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Static Synchronous Compensator for Improving Performance of Power System: a Review

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Abstract – *Flexible ac transmission systems (FACTS) controller can provide better control than conventional control and achieve fast control response time. Static synchronous compensator (STATCOM) is one of the key FACTS devices based on voltage source converter (VSC) technology whose capacitive or inductive output current can be controlled independent of the ac system voltage. In this review paper, the authors have tried to broadly categorize the research work done so far on the STATCOM. A substantial number of relevant research papers can be found on the plant, modeling, operation and control fundamentals of the STATCOM and their performance study.* ***Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: FACTS Device, STATCOM, Damping Controller, Model, Location*

I. Introduction

A power system is composed of many dynamic devices connected buses and loads. Power systems are non linear systems with a wide range of operating conditions and time varying configurations and parameters. Flexible ac transmission systems (FACTS) have been developed to improve the performance of weak ac systems and enhance transmission capabilities over long ac lines. FACTS controllers can be used in all the three states of the power system, namely: steady state, transient and post transient steady state. FACTS devices can regulate the active and reactive power as well as voltage-magnitude [1, 2]. Dynamic application of FACTS controllers includes transient stability improvement, oscillation damping (dynamic stability) and voltage stability enhancement [3, 4]. Facts controller can control shunt impedance, series impedance, voltage, current and phase angle [5]-[8]. The reasons of using FACTS are as follow [5]:

a) to provide better control than conventional control
b) to achieve fast control response time
c) to develop reliable and flexible control
d) to reduce the overall system losses
e) to achieve more economic operation than the building of a power plant or transmission line.

FACTS devices can be divided into three categories as shown in Fig. 1 [10]-[17]. In general, from control of view, FACTS controllers can be divided into four categories [18]: series controllers such as thyristor controlled series capacitor (TCSC) [19]-[21] and static synchronous series compensator (SSSC) [22]-[24], shunt controllers such as static var compensator (SVC) [25]-[28], STATCOM [29, 30] and STATCOM with energy-storage system [31], combined series-shunt controllers such as unified power flow controller (UPFC) [32]-[34] and combined series-series controllers such as interline power controller (IPFC) [35]-[37].

A good number of papers are available on modeling, simulation, operation and control fundamental of the FACTS devices [38]-[46]. Simulation of FACTS controllers is mainly done in the following two ways: (a) detailed calculations in 3 phase systems and (b) steady state and stability analyses [47]. A study comparing the effects of four FACTS controllers using eigenvalues analysis on power systems small signal angle stability presented in [48]. In [49] to reduce overall financial losses in the network due to voltage sags for three most widely used FACTS based devices are optimally placed using a genetic algorithm. A multivariable design of STATCOM ac and dc voltage PI control was presented in [50], but the structural complexity of the presented multivariable PI controllers with different channels reduces their applicability. A robust control for a SMIB with a STATCOM in [51] is designed using the recently developed nonlinear H_∞ theory. An approach to the problem of the STATCOM state feedback design based on a zero set concept is presented in [52], which computational examples show that it is possible to derive the state feedback controllers with better robustness properties than those achieved using the approaches utilizing linear matrix inequalities. In [53] a Mamdani-type fuzzy logic controller is designed and implemented in hardware for controlling a STATCOM, which is connected to a ten-bus multi-machine power system. The comparative performance of radial basis function network and fuzzy logic controlled voltage source converters based STATCOM in terms of increase in power handling capacity of the line, improvements in transient stability and damping of oscillations in the SMIB system and multi-machine system is presented in [54].

