A Comprehensive Survey of Coordinated Control Techniques of FACTS Controllers in Multi-Machine Power System Environments

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***Abstract*-This paper presents exhaustive review of various methods/techniques for coordinated control between FACTS controllers in multi-machine power systems. Authors strongly believe that this survey article will be very much useful to the researchers for finding out the relevant references in the field of coordination of FACTS Controllers.**

Index Terms- Control Coordination, Flexible AC Transmission System (FACTS), FACTS Controllers, Interactions, Voltage Stability, Power Systems.

I.INTRODUCTION

THE drive towards deregulated environment may result in simultaneous installation of different FACTS controllers in power system. These multiple FACTS controllers have the potential to interact with each other. This interaction may either deteriorate or enhance system stability depending upon the chosen controls and placement of FACTS controllers. Hence there is a need to study the interaction between the FACTS controllers.

The various interactions can potentially occur between the different FACTS controllers, as well as, between FACTS controllers and Power System Stabilizers (PSS) in a multi-machine power system environment. These likely interactions have been classified into different frequency ranges and various interaction problems between FACTS controllers or FACTS to PSS's from voltage stability/ small signal stability viewpoint are presented in [1]-[2].

There are several methods proposed in literatures for coordination of multiple FACTS controllers in multi-machine power systems from different operating conditions viewpoint [4]-[106]. Three broad categories such as a sensitivity based methods, optimization based method and artificial intelligence based techniques for coordination of FACTS controllers from different operating conditions in multi-machine power systems is classified in [3]. The various sensitivity based methods have been proposed in literatures includes eigen-value analysis based methods [4], [7]-[15], [76]-[77], modal analysis techniques [16]-[22], residue-based methods [23], [24]. There are various other techniques such as a pole placement techniques [25], frequency response techniques [26], root locus techniques [27], projective control methods [28]-[30], [95], non-linear feed control methods [31]-[32] for coordination of FACTS controllers and PSS. The various optimization based methods have been proposed in literatures for coordination includes a dynamic optimization programming algorithms [47], non-linear optimization programming techniques [48]-[52],[79], linear optimization programming techniques [53]-[55],[78],[97]-[98],[100]-[101],[104], immune-based optimization algorithms[56]. The various artificial intelligence (AI) based methods have been proposed in literatures that includes a genetic algorithms (GA) [63]-[66],[80]-[81],[103], tabu search algorithms [67],[82], simulated annealing (SA) based approach [68], particle swarm optimization (PSO) techniques [69],[85],[99], artificial neural networks (ANN) based algorithms [70],[96],fuzzy logic based approach [71]-[74],[83]-[84],[106], adaptive neuro-fuzzy inference system (ANIS) techniques [75], H-infinity optimization techniques [86]-[88], μ-synthesis techniques [89]-[91], linear matrix inequality technique [92], prony methods [93], riccati equations methods [94], relative gain array (RGA) theory [102], load flow control technique [105].

This paper is organized as follows: Section II discusses the types of interactions between FACTS controllers in multi-machine power systems. Section III presents the review of various techniques/methods for coordination of multiple FACTS controllers in multi-machine power systems. Section IV presents the summary of the paper. Section V presents the conclusions of the paper.

II. INTERACTIONS BETWEEN MULTIPLE FACTS CONTROLLERS

Types of Interactions of FACTS Controllers are presented in [1] includes

- Multiple FACTS controllers of a similar type
- Multiple FACTS controllers of a dissimilar type
- Multiple FACTS controllers and HVDC converter controllers

The various interactions that can potentially occur between the different FACTS controllers, as well as between FACTS and PSS's or HVDC controllers, in power system environments have been classified into different frequency ranges. The frequency ranges of the different control interactions have been classified includes [2]

- 0 Hz for steady state interactions
- 0-3/5 Hz for electro-mechanical oscillations
- 2-15 Hz for small-signal or control oscillations

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- 10-50/60 Hz for sub -synchronous resonance (SSR) interaction
- >15 Hz for electromagnetic transients, high frequency resonance or harmonic resonance interactions

In [2] two methods have been proposed to solve interaction phenomenon between dynamic loads and FACTS controllers in power systems. The first one is based on sensitivity and residues techniques and it takes into account the uncertain character of dynamic loads to compute the most efficient phase compensation for low frequency oscillations damping. The second approach consists on designing a robust damping controller by Linear Matrix Inequalities (LMI) techniques which gives a certain degree of stability and performances of the FACTS controllers in presence of dynamic loads uncertainties.

