

# **A Comprehensive Survey for Optimal Location and Coordinated Control Techniques for FACTS Controllers in Power System Environments and Applications**

Mr.P.S.Chindhi<sup>1</sup>, Prof .H.T.Jadhav<sup>2</sup>, Mr.V.S.Patil<sup>3</sup>

<sup>1</sup>(Electrical Engineering Dept., R.I.T.Rajaramnagr, Islampur Maharashtra, India)

<sup>2</sup>(Electrical Engineering Dept., R.I.T.Rajaramnagr, Islampur Maharashtra, India)

<sup>3</sup>(Electrical Engineering Dept., N.M.P.I. Peth, Islampur Maharashtra, India)

**ABSTRACT** : In this paper in-depth literature review on different techniques used for FACTS controller coordination in restructure multi-machine power system. It also reviews various techniques used allocation of FACTS controller in existing restructure power system it also gives idea regarding various applications of FACTS controllers in deregulated multi-machine power system. In this paper, author also listed practical installation of various FACTS controllers worldwide.

**Keywords** - FACTS devices, optimization techniques, power system stability, multi-machine system, Coordination Control.

## **I.INTRODUCTION**

Day by day the demand on power system increasing substantially due to increase in population and change in leaving standard of the people and also substantial growth in industry, while the modification and expansion of existing power system, that is generation, transmission and distribution network has been several restrictions, due to environmental restrictions and limited resources. Due to limited resources and environmental restrictions, existing transmission lines are getting highly loaded, and system stability becomes a power transfer-limiting factor. So for better utilization of available or present power system, flexible AC transmission systems (FACTS) controllers have been implemented. With the help of multiple FACTS controllers, we can easily control various parameters of transmission line such as line impedance, terminal voltage, and voltage angles.

Some of important possible benefits for FACTS controllers in restructure multi-machine power system Environments are listed below [1].

- The flow of power within the existing power system can be maintained as per the contract or as per the demand of the utilities.
- Secure loading of transmission lines nearer to their thermal limits.
- Increased dynamic and transient grid stability.
- Allows more active power in present lines by reducing reactive power flow in the line.
- Access to lower production cost.
- Environmental benefits.
- FACTS gadgets furnishes secure tie line connection with neighboring utilities by diminishing generally speaking crop save prerequisites on either sides.
- Operation speed of whole power system get improved with help of FACTS devices.

Interconnection of renewable and distributed generation and storages.

In existing power system the interaction of various FACTS controllers, as well as between power system stabilizer (PSS) or HVDC controller and different FACTS controllers in a multi-machine power system environment. The interaction of different FACTS controller and power system have been classified into different frequency ranges and various interaction problems between FACTS controller or FACTS controller to PSSs from voltage stability /small signal stability viewpoint are expressed in [2], [3].

In the past several decades, power system stabilizers (PSSs) have been regularly used to increase the system damping for low frequency oscillations. The power utilities worldwide are presently using PSSs as effective excitation controllers to improve the system stability [4], [5]. However, there have been problems experienced with PSSs over the years of operation. Some of these were due to restricted capability of PSS, in damping only local and not interarea modes of oscillations. In addition, PSSs will cause great variations in the

voltage profile under severe disturbances and they may even result in leading power factor operation and losing systems stability [6]. In reference [7] wide-area robust coordination approach of HVDC and FACTS controllers for damping multiple interarea oscillations stabilizing in large-scale power systems is presented.

There are several different methods proposed in literatures [8], [9], [10], [11], [12], [13], [14], and [15] for optimal location of FACTS controllers in both deregulated and privatization power systems by considering there different operating conditions viewpoint. References [16] [17], classifies three main techniques for the placement of FACTS controllers from different operating conditions viewpoint in multi-machine power systems, such as a sensitivity based methods, optimization based method, and artificial intelligence based method.

The various sensitivity based methods have been proposed in literatures includes jacobian based sensitivity method [18], eigen-value analysis based methods [19], [20], modal analysis techniques [21], [22], index methods [23], residue-based methods [24], [25], [26] some of other methods are pole placement techniques, frequency response techniques, root locus techniques, projective control method, non-linear feed control method, Lambda iteration method, Eigen-Sensitivity Theory of Augmented Matrix.