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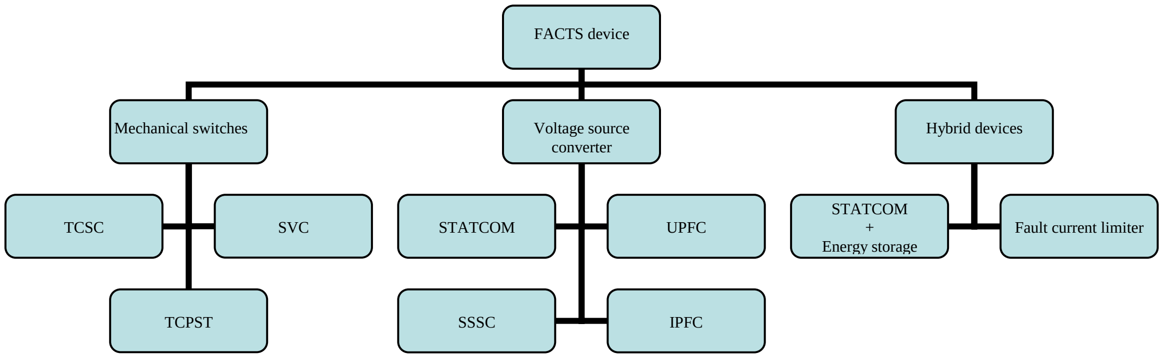


Fig. 1. Classification of FACTS devices

The design of a space vector pulse width modulated two-leg four-switch STATCOM to provide satisfactory performances in performing various reactive power flow control functions during steady-state and transient operations of power systems in [55] presented.

Shunts FACTS devices are used for controlling transmission voltage, power flow, reducing reactive loss, and damping of power system oscillations for high power transfer levels [56]. STATCOM is a kind of dynamic reactive power compensator, which has been developed in recent years. This paper presents a study of modeling, operation and control fundamentals of the STATCOM. The paper is structure as follows. The major advantages of the STATCOM over the SVC present in section II. The STATCOM operating principle and configurations is described in section III. The optimal location of FACTS devices in a power system is present in section IV. The application and modeling of the STATCOM are described in section V and VI, respectively. The damping control technique such as fuzzy controller and classic controller show in section VII. Finally, this paper concludes in section VI.

II. Shunt FACTS Controller

Shunt FACTS devices are classified into two categories, namely variable impedance type (SVC) and switching converter type (STATCOM) [57].

The voltage-current characteristic of SVC is shown in Fig. 2. The voltage U_{REF} is the voltage at the terminals of the SVC when it is neither absorbing nor generating any reactive power [58]. As shown in Fig. 3, the dynamic characteristics of an STATCOM is the plot of bus voltages versus current or reactive power. The controller can provide both capacitive and inductive compensation and is able to control output current over the rated maximum capacitive or inductive range independent of the AC system voltage [59]. As can be seen in the linear operating range the voltage-current characteristic and functional compensation capability of the SVC and STATCOM are similar.

The main advantage of a STATCOM over an SVC is its reduced size, much faster response and beyond the limitation of bus voltage, which results from the elimination of ac capacitor banks and reactors. Also STATCOM can serve as a controllable current source without changing the network structure parameters and beyond the limitation of bus voltage. The control objective of the SVC is to maintain a desired voltage at the high-voltage bus. The STATCOM can supply required reactive current even at low values of bus voltage, whereas the reactive current capability of SVC at its susceptance limits decrease linearly with decrease in bus voltage.

