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A Review on Power System Voltage Stability and Optimization Techniques

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ABSTRACT
Power system voltage stability is a one of the major focused areas in recent days due to mismatch between generation and demand. Maintenance of voltage stability is a challenging issue in planning and security assessment of power systems. Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the power system under normal operating conditions and after being subjected to a disturbance. Long-term voltage instability problems can occur in heavily loaded systems where the electrical distance is large between the generator and the load. Timely application of reactive power compensation or load shedding may prevent this type of voltage instability. System reactive power handling capacity can be improved with Flexible AC Transmission System (FACTS) devices. Identification of critical system locations to undertake appropriate remedial measures in operation is the concern. This paper reviews the performance of various types FACTS controllers in power system voltage stability problem and focuses on different optimization methods implemented for optimal placement and sizing of FACTS devices to minimize power losses.
Keywords: Power System Voltage Stability, Flexible AC transmission System (FACTS), FACTS Controllers, Optimization algorithms, Fault location identification.

I. INTRODUCTION

Historically the synchronous stability, low frequency oscillations (1-3 Hz) and sub-synchronous resonance phenomenon were the major challenges for both the planners and operators of power systems. The evolution of modern power systems with high levels of reactive power compensation and increased levels of system stress due to mismatch of power generation and load demand and continuous transmission system expansion have placed voltage stability as one of the primary concerns in system planning and operation. Voltage collapse phenomenon occurred in power systems of several developed as well as developing countries from the seventies onwards and attracted the attention of researchers in this area. Efficient algorithms for voltage stability assessment and enhancement are essential to ensure reliable system operation [1- 3]

Voltage stability like any other stability is a dynamic problem. However, from static analysis certain useful information such as loadability limit and proximity of the operating point to this limit can be obtained. The pattern of the voltage decay in the vicinity of voltage collapse point will not be known from static analysis. Dynamic analysis on the other hand can be used to study as to how the system proceeds towards voltage instability and collapse. In dynamic analysis, dynamic models of system components that influence voltage stability are included. The differential and algebraic equations characterizing the system dynamics are solved in order to assess the dynamic voltage stability [4-5].

The dynamic analysis can be either for a small-scale disturbance or for a large-scale disturbance. The small disturbance voltage stability is concerned with the voltage stability of an equilibrium point for small perturbations. The large disturbance voltage stability is concerned with the transition to and existence of a new stable state following a large disturbance like a sudden load increase, loss of a heavily loaded line, a major generator/transformer outage etc. An important aspect in both small-scale and large-scale disturbance voltage stability analyses is the proper representation of the load characteristics [6].

The P-V (Q-V) curves have been used to analyze voltage stability of a power system. P-V curves are useful to calculate the amount of corrective measure needed to achieve a desired MW margin. For constant current and constant admittance loads the system is voltage stable throughout the P-V curve. For constant power load, voltage stability limit and maximum loadability are the same [7].

Several indices have been evolved to find the nearness of the operating point to nose point. Most of the static conditions derived in the literature to predict voltage instability problem are related to singularity of the power flow Jacobian. The singularity of the Jacobian is necessary but not sufficient to indicate voltage instability (Sauer and

Pai, 1990) [8]. The common drawback of most of the indices such as minimum singular value, L-index etc., is that they are non-linear in nature. One cannot prescribe a threshold value of the above indices for taking timely corrective control action. Dynamic analysis generally requires simulation with dynamic representation of power system components. The load modeling is very important in dynamic analysis. In the literature, it is suggested that static load model can be used for power flow and also for dynamic simulation at locations that are far away from the disturbance. Induction motor models are recommended at locations that are closer to the disturbance. The voltage instability phenomenon caused by induction motor loads is fast. Therefore, to prevent such phenomenon, fast acting Var Compensators such as Static Var Compensator (SVC) (Hammad and El-Sadek, 1989) [9] & STATCOM, UPFC are being used.