The various optimization based methods have been proposed in literatures that include curved space optimization techniques [27], dynamic optimization programming algorithms [28], bellman's optimization principle [29], mixed integer-optimization programming techniques [30], [31], decomposition coordination methods [32], hybrid optimization programming algorithms [33], and non-linear optimization programming techniques [34], some of other methods are linear optimization programming techniques, immune based optimization algorithms, Mixed-Integer Linear Programming (MILP).

The various artificial intelligence (AI) based methods proposed in literature includes genetic algorithms (GA) [12], [35], [36], [37], [38], [39], micro- genetic algorithms (MGA) [40], tabu search algorithms [41], [42], [43], simulated annealing (SA) based approach [44], [45], graph search algorithms [46], particle swarm optimization (PSO) techniques [47], [48], ant colony optimization (ACO) algorithms [49], [50], fuzzy logic based approach [51],[52], artificial neural network (ANN) based algorithms [53], [54], Bacterial Swarming Algorithm (BSA) [55] some of other techniques/methods are improved evolutionary programming, non - dominated sorting genetic algorithm II (NSGA-II), Adaptive Hopfield Neural Network, augmented Lagrange multiplier approach, norm forms of diffeomorphism techniques, gravitational optimization techniques, benders decomposition techniques, evolution strategies algorithms, heuristic and algorithmic approach, hybrid meta-heuristic approach, energy approach, adaptive neuro-fuzzy inference system (ANIS) techniques, H-infinity optimization techniques,  $\mu$  -synthesis techniques, linear matrix inequality technique, prony methods, riccati equations methods, relative gain array (RGA) theory, Adaptive Neuro-Fuzzy Inference Systems (ANFIS).

## II. COORDINATION OF FACTS CONTROLLERS IN MULTI-MACHINE POWER SYSTEMS

The main function of FACTS controller coordination is to provide additional degree of freedom to control power flows and voltages in existing power system at key location of network. There are numbers of approaches proposed in literatures for coordination of multiple FACTS controllers in multi-machine power systems from different operating conditions viewpoint [56], [57], [58], [59], [60], [61], Three broad categories such as a sensitivity based methods, optimization based method and artificial intelligence based techniques for coordination of FACTS controllers from diverse managing conditions in multi-machine power systems is classified in [16], [17]. In 1995 Chen and Pahalawath, pole placement technique is used for state control for TCSC.

In power system there are mainly four types of FACTS controllers, which are presented in [1]. □

Series Controllers

- Shunt Controllers
- Combined series-series Controllers
- Combined series-shunt Controllers

Other FACTS controllers such as thyristor-controlled voltage limiter (TCVL), thyristor-controlled voltage regulator (TCVR), sen transformer and hybrid flow controller (HFC) are also used. In reference [62] the installation of one FACTS devices in the power system does not improve voltage stability and reduction in power system losses so multi-type FACTS devices are used to enhance both voltage stability margin and reduce losses in the system. For the better utilization of existing power system the proper coordination of one FACTS devices or multi-FACTS controller is necessary. The various types of interactions of FACTS controllers are presented in [63] includes,

- Multiple FACTS controllers of a similar kind.
- Multiple FACTS controllers of a dissimilar kind.
- Multiple FACTS controllers and HVDC converter controllers.

The various interactions that take place between the different types of 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 [64], [3].

- 0 Hz for steady-state interactions
- 0-3/5 Hz for electromechanical oscillations
- 2-15 Hz for small-signal or control oscillations
- 10-50/60 Hz for sub synchronous resonance (SSR).
- 5. >15 Hz for electromagnetic transients, high-frequency resonance or harmonic resonance interactions, and network-resonance interactions.

This paper is organized as follows: In Section II the detail discusses on various types/methods which are used for the interactions between FACTS controllers in restructure multi-machine power systems. In Section III presents the review on various techniques/methods used for placements of FACTS controllers in multi-machine power systems. In Section IV presents various applications of FACTS controller in restructure multi-machine power system and practical installations of various FACTS devices. Section V presents the conclusions of the paper.

