly relaxing the generators from unnoticed oscillations, which if not taken care off, may damage in due course. Thus, strengthening of transmission corridor improves overall network stability, security and reliability ensuring quick power oscillation damping. The controllers deployed in power network normally maintain the voltage profile and frequency of the system within the acceptable limits by modulating the various signals such as real and reactive power etc. Moreover, the oscillation damping under changing operating conditions needs to be very fast for system stabilization. It has been found that controllers in power network should be properly designed to respond in dynamical requirements both local and global. In large interconnected power system, the controllers (such as Power System Stabilizers (PSS), FACTS and HVDC etc.) are deployed for proper regulation of real and reactive power flow. The controller design and tuning in power network have been reported by researchers worldwide.

1.2.1 Power System Stabilizer (PSS)

PSS has been used to damp the electromechanical oscillations by introducing supplementary control signal for excitation system since 1960’s [6]. Various methods from conventional to intelligent techniques have been used for designing the PSS in order to improve the performance of the overall system. Initially, PSSs were tuned manually or some rule based method for limited operating conditions. The classical method used to tune the PSS control parameters were based on the phase compensation and the root locus methods. Various phase lag-lead compensation methods for designing the PSS parameters [7-8] have been mostly used in utilities due to ease in implementation along with flexibility and structural simplicity. Methods such as Ziegler-Nichols and Cohen-Coon were used to tune the parameters of PID based PSS to damp out low-frequency oscillations [9-10]. In these methods, a lack of robustness has been noticed with range of operating conditions. This may be further more due to non-linear load and different kinds of perturbation.

While handling uncertainties in power system operation, the emphasis should be given to design PSS which takes care of perturbation in the system around its nominal operating value in general to cover the relatively larger perturbation. H∞ based optimal PSS design has been reported in a generalized H∞ control framework [11]. This enables system to remain stable over changing network conditions. To improve the performance of PSS for dynamic stability, H2 and H∞ based robust control techniques have been used to design the controllers for the safe operation of the power system [12-13]. Parametric uncertainty in the system has been handled by Quantitative Feedback Theory (QFT) by solving an optimization problem by incorporating robustness in the controllers for single machine infinite bus system [14]. Abdel *et al*. reported the robust tuning of PSS for multi-machine power system by optimizing the eigenvalue based function [15]. Adaptive PSS with automatic voltage regulator has been reported to improve the terminal voltage control [16]. Design of PSS for system robustness with the digital redesign of sliding mode control; based on multi-rate output feedback for Single Machine Infinite Bus System (SMIB) has been reported in [17]. Peng Zhao *et al*. observed the similarity between adaptive control and recurrent neural networks and reported a new recurrent adaptive control scheme for the design of power system stabilizers to improve performance of the controller [18]. Shaoru Zhang *et al*. reported the use of proportional integral adaptive control which overcomes the drawback of time consumption and non-optimal design of PSS [19]. This concept shows improved performance of stabilizers in terms of dynamic performance and precise regulation. Rabih A. Jabr *et al*. reported conic programming to solve the robust PSS problems such as gain tuning and coordinated phase tuning [20]. Robustness of the controller is achieved by considering various operating conditions in the system. Design of power system stabilizers based on Sliding Mode Control (SMC) to enhance the stability and improve the dynamic response of multi-machine power system has been reported in [21]. The effectiveness of the proposed scheme has been analyzed with small signal stability for steady state operating conditions with parametric uncertainties. Techniques such as online adaptive control result in effective PSS designs/tuning for any changes in network conditions. Such techniques require extensive knowledge of the system dynamics; the estimators are slow in real time implementation and are less effective due to inaccurate state information. New techniques have also been used such as expert system, rule-based, fuzzy logic and neural network in PSS design.

Artificial Neural Network (ANN) is computational model based on the biological neural network. Many researchers have used ANN to enhance the damping of inter-area oscillations. ANN based PSS on improving damping over a wide range have been reported in [22-23]. In [23] Adaptive PSS was used to train the data set of ANN. He J. *et al*. [24] introduced adaptive PSS with recurrent neural network for improved system performance. Neural adaptive PSS was proposed by P. Shamsollahi *et al*. consisting of Adaptive Neuro Identifier (ANI) and Adaptive Neuro Controllers (ANC), which tracks dynamic plant characteristics [25]. These networks are trained online with back propagation method. For best performance of the system with change in operating conditions, modular ANN has been reported for PSS design which removes the drawback of interference caused by the conventional back propagation network [26]. Feed forward neural network has been proposed with hierarchical architecture for adaptive PSS to improve system stability [27]. Two subnetworks have been used; one of them is for identification of power system dynamics and other for stabilization. P. Shamsollahi *et al*. reported Neural Adaptive PSS (NAPSS) to damp both local and inter-area oscillations for five machine power systems [28]. Radial Basis Function Network (RBFN) used to tune PSS parameters by measuring the real-time machine loading is reported in [29]. Here, Orthogonal Least Square (OLS) algorithm has been developed for finding the network parameters and set of significant Radial Basis Functions (RBFs). The neural network has been used to tune the parameters of Fuzzy based PSS (FPSS), which makes it more effective in changing network conditions [30]. Dynamic back propagation method is used to train NAPSS (which has two subnetworks, one is neuro-identifier and second is neuro-controller) and effectiveness of controller has been reported in [31-32]. Radial Basis Function Adaptive Power System Stabilizer (RBFAPSS) has been reported to investigate the effect of loading variation and comparison has been made in terms of stability between ANNAPSS [33]. A Recurrent Neural Network (RNN) stabilizer controller has been reported to maintain the transient stability for variation in the system conditions online [34-35]. The method used RNN, which is connected in parallel to CPSS, thus easy to implement in real system. A large number of training is required in ANN based PSS. To overcome this problem, R. Segal *et al*. reported a self-tuning PSS based on ANN with varying system conditions which tune its parameters in real-time [36]. Active power, reactive power and voltages are used as the nodes in the input layer while PSS parameters are the output. Generalized neuron based adaptive PSS was reported to eliminate the drawback of large training time and large number of neurons which was used to train the controller in traditional ANN based PSS controller [37-40]. J.A.L. Barreiros *et al*. reported a neural PSS for enhancing the system performance in which set of gain scheduling PSS parameters are used to train the controller [41]. Pole placement technique was used to find the parameters at different perturbation in the network. Generalized neural adaptive PSS was reported by Chaturvedi *et al*., in which GN