A. Principal Causes of Voltage Stability Problems

Some of the main causes for occurrence of voltage instability are due to unsuitable locations of FACTS controllers, high reactive power consumption at heavy Loads, occurrence of contingencies, reverse operation of ON Load Tap-Changer (OLTC), voltage sources too far from load centers, poor coordination between multiple FACTS controllers, presence of constant power loads, difference in transmission of reactive power under heavy loads [1].

B. Prevention of Voltage Nstability

Prevention of voltage instability can be accomplished by various methods. Few of them are i. by placement of Series or Shunt Capacitors, ii. by placement of FACTS Controllers. iii. Coordination of Multiple FACTS Controllers. iv. Generation rescheduling. v. Under-Voltage Load Shedding. vi. Blocking of Tap-Changer under Reverse Operation. vii. Installation of Synchronous Condensers [1].

II. FLEXIBLE AC TRANSMISSION SYSTEM (FACTS) DEVICES

FACTS devices are used for control of transmission voltage and power flow, reducing reactive losses and damping of power system oscillations for high power transfer levels. FACTS controllers are used in power systems to increase the transmission capacity of the line and to provide the optimum utilization of the existing power systems controllability.

FACTS devices are cost effective alternatives to new transmission line construction. The concept of FACTS embraces a wide variety of tasks pertaining to both networks and consumers problems, especially related to power quality issues. FACTS devices can be categorized into series and shunt devices.

A. Shunt Facts Devices

The shunt devices are primarily used for reactive power compensation and therefore voltage control. The series devices are compensating reactive power. With their influence on the effective impedance on the line they have an influence on stability and power flow. These devices are installed on platforms in series to the line. Most manufacturers count Series Compensation, which is usually used in a fixed configuration, as a FACTS-device. The reason is that most parts and the system setup require the same knowledge as for the other FACTS-devices.

More and more growing importance are getting the FACTS-devices in shunt and series configuration. These devices are used for power flow controllability. The higher volatility of power flows due to the energy market activities requires a more flexible usage of the transmission capacity. Power flow control devices shift power flows from overloaded parts of the power system to areas with free transmission capability [3].

i. Static Var Compensator

SVC is a shunt connected FACTS device, which can be used in Voltage control mode or Var control mode. Here the term static is used to indicate that SVC has no rotating part unlike synchronous machine. SVC is used in voltage control mode by controlling the reactive var in the system where it is connected. SVC can draw leading or lagging var to control the voltage fluctuation or voltage regulation in the system. If there is a dip in the voltage then it supplies reactive power and if there is a rise in the voltage then it absorbs reactive power. So the SVC can be used as a source or sink of reactive Var in accordance to the need of system. [10].

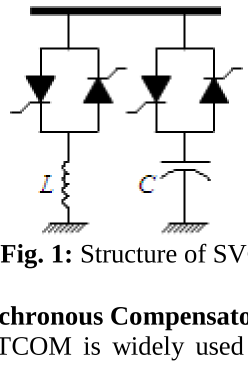

Fig. 1: Structure of SVC

ii. Static Synchronous Compensator

STATCOM is widely used dynamic shunt compensator for controlling reactive power in transmission and distribution. STATCOM has a small size, a faster speed, a wide operation range has a great advantage in performance and can effectively compensate the reactive power, suppress harmonic current and provide voltage support for transmission system, it will be more and more widely used [11].

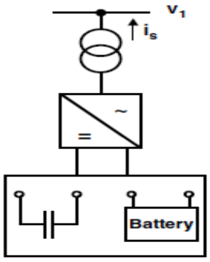

Fig. 2: Structure of STATCOM

B. Series Facts Devices

Series capacitive compensation in AC transmission systems can yield several benefits, such as increased power transfer capability and enhanced transient stability [12]. Series devices are developed from fixed or mechanically switched compensations to the Thyristor Controlled Series Compensation (TCSC) or even Voltage Source Converter based devices. Reactive power compensation is provided to minimize power transmission losses, to maintain power transmission capability and to maintain the supply voltage. Series compensation controls the line impedance of a transmission line; namely the change of impedance by either inductive or capacitive compensation [3].

i. Thyristor Controlled Series Capacitor (TCSC)

TCSC controllers use thyristor-controlled reactor (TCR) in parallel with capacitor segments of series capacitor bank. The combination of TCR and capacitor allow the capacitive reactance to be smoothly controlled over a wide range and switched upon command to a condition where the bi-directional thyristor pairs conduct continuously and insert an inductive reactance into the line. TCSC is an effective and economical means of solving problems of transient stability, dynamic stability, steady state stability and voltage stability in long transmission lines [13].