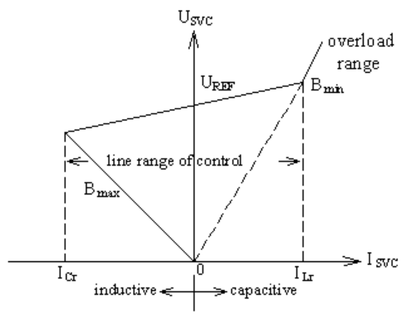


Fig. 2. Terminal characteristic of the SVC

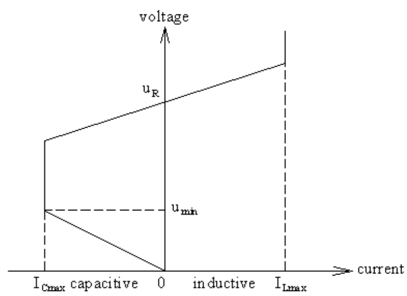


Fig. 3. Terminal characteristic of the STATCOM

The ability of STATCOM to produce full capacitive output current at low system voltage also make it highly effective in improving the transient stability. With proper choice of design rating and thermal design, STATCOM can have short time overload capability, enhance system transfer limit and improve its dynamic behavior significantly especially in the interconnected power systems. The STATCOM provides much faster response and beyond the limitation of bus voltage as compared to the SVC. The STATCOM does not employ capacitor or reactor banks to produce reactive power as the SVC do. A STATCOM response is ten times faster than that of an SVC due to turn-on and turn-off control of the STATCOM [60].

III. Construction and Operation

The STATCOM is given this name because in a steady state operating regime it replicates the operating characteristics of a rotating synchronous compensator without the mechanical inertia. A STATCOM is a controlled reactive power source. It provides voltage support by generating or absorbing reactive power at the point of common coupling without the need of large external reactors or capacitor banks [61]. The voltage of STATCOM is synchronized with voltage of the line to which the STATCOM system is connected [62].

The configuration of a STATCOM connected to bus M of a transmission line is shown in Fig. 4. Basically it consists of a step-down transformer (SDT) with a leakage reactance X_{SDT}, a three phase voltage source converter (VSC) and a dc capacitor. The STATCOM is assumed to be based on pulse width modulation (PWM) converters [63, 64]. The operation of STATCOM is fundamentally different from that of conventional SVC.

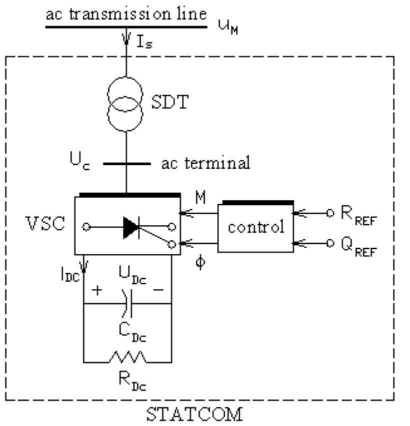
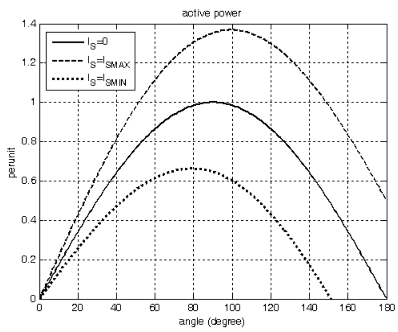


Fig. 4. STATCOM functional model

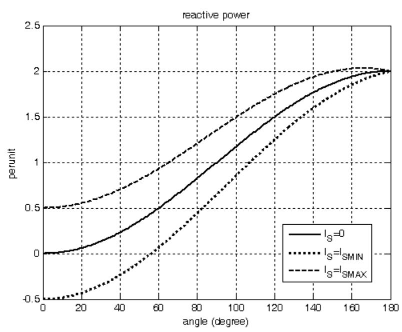
The principle of STATCOM operation is as follows. The basic objective of a VSC is to produce a sinusoidal ac voltage with minimal harmonic distortion from a dc voltage [65, 66]. The dc voltage across the dc capacitor (C_{DC}) of the STATCOM is controlled to be constant for normal operation of the PWM inverter. The dc capacitor has the function of establishing an energy balance between the input and output during the dynamic change of the var output. If the compensator supplies only reactive power, the active power provided by the dc capacitor is zero. Therefore, the capacitor does not change its voltage. If the voltage magnitudes are equal, the reactive power exchange is zero. The size of the capacitor is primarily determined by the ripple input current encountered with the particular converter design.