(Generalized Neural) acts as a predictor as well as a controller and helps to provide better damping at different system operating conditions [42]. An adaptive fuzzy logic PSS and genetic algorithm based PSS have been reported for improved damping at different operating condition [43-44].

To address uncertainty and inaccuracy in the system Fuzzy Logic was developed by Lofti Zadeh in 1965 [45]. Analysis and design of fuzzy based PSS for multi-machine system have been reported in [46]. Robustness of the fuzzy logic PSS (FPSS) is investigated with non-linear simulation and applied to multi-machine system [47]. Results demonstrate the effectiveness of FPSS over the CPSS in terms of system stability. A micro-computer based FPSS applied in real time frame for multi-machine system to calculate its efficiency has been reported in [48]. A novel PSS has been reported based on fuzzy logic set theory for a synchronous machine infinite bus system in time domain simulation. Weighted summation of all the electrical and mechanical states are used as input signals to the excitation system of the fuzzy logic controller. Results demonstrate the effectiveness of proposed controller over a wide range of operating conditions [49]. An adaptive fuzzy logic power system stabilizers design was reported for oscillation damping and enhancing the stability margins of the system. This controller utilizes the multi-zonal PID structure with fuzzy logic variable gain to introduce proper damping. The parallel operation was introduced between both the conventional PSS and fuzzy logic based PSS with simple switching criterion for damping action under small as well as large perturbation in the system [50]. The design procedure of fuzzy based PSS with its effectiveness for multi-machine power system was reported in [51]. Speed deviation and its derivative are used as the input signals for FPSS with Normalized Sum-Squared Deviation (NSSD) index for designing the controller. For assigning the gain of PI and PID based PSS, a new design procedure was reported in [52]. Parameters of this controller are tuned online with fuzzy rule base, and fuzzy inference mechanism is used for calculating the speed of the synchronous generator and its derivative. J. Lu *et al*. proposed an approach for designing fuzzy based PSS which includes two linear stabilizers for incorporating two extreme loading (heavy and light loads) of the network [53]. Least square error criterion has been used to design the controller. An indirect adaptive Fuzzy Logic PSS (FLPSS) was reported using the concept of fuzzy basis functions [54]. The power system was modeled by two unknown nonlinear differential equations which included the state of the system. Lyapunov's synthesis method was used to adapt fuzzy logic systems. A. L. Elshafei *et al*. proposed a new fuzzy logic based PSS controller which has the capability to tune its rule base online for single machine as well as for multi-machine system [55]. The adaptive nature of this controller reduces the size of the rule base and improves performance of the system. Adaptive fuzzy controller consisting of self-learning fuzzy logic with a reference model has been reported in [56]. Offline model identification was used to obtained dynamic equivalent reference model. The proposed technique demonstrates effectiveness of improved system stability. P. Mitra *et al*. reported a fuzzy PSS which uses tie-line power and rotor angular speed as new input signals [57]. This approach gives better system response as compared to CPSS and fuzzy PSS, with speed and acceleration as input signals. The problem of global tuning of fuzzy PSS has been reported in multi-machine power system for power oscillation damping with the use of global optimization technique [58]. Adaptive FPSS controllers consisting of Generalized Neuron (GN) based predictor and fuzzy logic controller has been reported in [59]. Parameters of Adaptive Fuzzy PSS (AFPSS) controllers are decided based on the GN-predictor output and current system conditions. So, the response of the proposed controller is better as compared to conventional PSS under dynamic system conditions.

M. Soliman *et al*. reported design of model-based fuzzy PSS with new Linear Matrix Inequality (LMI) static output feedback concept which guarantees stability as well as better performance of power systems [60]. A power system model was approximated by a set of Takagi–Sugeno (T-S) fuzzy models to account for uncertainties and nonlinearities in large scale power systems [61-62]. Ramirez *et al.* reported a self-tuned fuzzy logic PSS for improved oscillation damping which is based on the simple fuzzy logic controller that possesses significant reduction in rule base with lesser tuning parameters and simple control algorithm [63]. Hasan *et al*. reported the effect of reactive power variation signal on the classical PSS in addition to the change in real power and change in angular speed. The communication lines active power variance signal ($\Delta P_{tie\text{-}line}$) used as one of the input signal for fuzzy multi-input PSS which shows the improved system oscillation damping [64].

