CHAPTER-2

LITERATURE REVIEW
FACTS controllers have been widely investigated since its inception in 1972 when it was first established by Hingorani in 1988 with the advancement in power electronics devices. Over the years its application potential has been immense and it has been widely acknowledged as a boon to electrical utilities which has lead to numerous research papers and fact findings appear in the area of Flexible AC Transmission Systems. In an attempt to reap utmost benefit in current deregulated power system structure numerous control methodologies and optimisation techniques are applied in this domain in order to attain various degrees of system modelling. The literature available in the area of FACTS technology and its implementation is definitely extensive; however an unostentatious attempt has been made in this section to discuss the most significant work relevant to the research area proposed in this thesis.

The literature review is organized as follows:

- FACTS devices implementation in power transmission system.
- Modelling and control of FACTS devices for secured OPF.
- Modelling of FACTS controller for transient stability and voltage stability enhancement.

This section presents an overview of substantial research work based on various FACTS devices broadly in the domain of optimal power flow approach and power
system stability enhancement. The literature survey with respect to FACTS implementation in stability is confined to transient stability and voltage stability issues as these two vital stability problem are the research area of thesis work with TCSC implementation. Although the literature survey presents a broad overview of various FACTS devices it imminently projects TCSC as one of the most versatile and distinguished series FACTS controller having immense application potential. Further, all the vital attributes about FACTS devices is well documented in the literature [30, 31, 32, 34].

2.1 FACTS DEVICES IMPLEMENTATION IN POWER TRANSMISSION SYSTEM

In a deregulated power industry where demand for services becomes pre-eminent, it is imperative to explore the application potential of FACTS devices [47]. The installation of FACTS controller in power system is governed by three basic criteria [48]:

- Choice of FACTS devices.
- Location of FACTS device for maximum benefit
- Capacity of FACTS device

FACTS devices modelling and integration for power flow studies and its application in power flow control is provided in [49]. Implementation of multiple TCSC for relieving system overload under single contingency is provided in [50]. However the work proposed emphasizes on eradicating transmission line violation rather than reducing operating cost. Utilisation of expected cost for FACTS allocation in order to improve voltage stability has been applied in [51]. Power system stability as well as overall performance can be improved by utilizing FACTS devices [52].

FACTS device location is basically governed by static and dynamic performance of the system. Optimal location of series FACTS device based on an overload sensitivity factor is provide in [53] for static congestion management. Security violation and congestion on transmission line is a result of competitive electricity market and FACTS device provides a suitable solution by security constrained optimal power flow with appropriate location, size modelling and controller interactions. Among various FACTS devices, TCSC is considered most apt
to reduced transmission line congestion and optimum grid infrastructure utilisation. Determination of suitable FACTS location is done by loss sensitivity factor in [54].

FACTS devices provide a better alternative to effectively cater to issues related to efficient power system operation and control in a deregulated structure of electricity market [17]. The authors in [55] have presented control strategy and a common structure model for series connected FACTS devices. However, the benefits and performance of FACTS controllers are determined by their location and size with minimized number and maximized benefits through efficient optimisation methods owing to their high cost [56, 57]. The work depicts the operating principles and modelling of some relevant FACTS devices like UPFC and TCSC. The authors have stated the benefits of FACTS devices to improvise the system dynamic behaviour by regulating the transmission line parameters and variables such as voltage angle, line impedance in swift and effective manner [58, 59].

2.2 MODELLING AND CONTROL OF FACTS DEVICE FOR SECURED OPF

OPF studies are considered pivotal for Energy Management System which supervises the system performance in real time and estimates the finest settings of control variables. Devaraj et al. [60] presented a real coded genetic algorithm approach for improving secured OPF profile by adjustment of phase-shifting transformers and the algorithm performance was tested on IEEE 30 and 118 bus system. Yumbla et al. [61] demonstrated a new algorithm of PSO with Reconstruction Operators for secured OPF solution. The pre and post contingency points are found and performance index based contingency ranking system is used. Somasundaram et al. [62] proposed an EP based secured OPF and suggest that the algorithm performs better as it is independent of the nature of search space. Zwe-Lee Gaing et al. [63] presented a Real coded Mixed Integer Genetic Algorithm based secured OPF approach which not only accounts for the generation cost but also transmission security, transmission loss and voltage profile of the bus. Canizares et al. [64] demonstrated two OPF methods on IEEE 118 bus system where both the techniques were multi objective optimisation problem which aimed at reducing transmission loss and generation cost along with improving voltage stability. Worawat Nakawiro et al. [65] provided a GA-ANN based approach to minimize the system loss with reactive power dispatch by offline training
of ANN which would substitute the OPF online. The method was tested on IEEE 30 bus system and was found to be faster compared to conventional techniques.