The charged capacitor C_{DC} provides a dc voltage to the converter, which produces a set of controllable three-phase output voltages with the frequency of the ac power system [67]. The current on the dc side is mainly a ripple of magnitude much smaller than the ac line currents. In this representation, the series inductance L_S accounts for the leakage of the transformer and R_S represents the active losses of the inverter and transformer. The R_{DC} represent the sum of the switching losses of the inverter and power losses in the capacitor. In STATCOM the maximum current is given by the difference in voltage between the converter terminal voltage and the power system voltage, and by the phase reactance. Under steady state conditions and ignoring the losses the exchange of active power and the dc current are zero. Figs. 5 and 6 show the power-angle curves of the machine for three cases: the STATCOM operates at its full capacitive rating (I_S=I_{SMAX}) as well as at full inductive rating (I_S=I_{SMIN}) and without the STATCOM (I_S= 0).

A typical variation of reactive power supplied by the STATCOM (when it operates at full inductive and capacitive ratings) is shown in Figs. 7 and 8. In practice, the STATCOM can operate anywhere in between the two curves. Fig. 9 show the amplitude of STATCOM bus voltage for three cases. It can observed that for a given δ, the value of P_E can be controlled by adjusting I_S. The reactive current I_S can be set within its maximum capacity and inductive limits even under strongly reduced voltage conditions.