Genetic Algorithm (GA) is the global search technique which mimics the process of natural evolution [65]. GA has been extensively studied by researchers for parameter tuning of power system stabilizers. Abdel *et al*. used GA for tuning of PSS parameters by digital simulation of linearized model of the single machine infinite bus system for some change in system operating conditions [66]. Multi-machine PSS design with optimal multi-objective problem using GA was reported in [67]. Abido *et al*. applied GA for finding the optimal setting of rule-based PSS which improves the performance of system significantly [68]. GA has also been applied in [69] to tune the parameters of a neuro-fuzzy PSS. To determine the optimal parameters of the “If and Then” parts membership functions, a suitable fitness function was employed during the learning process. The proposed controller was performed on SMIB system which shows improved dynamic performance of the system under varying system conditions. Hybrid Genetic Local Search (GLS) algorithm is used to tune the parameters of PSS. This algorithm hybridizes GA with the heuristic local search to overcome their shortcomings and combine their strengths [70]. A multi-objective function has been formulated in [71] to calculate complete objective function including damping ratio and damping factor of electromechanical modes. GA has been used for robustly selecting parameters of PSS for optimizing eigenvalue based multi-objective function. It is difficult to work in binary representation when search space is in continuous form with large dimensions. To simplify this, Real-Coded Genetic Algorithm (RCGA) was employed to search optimal parameters of PSS for system oscillation damping [72]. Design of robust PSS and optimal location using genetic algorithms to assure maximum damping under different system operating conditions have been reported by [73]. Power system stabilizer based on the PID controllers tuned by GA to reach optimal global stability has been reported in [74-76].

Particle swarm optimization was developed by Eberhart and Kennedy in 1995 which is based on the social behavior of bird flocking [77]. Abido *et al.* reported the use of PSO technique to search the optimal parameters of PSS. Eigenvalues based function were used as an objective to be minimized by PSO. Results show the effectiveness of proposed controller under different dynamic conditions [78]. El-Zonkoly *et al*. reported the use of PSO for tuning of PSS and AVR simultaneously in multi-machine power system for New England system [79]. A modified PSO was presented for design of optimal Power System Stabilizer (PSS) which shows effectiveness of the designed PSS for different perturbation [80]. A simple design technique for PSS has been reported which is based on PSO that minimizes overshoot of the system parameters, so that the control parameters may within their physical and practical limits [81]. PSO was used to design a robust PSS by considering the problem based on time domain optimization function, and also used to search optimal parameters of PSS to improve the stability

[82]. El-Zonkoly *et al*. used PSO for optimal tuning of parameters of lead-lag block of PSS and fuzzy logic based PSS for damping of oscillations in the multi-machine power system [83]. Mahdiyeh Eslami *et al*. reported a novel algorithm to design the parameters of PSS with multi-objective optimization problem termed as Particle Swarm Optimization with the Passive Congregation (PSOPC) [84]. The objective function used to maximize includes the damping ratio and damping factor. Robust tuning of PSS parameter has been designed by PSO for multi-machine power system to damp the power oscillation when change in operating conditions occurs in the system [85-91].

Tabu search is a mathematical optimization technique to search optimal solution by using memory structures [92]. It is a meta-heuristic algorithm with the ability to escape from the local optimal solution. Abido *et al*. reported the use of tabu search algorithm for optimal tuning of Conventional Power System Stabilizers (CPSS) parameters for Single Machine Infinite Bus (SMIB) system and multi-machine power systems on various operating conditions [93]. Performance enhancement of PSS through excitation control and Static Phase Shifter (SPS) was reported in [94]. The problem was formulated as an eigenvalue-based objective function to be minimized by tabu search algorithm to find optimal control parameters. In addition to this, tabu search algorithm has been used for designing PSS to damp the power oscillations at different system operating conditions by many researchers [95-97].

An improved swarm optimization technique has been used to design optimal parameters of PSS to reduce low-frequency oscillations in a multi-generator power plant [98]. A robust control using fuzzy controller by satisfying linear matrix inequality conditions for improving the stability at multiple system operating conditions has been reported in [99]. A novel model decomposition control method was proposed with its application to tune the parameters of power system stabilizers for damping inter-area mode of oscillations while reducing the interaction among different modes [100]. Evolutionary Programming (EP) has also played its role in damping inter-area oscillations in the power systems. Dill and Silva *et al*. used evolutionary programming to solve the multi-objective problem based on the pseudospectral analysis [101]. Differential Evolution (DE) is a numeric optimization algorithm developed by Storn and Price, which fulfilled the requirement of fast convergence with good consistency. A differential evolution algorithm to damp inter-area oscillation by optimal tuning of PSS has been reported in [102]. A hybridized differential evolution with PSO algorithm has been used by Zhang *et al*. for designing robust PSS in single machine infinite bus system [103]. Ant Bee Colony (ABC) approach has also been used to design the PID based power system stabilizers for modified Philip-Heffron's model to damp power oscillation as quickly as possible [104-105]. Sheeba *et al*. reported the use of ant colony optimization algorithm to drive the controller structure for multi-machine system [106]. Zhe Sun *et al*. reported differential evolution algorithm for tuning type–2 fuzzy logic power system stabilizer which shows effectiveness of proposed approach for power oscillation damping in power system [107]. An Innovative Cuckoo Search Optimization technique has been used to design PSS in a multi-machine power system for improving system stability [108].