### **III. FACTS CONTROLLERS ALLOCATION TECHNIQUES/METHODS**

There are mainly three broad techniques for the allocation of FACTS controllers in multi-machine power system at suitable location are,

- Sensitivity Based Method (SBM)
- Optimization Based Method and (OBM)
- Artificial Intelligence Techniques(AIT)

In this paper review on optimal allocation of FACTS controller is carried out by considering intelligence based techniques such as Genetic Algorithm (GA), Tabu Search optimization (TSO), Artificial Neural Network (ANN), Ant Colony optimization (ACO) algorithm, Expert Search (ES), Particle Swarm Optimization (PSO), Simulated Annealing (SA) approach, Fuzzy Logic (FL) based approach, Bees Algorithm.

Genetic algorithm was invented by David Goldberg in 1975, Holland. At initial stage GA where mainly used for aircraft landing structure weight optimization, mass spring dashpot design, VLSI circuit layout, traveling salesman problem optimization, image processing etc. Then GA where implemented in electrical field to study load flow problems and to find out voltage stability, load forecasting, GA where also used to solve economic load dispatch problems, generator scheduling. Then later GA has been addressed for optimal location of FACTS devices in existing power system.

In reference [35] optimal location of given phase shifter in the French network is carried out in order to reduce the flow in the heavily loaded lines and to reduce cost of production. In [12], a genetic algorithm (GA) based method has been proposed for determine the optimal placement of FACTS controllers in power system with the consideration of bid offers of the market participants (suppliers and consumers) and the investment costs of FACTS devices. Gerbex et al. [64] used maximum 50 FACTS devices in the IEEE 118 bus network, but he does not considered computational time required and insatallion cost during the optimization. In reference [55] bacterial swarming algorithm (BSA) is used for optimal placement of FACTS devices to enhance the performance of power system and also to get optimal power flow (OPF) solution. Here mainly two factors are taken in to consideration that is maximization of system loadability by considering system security margin and minimization fuel cost, which is required for total generation. In this paper to improve the performance of the system, two objective functions are simultaneously considered.

Made Wartana and Ni Putu Agustini [67] later studied about optimal location of one type of FACTS controller that is UPFC by using Non-dominated Sorting Genetic Algorithm II (NSGA-II) for maximizing system loadability and minimizing active power losses considering system stability margins. In this paper for optimal location of one type of FACTS devices slandered IEEE 30-bus system and Java-Bali 24-bus of Indonesian is taken in to consideration.

In reference [68] multiobjective mathematical programming (MMP) method and  $\epsilon$ -constraint method is proposed to solve the multiobjective optimal location of FACTS controller using the general arithmetical modelling system (GAMS) , Here the principle constrains considered are total fuel cost, power losses, system loadability, and installation cost of FACTS devices.

#### **IV. FACTS APPLICATIONS**

The various applications of FACTS controllers/devices in restructured multi-machine power systems to enhance power system performance. One of the greatest advantages of utilizing FACTS controllers in power system is that, FACTS controller can be used in three states of the power system.

- Steady state,
- Transient and
- Post transient steady state.

However, the conventional devices find little application during system transient or contingency condition.

##### **A) Steady State Application**

Various steady state applications of FACTS controllers includes control of voltage (low and high), increase of thermal loading limit, post-contingency voltage control, loop flows control, reduction in short circuit level and power flow control.

- Power Flow Balancing and Control
- Available Transfer Capability (ATC) Improvement
- Loading Margin Improvement
- Congestion Management
- Reactive Power and Voltage Control

##### **B) Dynamic Application**

Various Dynamic applications of FACTS controllers include oscillation damping (dynamic stability), transient stability improvement and voltage stability enhancement. One of the most important capabilities expected of FACTS applications is to reduce the impact of the primary disturbance.

