CHAPTER 5

ACTIVE POWER COMPENSATION OF STATCOM WITH ENERGY STORAGE SYSTEMS

5.1 INTRODUCTION

A STATCOM is a second generation FACTS controller based on a self-commutated solid-state voltage source inverter. It has been used with great success to provide reactive power/voltage control and transient stability enhancement. A STATCOM, however, can only absorb/inject reactive power, and consequently is limited in the degree of freedom and sustained action in which it can help the power grid (Chen 1996). The addition of energy storage allows the STATCOM to inject and/or absorb active and reactive power simultaneously, and therefore provides additional benefits and improvements in the system.

The voltage source inverter front-end of a STATCOM can be easily interconnected with an energy storage source. This viable technology is applicable for high power utility and defense applications. With Energy Storage Systems (ESS), STATCOM can provide the ride through over outages and voltage collapses (Arsoy et al. 2003). The VSC may operate as a backup power supply if energy storage capability is available on the DC side, the development of energy storage elements reduces voltage quality problems related to voltage sags and interruptions by serving as a driving force. Power oscillation occurs when there is a trip
of transmission lines, loss of generation, or large changes in electric load. The possible benefits of integrating ESS into a STATCOM are

- Compensation of sudden active load changes for the reduction of voltage phase jumps in weak networks
- Compensation of a cyclic load for the improvement of the power quality at the PCC

5.2 ENERGY STORAGE SYSTEM

Recent developments and advances in energy storage and power electronics technologies are making the application of energy storage technologies a viable solution for modern power applications. Viable storage technologies include batteries, flywheels, ultra capacitors, and superconducting energy storage systems. These technologies are now seen more as a tool to enhance system stability, aid power transfer and improve power quality in power systems (Boyes 2000, Paul Butler et al. 2002).

ESS can increase system reliability and dynamic stability, improve power quality and enhance transmission capacity of the transmission grid in a high power application (Panda and Patel 2007). For a high power application, the use of short-term (cycles to seconds) energy storage integrated with a FACTS controller, could offer the following distinct advantages:

- Provide system damping, while maintaining constant voltage following a disturbance
- Provide additional damping in situations where the dynamic reactive power provided by traditional FACTS controllers with similar ratings is inadequate. Alternatively, it could provide the same amount of damping at less cost.

- Damping of oscillation, by repeatedly interchanging small amounts of real power with the system, would be an excellent ESS application.

- Provide energy to maintain the speed of locally connected induction motors during a power system disturbance. This may prevent a voltage collapse in areas where there is a large concentration of induction motors that would otherwise stall.

The voltage sag mitigation techniques investigated by the aforementioned works aim to reduce the impact of voltage sags on some particularly protected loads. This work will instead describe control strategies for a STATCOM with ESS to provide high speed real and reactive power control and enhance the power flow in a line with cyclic loads. The study is focused on the voltage fluctuations caused by sudden changes in the load connected at the PCC. The STATCOM does not employ capacitor or reactor banks to produce reactive power but is used to maintain a constant DC voltage in order to allow the operation of the voltage source converter.

5.2.1 Energy Storage using Capacitors

The amount of energy a capacitor is capable of storing can be increased by either increasing the capacitance or the voltage stored on the capacitor. The stored voltage is limited by the voltage-withstand-strength.
of the dielectric. Capacitance can be increased by increasing the area of the plates, increasing the permittivity, or decreasing the distance between the plates. The turn-around efficiency when charging/discharging capacitors is also an important consideration, as is response time. The Effective Series Resistance (ESR) of the capacitor has a significant impact on both.

Several varieties of advanced capacitors are in development, with several available commercially for low power applications and these capacitors have the following characteristics: higher permittivity, higher surface areas, or higher voltage-withstand capabilities. Ceramic hyper capacitors have both a fairly high voltage-withstand (about 1 kV) and a high dielectric strength, making them good candidates for future storage applications. In addition, hyper capacitors have low ESR values. UCAP also known as super capacitors are double layer capacitors that increase energy storage capability due to a large increase in surface area through use of a porous electrolyte but they still have relatively low permittivity and voltage-withstand capabilities.

5.2.2 Energy Storage using Batteries

Batteries are one of the most cost-effective energy storage technologies available, with energy stored electrochemically. A battery system is made up of a set of low-voltage/power battery modules connected in parallel and series to achieve a desired electrical characteristic. Key factors of batteries for storage applications include: high energy density, high energy capability, round trip efficiency, cycling capability, life span and initial cost.

Batteries store energy in electrochemical form. Batteries require an AC/DC power conversion unit. Due to the chemical kinetics involved,
batteries cannot operate at high power levels for long time periods. In addition, rapid, deep discharges may lead to early replacement of the battery, since heating resulting in this kind of operation reduces battery lifetime. There are also environmental concerns related to battery storage due to toxic gas generation during battery charge/discharge. The disposal of hazardous materials presents some battery disposal problems. The disposal problem varies with battery technology.