1.2.2 Flexible AC Transmission Systems (FACTS)

FACTS devices have been found to be the best for controlling different variables such as voltages, currents, real power and reactive power, thereby offering improved system performance and enhanced Available Transfer Capacity of existing power network in the vicinity. FACTS devices have been found more economical alternatives as compared to constructing new transmission lines. It has been noticed that these devices enhance not only the steady state stability but also the transient stability which in turn ensures system security and reliability along with network availability. The damping of low-frequency oscillations as well as voltage regulation has been one of the most powerful outcomes due to fast power flow control with these devices. However, for proper operation of these devices, supplementary controller may be added to enhance the damping of electromechanical oscillatory modes, while meeting the primary goal. Such controllers perform satisfactorily in the presence of many modes of power swings, and also over a wide range of operation. The developments of these devices are greatly supported by advancement in new semiconductor devices such as GTO (Gate Turn-Off) and IGBT (Insulated-Gate Bipolar Transistor). FACTS based controllers such as STATCOM, SSSC and UPFC can be effectively used for damping of inter-area oscillations [1-3]. Among these devices, UPFC has been proved to be the best because of its versatility and quick response to power oscillation damping. It is a multi-functional FACTS controller with capability of controlling all three parameters that dictate power flow over power transmission line, i.e., line voltage, phase angle and impedance, with internal reactive power generation in real time. Many researchers have reported the design of these FACTS devices to regulate the power flow and maintain voltage profile in the system as desired.

1.2.2.1 Static Synchronous Compensator (STATCOM)

STATCOM provides flexible reactive power at key points of the transmission system through enhanced speed and performance. There are various topologies available for fully controllable power electronic valves with (Pulse Width Modulation) PWM based converter control. K.V. Patil *et al*. used STATCOM to damp the torsional oscillations in the system due to the series compensated AC system. Voltage Source Inverter based STATCOM equipped with PI-controller has been considered which used to regulate the generator terminal voltage. Generator speed deviation is used as an additional input to the PI-Controller. Time domain simulation has been carried out to show the effectiveness of the scheme for three-phase fault [109]. H. F. Wang established linearized Phillips-Heffron's model of an STATCOM connected power system and analyzed the damping effect of well-designed STATCOM to reduce the oscillations in the system [110]. Single Machine Infinite Bus (SMIB) system and multi-machine power system is considered to show effectiveness of STATCOM to damp the oscillation in the system. Traditional PI-controllers gives poor response in terms of damping high-frequency oscillations between capacitance and inductance of the Current Source Inverter (CSI) output filter. A new approach for the control dynamics of CSI based STATCOM has been reported in [111]. Steady state characteristic of CSI based STATCOM with d-q frame model has been reported which includes fast AC current control inner loop and slower dc current control outer loop. Nadarajah Mithulananthan *et al*. compares the performance of different controllers such as PSS, Static Var Compensators (SVCs) and STATCOMs for eliminating the undesirable inter-area oscillations. The problem is analyzed by Hopf bifurcations viewpoint with extended eigenvalue analysis for the study of different controllers, their locations and use of control signals for damping inter-area oscillations [112]. H.F. Wang studied the negative interactions between STATCOM AC and DC control which shows that the conventional arrangement of the various control functions of the STATCOM may not be always appropriate. A multivariable design of DC control and STATCOM AC was reported in [113] where a single two variable controller is designed to perform STATCOM AC and DC control function. Coordinated design of STATCOM with PSS based damping stabilizers have been reported by M.A. Abido in [114]. Singular value decomposition approach is used to assess the controllability of electromechanical mode of oscillations with different control inputs. The problem of controller design is formulated in optimization problem, and Real-Coded Genetic Algorithm (RCGA) is used to search optimal values of controller's parameters. Results show the effectiveness and robustness of controller for enhancing system dynamics and stability. Optimal neuro-fuzzy controller is designed for STATCOM in 12-bus benchmark system [115]. Action-Dependent Heuristic Dynamic Programming (ADHDP) method is used to implement the controller which is a member of Adaptive Critic Design (ACD) family. Wei Qiao *et al*. [116] reported a novel Interface Neuro Controller (INC) for coordinated reactive power control between STATCOM and large wind farms. Radial basis function and heuristic dynamic programming were used to design Interface Neuro Controller and therefore, improves the damping in power system after any fault occurs in the grid. In recent years, with deployment of PMU into the network, remote signals can be made available as input signal for controllers. Design of Wide-Area Damping Controllers (WADC) in supplement to the FACTS controller, considering signal time delays has been reported in [117]. The delay margin is introduced as an additional performance index for WADCs based FACTS devices to damp inter-area oscillations. Mebtu Beza *et al*. reported the design of adaptive power oscillation damping for STATCOM equipped with energy storage [118]. A signal estimation technique based on a modified Recursive Least Square (RLS) algorithm has been used which allows a fast and selective estimation of electromechanical oscillations with local signals. This method shows the effectiveness in increasing the damping of the system oscillations.