III. CLASSIFICATION OF FACTS CONTROLLERS COORDINATION TECHNIQUES

Coordination techniques of FACTS controllers are classified in three broad categories as sensitivity based methods, optimization based method, and artificial intelligence based techniques [3].

A. Sensitivity Based Methods

There are various sensitivity based methods such as a modal or eigen-value analysis, and index method. An eigen value analysis approach has been addressed for modeling and simulation of SVC and TCSC to study their limits on maximum loadability point in [4], [5]. A new methodology has been addressed for the solution of voltage stability when a contingency has occurred, using coordinated control of FACTS devices located in different areas of a power system. An analysis of the initial conditions to determine the voltage stability margins and a contingency analysis to determine the critical nodes and the voltage variations are conducted. The response is carried out by the coordination of multiple type FACTS controllers, which compensate the reactive power, improving the voltage stability margin of the critical modes [6]. In [7], an eigen value analysis approach has been addressed for the problem of the most effective selection of generating units to be equipped with excitation system stabilizers in multi-machine power systems which exhibit dynamic instability and poor damping of several inter machine modes of oscillations. A new coordination synthesis method using as an eigen value sensitivity analysis and linear programming has been addressed for simultaneous able to select the generators to which the PSS can be effectively applied and to synthesize the adequate transfer function of the PSSs for these generators [8]. Abdalle et al. suggested an eigen value analysis approach for a sequential procedure of coordinated stabilization in a multi-machine power system with arbitrary complexity of the system model [9]. In [10], an eigen value analysis technique has been addressed for designing PSS in multi-machine power system. Xu and Zaid et al. presented a systematic method based on an eigen-value sensitivity analysis and linear programming for the tuning of multiple FACTS controllers in power system [11]. An eigen value sensitivity based analysis approach has been addressed for robust design of FACTS controllers in multi-machine power systems [12]. In [13], an eigen value sensitivity based analysis approach has been addressed for control coordination of series and shunt FACTS controllers in a multi-machine power system for series and shunt FACTS controllers considered are SVC, TCSC and SVC-TCSC combination. Chung et al. has been suggested a probabilistic eigen sensitivity based analysis for the selection of robust PSS location, parameters, and coordination for enhance the damping of multiple electro-mechanical modes in a multi-machine power systems over a large and pre-specified set of operating conditions [14]. An eigen value sensitivity based analysis approach has been addressed for design and coordinate multiple stabilizers in order to enhance the electro-mechanical transient behaviour of power systems [15]. In [16], a modal analysis technique has been addressed for coordinated control of inter-area oscillation in the china southern power grid for parameter setting of selected power system stabilizers (PSS) and HVDC damping controllers. In [17], a Decentralized Modal Control (DMC) algorithm has been addressed for simultaneously selecting the power system stabilizers (PSS) parameters in multi-machine power system in order to enhance damping of the power system oscillations. An eigen value sensitivity based analysis approach has been addressed for coordinated control of SVC and PSSs in power system in order to enhance damping power system oscillations [18]. In [19], an eigen-value sensitivity based analysis approach has been addressed for the evaluation and interpretation of eigen-value sensitivity, in the context of the analysis and control of oscillatory stability in multi-machine power systems. A modal analysis reduction technique has been suggested for multi-variable control design for damping inter-area oscillations of bulk power systems in order to raise precision and facilitate design procedures in [20]. A modal analysis based technique has been presented for design of robust controllers for damping inter-area oscillations application to the European power system [21]. Gasca and Chow et al. has suggested a modal analysis based technique for the design of damping controllers in multi-machine power system or inter-area oscillations [22]. In [23], a residue based method has been presented for coordinated control of multiple FACTS controllers as well as to minimize the potential for adverse interaction between control loops. Ammari et al. [24] has addressed sensitivity and residues based techniques for robust solution for the interaction phenomena between dynamic loads and FACTS controllers for enhance damping of power system oscillations. In [25], a sensitivity based techniques such as a linear matrix inequalities techniques has been proposed for the design of robust PSS which places the system poles in acceptable region in the complex plane for a given set of operating and system conditions to enhance the damping of power system oscillations over the entire set of operating conditions. A frequency response technique has been used for coordinated design of under-excitation limiters and power system stabilizers (PSS) in power system for enhance the electro-mechanical damping of power system oscillations [26]. A root locus technique has been proposed for design of power system stabilizers (PSS) for damping out tie-line power oscillations in power system to enhance the damping of power system oscillations for different combinations of power system stabilizers parameters [27]. In [28], a projective control method has been addressed for coordinated control of two FACTS devices such as TCSC and Thyristor Controlled Phase Angle Regulator (TCPAR) for damping inter-area oscillations to enhance the power transfers and damping of power system oscillations. In [29], [30], a projective control method has been addressed for coordinated control of TCSC and SVC for enhancing the dynamic performance of a power system. Tan and Wang et al. showed that an adaptive non-linear coordinated design technique for coordinated design of series and shunt FACTS controllers such as a Static Phase Shifter (SPS) and a Static VAR Compensators (SVC) controller in power systems environments for enhance the transient stability of the power system [31]. A non-linear technique has been proposed for robust non-linear coordinated excitation and SVC control for power systems for enhance the transient stability of the power systems [32]. In [33], a new method has been proposed for the design of power system controllers aimed at damping out electro-mechanical oscillations used for applied to the design of both PSS for synchronous generators and supplementary signals associated to other damping sources. Milanovic and Hiskens et al. suggested a new method for tuning of SVC controllers in the presence of load parameters uncertainty to enhance the damping of electro-mechanical oscillations in power systems [34]. Canizares and Faur et al. presented the steady-state models with controls of two FACTS controllers, namely SVC and TCSC, to study their effect on voltage collapse phenomena in power system to increase system loadability [35]. Lie et al. presented a linear optimal controller for the designed to implement multiple variable series compensators in transmission networks of inter-connected power system is utilized to damp inter-area oscillations and enhance power system damping [36]. An application of a normalized H_∞ loop shaping techniques has been proposed for design and simplification of damping FACTS controllers in the linear matrix inequalities (LMI) framework in power system for enhance damping inter-area oscillation of power system [37]. In [38], a linear optimal controller has been addressed for the designed to implement multiple variable series compensators (VSCs) in transmission network of interconnected power system is utilized to damp inter-area oscillations and enhance power system damping during large disturbances. In [39], a new electricity trading arrangement has been addressed for the coordination of power flow control in a large power system, managing transmission constraints to meet the security standards against the back ground of this open market structure. An automatic control and coordination of power flow could be formulated as a multi-variable system design problem. The coordinated power flow control should address the following points such as elimination of interaction between FACTS controllers, ensuring system stability of the control process, security transmission system for both pre and post fault, and achieving optimal and economic power flow.

