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 flexible ac transmission systems (FACTS) devices based on voltage source converter (VSC) technology whose capacitive or inductive output current can be controlled independent of the ac system voltage. This paper presents a study of modeling, operation and control fundamentals of the STATCOM.

Keywords— FACTS Device; STATCOM; Damping Controller; Location; Construction.

I. INTRODUCTION

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. Facts controller can control shunt impedance, series impedance, voltage, current and phase angle [3]. FACTS devices can be divided into three categories as shown in Fig. 1. In general, from control of view, FACTS controllers can be divided into four categories [4]: series controllers such as thyristor controlled series capacitor (TCSC) [5] and static synchronous series compensator (SSSC) [6], shunt controllers such as static var compensator (SVC) [7], STATCOM [8] and STATCOM with energy-storage system [9], combined series-shunt controllers such as unified power flow controller (UPFC) [10] and combined series-series controllers such as interline power controller (IPFC) [11].

A good number of papers are available on modeling, simulation, operation and control fundamental of the FACTS devices. 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 [12]. In [13] 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. A study comparing the effects of four FACTS controllers using eigenvalues analysis on power systems small signal angle stability presented in [14]. 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. STATCOM is a kind of dynamic reactive power compensator, which has been developed in recent years. 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). The voltage-current characteristic of SVC and STATCOM are shown in Fig. 2. 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. 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.

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. The configuration of a STATCOM connected to bus M of a transmission line is shown in Fig. 3. 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 [15]. The operation of STATCOM is fundamentally different from that of conventional SVC.

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 [16].

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 contr-
ollable three-phase output voltages with the frequency of the ac power system [17]. 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. 4 and 5 shows 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 ($I_S=0$).

Fig. 6 show the amplitude of STATCOM bus voltage for three cases. In practice, the STATCOM can operate anywhere in between the two curves. It can observed that for a given $\delta$, 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.

In [18] 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.

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 [19, 20, 21]. There are several methods for finding optimal locations of FACTS devices in both vertically integrated and unbundled power systems.

In [22] an algorithm for find the best location for the FACTS devices in multi-machine power systems using genetic algorithm is proposed. In [23] three criteria are considered for FACTS optimal allocations: available transfer capability criterion, steady state stability criterion and economic criterion. An alternative model that can optimize the placement of FACT devices based on multiple time periods with losses considered proposed in [24]. In [25] 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 [26]. 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 [27]. 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 [28]. 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 [29], dynamic compensation and stability improvement [30], enhancement of transient stability [31], voltage flicker control [32], damping of sub synchronous oscillations in EHV series compensated systems [33] and power quality improvement [34].

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 [35]. In [36] 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 [37]. Three models have been investigated for STATCOM: approximate model, detailed model and average model.

A. 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 [38]. The approximate model of the STATCOM is show in Fig. 7.

\[ u_c(t) = U_c \sin(\omega t - \theta_c) \]  

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The relationship between STATCOM ac voltage \( U_c \) and \( U_{dc} \) is:

\[ U_c = k M_R U_{dc} \theta_c \]  

(2)

The equivalent model of the STATCOM is show in Fig. 8. Two control signals can be applied to the STATCOM are magnitude control \( M_R \) and phase angle defined by PWM \( (\theta_c) \), 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:

\[
\frac{d}{dt} U_{dc} = \frac{k M_R C_{dc}}{U_{dc}} (I_{ud} \cos \theta_c + I_{sq} \sin \theta_c) - \frac{U_{dc}}{R_{dc}} 
\]  

(3)

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

C. Average Model in Stationary Coordinates

This model based on the dq representation, is derived in the stationary and synchronous frame of reference [39]. This model is used for the VSC and study the dynamics of theses control loops.

The circuit equivalent of STATCOM in dq synchronous frame is given in Fig. 9, where \( \omega \) is rotation speed, \( S_0 \) and \( S_0 \) are d-axis and q-axis synchronous reference frame inverter switching function, \( U_{sd} \) and \( U_{sq} \) d-axis and q-axis are synchronous reference frame source voltage, \( i_d \) and \( i_q \) are synchronous reference frame STATCOM current [40]. \( R_S \) and \( L_S \) mean line resistance and inductance, respectively.
Nonlinear such as adaptive control, particle swarm optimization and loop-shaping [46], controllers by the phase compensation method and fuzzy controller [47], and c) empirical methods such as Tabu search algorithm [48] and genetic algorithm [49].

A nonlinear controller which performance depends on the location of fault and on the location of the STATCOM is proposed in [50]. 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 [46].

VIII. Conclusion

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.

REFERENCES