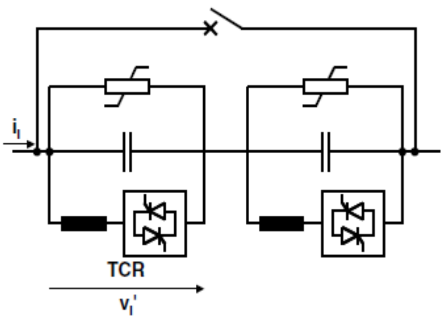

Fig. 3: Structure of TCSC

ii. Static Synchronous Series Compensator

SSSC is a series FACT device. The operating principle is similar to STATCOM but more complicated as it requires platform mounting and protection. [1-3]. SSSC consists of VSC and DC link capacitor and a coupling transformer. SSSC is able to generate a compensating voltage and is controllable over the capacitive or inductive range. Also the SSSC has the ability of interfacing with external DC power supply to provide compensation. This compensation can be achieved by injecting the phase voltage into the transmission line through the coupling transformer, so the active power flow can be directly controlled. SSSC injects voltage in series with the transmission line at 90° to line current. As per requirement, voltage can be injected in quadrature with line current in inductive or capacitive mode [14].

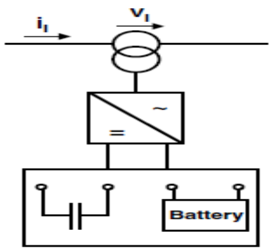

Fig. 4: Structure of SSSC

C. Combined Shunt and Series Facts Devices

i. Unified Power Flow Controller

The Unified Power Flow Controller (UPFC) is a novel power transmission controller. The UPFC provides a full dynamic control of transmission parameters, voltage, line impedance and phase angle [15]. The UPFC consists of a series device acts as a controllable voltage source Vc, whereas the shunt device acts as a controllable current source IC. The main purpose of the shunt device is to regulate the dc link voltage by adjusting the amount of active power drawn from the transmission line. In addition, the shunt device has the capability of controlling reactive power.

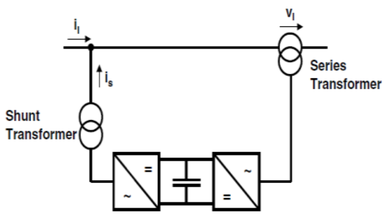

Fig. 6: Unified power Flow Controller

ii. Dynamic Power Flow Controller (DPFC)

The DPFC consists of one shunt and several series-connected converters. The shunt converter is similar as a STATCOM, while the series converter employs the D-FACTS concept, which is to use multiple single-phase converters instead of one large rated converter. Each converter within the DPFC is independent and has its own dc capacitor to provide the required dc voltage [16].

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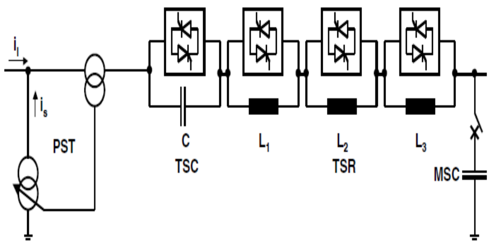

Fig. 7: Dynamic Power Flow Controller

III. POWER SYSTEM OPTIMIZATION TECHNIQUES

The selection of location to place the FACTS device on the transmission line plays a vital role in maintaining the power system stability. Various optimization techniques have been proposed and implemented in the last few decades. Recent advances in computer engineering and the complexity associated with power system optimization have resulted in the need to develop programming techniques that can be used to find the optimal location for placing the FACTS devices. These include dynamic programming, Lagrange multiplier methods, heuristic techniques, and evolutionary techniques such as genetic algorithms. These techniques are often hybridized with many other intelligent system techniques, including artificial neural networks (ANN), expert systems (ES), tabu search algorithms (TS), and fuzzy logic (FL) [17].