In [40], a new real and reactive power coordination method has been proposed for UPFC to improve the performance of the UPFC control. In [41], a new methodology has been proposed for transmission network voltage regulation through coordinated automatic control of reactive power. A new method has been suggested for the potential application of coordinated secondary voltage control by multiple FACTS voltage controllers in eliminating voltage violations in power system contingencies in order to achieve more efficient voltage regulation in a power system. The coordinated secondary voltage control is assigned to the SVCs and Static Compensators (STATCOM) in order to eliminate voltage violations in power system contingencies [42]. Fan et al. addressed a new coordinated control strategy for optimal coordinated Power Electronic Transformers (PET) and generator excitation control for power system to improve the system stability by a generator-PET unit [43]. In [44], a new multi-variable dynamic model and a control approach has been addressed for a Voltage Source Converter (VSC) based on adapting instantaneous real and reactive power components as the VSC dynamic variable. Use of this power component as the dynamic variables reduces the degree of non-linearities of the VSC model in comparison with the conventional VSC model that uses dq current components as variables. Furthermore, since wave forms of power components are independent of the selected qd coordinates, the proposed control is more robust to the conventionally un-modeled dynamics such as dynamic of the VSC phase locked loop system. A new methodology has been proposed for decentralized optimal power flow control for overlapping area in power systems for the enhancement of the system security [45]. Iravani et al. have been presented a theoretical back ground and the methodology of development of a software tool for off-line coordination of power system controllers in either a high frequency range (5-55Hz) or a low frequency range (0.1-2Hz) [46]. The controllers considered for coordination are voltage regulators, PSS, speed governors, main and auxiliary controllers of HVDC converters, and main and auxiliary controllers of SVC. A new methodology has been proposed for designing a coordinated controller for a synchronous generator excitation and SVC in power system is to extend the operational margin of stability, whilst satisfying control requirements by introducing an integrated multi-variable controller to control both the generator exciter and the firing angle of the thyristor controlled reactor of TCR-FC compensators [47]. In [76], an eigen-value analysis technique is used for coordinated control of PSS and FACTS controllers to enhance damping of power system oscillations in multi-machine power system. A sensitivity based analysis approach is used to find out an inter-coupling between a variation of set points of different FACTS devices and a volume of load shedding with a variation of active power flow in transmission lines [77]. In [82], robust frequency stabilization is used for coordinated control of Superconducting Magnetic Energy