- Dynamic Voltage Control
- Oscillation Damping
- Transient Stability Enhancement
- Subsynchronous Resonance (SSR) Elimination
- Power Systems Interconnection

The complete practical list of various FACTS devices/controllers installed worldwide are expressed in [66], [64], [63], [1].

**TABLE I. INSTALLATION OF TCSC**

<b>Sr.No.</b>	<b>Country</b>	<b>In Service Year</b>	<b>System Voltage in (kV)</b>	<b>Purpose/Application</b>
01	USA	1992	230	To control the line parameters such as impedance, line current etc.
02	USA	1993	500	To control power flow and to increased loading capacity.
03	USA	1998	138	For dynamic voltage support and added real power supply facility.
04	Sweden	1998	400	Power oscillation mitigation and sub synchronous resonance mitigation.
05	Brazil	1999	500	For low frequency oscillation damping.
06	China	2002	500	Stability improvement, and for low-frequency oscillation mitigation.
07	South Korea	2003	154	Added real power supply facility and dynamic voltage support in south korea.
08	China	2004	220	Increase stability margin, suppress low frequency oscillation.
09	India	2004	400	Compensation, Damping interregional power oscillation.
10	India	2006	400	To improve transmission performance & the reliability of over head line

**TABLE II. INSTALLATION OF STATCOM**

<b>Sr.No.</b>	<b>Country</b>	<b>In Service Year</b>	<b>System Voltage in (kV)</b>	<b>Purpose/Application</b>
01	Japan	1991	154	Power system voltage stabilization.
02	Japan	1992	500	Reactive power compensation.
03	USA	1995	161	To regulate bus voltage.
04	USA	2001	115	Dynamic reactive compensation during critical contingencies.

05	UK	2001	400	Dynamic reactive power compensation.
06	USA	2003	138	dynamic var control during peak load conditions.

**TABLE III. INSTALLATION OF UPFC, FSC, SC AND TPSC**

<b>Sr.No.</b>	<b>Country</b>	<b>In Service Year</b>	<b>System Voltage in (kV)</b>	<b>Purpose/Application</b>
01	USA	1998	138	To control bus voltage, real power, reactive power in the system.
02	India	2009	400	To enhancement of transmission capacity of north grid.
03	Brazil	2008	500	To avoid transmission losses and to maintain voltage stability.
04	China	2006	500	To increase transfer capability of existing power lines.
05	USA	2006	500	To increase power transfer capacity for next few years.
06	USA	2006	145	To increase reliability and capacity of transmission line.
07	South Africa	2003	400	To upgrade the existing transmission line.
08	Brazil	2003	525	To maintain power flow in the system
09	Brazil	2004	500	To increase power transfer capacity in present system.
10	Brazil	1999	500	To interconnect north-south line.
11	South Africa	2003	400	To upgrade the existing transmission line.
12	Canada	1993	735	To increase the line loading closer to thermal limits.



13	California	2005	500	To increase the system security.
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UPFC- Unified Power Flow Controller, FSC- Fixed Series Capacitors, SC-Series Capacitor  
 TPSC- Thyristor-Protected Series Capacitors, TCSC -Thyristor Control Series Capacitor  
 STATCOM-Static Synchronous Compensator

## V. CONCLUSION

Many researchers tried to attempt review on various optimization based methods which are used for coordination control of FACTS devices and optimal placement of FACTS controllers in multi-machine power system to achieve significant improvement in operating parameters such reactive power, real power, voltage magnitudes and phase angles at all nodes of the network of the system but not mentioned the actual practical installation of various FACTS devices in power system in the world and its applications. So in this paper author tried to attempt various methods which are used for coordination control of FACTS devices and optimal allocation of FACTS devices in multi-machine power system along with actual practical installation of various FACTS devices worldwide and also another tried to attempt various applications of FACTS device in multi-machine power system such as steady state applications, dynamic application.

I believe that this paper will helpful to other researchers for finding out the relevant references as well as the previous research work done in the area of optimal placement and co-ordination of FACTS Controllers for the various methods/techniques for co-ordination and placement of FACTS controllers in restructure power system. So that further research work can be easily carried out.

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