1.2.2.2 Static Synchronous Series Compensator (SSSC)

Static Synchronous Series Compensator (SSSC) is a series connected FACTS device used to control the power flow by injecting compensating voltage in to the line which is almost in quadrature with the line current, thus emulating the reactance of the transmission line [4]. Therefore, when SSSC emulates the reactance in series with the line, power flow in the line increases when the emulated reactance is capacitive and power flow decreases when the emulated reactance is inductive. Laszlo Gyugyi *et al*. describes an approach for controllable series compensation with synchronous voltage source implemented by GTO based Voltage Source Inverter (VSI) [119]. SSSC controller provides compensating voltage with an identical inductive and capacitive range, independent of the magnitude of the line current. Pillai. G.N. *et al*. reported the use of SSSC with a fixed capacitor to avoid torsional mode of oscillation in the series compensated transmission line [120]. For the realization of SSSC, 48-step harmonic neutralized inverter is used. The system has been studied through EMTDC/PSCAD simulation and also eigenvalues analysis. It has been shown that SSSC with fixed capacitor improves damping of the controller for power oscillation as well as for torsional mode of oscillations. M. M. Farsangi *et al*. reported a method to select input signals for various FACTS devices connected in the small or large system [121]. Various controllable analysis were used to select best input signals for SVC, SSSC and UPFC for enhancing the damping of inter-area oscillations. A novel control strategy for mitigation of Sub-Synchronous Resonance (SSR) using SSSC which constitutes three single phase VSC has been reported in [122-124]. Mitigation of subsynchronous resonance is done by increasing the network damping for those frequency that are critical for generator turbine shaft. IEEE Benchmark model has been used to show the effectiveness of the proposed concept for damping in the system. Dipendra Rai *et al*. reported the use of imbalanced series capacitive compensation concept for enhancing the damping of power swings as well as torsional oscillations [125]. A comparative effectiveness of two “hybrid” series capacitive compensation schemes has been evaluated for damping of inter-area oscillations. The effectiveness of the schemes has been evaluated in EMTP-RV time simulation program for various network conditions to damp out inter-area oscillations. A.H.M.A. Rahim *et al*. reported the use of Artificial Bee Colony (ABC) optimization algorithm to design the parameters of PID controller with Static Synchronous Series Compensator (SSSC) control [126]. A simple pole-placement technique was used to get the range of parameters and was used as an input to the ABC algorithm. To compensate load changes and suppress oscillations, use of SSSC can be considered as one of the effective approaches. Ali Darvish Falehi *et al*. reported the Hierarchical Adaptive Neuro-Fuzzy Inference System Controller–SSSC (HANFISC–SSSC) to eliminate both tie-line power exchange deviations and low-frequency oscillations [127].

1.2.2.3 Unified Power Flow Controller (UPFC)

Unified Power Flow Controller (UPFC) is the most versatile FACTS device with the ability to adjust bus voltage, phase angles between two buses and transmission line reactance. It operates by controlling the in-phase voltage, quadrature voltage and shunt compensation. H. F. Wang reported a non-linear model to represents multi-machine model installed with UPFC. Phillips-Heffron model is then derived for the study of oscillations in the system. The impact of UPFC control function on system stability has been presented for three machine power system in [128]. In this a new power frequency UPFC model with the dynamic of DC-link capacitor has been reported. Main control of UPFC is realized as the combination of four control functions (amplitude modulation ratios (m_e and m_b) and phase angles (δ_e and δ_b) for both series and shunt converters). Simulation carried out on 4 generator power system with the added supplementary control for UPFC to improve the system dynamic performance is shown in [129]. H.F. Wang *et al*. reported the effect of UPFC on the stability of power oscillation with linearized Phillips-Heffron model and also the studies the selection of control signals for designing UPFC damping controller [130]. Coordinated excitation and UPFC control has been reported to improve both voltage stability and transient stability [131]. Direct feedback technique with local measurement has been used to design the excitation controller. Shunt part of the UPFC is used to control the voltage stability whereas the series part of UPFC is used to damp out the power oscillation in transient condition. In [132], UPFC has been used to regulate the power flow over two parallel corridors and has also been used to maintain voltage profile in the system. For accurate controller parameters, detailed dynamic generator model has been used in the system modeling. Root locus method along with pole assignment technique has been used for calculating gains of PI-controller to improve system dynamic performance. B.C. Pal *et al*. reported an H-infinite mixed sensitivity design for damping device of UPFC in linear matrix inequality framework [133]. The proposed controller gives adequate damping to inter-area oscillation over wide range of operational shift in the system. DC voltage regulator adversely affects the damping capability of UPFC. Design of UPFC with DC voltage regulator and damping controller has been reported in [134]. N. Tambey *et al*. studied the effectiveness of input control parameters of UPFC (amplitude modulation ratio and phase angle) for damping the power oscillations using controllability index. Investigation shows that the damping controller parameter m_b and δ_e prove best for providing robust dynamic performance in the system. Kwang M. Son *et al*. reported newton type current injection model for UPFC to reduce the low-frequency oscillation in the system at different operating conditions for sample two area power systems [135]. J. Hao *et al*. reported the mathematical model to examine the optimal location and parameters of UPFC to increase the loadability in the network subject to voltage level and transmission line capacity [136]. Self-adaptive evolutionary programming algorithm has been used to solve the non-linear problem. Ali T. Al-Awami *et al*. proposed robust UPFC based stabilizer to eliminate power oscillations as quick as possible [137]. Singular value decomposition is used to evaluate the potential of UPFC to improve the dynamic stability of the system. PSO technique is used to find optimal controller parameters for a wide range of operating conditions. Model controllability indices have been proposed by B. Kalyan Kumar *et al*. for optimal location of FACTS devices to ensure the quick damping in inter-area mode of oscillations [138]. A new evolutionary Bacteria Foraging algorithm has been used by M. Tripathy *et al*. for optimal location of UPFC and its controller design along with tuning of transformer taps positions. Minimization of real power loss with voltage stability limits is also considered in mesh power network [139]. Ali T. Al-Awami *et al*. reported supplementary controller in addition to the UPFC for enhancing the damping of low-frequency oscillations. The potential of UPFC controller is measured by singular value decomposition analysis and PSO technique is used for the individual design of UPFC controller parameters which show the effectiveness of proposed concept tested through eigenvalue analysis [140]. Optimal neuro controller supplementing to UPFC has been reported by Swakshar Ray *et al*. in [141]. Wide area signals are used to give input to the supplementary controller of UPFC to enhance the damping of low-frequency oscillations. Mahyar Zarghami *et al*. reported the utilization of ultra-capacitors also known as Electrochemical Capacitors (EC) in multiple UPFC for damping low-frequency oscillation in bulk power network [142]. A new control concept has been used here for directly controlling sending and receiving end voltages of UPFC and better utilizes the storage energy in electrochemical controllers. Shahrokh Shojaeian *et al*. reported an Adaptive Input-Output Feedback Linearization Control (AIFLC) approach for multi-machine multi-UPFC connected power system for damping of low-frequency oscillations [143]. Osvaldo Rodríguez *et al*. studied the non-linear interaction of UPFC with power system through model series method [144]. Model series method is an analytical tool which can characterize nonlinear effect due to small perturbation.