Storage (SMES) and Static Synchronous Series Compensator (SSSC) to enhance the robustness of frequency stabilizers against uncertainties. In [86], an H-infinity optimization technique has been used for simultaneous tuning of TCSC controllers in power system for a wide range of operating conditions. Zhao and Jiang et al. suggested a H-infinity optimization technique for simultaneous tuning of SVC controllers design to improve the damping power system [87]. Chaudhuri and Pal et al. suggested a H-infinity damping control design optimization technique based on the mixed sensitivity formulation in a linear matrix inequality (LMI) framework for robust damping control design for multiple swing modes damping in a typical power system model using global stabilizing signals [88]. A systematic procedure for the synthesis of a Supplementary Damping Controller (SDC) for Static Var Compensator (SVC) for a wide range of operating conditions is used for testing in multi-machine power systems to enhance the damping of the inter-area oscillations, providing robust stability and good performance characteristics both in frequency domain and time domain [89]. Yue and Shlueter et al. presented a multiple bifurcation phenomena for three kinds of μ -synthesis robust controls are designed such as μ -synthesis power system stabilizer (MPSS), μ -synthesis SVC control (MSVC), and a mixed MPSS/MSVC control [90]. In [91], a bifurcation subsystem based methodology has been proposed for μ -synthesis power system stabilizers design in a two-area power system. A several control design techniques [92] such as the classical phase compensation approach, the μ -synthesis, and a linear matrix inequality technique has been used for coordinate two PSS to stabilize a 5-machine equivalent of the South/ Southeast Brazilian power system. In [93], a Prony methods based on Prony signal analysis and incorporates both local and inter-area electro-mechanical oscillatory modes along with root locus and sequential decentralized control techniques has been used for PSSs design in multi-machine power systems. A design method that explicitly considers both the coordination and the robustness issues has been proposed for coordinated design of power system stabilizers and supplementary control of FACTS devices to enhance the robustness of the control scheme for drastic changes in the operating condition [94]. This method is based on the formulation and solution of an augmented Riccati equation. In [95], a projective control principle based on eigen-value analysis has been presented for coordinated control design of supplementary damping controller of HVDC and SVC in power system to enhance the damping of power system oscillations.

B. Optimization Based Techniques

This section reviews the coordination of FACTS controllers based on various optimization techniques such as a linear and quadratic programming, non-linear optimization programming, integer and mixed integer optimization programming, and dynamic optimization programming.

1. Non-linear Optimization Programming Techniques

In [48], a new method based on the optimization method is called non-linear optimization programming technique has been addressed for tuning the parameters of the PSS for enhancing small-signal stability. A non-linear optimization programming techniques has been addressed for simultaneous coordinated tuning of PSS and FACTS controllers for damping power system oscillations in multi-machine power systems [49]. Lei et al. suggested a sequential quadratic programming algorithm for optimization and coordination of FACTS device stabilizers (FDS) and power system stabilizers (PSS) in a multi-machine power system to improve system dynamic performance [50]. A non-linear programming based algorithm has been proposed for the design of power system damping controllers for damp electro-mechanical oscillations in power systems [51]. A non-linear programming based algorithm has been proposed for the design of simultaneous coordinated tuning of PSS and FACTS controllers for damping power system oscillations in multi-machine power systems [52]. Simoes et al. presented a non-linear optimization technique is used to coordinated control of Power Oscillation Damping (POD) controllers implemented in the two TCSC of the Brazilian North-South (NS) inter-connection, in the year 1999, were solely intended to damp the low-frequency NS oscillation mode [79].