Banu et al. [66] developed secured OPF solution with inclusion of FACTS device. A new approach of enhanced Genetic Algorithm was used for installation of TCSC during the event of contingencies by selecting the most overloaded lines. Prasanna et al. [67] presented an innovative combined algorithm for multi area secured OPF using Fuzzy logic in EP and Tabu search and naming the hybrid technique as Fuzzy Muted Evolutionary Programming and Fuzzy guided Tabu Search. The effectiveness of the proposed algorithm was tested on IEEE 30 bus system and fuzzy was used to enhance the adaptability of the algorithm.

Nagalakshmi et al. [68] have proposed an algorithm for the optimal location and control of Flexible AC Transmission System (FACTS) devices for enhancing the loadability in transmission system using particle swarm optimisation (PSO) and differential evolution (DE) for pool and hybrid model in deregulated electricity market. This approach uses AC load flow equations with the constraints on power generation, transmission line flow, magnitude of bus voltages and FACTS device settings and TCSC was the chosen FACTS controller investigated on two test system for maximum loadability, computation time and convergence characteristics. Shanmukha Sundar et al. [69] have focused on the secured optimal power flow solution and enhancement of system performance without sacrificing the security of the system via optimal location and optimal sizing of TCSC under normal and network contingency conditions. Two different placement methods have been introduced under normal and network contingency conditions and were demonstrated with examples for secured OPF with optimal placement and optimal sizing of TCSC controller. This was based on static considerations.

Duong et al. [70] have discussed the importance of enhancement of secured optimal power flow under normal and contingencies operating condition using FACTS devices in deregulated power systems. TCSC by controlling the power flows in the network could help to reduce the flows in heavily loaded lines, remove overload, enhanced system performance. Suitable location of TCSC could be very effective to system performance. Therefore, it was important to obtain optimal location for placement of these devices. They applied the minimum cut methodology
for proper location of TCSC which suffered from the limitation of reduced number of branches for investigation thereby limiting the search scope.

Amjadi et al. [71] have proposed a solution method for solving security constraints based optimal power flow (OPF-SC) problem, which provides improvisation to bacterial foraging (BF) technique. The OPF-SC works on complex discontinuous solution space and is a nonlinear optimisation problem. BF is an advanced stochastic search method offering good resolution, improved exploitation and better local search abilities. The proposed improved version of BF (IBF) retains the benefits of BF, and enhances it further to include various domain of the solution space avoiding being trapped in local minima. The solution strategy developed solves the OPF-SC problem effectively which is candidly illustrated with test systems.

Nireekshana et al. [72] has shown that in power systems deregulation operation finding and enhancing of Available Transfer Capability (ATC) are vital issues. This paper emphasizes the implementation of FACTs devices, like TCSC and SVC to cause maximize power transfer during steady state and contingency situations. Continuation Power Flow technique is recommended for computation of ATC taking into account both voltage profile and thermal limits. The optimisation tool used is Real-code Genetic Algorithm to obtain the location and regulating parameters of TCSC and SVC. The testing is done on IEEE 14-bus and IEEE 24-bus system using the given method to check system reliability for normal and different contingency cases.

Ali et al. [73] have proposed Bacteria Foraging Optimisation Algorithm based Thyristor Controlled Series Capacitor in order to reduce and suppress oscillations in a multimachine power system. An eigen value based objective function was proposed to verify wide range of loading conditions of TCSC and was formulated as an optimisation problem. The proposed technique was compared with GA while being used to search for optimal controller parameters and results clearly depicted its superiority in tuning TCSC controller.

Tiwari et al. [74] have proposed a reliable approach for optimisation based on investment cost recovery for precise allocation of TCSC in double auction power market. The intent is to maximize the social welfare by minimizing the device cost which is primarily possible by suitable location and rating of single TCSC in the
system. The comparison was done on some existing method based on optimal generation as well as load patterns to check its impact on social welfare on 5-bus system, modified IEEE 14-bus system and 246-bus Indian practical Northern Regional Power Grid system.

To alleviate small signal oscillations in a multi machine power system, Mondal et al. [75] have explored PSO for choosing the optimal location and setting parameters of SVC and TCSC controllers. An effort has also been prepared to compare the presentation of the TCSC controller with SVC in mitigating the small signal stability problem. Simulations were performed in a multi machine system for two common contingencies, e.g., load increase and transmission line outage to demonstrate the validity of their suggested techniques. Using eigen value and time domain response, the effects of small signal stability study have been symbolized. It has been viewed that the TCSC controller is more efficient than SVC even during higher loading in mitigating the small signal stability problem.