Some other researches have been done for damping of local and inter-area oscillation with the adequate design of power system stabilizers and FACTS devices. Pandey R. K. *et al*. have reported an analytical approach for control design of Unified Power Flow Controller (UPFC) which has been supplemented by Power Oscillation Damping (POD) controller [145]. Various methods (such as Minimum Singular Value (MSV), Hankel Singular Value (HSV), Direct Component of Torque (DCT) and residue methods) have been used to find out the most effective input control parameters of UPFC for improved power oscillation damping. Results show the effectiveness of all the techniques used to identify the input control parameters of UPFC for adequate damping at various system operating conditions. A generalized small signal stability model for design and analysis of FACTS (STATCOM, SSSC and UPFC) devices have been reported in [146]. Pandey R. K. *et al*. reported an optimal Power Oscillation Damping (POD) controller for UPFC [147]. Single Machine Infinite Bus (SMIB) system and two area power system are used to study the performance of the controller. The controller is used to design with the concept of Eigenvalue Assignment Technique (EAT) for variety of system operating conditions (such as change in system loading and transmission line length). Controller performances show the reduction in the settling time and overshoot/undershoot of all the state variables in the network. This proposed approach gives relaxation in assigning the elements of Q matrix for the formulation of control strategy. In [148], an optimal POD design with SSSC has been presented for two area power network. Eigenvalue assignment technique is used for designing the proper controller which ensures level of relative stability. SSSC enhances the Available Transfer Capacity (ATC) of the transmission line as line length increases. Pandey R. K.

reported Multi-Stage LQR (MSLQR) concept based on the State Predominant Approach which minimizes the overshoot and settling time [149-150]. This concept eliminates the tedious part of assigning the elements of the weighting matrix Q. Selection of Q matrix has been directly linked with the real part of eigenvalues of the system. With Q matrix, feedback gain matrix K is calculated for ensuring system stabilization.

1.2.3 Coordination between PSS and FACTS Devices

To improve the system performances, many design procedures of controllers have been used, but the interaction among all the controllers may destabilize the system and increase the local and inter-area oscillations. Thus a control strategy is required so that all the controllers connected in the network coordinate with each other and give benefit of multiple controllers, thereby enhancing the system stability and reducing any possible negative interactions among the different controllers [151]. Many researchers reported the work of coordination between PSSs and FACTS devices to enhance the damping of the power oscillations. M.A. Abido *et al*. reported the use of Simulated Annealing (SA) based approach for the tuning of Power System Stabilizers (PSSs) and FACTS devices for proper operation of the network at various operating conditions [152]. Eigenvalue-based problem has been formulated as an objective function, and SA algorithm has been used to search the optimal parameters of the controllers in the search space. Nonlinear simulation shows the effect of SA based tuning of PSSs and FACTS in wide range of loading conditions. M.A. Abido *et al*. used pole placement technique for the design of PSSs and Thyristor Controlled Series Capacitor (TCSC) based stabilizers [153]. SA algorithm is used for the optimal parameter selection of PSS and TCSC. This approach examined on a weak network with various disturbances, loading conditions, and system parameter variations. Power system stability enhancement through coordination of PSS and SVC with the use of real coded genetic algorithm for selecting optimal control parameters of both the controllers has been reported in [154]. Effectiveness of the scheme is evaluated in terms of damping torque coefficient for various operating conditions. Real-coded genetic algorithm has been also employed for the design of excitation and TCSC based stabilizers [155]. H. Shayeghi *et al*. reported a new design procedure for coordination of PSS and TCSC controllers in multi-machine power system [156]. The coordination design among the controllers is converted into an optimization problem, and PSO technique is used to solve this objective function. The fitness value includes the oscillatory characteristics between areas and thus improves interaction among the controllers. T.T. Nguyen *et al*. proposed an optimal design procedure for proper interaction of PSS and FACTS devices [157]. A constrained optimization approach has been used for minimizing the eigenvalue-based objective function and results show the effectiveness with enhanced system stability. A robust method for combined design of PSS and STATCOM to improve the damping of power oscillation is reported by Ahmad Rohani *et al*. in [158]. Fuzzy Logic Controller (FLC) has been used to design the PSS while PSO technique has been used to search the optimal control parameters of STATCOM connected in single machine infinite bus system. Simulation results show the excellent capability of proposed scheme to damp out low-frequency oscillation and enhance system stability. Sidhartha Panda *et al*. investigated the application of Non-Dominated Sorting in Genetic Algorithms-II (NSGA-II) for the tuning of a PID controller for FACTS based stabilizer [159]. The objective was to improve damping in the system subjected to a disturbance with minimum control effort. This technique was applied to generate Pareto set of global optimal solutions to the given multi-objective optimization problem. An application of probability theory has been used for the coordination of PSS and SVC devices for enhancing the electromechanical mode of oscillation in multi-area system over wide range of operating conditions. A probability eigenvalue-based objective function has been used for the proper interaction of PSS and SVC [160]. F. S. AL-Ismail *et al*. reported the design of STATCOM based damping stabilizers and its effect in enhancing the damping in low-frequency oscillations [161]. This STATCOM based stabilizer was performed on a Real-Time Digital Simulator (RTDS). The nonlinear time domain simulation has been reported to validate the damping stabilizers at low-frequency oscillations. Results show the effectiveness of the stabilizer in terms of damping and system stability. Lokman H. Hassan *et al*. reported the coordinated design between PSS and UPFC by using GA algorithm [162]. Multi-objective problem was formulated to maximize damping ratio(s) of electromechanical modes for different PSS and UPFC. GA finds the optimal location of UPFC and PSS along with their control parameter tuning resulting in effective damping of inter-area modes of oscillations.

