CHAPTER THREE

STATCOM Based on Voltage Source Converter

3.1 Introduction

Flexible AC transmission system (FACTS) controllers are power electronics based controllers. With the applications of FACTS technology, bus voltage magnitude and power flow along the transmission lines can be more flexibly controlled .Among the FACTS controllers, the most advanced type is the controller that employs Voltage Sourced Converter (VSC) as synchronous sources. Representative of the VSC type FACTS controllers are the Static Synchronous Compensator (STATCOM), which is a shunt type controller, the Static Series Compensator (SSSC), which is a series type controller and the Unified Power Flow Controller (UPFC), a combined series-shunt type controller. Of all the VSC the most widely used is the STATCOM. It can provide bus voltage magnitude control. Computation and control of power flow for power systems embedded with STATCOM appear to be fundamental for power system analysis and planning purposes. Power flow studies incorporating STATCOM requires accurate model in solution algorithms.

There are mainly two models of STATCOM which have well tested in power systems. There are the Current Injection Model (CIM) and the Power Injection Model (PIM). The CIM STATCOM has a current source connected in shunt the bus for 66 voltage magnitude control. The PIM models the STATCOM as shunt voltage source behind an equivalent reactance or impedance, which is also referred to as voltage source model (VSM). This steady state power injection model of STATCOM has proved reliable when incorporated in power systems and is well documented.

The STATCOM is a VSC system whose prime function is to exchange reactive power with the host AC system. In an electric power transmission system, the STATCOM can be used to increase the line power transmission capacity, to enhance the voltage/angle stability or to damp the system oscillatory modes. In a distribution system, the STATCOM is mainly used for voltage regulation; however, it can also supply real power to the loads in the case of a blackout if it is augmented with an energy storage device, for example, a battery storage system. Moreover, the STATCOM may also be employed to balance a distribution network by compensating for load imbalances.

3.2 Voltage source converter

Several VSC topologies are currently used in actual power system operations, such as the single-phase full bridge (H-bridge), the conventional three-phase, two-level converter, and the three-phase, three-level converter based on the neutral-point-clamped converter. There are other VSC topologies that are based on combinations of the neutral-point-clamped and multilevel converters. The common purposes of these topologies are: to minimize the operating frequency of the semiconductors inside the VSC and to produce a high-quality sinusoidal voltage waveform with minimum or no filtering requirements.

The topology of a conventional two-level VSC using IGBT switches is shown in Figure (3.1). It consists of six IGBTs, with two IGBTs placed on each leg. Moreover, each IGBT is provided with a diode connected in an anti-parallel connection to allow bidirectional current flow. Two equally sized capacitors are placed on the DC side to provide a source of reactive power [6].