2. Linear Optimization Programming Techniques

In [53], a systematic optimization method has been addressed for the design of a linear optimal power system stabilizer, under the conditions of pre-specified closed loop dominant eigen-value locations and feedback gain limit constraints. A linear programming algorithm has been used for simultaneous coordination of PSS and FACTS device stabilizers in a multi-machine power system for enhancing dynamic performance of the rotor modes of oscillations [54]. Feng et al. suggested a comprehensive approach for determination of preventive and corrective control strategies to contain voltage collapse in stressed power systems [55]. An immune-based algorithm has been addressed for optimal coordination of local physically based controllers in order to presence or retain mid and long term voltage stability [56]. A design approach such as non-linear constrained optimization has been proposed for robust design and coordination of multiple damping controllers in multi-machine power system [57]. In [58], a new technique has been suggested for coordinated local and centralized control in distribution management systems. Glanzmann and Anderson et al. suggested a supervisory controller based on optimal power flow (OPF) with multiple objective for derived in order to avoid congestion provide secure transmission and minimize active power losses. The contribution of SVC, TCSC and TCPST in coordinated control and achieved improvements is presented [59]. In [60]-[61], a new methodology has been proposed for the coordinated design of robust decentralized power system damping controllers to provide controllers capable of fulfilling various practical requirements of the oscillations damping problem, which could not be simultaneously satisfied by the majority of the robust approaches. In [62], a new methodology has been proposed for coordinated control of FACTS devices in power system for security enhancement. In [78], an optimization technique is used to tuning of power system stabilizers in power systems. Nguyen, and Gianto et al. [97]-[98] has been proposed a optimization based technique for control coordination of PSSs and FACTS controllers for Optimal oscillations damping in multi-machine power system. Najafi and Kazemi et al. [100] suggested an optimization based technique for coordination of PSSs and FACTS damping controllers in large power systems for dynamic stability improvement. In [101], an approach has been presented for coordinated wide area control of FACTS controllers for congestion management. In [104], an optimization based approach has been suggested for power system optimization and coordination of FACTS controllers to significant transient stability improvement and effective power oscillation damping.

C. Artificial Intelligence (AI) Based Techniques

This section reviews the coordinated control of FACTS controllers based on various Artificial Intelligence based techniques such as genetic algorithm (GA), expert system (ES), artificial neural network (ANN), tabu search optimization, ant colony optimization algorithm, simulated annealing approach, particle swarm optimization algorithm, and fuzzy logic based approach.

1. Genetic Algorithm(GA)

GA is a global search technique based on mechanics of natural selection and genetics. It is a general purpose optimization algorithm that is distinguished from conventional optimization techniques by the use of concepts of population genetics to guide the optimization search. Instead of point to point search, GA searches from population to population. The advantages of GA over traditional techniques is that it needs only rough information of the objective function and places no restriction such as differentiability and convexity on the objective function, the method works with a set of solutions from one generation to next, and not a single solution, thus making it less likely to converge on local minima, and the solutions developed are randomly based on the probability rate of the genetic operators such as mutation and crossover; the initial solutions thus would not dictate the search direction of GA.A major disadvantage of GA method is that it requires tremendously high time.