(a) Active power



(b) Reactive power

Figs. 5. Power-angle curve with a STATCOM

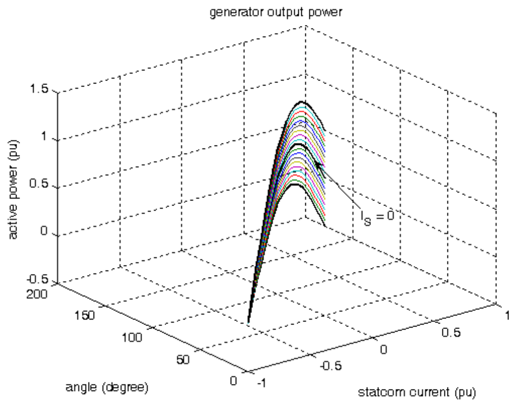


Fig. 6. Effect of STATCOM current and generator angle on output active power

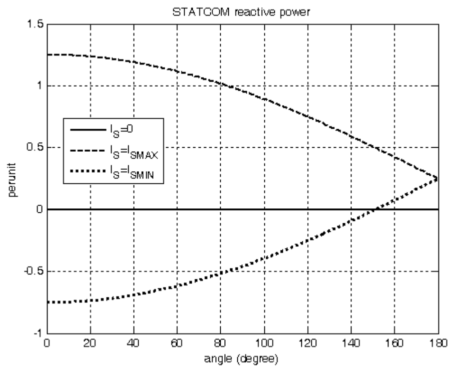


Fig. 7. Reactive power supplied by the STATCOM

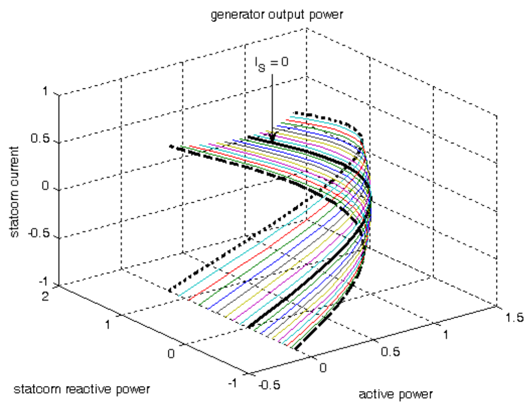


Fig. 8. Effect of STATCOM current on output power of the machine

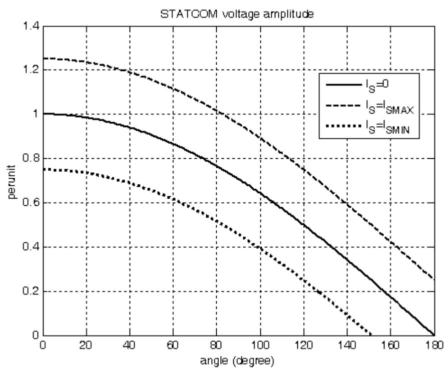


Fig. 9. Amplitude of STATCOM bus voltage

The reactive power output of STATCOM is inversely proportional to bus voltage and thus is less affected by voltage reduction than the other FACTS devices discussed [68]. In [69] configuration STATCOM using hybrid multi-inverters with potential that the harmonic contents of output voltage/current would be less than the conventional STATCOM is proposed. In [70] two controller structures for the STATCOM based on vector control scheme based on a nonlinear state feedback controller for control of reactive current using STATCOM is proposed.

IV. Optimal Location

Different FACTS devices and their different location have varying advantages. The optimization of location of FACTS devices depends on the amount of local load, the location of the devices, their types, their sizes, improvement stability, the line loading and system initial operating conditions [71]-[76]. The FACTS devices are optimal placed in order to maximize the power system security keeping minimal FACTS investment costs [77].

There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems. In [78] an algorithm for find the best location for the FACTS devices in multi-machine power systems using genetic algorithm is proposed. A residue factor method based on the relative participation of the parameters of FACTS controller to the critical mode to find the optimal location of the three types of FACTS controllers include TCSC, SVC and UPFC is proposed in [79]. In [80] three criteria are considered for FACTS optimal allocations: available transfer capability criterion, steady state stability criterion and economic criterion. A location index to determine the optimal location of FACTS devices in a large power system and determines the optimal control parameters for FACTS in addition to the optimal solution proposed in [81]. An alternative model that can optimize the placement of FACT devices based on multiple time periods with losses considered proposed in [82]. In [56] the optimal location of a shunt FACT device is investigate for an actual line model of a transmission line having series compensation at the center to get the highest possible benefit.

V. Application

STATCOM improve the static and dynamic voltage stability of the bus on power system and keep the voltage of the electric network in the receivable operating mode [83]. A STATCOM is a voltage sourced converter based shunt FACTS device, which is capable enhancing the power system damping by injection controllable reactive power into the system [84]. STATCOM is an active device, which can inject both real and reactive power to the system in a very short time and therefore has the ability to improve the damping and voltage profiles of the system [85]. A STATCOM with energy storage system such as superconducting magnetic energy storage (SMES) and battery energy storage system (BESS) can control both the reactive and the active power, thus providing more flexible power system operation. Typical applications of STATCOM are low frequency oscillation (LFO) damping [86], dynamic compensation and stability improvement [87], enhancement of transient stability [51], voltage flicker control [88], damping of sub synchronous oscillations in EHV series compensated systems [89] and power quality improvement [90].

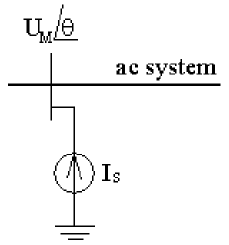
An automatic reactive-power control of an isolated wind-diesel hybrid power system having an induction generator for a wind-energy-conversion system and synchronous generator for a diesel-generator set is presented in [91]. The application of Hilbert transform based signal analysis techniques to the study of subsynchronous torsional oscillations in power systems with FACTS controllers is discusses in [92]. The results of a study on the application of the STATCOM for damping of torsional oscillations that occur in a series compensated ac system are presented in [93].