1.2.4 Summary of Literature Survey

Summary of some research work related to power oscillations damping reported by the researchers are following:

I. The design of Power System Stabilizers (PSSs) with various methods from conventional to the new heuristic optimization techniques have been attempted by researchers to damp out the electromechanical oscillation in the system.

II. Design of FACTS devices (STATCOM, SSSC and UPFC etc.) with control strategy like LQR control, intelligent optimization techniques (GA, PSO, BAT, GSA and hybrid heuristic techniques), Eigenvalue Assignment Technique (EAT), Wide-Area Damping Controller (WADC) have been used to damp out the inter-area oscillation for various system operating conditions.

III. Coordination concepts for different PSS and FACTS devices to reduce the power oscillation damping have also been reported.

IV. Many control algorithms have been proposed for PSS design to have the capability of dynamic control parameter tuning such as adaptive technique, neural network and even genetic algorithm, however these algorithms have some problem as they are also trained offline for different system operating conditions based on operational shift, but in online condition, these controls do not update their parameters, (if not trained in offline at particular operating conditions) so their performance highly depends on the quality of offline training.

V. In order to overcome the problem of oscillation damping when the system operating condition changes, the dynamical retuning of existing controllers are required as quickly as possible so that very fast damping may be ensured.

In this research work, an approach based on the knowledge domain states mapping concept has been evolved for operational shift linked parameters database generation offline initially, and may be an upcoming controller parameters updates on the same basis in online mode. The most added advantage of the method proposed has been to give flexibility in controller integration by design methodology which can be very effective for upcoming power network globally with slight augmentation using intelligent techniques, this will certainly not only extend the operational life of existing controllers of power system but also add reliability and availability of existing network.

1.3 OBJECTIVE

The well-known dynamical change in loading pattern is one aspect which needs to be addressed by all the controllers connected in the network including generator units by effective PSS functioning and FACTS devices by modulating power flow in the network. This can only be achieved by parameters retuning as operating condition changes. Normally PSS are tuned at the time of system planning, and thereafter commissioning of plants in Grid-connected mode. The history of researches carried out on PSS presents sufficient literature on the adjustment of parameters in a limited domain. However, practically system loading and external disturbance may force the local mode of oscillations to aggravate due to the limited capacity of designed parameters. In multi-area power network, the interactions are quite often which may lead to unacceptable generator behavior to either tripping or cascaded outage. To avoid this phenomenon, an alternate new concept has been proposed to provide the flexibility in control range itself of each PSS settings at design stage employing a range of parameters linked with the operational shift with proposed Knowledge Domain concept. The Knowledge Domain Inference Mechanism (KDIM) has been developed offline for almost all the operating conditions possible with heuristic optimization techniques. The knowledge domain up-gradation is ensured with changing system conditions. Thus, new sets of parameters are available which can be mapped with inference mechanism dynamically to have better performance of system recovery even with relatively larger perturbation. The additional control flexibility has been introduced with FACTS controller to assist the existing PSSs at all the generating units when the designed range is likely to be exhausted. In this concept, the onset of range getting exhausted is detected with signaling of rotor angle oscillations and other states of the system and the FACTS controller is intelligently introduced in the overall framework almost in minimum time. The structure so proposed is an evolving concept of self-healing grid module employing FACTS as ancillary service to the network driven by dynamical knowledge domain inference mechanism which ensures quick oscillation damping even if the generator control module is having no further margin in controller parameters.

The main objective of the research can be summarized as follows:

I. Evolve a **hierarchical control structure** for quick power oscillation damping- both local mode and inter-area oscillations.