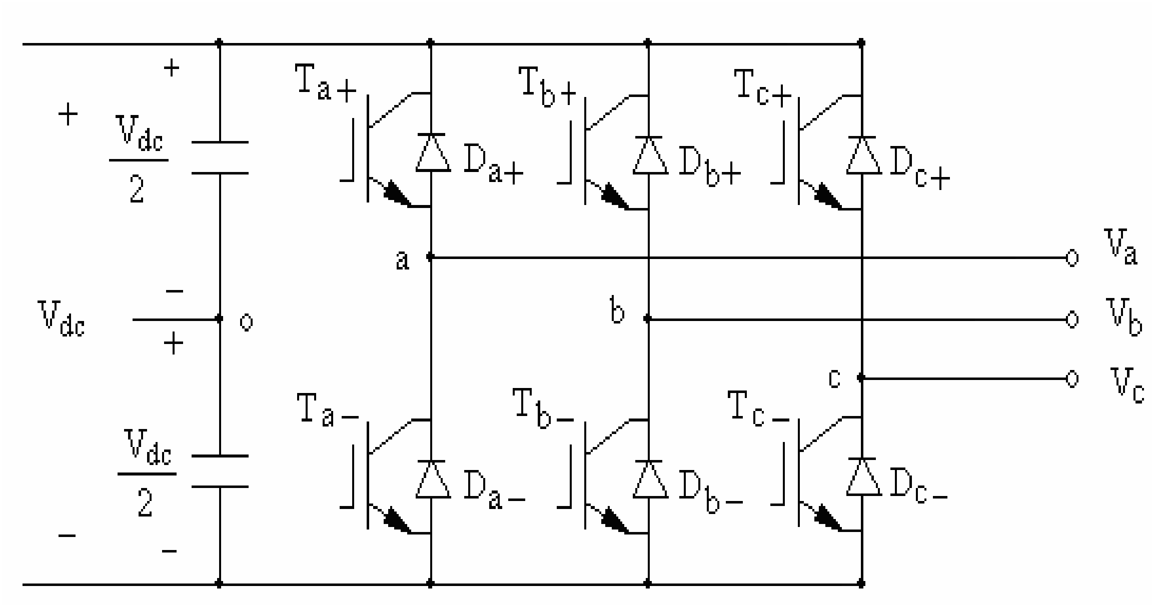

Figure (3.1) Topology of a three-phase, two-level VSC using IGBTs

The switching control module, not shown in the circuit of Figure 3.1, is an integral component of the VSC. Its duty is to control the switching sequence of the various semiconductor devices in the VSC, aiming at producing an output voltage waveform, which is close to a sinusoidal waveform as near as possible, with high power controllability and minimum switching loss. The current VSC switching strategies aimed at utility application may be classified into two main categories:

1. Fundamental frequency switching: the switching of each semiconductor device has only one turn-on, turn-off per power cycle. The output waveform is a quasi-square wave which often has an unacceptable high harmonic content. It is current practice to use several six-pulse VSCs, arranged to form a multiple structure, to achieve better waveform quality and high power ratings.

2. Pulse-Width-Modulation (PWM): the switches are forced to be turned on and off at a rate considerably higher than the fundamental frequency. The output wave is chopped and the width of the resulting pulse is modulated. Undesirable harmonics in the output waveform are shifted to the higher frequencies, and filtering requirements are much reduced. The

sinusoidal PWM scheme remains one of the most popular because of its simplicity and effectiveness.

These switching techniques are, however, far from perfect. The fundamental frequency switching technique requires complex transformer arrangements to achieve an acceptable level of waveform distortion. The PWM technique incurs high switching loss, but it is expected that future semiconductor devices will reduce this by a significant margin, making PWM the perfect switching technique [6].

3.3 Pulse-Width Modulation Control

The basic PWM switching scheme can be explained using the simple one-leg switch mode inverter shown in Figure (3.2)

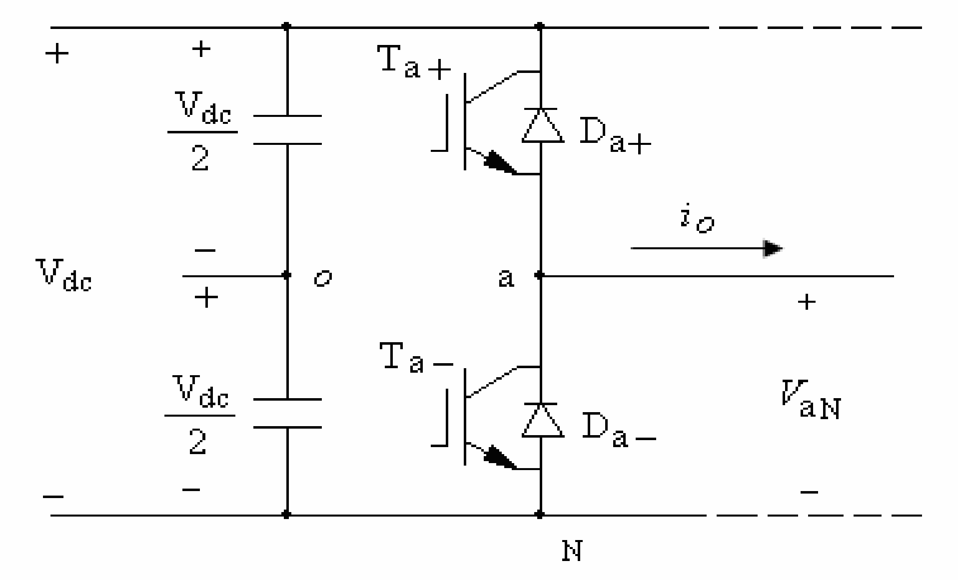

Figure (3.2) One-leg switch-mode inverter

In order to produce a sinusoidal output voltage waveform at a desired frequency, a sinusoidal control signal at the desired frequency is compared with a triangle waveform, as shown in Figure (3.3.a). The frequency of the triangular waveform establishes the inverter switching frequency f_s, and is generally kept constant along with its amplitude V_{tri}. The frequency f_s is also called the carrier frequency. The control signal