In [63], a genetic algorithm based on the method of inequalities has been addressed for the coordinated synthesis PSS parameters in a multi-machine power system in order to enhance overall system small signal stability. In [64], GA is applied for the simultaneously tuning multiple power system damping controllers in power system over a pre-specified set of operating conditions. Congestion in the transmission lines is one of the technical problems that appear particularly in the deregulated environment. These are two types of congestion management methodologies to relieve it. One is non-cost free methods and another is cost free methods, among these, later method relives the congestion technically whereas the former is related with the economics. Reddy et al. presented the congestion management is relieved using cost free methods for using FACTS devices, congestion can be reduced without disturbing the economic matters [65]. TCSC and UPFC are two mainly emerging FACTS devices and they are used to reduce the congestion. In congestion management, the objective function is non-linear hence in solving this function Genetic Algorithm (GA) technique is used to obtain the global optimal solution. A systematic procedure has been addressed for modeling and simulation of a power system installed with Power System Stabilizers (PSS) and FACTS based controllers to avoid adverse interaction, PSS and FACTS based controller are simultaneously designed employing genetic algorithms (GA) [66]. In [80], a robust controller design technique based on genetic algorithm is used to simultaneously tune PSS for multiple operating conditions. In [81], a genetic algorithm is used for the simultaneous stabilization of multi-machine power systems over a wide range of operating conditions via single setting power system stabilizers. Sebaa and Boudour et al. [103] has been suggested a genetic algorithm for coordinated design of PSSs and SVC-based controllers in power system to enhance power system dynamic stability.

2. Tabu Search Algorithms

Tabu search (TS) algorithm was originally proposed as an optimization tool by Glover in 1977 [3]. It is a conceptually simple and an elegant iterative technique for finding good solutions to optimization problems. In general terms, TS is characterized by its ability to escape local optima by using a short term memory of recent solutions called the tabu list. Moreover, tabu search permits back tracking to previous solutions by using the aspiration criterion [3]. Reference [67], a tabu search algorithm has been addressed for robust tuning of power system stabilizers in multi-machine power systems, operating at different loading conditions.

3. Simulated Annealing Algorithms

In the last few years, Simulated Annealing (SA) algorithm appeared as a promising heuristic algorithm for handling the combinatorial optimization problems. It has been theoretically proved that the SA algorithm converges to the optimum solution. The SA algorithm is robust i.e. the final solution quality does not strongly depend on the choice of the initial solution. Therefore, the algorithm can be used to improve the solution of other methods. Another strong feature of SA algorithm is that a complicated mathematical model is not needed and the constraints can be easily incorporated unlike the gradient descent technique, SA is a derivative free optimization algorithm and no sensitivity analysis is required to evaluate the objective function. This feature simplifies the constraints imposed on the objective function considered [3].

In [68], a simulated annealing based algorithm has been addressed for PSS and FACTS based stabilizers tuning in power systems. The design problem of PSS and FACTS based stabilizes is formulated as an optimization problem. An eigen value based objective function is used to increase the system damping. Then SA algorithm is employed to search for optimal stabilizer parameters. Different control schemes have been proposed in and tested on a weakly connected power system with different disturbances loading conditions and parameter variations.

4. Particle Swarm Optimization (PSO) Algorithms

Recently, Particle Swarm Optimization (PSO) algorithm appeared as a promising algorithm for handling the optimization problems [3]. PSO shares many similarities with GA optimization technique, like initialization of population of random solutions and search for the optimal by updating generations. However, unlike GA, PSO has no evolution operators such as crossover and mutation. One of the most promising advantages of PSO over GA is its algorithmic simplicity as it uses a few parameters and easy to implement. In PSO, the potential solutions, called particle, fly through the problem space by following the current optimum particles.

References [69], [85], a PSO algorithm has been suggested for coordinated design of a TCSC controller and PSS in power systems for enhancing the power system stability. The design problem of PSS and TCSC based controllers is formulated as a time domain based optimization problem. PSO algorithm is employed to search for optimal controller parameters, by minimizing the time domain based objective function, in which the deviation in the oscillatory rotor speed of the generator is involved. Controllers are designed independently first and then in a coordinated manner for individual and coordinated application. The proposed controllers are tested on a weakly connected power system. Panda and Aril et al. [99] suggested a PSO technique for robust coordinated design of PSSs in multi-machine power system to enhance the stability performance of the power system.

5. Artificial Neural Network (ANN) Optimization Algorithms

The starting point of ANN was the training algorithm proposed by Hebb in 1949, which demonstrated how a network of neurons could exhibit learning behaviour. ANN are mainly categorized by their architecture (number of layers), topology (connectivity pattern, feed forward etc.) and learning regime. Most of the applications of an ANN in the power systems use multi-layer feed forward network. The main advantages of ANN are it is fast possesses learning ability, adapts to the data, robust and appropriate for non-linear modeling. These advantages suggest the use of ANN for voltage security monitoring and control through the neural network training is generally computationally expensive, it takes negligible time to evaluate voltage stability once the network has been trained. Despite the advantages, some disadvantages of the ANN are large dimensionality selection of the optimum configuration, the choice of training methodology, the black-box representation of ANN they lack explanation capabilities and so decisions are not audible, and the fact that results are always generated even if the input data are unreasonable.