A brief survey on optimization techniques used in power system are discussed further.

In 2002, A. G. Bakirtzis, P. N. Biskas, C. E. Zoumas, and V. Petridis published a paper on "**Optimal power flow by enhanced genetic algorithm**", IEEE Transactions on Power Systems, vol. 17, no. 2. It presents an Enhanced Genetic Algorithm for the solution of optimal power flow with both continuous and discrete control variables. The advantage of using this method is its modeling flexibility.

In 2003, S.Gerbex, et.al presented a paper "**Optimal location of FACTS devices to enhance power system security**" in IEEE Bologna Power Tech Conference in Bologna, Italy from 23-26 June. In this paper, three heuristic methods Simulated Annealing (SA), Tabu Search (TS) and Genetic Algorithms (GA) are compared by using the parameters: location of devices, their types and sizes. Five types of FACTS (TCSC, TCVR, TCPST, SVC and UPFC) devices were modeled. Power system security was employed as a measure of performance It concluded that although the three methods lead to similar results, Tabu Search and Genetic Algorithms converges faster than Simulated Annealing [19].

In 2005, Weerakorn Ongsakul, et.al "**Optimal Allocation of FACTS Devices to Enhance Total Transfer Capability Using Evolutionary Programming**" in IEEE Transactions, an evolutionary programming (EP) is proposed to determine the optimal allocation of FACTS devices for maximizing the total transfer capability (TTC) of power transactions between source and sink areas in deregulated power system. Results from the test system indicate that optimally placed OPF with FACTS devices could enhance the TTC value far more than OPF without the FACTS devices [20].

In 2006, Sidhartha Panda, et.al proposed a paper "**Improving power system transient stability with an off–centre location of shunt FACTS devices**" in Journal of Electrical Engineering. It describes that when shunt FACTS (SVC and STATCOM) devices are placed at the center of the transmission line, they controls the power flow and if they locate the FACTS devices at the off-centre of transmission line, it increases system stability [21]. The paper concluded that when FACTS devices are placed at off centre position they can give better performance and best results to maintain power system stability.

In 2007, J. Nikoukar, M. Jazaeri presented a paper "**Genetic Algorithm Applied to Optimal Location of FACTS Devices in a Power System**" in Proc. of the 3rd IASME/WSEAS Int. Conf. on Energy, Environment, Ecosystems and Sustainable Development in Agios Nikolaos, Greece. This paper proposed a genetic algorithm to determine the location of multiple FACTS devices in a power system. The simulation performed on IEEE 30 bus system results proved that the method is efficient and also optimizes the location, type and rated value of the FACTS device [22].

In 2008, K.Vijayakumar, R.P Kumudinidevi published a paper "**A hybrid genetic algorithm for optimal power flow incorporating FACTS devices**" in Asian Journal of Scientific Research. In this paper, a Genetic algorithm is proposed which simultaneously can find optimal generation, optimal choice, and location of FACTS devices subjected to equality and inequality constraints [23].

In 2009, S. Auchariyamet, S. Sirisumrannukul published a paper on "**Optimal Reactive Power Planning with FACTS devices by Particle Swarm Technique**". This paper explained a particle swarm optimization based technique to determine the optimal location of SVC and TCSC for reactive power planning [24].

In 2010, a paper "**Optimal Allocation Of FACTS Devices In Deregulated Electricity Market Using Bees Algorithm**" of R.Mohamad Idris, et.al was published in WSEAS Transactions On Power Systems. Here a traditional method BA was taken to optimize the parameters of FACTS devices to increase available transfer capacity in a power system [25]. The parameters were: location, types and sizes. The FACTS devices used are TCSC, SVC, UPFC and TCPST. Simulations were performed in IEEE 9 and 118 bus system. The method was also compared with GA for the results. They concluded that BA is best to optimize the FACTS devices.