Chang [76] had suggested the multi-objective optimal TCSC installation approach suggested that uses the performance index sensitivity factor technique to explore which lines were most required for TCSC installation and with the lines précised for TCSC installation and the multi-objective function containing of maximum system load ability and minimum TCSC installation cost, the problem to find out the capability for each TCSC installation was next devised as a multi-objective optimisation problem and worked out by employing the fitness sharing multi-objective particle swarm optimisation method. At last, in the Pareto front set attained, the solution with the TCSC installations that can formulate the power system offer the necessary load ability with biggest utilisation index value was suggested. To authenticate the presentation of the suggested method, the adapted IEEE-14 buses, IEEE-118 buses systems and a practical power system were applied.

The authors in [77] emphasize on power system security as a pivotal issue in deregulated and competitive electricity market. They present a dynamic security constrained optimal dispatch approach for calculation of stability margin of the system. The work shows a hybrid approach for calculation of approximate unstable equilibrium point illustrated on two test systems.
The literature review candidly exhibits that OPF is vital for power system operation and control. However, in the current electricity market scenario which is marked by large interconnected power systems and deregulated power markets security constrained OPF computation is essential to be integrated in system for reliable power system planning, operation and real time control. Therefore the focus is to estimate system robustness with respect to credible contingencies and the operating cost involved under such circumstances. So, numerous computational tools have developed over the years as depicted in literature as a natural extension to conventional OPF formulation. The current work proposed in the thesis primarily focuses on developing new stochastic algorithm to generate secured OPF solution and derive improved results as compared to that presented in literature. Incorporation of FACTS device elevates the system performance and same has been reported in literature. Thus the research work includes the most prominent series connected FACTS device i.e. TCSC for secured OPF formulation.

2.3 MODELLING OF FACTS CONTROLLER FOR TRANSIENT STABILITY AND VOLTAGE STABILITY ENHANCEMENT.

Power system stability has been a major concern for power engineers for maintaining reliable power system operation and has been perceived as a vital research area to generate measures for damping oscillations for transient stability, maintaining voltage stability and minimizing frequency deviation for attaining frequency stability. FACTS controller provide high speed reliable control and can be aptly utilised for improving transient stability margin, regulating voltage at critical buses and phase angle control at the end of transmission lines. The PSS are considered as most routine devices to damp out power system oscillations but sometime are inadequate to damp out inter area oscillations and thus FACTS device implementation is now considered inevitable for meeting stability criteria. So, most research work has focused on providing control schemes for PSS and FACTS device coordinated operation by simultaneous tuning of their parameters.

Xiaolu et al. [78] presented a fundamental frequency model of TCSC providing the factors that affect transient stability of TCSC with variation in operating condition with TCSC inclusion as variable impedance. The thyristor triggering logic and synchronization system is included in the model to perform time domain
simulation. The model however is designed to operate suitably only for the capacitive mode of TCSC operation.

Wang and Swift [79] gave the unified Philips-Heffron model of power system with FACTS device which is accepted as a powerful tool for designing damping controllers using linear control theory. The work proposed by the authors provides the effectiveness of FACTS devices namely SVC, controllable series compensator and phase shifter in suppressing power system oscillations. A method of non-linear control scheme for transient stability improvement using TCSC controller has been presented by Jiang and Lei [80]. Non-linear mathematical model of single machine infinite bus system is transformed to its linear model by feedback linearization method. The proposed control technique is designed for TCSC based controller and the dynamic performance improvements are validated on the test system.

A TCSC controller design and performance for improving transient stability for different input signals has been proposed by Del Rosso et al. [81]. The authors present the analysis of designing a TCSC controller for stability enhancement considering interactions among control signals. The performance of the proposed method has been tested on 89 bus, 72 machine model of Argentina power grid by selection of appropriate input signals.

The research work developed by Shayeghi et al. [82] provided power system stability improvement by coordination of TCSC and excitation system control. The work displays a global tuning requirement for FACTS device stabilisers and PSS which is an integral part of any power system under consideration. The multi machine test system is tested with TCSC and PSS and effectiveness of tuning procedure is to improve power system damping by their coordinated control.

TCSC was described as a first order lag element by Geng et al. [83] and further the authors also suggested the factors affecting the transient response of TCSC. The authors provide the mathematical model and also assert that the choice of synchronizing signal has relevant thrust on TCSC transient behaviour. Abdel-Magid and Abido [84] gave a linearized incremental model for coordinated design of TCSC and PSS to improve stability over a wide range of loading condition. The problem formulation is based on eigen value objective function and real coded genetic Algorithm is utilised to search for optimal parameters of controllers and proposed
method was tested on a weak connected system. The robustness of the proposed approach was determined on the basis of non-linear simulation results, eigen value analysis, damping torque coefficient analysis which was performed on various loading conditions. The authors provided power system dynamics improvement with use of three FACTS device namely thyristor controlled phase shifting transformer (TCPST), thyristor controlled series capacitor (TCSC) and unified power flow controller (UPFC) [48]. The energy function method is the control strategy implemented for damping electromechanical oscillations and its effectiveness is justified by damping large and small signal disturbances with respect to various loading conditions. Also the authors have utilised control inputs that are derived from locally measurable variables.