VI. Modeling

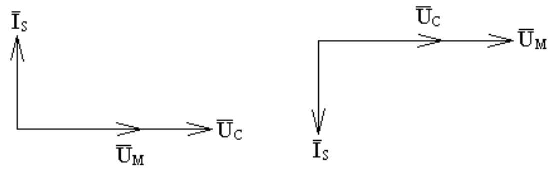
Models for power system components have to be selected according to the proposed of the system study. A STATCOM is a multiple input multiple output variables. Several distinct models have been proposed to represent STATCOM in static and dynamic analysis [94]. In [95] shunt inverter or STATCOM is modeled as three-phase multi pulse converter and series inverter. The different models, based on the assumption that voltages and currents are sinusoidal, balanced and operate near fundamental frequency, are proposed in [96]. Three models have been investigated for STATCOM: approximate model, detailed model and average model. The effects of STATCOM using eigenvalues analysis on power systems small signal stability presented in [97], which the simulation of system dynamic behavior is mainly done in the following two cases: classical model and classical flux-decay model equipped with automatic voltage regulator (AVR). A feedback control strategy based on the detailed small-signal model for balancing individual dc capacitor voltages in a three-phase cascade multilevel inverter-based static synchronous compensator is presented in [98]. In [99] proposed a current injection model of FACTS controllers is adopted for studying dynamic stability of power system which can be easily applied to the linear and the nonlinear analysis, and adopt any kind of VSI type FACTS controllers regardless of model types.

VI.1. Approximate Model

The STATCOM is modeled as a reactive current source with a time delay. The injected current of the STATCOM is always in quadrature with its terminal voltage and dose not change the angle of the voltage at connected bus [100]. The approximate model of the STATCOM is show in Fig. 10.



(a) Mathematical model of STATCOM



(b) Power exchange operation

Figs. 10. The STATCOM principle diagram

VI.2. Detailed Model

The static power converters are nonlinear in nature and consequently they generate harmonics into the supply. Ideally the inverter output voltage is phase with the voltage at the common connection point. The VSC converters an dc voltage (U_{DC}) into a controllable ac output voltage $u_C(t)$ at fundamental frequency, with rapidly controllable amplitude (U_C) and phase angle (θ_C), behind the leakage with neglecting harmonics is:

$$u_C\left(t\right) = U_C \, sin\left(\omega t - \theta_C\right) \tag{1}$$

The relationship between STATCOM ac voltage U_C and U_{DC} is:

$$\bar{U}_C = k\, M_R\, U_{DC} \angle \theta_C \tag{2}$$

The equivalent model of the STATCOM is show in Fig. 11. Two control signals can be applied to the STATCOM are magnitude control (M_R) and phase angle defined by PWM (θ_C), where M_R is a factor that relates the dc voltage to the peak voltage on the ac side.

The STATCOM is modeled as a VSC behind a SDT by a first order differential equation. If M_R is modulation ratio defined by PWM, the voltage current relationships in the STATCOM are expressed as:

$$\frac{d}{dt} u_{DC} = \frac{k\, M_R}{C_{DC}} \left(I_{sd} \cos\theta_C + I_{sq} \sin\theta_C \right) - \frac{U_{DC}}{R_{DC}} \tag{3}$$

where I_{sd} and I_{sq} are components of STATCOM current and k is the ratio between ac voltage to dc voltage depending on the inverter structure.

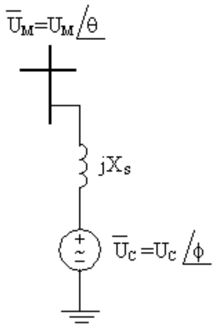


Fig. 11. Equivalent model of the STATCOM

VI.3. Average Model in Stationary Coordinates

This model based on the dq representation, is derived in the stationary and synchronous frame of reference [101]. This model is used for the VSC and study the dynamics of theses control loops [102]-[106].

The circuit equivalent of STACOM in dq synchronous frame is given in Fig. 12, where ω is rotation speed, S_D and S_Q are d-axis and q-axis synchronous reference frame inverter switching function, U_{cd} and U_{cq} d-axis and q-axis are synchronous reference frame source voltage, i_q and i_d are synchronous reference frame STATCOM current [107]. R_S and L_S mean line resistance and inductance, respectively.