In 2011, F.S. AL-Ismail, M.A. Abido published the paper "**The impact of statcom based stabilizers on power system Stability, using intelligent computational optimization Approach**". The paper explains the application of STATCOM based stabilizers for power system stability. The Stabilizer tuning parameters are optimized by using Tabu Search, Genetic Algoritm, Simulated Annealing, Differential Evolution, Evolutionary programming and particle swarm optimization. The DE as well as PSO based stabilizer shows an enormous improvement in terms of overshoot magnitude and settling time as well as the stability of the power system is increased [26].

In 2012, V.Ravi Dr.K.Duraiswamy has presented a paper "**Effective Optimization Technique for Power System Stabilization using Artificial Bee Colony**" in the 2012 International conference on computer communication and informatics- IEEE at Coimbatore, India. They explained application of Artificial Bee Colony Algorithm for power system optimization. The objectives of the multi-machine system shows better convergence with ABC technique [27].

Whei-Min Lin, Kai-Hung Lu, et.al presented their paper "**Optimal Location Of FACTS For Voltage Stability Using Modified Particle Swarm Optimization**" in Proceedings of The International Multi Conference of Engineers And Computer Scientists, 14-16 March in Hong Kong. In this paper, MPSO technique was proposed to optimize the location of UPFC with ECI model to increase voltage stability [28]. Simulation was done in IEEE 30 bus system. They concluded that the MPSO gave best performance to optimize the UPFC to improve voltage stability. Simulation presented that the technique achieved best results after optimization.

Mahdi M. M. El-arini, Raef S. S. Ahmed, published a paper on "**Optimal Location of Facts Devices to Improve Power Systems Performance**". The paper describes a novel algorithm for finding the optimal location of FACTS devices based Elitist Non Dominated Sorting Genetic Algorithm (NSGA-II). IEEE-14 bus is used to test the performance of the method. The results proved that NSGA-II performed well when the optimal power flow and optimal location parameters are considered [29].

In 2013, Tissa Tom and Rinku Scaria in their paper "**Active and Reactive Power Compensation in Distribution System Based on Biogeography Based Optimization Technique**" had proposed a Bigeography Based Optimization technique for active and reactive power compensation of distributed systems. It is tested on the IEEE 13 bus system. It is proved that the active power and reactive power loss are reduced by a considerable percentage [30].

In the paper "**Power System Stability by Reducing Power Losses using Optimization Techniques**", S.N. Deepa and J. Rizwana had compared two optimization techniques Particle Swarm Optimization and Modified Particle Swarm Optimization (MPSO) to reduce the active and reactive power losses by testing them on IEEE 3-bus and 6-bus systems. The test results proved that the performance of MPSO is superior to PSO in optimizing the power system [31].

Dan Cristian, Constantin Barbulescu, Stefan Kilyeni, Vasile Popescu, in their paper "**Particle Swarm Optimization Techniques-Power Systems Applications**" has suggested that compared to other evolutionary techniques, Particle Swarm Optimization has better global search performance and faster converges faster[32].

Rekha R & Kannan G in their paper "**A Comparative Analysis on Reactive Power Optimization Using Various Techniques in Deregulated Power System**" had proposed a mathematical model of reactive power optimization using PSO and GA. Gauss -Seidel method is used in conjunction with PSO to obtain the optimal power value. Finally its proved that PSO has higher performance than Genetic Algorithm [33].

In 2014, the paper "**A Hybrid Meta-Heuristics Optimization Technique for Loss Minimization and Cluster Identification in Power System Network**" published by S. A. Jumaat , I.Musirin, M. M. Othman and H. Mokhlis introduced a new approach for optimizing the transmission loss, improving the voltage and monitoring the cost of installation. The meta-heuristic technique "Evolutionary Particle Swarm Optimization" is feasible with PSO and Evolutionary Programming for cluster development when tested on IEEE 30 bus system [34].

Chichebe. M. Akachukwu, Abiodun M. Aibinu, Mark N. Nwohu and 4Habeeb Bello Salau, in their paper "**A Decade Survey of Engineering Applications of Genetic Algorithm in Power System Optimization**" presented a survey on the

Genetic Algorithm techniques used for power system optimization. It presented a decade review on various applications of Genetic algorithms for power system optimization [35].