$V_{control}$ is used to modulate the switch duty ratio and has a frequency f_1, which is the desired fundamental frequency of the inverter voltage output (f_1 is also called the modulating frequency), recognizing that the inverter output voltage will not be a perfect sine wave and will contain voltage components at harmonic frequencies of f_1. The amplitude modulation ratio m_a is defined as

$$m_a = \frac{V_{control}}{V_{tri}} \qquad (3.1)$$

Where: $V_{control}$ is the peak amplitude of the control signal

The frequency modulation ratio m_f is defined as

$$m_f = \frac{f_s}{f_1} \qquad (3.2)$$

In the inverter of Figure (3.2), the switches T_{a+} and T_{a-} are controlled based on the comparison of $V_{control}$ and V_{tri}, and the following output voltage results, independent of the direction of the current i_o:

$V_{control} > V_{tri}$, T_{a+} is on, $V_{ao} = \frac{V_{dc}}{2}$

Or

$V_{control} < V_{tri}$, T_{a-} is on, $V_{ao} = -\frac{V_{dc}}{2}$ (3.3)

Since the two switches are never off simultaneously, the output voltage V_{ao} fluctuates between two values ($\frac{V_{dc}}{2}$ *and* $-\frac{V_{dc}}{2}$). The voltage V_{ao} and its fundamental frequency component (dashed curve) are shown in Figure (3.3 b).