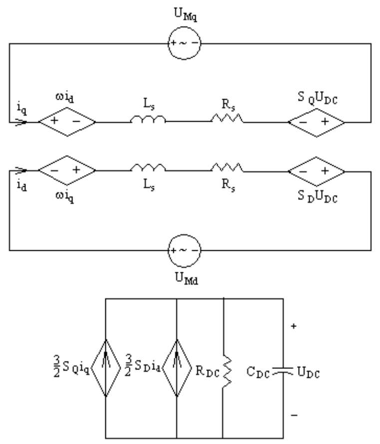


Fig. 12. The circuit equivalent of STATCOM in qd reference frame

VII. Damping Control Strategies

Power system oscillations are a characteristic of the system and they are inventible. Power system oscillations are initiated by normal small changes in system loads, and they become much worse following a large disturbance [108]. Damping the oscillations is not only important in increasing the transmission capability but also for stabilization of power system conditions after critical faults [109, 110]. STATCOM can increase power system stability by damping power oscillations. Various control approaches for damping controller of the STATCOM that is a nonlinear system have been reported recently. Design of dynamic is for steady state, transient stability and eigenvalue studies [111, 112].

A complete control system for STATCOM applications basically consists of two main parts: external and internal controls. The external control depends on the power system network to which the STATCOM is connected. The internal control mainly depends on the VSC topologies. An ideal internal control should instantaneously respond to a given command, which is generated by the corresponding external controller [113].

Damping controllers devised for STATCOM to improve the dynamic of power systems can be classified as continuous and discontinuous control [114].

The controllers on the basis of design and analytic approach can be divided into three main groups: a) linear such as lag-lead controllers, conventional PID controllers [115] and the linear quadratic regulators and pole assignment [116, 117], b) nonlinear such as adaptive control, particle swarm optimization and loop-shaping [118, 119], controllers by the phase compensation method and fuzzy controller [120], and c) empirical such as Tabu search algorithm [121] and genetic algorithm [122].

A nonlinear controller which performance depends on the location of fault and on the location of the STATCOM is proposed in [123]. Design of a fixed parameter robust STATCOM controller for a high order multi-machine power system through an H_∞ based graphical loop-shaping procedure by embedding a particle swarm is presented in [118]. In [124], the STATCOM-based controllers' parameters are optimized over a wide range of operating conditions and system parameter uncertainties in order to enhancing dynamic stability, which it is tested through eigen value analysis and time domain simulation.

VIII. Coordinated Control

Several papers have discussed the configurations and control strategies for the coordinated control of FACTS devices to improve power system dynamic [125, 126] such as power system stabilizer (PSS) and FACTS damping controller have been widely used to improve power system stability [127].

A dynamic approach that coordinate the expertise of power system engineer with asymmetric distribution reactive power compensation for shunt FACTS technology to reduce the asymmetrical voltage and enhance the system loadability in unbalanced distribution network is presented in [128]. A particle swarm optimization approach for the design of optimal PSS and FACTS power oscillation damping (POD) in multi-machine power system is proposed in [129]. In [130] provides a detailed analysis of the dynamic model of the STATCOM in transient simulations, and a coordinated control scheme for STATCOM and excitation control for single machine system is proposed based on feedback linearization and robust control theories.

IX. Conclusion

FACTS controllers have the flexibility of controlling both real and reactive power, which in addition to this control could provide an excellent tool for improving power system dynamics. A general review of classification FACTS controller devices is presented. STATCOM is a flexible ac transmission system device, which is connected as a shunt to the network, for generating or absorbing reactive power. STATCOM functions as a synchronous voltage source. It can provide reactive power compensation without the dependence on the ac system voltage.

In this paper some research has been carried out on the modeling, operation and the various control techniques of STATCOM to achieve good dynamic response. Performance comparison of different shunt FACTS controllers has been reviewed. A brief review of STATCOM operation and applications with identification of optimal locations of STATCOM has been discussed. Three models for STATCOM in power system have been presented. The control strategies for damping power oscillation by using of STATCOM were discussed.

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