Application of artificial intelligence and stochastic algorithm like Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), Differential Evolution (DE), Artificial Neural Networks (ANN) have emerged as complementary tools for mathematical analysis and optimisation methods for power system control. These algorithms are most suitable for multi objective optimisation and are considered popular design tools due to their versatility and ability.

From literature survey it is comprehended that a vast research work is dedicated to the domain of improving the performance of power system subjected to disturbance and as evident from literature TCSC is identified as the most adaptable device suitable for enhancing system damping and improving transient stability performance. As design of such controller is a multi objective optimisation problem, modern population based optimisation methods are used to achieve the desired objective with minimum control efforts. This thesis investigates the design of PSO based TCSC controller which will supplement and act in coordination with PSS damping for improving power system stability subject to disturbances.

In the last few decades, plethora of factors has caused the power system operation to be more stressed and to state few of those which includes bulk transmittable power in long transmission lines, variable loading patterns in competitive electricity markets, penetration of renewable energy like wind energy into existing system causing uncoordinated controls and substantial growth in interconnections. These conditions have paved the way for occurrence of voltage instability and if such conditions prevail for long period of time it would ultimately
lead to voltage collapse. Therefore, voltage stability has now been considered as one of the prominent research areas in the field of power system. As OPF formulation forms the backbone of reliable power system operation, secured OPF models with additional constraints of inclusion of voltage stability is widely conceptualized and implemented for stability enhancement of electricity markets. This section provides several works as available in literature which explores precise and constructive techniques for inclusion of voltage stability into OPF formulation. FACTS controllers are progressively being used to provide voltage and power flow controls and their insertion is found to be highly effectual in preventing voltage instability [85]. In most of the previous works on voltage stability improvement, only normal operating condition is considered [86, 87] but voltage instability is usually caused by contingencies.

Implementation of minimum singular value approach for voltage stability enhancement with OPF formulation has been suggested in [88] where the results are validated on a 64 bus CIGRE test system. The authors in [89] proposed a hybrid OPF formulation which would emphasize simultaneously on minimizing generation cost and retention of voltage security levels at variable loading conditions. The numerical analysis to provide appropriate adjustments of control parameters was performed on IEEE 57 bus test system which accounted for voltage stability. The maximization of static voltage stability margin and the reduction of total real power losses are discussed by the authors where proper placement of SVC and TCSC reduces transmission losses, increases the available transfer capacity, and improves the voltage profile [90].

Voltage stability constrained OPF designed for multiple contingency problems have been proposed by authors in [91]. The distance between current operating point and the point of voltage collapse in terms of load power in MW is conceptualized as the voltage stability index. Selection of control parameters for enhancing voltage stability margin in OPF formulation is proposed by providing margin enhancement constraints. The OPF solution is generated with non-linear interior point method and results are validated on IEEE 118 bus system.

Numerous voltage stability indices are reported in literature for asserting and predicting the system state with regards to its proximity to voltage instability. The voltage stability indices are mostly grouped into two basic categories: those which
predict the weakest bus susceptible to voltage instability such as L-index and voltage stability index [92] and the other category includes the index which identifies the most critical transmission line such as line stability index [93] and line voltage factor [94]. A method for real time assessment of voltage stability along with load variation is presented using feed forward back propagation network and tested on IEEE 14 and 30 bus power systems [95].

As evident from literature survey, voltage stability concern is immense in the present scenario power market and OPF coupled with voltage stability is one of the prime objectives of research work presented in the thesis. The work focuses on minimization of voltage deviation and retention of voltage stability in the buses under variable loading conditions. To further improve the system performance, TCSC placement is optimised for ensuring secured OPF based voltage stability.

The exhaustive literature reveals the requirement to develop control methodologies for improving power system performance subjected to disturbances. It is observed that most of the methods tend to improve only one type of stability performance i.e. either improving oscillatory stability performance or the system voltage profile. So, the work presented in this thesis will explicitly bring out the versatility of FACTS controller which is suited best to upgrade the overall system performance. As it is evident from literature survey that TCSC is one of the most adaptable FACTS devices, the proposed work is an attempt to exploit its benefit as a controller designed with optimal parameters to improve the system performance.