Etingov et al. suggested an emergency control system based on the ANN technique for finding a coordinated control system action (load shedding, generation tripping) to prevent the violation of power system stability. [70]. Nguyen, and Gianto et al. [96] has been proposed a neural networks approach for online control coordination which leads to adaptive power system stabilizers (PSSs) and/or supplementary damping controllers of Flexible AC Transmission System (FACTSs) devices for enhancing the stability of the electro-mechanical modes in a multi-machine power system.

6. Fuzzy logic (FL) Algorithms

Fuzzy logic was developed by Zadeh in 1964 to address uncertainty and imprecision which widely exist in the engineering problems and it was first introduced in 1979 for solving power system problems. Fuzzy set theory can be considered as a generation of the classical set theory. In classical set theory an element of the universe either belongs to or does not belong to the set. Thus the degree of associations of an element is crisp. In a fuzzy set theory the association of an element can be continuously varying. Mathematically, a fuzzy set is a mapping (known as membership function) from the universe of discourse to the closed interval [0, 1]. The membership function is usually designed by taking into consideration the requirement and constraints of the problem. Fuzzy logic implements human experiences and preferences via membership functions and fuzzy rules. Due to the use of fuzzy variables, the system can be made understandable to a non-expert operator. In this way, fuzzy logic can be used as a general methodology to incorporate knowledge, heuristics or theory into controllers and decision makers. The advantages of fuzzy set theory are more accurately represents the operational constraints of power systems, and fuzzified constraints are softer than traditional constraints.

In [71], a fuzzy set theory based algorithms has been suggested for coordinate stabilizers so as to increase the operational dynamic stability margin of power system for TCSC and UPFC in power system environments. A new fuzzy algorithm has been addressed for enhancing the performance of output feedback controllers [72]. This fuzzy system has a simple structure and acts as a non-linear function so that the gain of the controller is not constant but changes according to the error value. A hybrid fuzzy logic algorithm has been proposed for the coordination of FACTS controllers in power system. The coordination method is well suitable to series connected FACTS devices like TCSC, SSSC in damping multi-modal oscillations in multi-machine power systems [73]. In [74], a fuzzy logic based algorithms has been proposed for power system governing multiple FACTS devices using fuzzy reasoning in order to meet the requirements for power flow. A fuzzy logic coordination algorithm has been proposed to deals with the control of the series FACTS devices for the coordination between their transient stability controller and Power Oscillation Damping (POD) controller in multi-machine power system environments [75]. A fuzzy logic based method is used for decentralized coordination of FACTS devices for power system stability enhancement in [83]. A fuzzy logic based method has been used for coordinated control of TCSC and UPFC in power systems to increase the operational dynamic stability margin of power system [84]. In [102], a relative gain array (RGA) theory has been proposed for interaction analysis and coordination control between SSSC and SVC. Reference [105], a load flow control technique has been proposed for coordinated control of FACTS controllers in power system for enhancing steady dynamic performance of power systems during normal and abnormal operation conditions. Qing and Zengzing et al. [106] has been suggested a fuzzy immune co-evolutionary algorithm for coordinated control of SSSC and static compensator (STATCOM) in power system.

IV. SUMMARY OF THE PAPER

The following tables give summary of the paper as:

A. Methods/Techniques for Coordination of FACTS controllers

1. Methods/Techniques point of view

Methods/Techniques	Total No. of Literatures Reviews out of 101 Literatures	% of Literatures Reviews out of 101 Literatures
Sensitivity based methods	56	55.45
Optimization based methods	22	21.78
AI-based techniques	23	22.77

2. Operating Parameters point of view

Operating Parameters of Power systems	Total No. of Literatures Reviews out of 101 Literatures	% of Literatures Reviews out of 101 Literatures
Damping of power system oscillations	34	33.66
Voltage Profile	05	4.95
Security of the power system	04	3.96
Small signal stability, transient stability	13	12.87
Power transfer capability through the lines	02	1.98
Dynamic performances of power systems	09	8.91
The loadability of the power system network	02	1.98
Others parameters point of view	32	31.68