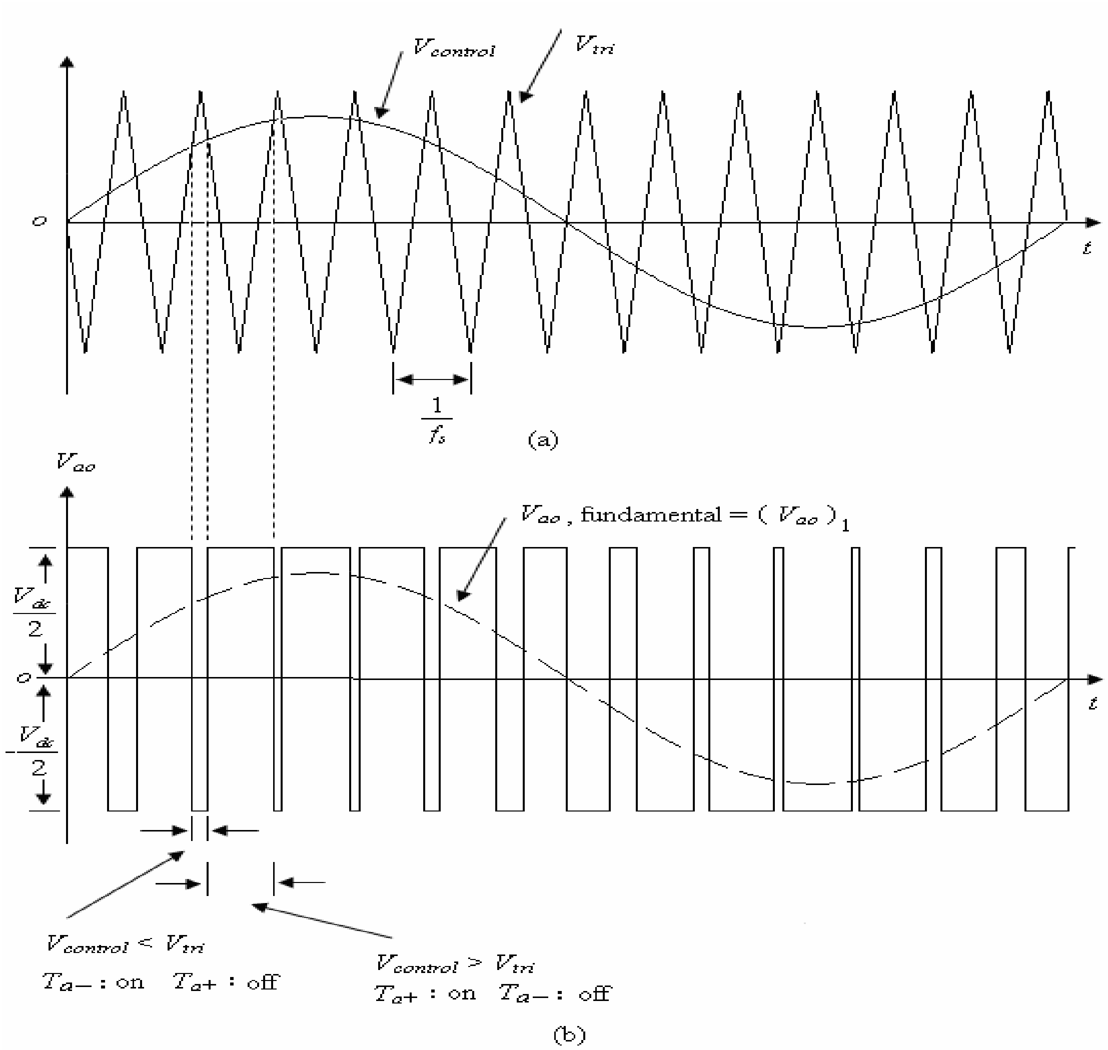

Figure (3.3) Operation of a pulse-width modulator: (a) comparison of a sinusoidal fundamental frequency with a high frequency triangular signal; (b) resulting train of square-waves.

With PWM, it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern, which can be done almost instantaneously. Hereby, PWM offers the possibility to control both the active and the reactive power independently.

This makes the PWM VSC close to an ideal component in the transmission network. From a system point of view, it acts as a motor or generator without a mass that can control the active and the reactive power almost instantaneously. Furthermore, it does not contribute to the short circuit power as the ac current can be controlled [6].

3.4 Principle of Voltage Source Converter Operation

Consider a VSC connected to an AC system through a lossless reactor as illustrated in Figure (3.4) the converter produces an AC voltage with a fundamental frequency equal to that of the AC reference voltage. The voltage at the supply bus is assumed to be $V_s \angle 0^0$, and the AC voltage produced by the VSC is taken to be $V_{sh} \angle \delta_{sh}$. X_l is the reactance of the converter reactor.

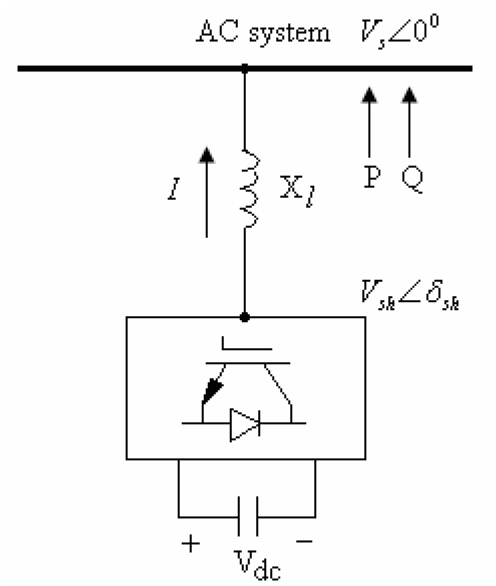

Figure (3.4) A VSC connected to an AC system.

The active and the reactive power can be expressed respectively as

$$P = \frac{V_{sh} V_s}{X_l} \sin \delta_{sh} \tag{3.4}$$

$$Q = \frac{V_{sh} V_s}{X_l} \cos \delta_{sh} - \frac{V_s^2}{X_l} \tag{3.5}$$

With respect to these two Equations, the following observations are noticed:

1. The active power flow between the AC source and the VSC is controlled by the phase angle δ_{sh}. The active power flows into the AC source from the VSC for $\delta_{sh} > 0$, and flows out of the AC source from the VSC for $\delta_{sh} < 0$,

2. The reactive power flow is determined mainly by the amplitude of the AC source voltage V_s, and the VSC output fundamental voltage V_{sh}, as the angle δ_{sh} is generally small. For $V_{sh} > V_s$, the VSC generates reactive power and while it consumes reactive power when $V_{sh} < V_s$ [6].