In the paper "**Optimal Capacitor Placement and Sizing for Enhancement of Distribution System Reliability and Power Quality Using PSO**", Pravin Machhindra Sonwane, Bansidhar Eknath Kushare presented a technique for optimal capacitor placement to enhance the reliability and its sizing using PSO. The optimal capacitor placement improves the power factor, reduces the power losses and helps in maintaining the voltage profile [36].

In 2015, S. Mandal, K. K. Mandal, B. Tudu published a paper on " **A New Self Adaptive Particle Swarm Optimization Technique For Optimal Design of a Hybrid Power System**". This paper implemented a improved particle swarm optimization technique for optimal design of PV-wind battery with diesel generator backup hybrid system [37].

In the paper "**Optimal Placement of Interline Power Flow Controller (IPFC) to enhance Voltage Stability**" published by B.V.Rami Reddy, Y.V.Siva Reddy , P.Sujatha, a combination of fuzzy logic and genetic algorithm is proposed. The genetic algorithm is used to find the optimal location to place the Interline Power Flow Controller where as the fuzzy system is used to determine the injected capacity of IPFC. The Power flow analysis is later carried out by the Newton Raphson Method. The performance of the proposed method is tested on a IEEE 30 bus system [38].

In 2016, J.STEFFY AMIRTHAM, Mrs.V.UMA in their paper "**Optimal Location of Unified Power Flow Controller Enhancing System Security**", had proposed a method to find the optimal location for UPFC based on real power performance index in the power system network. The UPFC is modeled by power injection model. PSO is used to solve the Optimal Power Flow problem. [39].

Indrajit N. Trivedi, Pradeep Jangir, Narottam Jangir, Siddharth A. Parmar, Motilal Bhoye Arvind Kumar, in the paper "**Voltage Stability Enhancement and Voltage Deviation Minimization Using Multi-Verse Optimizer Algorithm**", proposed a meta-heuristic technique Multi-Verse Optimizer (MVO). IEEE-30 bus system is used for testing. MVO is compared with Flower Pollination Algorithm (FPA) and Particle Swarm Optimization. It is observed that MVO gives better optimization values compared with the other two. Also MVO has faster convergence [40].

Himmat Singh, Laxmi Srivastava, in their paper "**Optimal VAR control for real power loss minimization and voltage stability improvement using Hybrid Multi-Swarm PSO**", presented a Hybrid Multi-Swarm particle Swarm Optimization (HMPSO) algorithm for a multi-objective optimal reactive power control for minimizing the real power loss and improving the voltage stability. The results are obtained by testing on a IEEE 30 bus system. The results are compared with those obtained using classical DE, classical PSO and modified DE algorithms. HMPSO has superior performance and efficiency compared to the other three [41].

The paper "**Multi Objective Optimization for Optimal Power Flow with IPFC using PSO**" presented by J.Praveen and Dr. B.Srinivasa Rao proposed the usage of Imterline Power Flow Controller for maintaining the power system stability. The Particle Swarm Optimization technique is used to identify the optimal location for placing the IPFC. The objectives considered are generation cost, transmission losses and L-index [42].

Indrajit N. Trivedi, Pradeep Jangir, Narottam Jangir, Siddharth A. Parmar, Motilal Bhoye, Arvind Kumar, in their paper "**Voltage Stability Enhancement and Voltage Deviation Minimization Using BAT optimization Algorithm**", explained the application of a novel meta-heuristic BAT Optimization Algorithm (BOA). IEEE 30 bus system is used for testing. BOA provides better optimization compared to Flower Pollination Algorithm and Particle Swarm Optimization. The parameters considered are Fuel cost reduction, voltage deviation minimization and voltage stability improvement [43].

IV. CONCLUSIONS

The operation of various FACTS devices is explained in this paper. The application of suitable FACTS controller enhances the power system stability. A detailed study of the optimization techniques is carried out. The current trend is mostly on the usage of meta-heuristic genetic algorithms to find the optimal location for placing the FACTS device.

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