From above tables it is concluded that the 55.45% of total literatures are reviews based on sensitivity methods, 21.78% of total literatures are reviews based on optimization programming, and the 22.77% of total literatures are reviews on AI based techniques regarding with coordination of FACTS controllers in multi-machine power systems. It is also concludes that the 33.66% of total literatures are reviews carryout from damping of power system oscillations, 4.95% of total literatures are reviews carryout from voltage stability, 3.96% of total literatures are reviews carryout from security of power system, 12.87% of total literatures are reviews carryout from small signal/transient/dynamic stability, 1.98% of total literatures are reviews carryout from power transfer capability through the lines, 8.91% of total literatures are reviews carryout from dynamic performance of power system, 1.98% of total literatures are reviews carryout from the loadability of power system, and 31.68% of total literatures are reviews carryout from other parameters viewpoints.

Finally it is concluded that the maximum research work carryout from damping of power system oscillations and voltage stability point of view regarding with coordination of FACTS controllers in multi-machine power systems.

V.CONCLUSIONS

In this paper an attempt has been made to reviews, various AI based optimization methods used for coordination of FACTS controllers. Even through, excellent advancements have been made in classical methods i. e. sensitivity based method, they suffer with the following disadvantages: In most cases, mathematical formulations have to be simplified to get the solutions because of the extremely limited capability to solve real-word large-scale power system problems. They are weak in handling qualitative constraints. They have poor convergence, may get stuck at local optimum, they can find only a single optimized solution in a single simulation run, they become too slow if number of variables are large and they are computationally expensive for solution of a large power system.

Whereas, the major advantage of the AI based optimization methods is that they are relatively versatile for handling various qualitative constraints. AI methods can find multiple optimal solutions in single simulation run. So they are quite suitable in solving multi-objective optimization problems for coordination of FACTS controllers in multi-machine power system. In most cases, they can find the global optimum solution. The main advantages of ANN are: possesses learning ability, fast, appropriate for non-linear modeling, etc. whereas, large dimensionality and the choice of training methodology are some disadvantages of ANN. The advantages of Fuzzy method are: Accurately represents the operational constraints and fuzzified constraints are softer than traditional constraints. The advantages of GA methods are: It only uses the values of the objective function and less likely to get trapped at a local optimum. Higher computational time is its disadvantage. The advantages of EP are adaptability to change, ability to generate good enough solutions and rapid convergence. ACO and PSO are the latest entry in the field of optimization. The main advantages of ACO are positive feedback for recovery of good solutions, distributed computation, which avoids premature convergence. It has been mainly used in finding the shortest route in transmission network, short-term generation scheduling and optimal unit commitment. PSO can be used to solve complex optimization problems, which are non-linear, non-differentiable and multi-model. The main merits of PSO are its fast convergence speed and it can be realized simply for less parameters need adjusting. PSO has been mainly used to solve Bi-objective generation scheduling, optimal reactive power dispatch and to minimize total cost of power generation. The applications of ACO and PSO for coordination of FACTS controllers in multi-machine power system.

This paper has also addressed a survey of several technical literature concerned with various techniques/methods for coordination of multiple FACTS controllers in multi-machine power system environments to show that the achieve significant improvements in operating parameters of the power systems such as small signal stability, transient stability, damping of power system oscillations, security of the power system, less active power loss, voltage profile, congestion management, quality of the power system, efficiency of power system operations, power transfer capability through the lines, dynamic performances of power systems, and the loadability of the power system network also increased. This review also shows that installing multiple controllers on the system may not improve the dynamic performance due to undesirable interactions. The tuning of one controller may affect other controllers and thus lead to unstable conditions. These issues should be taken into consideration when designing systems with multiple controllers. The implementation of a coordinated controller tuning procedure to avoid undesirable interactions in power systems, and thus improve overall dynamic performance is under this review.

Authors strongly believe that this survey article will be very much useful to the researchers for finding out the relevant references as well as the previous work done in the field of coordination of FACTS Controllers for the various methods/techniques for coordination of FACTS controllers in multi-machine power systems. So that further research work can be carried out.

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