II. Develop a **Knowledge Domain Structure** for all existing controllers connected in the system offline initially, for almost all possible operating conditions with known optimization techniques.

III. **Intelligent Controller Tuning and Controller Switching/Sharing Concept** have been developed for quick oscillation damping as operating conditions change.

IV. Tuning of the control parameters are mapped in **dynamical mode – Linked with Knowledge Domain**

V. In the situation of inadequate control capacity for system stabilization within desired limits, another control supplements existing control based on intelligent approach viewed as ancillary **-Control Shifting/Sharing Concept.**

VI. Validation of proposed concept in PSCAD/EMTDC software.

1.4 THESIS STRUCTURE

Chapter 1 Prologue

This Chapter presents motivation of the research work along with various literature reported on power oscillations arising due to dynamic changes and recovery methodology of power network. Based on the existing trend of controller functioning, it has been found that the Knowledge Domain States Mapping Concept for intelligent power flow control may be an effective way to have better system performance which can ensure overall system stability along with security and reliability. The objectives of research work are detailed along with contribution in operational behavior.

Chapter 2 Concept of Smart Power Flow Control

In Chapter 2 Concept of Smart Power Flow Control has been proposed. The system regulation has been addressed with intelligent power control concept which deploys controller structure depending upon the system requirements such as operational shift. Since the operational shift is observed with many external effects such as loading patterns, inadequate transmission capacity of interconnected line and also imprecise controller parameters for a given controller structure apart from the different rating of generating units which might cause local mode oscillations and if not addressed by PSSs may transfer as inter-area oscillations unnoticeably for another operational point slight change. Thus controller induction and parametric tuning at plant level and transmission level as well are required, which has been viewed and proposed as concept of smart power flow control with knowledge domain states mapping for intelligent power oscillation damping as the dynamical operational shift occurs in the system.

Chapter 3 Network Representation

This chapter presents a modular mathematical model of multi-area power system comprising of detailed dynamics of each subsystem and controllers as well. The proposed model can be extended for any number of generators with any number of areas in the system utilizing the beauty of block matrix formulation. The system representation for each machine along with Power System Stabilizers (PSS) has been derived and interfaced with FACTS devices (STATCOM, SSSC and UPFC) in state space framework. The model derived is general enough and can accommodate other supplementary controllers with suitable interface variables (like LQR Controller, POD Controller, Multi-Stage LQR (MSLQR) Controller (based on State Predominant Concept) and proposed Integrated MSLQR-POD controller) for improved system stability.

Chapter 4 Heuristic Approach for Controllers Tuning

In Chapter 4 Heuristic Approach for Controllers Tuning, intelligent heuristic optimization techniques (PSO, FA and GSA) have been discussed for the development of knowledge domain structure of all the controllers connected in the system. The parameters of controllers have been tuned with various heuristic approaches and comparison has been done for better performance.

Chapter 5 System Studies

In Chapter 5, system Studies have been extensively carried out for various operational shift. The model developed has been effectively used to simulate all possible conditions which demonstrate the effectiveness of the proposed concept of knowledge domain states mapping for intelligent power flow control. A rigorous system study has been done under variety of dynamical changes, the controller tuning by all heuristic approaches mentioned in Chapter 4 has been done and results demonstrate the best system response and appropriate tuning method. The overall system considered has been subjected to on-going perturbation along with associated control strategy such as PSS alone and also coordination of PSS with FACTS devices. The results with such controller structure demonstrate the concept of intelligent power control concept under variety of operational conditions. The concept of intelligent controller (hierarchical control structure) augmentation such as parametric range extension and controller sharing and shifting has been extensively studied for large system.

Chapter 6 Epilogue

This chapter presents the critical evaluation of Chapter-wise conclusion and suggests scope of the future work looking into other upcoming intelligent controller configurations in large power network.

1.5 CONTRIBUTIONS

The main contribution of the research work can be summarized as:

1. Knowledge Domain States Mapping Concept has been developed for intelligent power flow control in dynamic network with changing operating conditions.
2. Particle Swarm Optimization (PSO), Firefly Algorithm (FA) and Gravitational Search Algorithm (GSA) optimization techniques are used to develop the knowledge domain inference mechanism for all the controller's parameters connected in the network by minimizing cost function J (J=ITAE performance indices).
3. Proposed concept demonstrates the fast system oscillation damping with intelligent power flow controller utilizing knowledge domain states mapping concept as system operating condition changes with time. It has been observed that retuning of respective control parameters from the knowledge domain effectively enhances the oscillation damping in overall system, and thus is the most recommended methodology in evolving power system with many upcoming additions of components such as network/generation expansion, controller induction and load changes unnoticeably as well.
4. Controller shifting / sharing concept has also been analyzed by introducing FACTS in the system when PSS fails to stabilize the system at certain system operating condition due to parametric limitation.

5. Integrated MSLQR-POD FACTS Controller and Modified-MSLQR Controller have been designed, and results show better response as compared to previously reported FACTS Controllers.
6. Validation of proposed concept has been done in PSCAD software.

1.6 CONCLUSION

This chapter presents motivation of the research work along with various literature reported on power oscillations arising due to dynamic changes and recovery methodology of power network. Based on the existing trend of controller functioning, it has been found that the Knowledge Domain States Mapping Concept for intelligent power flow control may be an effective way to have better system performance which can ensure overall system stability along with security and reliability. The objectives of research work are detailed along with contribution in operational behavior.