Because of its key steady-state operational characteristics and impact on system voltage and power flow control, the VSC is becoming the basic building block employed in the new generation of FACTS controllers.

The dynamic equations describe voltage source converters in open literature are:

$$\frac{di_{gd}}{dt} = -\frac{R}{L} i_{gd} + \frac{(v_{gd} - v_{cd} + \omega L i_{gq})}{L} \tag{3.6}$$

$$\frac{di_{gq}}{dt} = -\frac{R}{L} i_{gq} + \frac{(v_{gq} - v_{cq} - \omega L i_{gd})}{L} \tag{3.7}$$

$$\frac{dv_{dc}}{dt} = \frac{M_d i_d + M_q i_q}{C} \tag{3.8}$$

Where dq modulation index components are calculated as:

$$M_d = \tfrac{1}{2} M \cos\delta \tag{3.9}$$

$$M_q = \tfrac{1}{2} M \sin\delta \tag{3.10}$$

M is the modulation index and δ is the load angle between the converter terminal voltage V_c and the grid voltage V_g.

3.5 Control of STATCOM

The common feature of all VSC configurations is the generation of a fundamental frequency AC voltage from a DC voltage. The control of this voltage in both phase and magnitude is the basic function of the VSC. The phase angle and therefore the active power transfer are controlled by shifting the fundamental frequency voltage produced by the converter. While the reactive power flow is controlled by adjusts the converter voltage. The active and reactive power transfer can be either from the AC system to the converter or vice versa depending on the sign of the phase angle difference and voltage amplitude.

In a VSC, the control of reactive power flow is done by means Of PWM technique. With PWM modulation, the VSC controller can adjust the modulation index (*M*), and converter phase angle (δ) to give any combination of voltage and phase shift and hence, control the STATCOM reactive power flow. Vector control is the most popular technique to modify *M* and δ to achieve the desired control function.

In vector control the three-phase rotating voltage and current are transformed to the *dq* reference before calculating the modulation index and the phase angle. It is then synchronized with the ac three-phase voltages using a phase-locked-loop (PLL). The controlled variable is forced to follow the reference values to generate the desired values of *M* and δ and fed their values to the VSC. The control system of the VSC converters is composed of the inner controller and the outer controller. The main function of the inner controller is to control the currents in the complete range of actuation, and to ensure that the converter is not overloaded to protect the converter from transient. The outer controller is responsible for supplying the reference values to the inner controller.

3.5.1 Inner control

To ensure independent control of active and reactive power, the following new control variables are introduced:

$$u_d = v_{gd} - v_{cd} + \omega L i_{gq} \quad (3.11)$$

$$u_q = v_{gq} - v_{cq} - \omega L i_{gd} \quad (3.12)$$

These new control variables are obtained from a number of PI controllers as follows:

$$u_d = k_{pi}(i_{gd}^* - i_{gd}) + k_{ii}(i_{gd}^* - i_{gd}) \quad (3.13)$$

$$u_q = k_{pi}(i_{gq}^* - i_{gq}) + k_{ii}(i_{gq}^* - i_{gq}) \quad (3.14)$$

The inner control is shown in Figure (3.5)

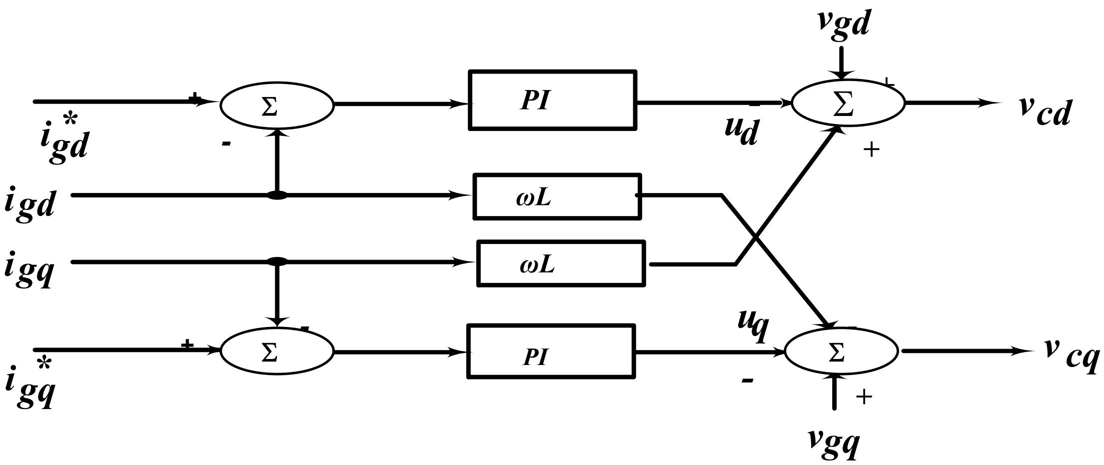

Figure (3.5) Inner control

3.5.2 Outer control

The STATCOM is design to control the dc voltage in d-axis and ac voltage in q-axis. Therefore the references dq- current components are found from the outer controls as follow:

$$i_{gd}^* = k_p(V_{dc}^* - V_{dc}) + k_i(V_{dc}^* - V_{dc}) \quad (3.15)$$

$$i_{gq}^* = k_p(V_{ac}^* - V_{ac}) + k_i(V_{ac}^* - V_{ac}) \quad (3.16)$$

The complete control block are shown in Figure (3.6)

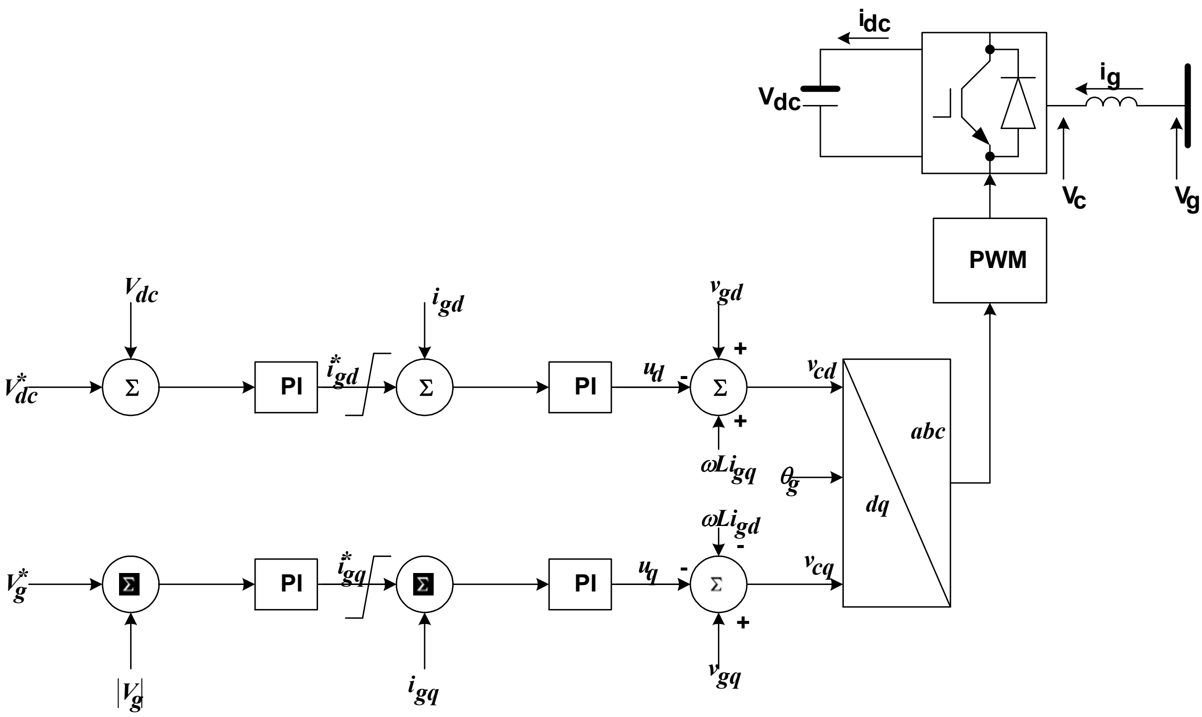

Figure (3.6) complete diagram of STATCOM