Batteries can be designed for bulk energy storage or for rapid charge/discharge. Lead-acid batteries still represent a low-cost option for most applications requiring large storage capabilities, with the low energy density and limited cycle life as the chief disadvantages. Some of the disadvantages of BESS include limited life cycle, voltage and current limitations, and potential environmental hazards.

5.2.3 Energy Storage using SMES

SMES device was first proposed as an energy storage technology in the 1970s although the superconductor was discovered already in 1911. The characteristics of a SMES system such as rapid response (milliseconds), high power (multi-MW), high efficiency, and four-quadrant control can meet the power industry’s demands for more flexible, reliable and fast active power compensation devices. SMES systems can provide improved system reliability, dynamic stability, enhanced power quality and area protection (Padimiti and Chowdhury 2007).

Although superconductivity was discovered in 1911, it was not until the 1970s that SMES was first proposed as an energy storage technology for power systems (Boom and Peterson 1972). SMES systems
have attracted the attention of both electric utilities and the military due to their fast response and high efficiency about 95%.

A SMES unit stores energy in the magnetic field created by the DC current through the superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature (Ise et al. 1987). The inductively stored energy (in joules) and the rated power (in watts) are commonly given specifications for SMES devices. The one major advantage of the SMES coil is that it can discharge large amounts of power for a small period of time, also unlimited number of charging and discharging cycles can be carried out (Buckles and Hassenzahl 2000).

In SMES systems, it is the Power Conditioning System (PCS) that handles the power transfer between the superconducting coil and the AC system (Padimiti and Chowdhury 2007). According to topology configuration, there are three kinds of PCSs for SMES, namely, the thyristor-based PCS (Nitta et al. 1985, Ise et al. 1987), VSC based PCS (Tripathy and Juengst 1997) and CSC based PCS (Jun et al. 2003). The thyristor-based SMES can control mainly the active power, and has little ability to control the reactive power, also the controls of active and reactive powers are not independent (Rabbani et al. 1999). On the other hand, both the VSC and CSC-based SMES can control both active and reactive powers independently and simultaneously. Therefore, the applications in which mainly the active power control is required, the thyristor based SMES is used (Wu and Lee 1991) while the applications, in which reactive power or both active and reactive power controls are required, the VSC (Yu et al. 2002) or CSC-based SMES (Dong et al. 2002) is used.
5.2.4 Comparison between SMES and other Energy Storage Devices

There are several reasons for using SMES instead of other energy storage methods. Depending on the power conversion unit’s control loop and switching characteristics, the SMES device can respond very rapidly (MWs/ mili-seconds) to power demands from maximum charge to maximum discharge. Power is available almost instantaneously and very high power output can be provided for a brief period of time. Other energy storage methods have a substantial time delay associated with the energy conversion of stored mechanical energy back into electricity. Another advantage is that the loss of power is less than other storage methods because electric currents encounter almost no resistance. Additionally the main parts in a SMES are motionless, which results in high reliability.

SMES systems can offer very reliable and long lifetime service (Luongo et al. 2003), though the cost of SMES is currently high when compared to all other storage technologies.

SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. No conversion of energy from one form to another is required; consequently SMES has inherently high storage efficiency, a 95% or greater round trip efficiency. Among all energy storage systems SMES is suitable for high power applications. From economical point of view if SMES is connected to an already existing FACTS device, the cost of the DC - AC converter can be avoided.
5.3 THE SMES SYSTEM AND ITS ROLE IN POWER SYSTEMS

IEEE defines SMES as “A superconducting magnetic energy storage device containing electronic converters that rapidly injects and/or absorbs real and/or reactive power or dynamically controls power flow in an ac system”. It can be seen from Figure 5.1 that, a SMES system connected to a power system consists of several subsystems. A large superconducting coil is contained in a cryostat that consists of a vacuum vessel and contains liquid vessel that cools the coil. A refrigerator in the cryogenic system keeps the temperature of the superconductor well below the critical temperature.

A typical SMES system includes three parts: superconducting coil, power conditioning system and cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The Power Conditioning System (PCS) uses an inverter/rectifier to transform AC power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2-3% energy loss in each direction. Due to the energy requirements of refrigeration and the high cost of superconducting wire, SMES is currently used for short duration energy storage but SMES is most commonly devoted to improving power quality.

During SMES operation, the magnet coils has to remain superconducting. It allows the SMES system to respond within tens of milliseconds to power demands that could include a change from maximum charge rate to maximum discharge power. A transformer
provides the connection to the AC power system and the superconducting coil and reduces the operating voltage to acceptable levels for the PCS.

![Figure 5.1 Basic components of a SMES system](image1)

The converter/SMES system is highly efficient, as there is no energy conversion from one form to another. Converters may produce harmonics on the AC bus and in the terminal voltage of the coil. Using higher pulse converters harmonics can be reduced. For this purpose a 48-pulse VSC is chosen for the proposed work.

![Figure 5.2 PCS for SMES-based FACTS devices](image2)
In SMES, the DC current flowing through a superconducting wire in a large magnet creates the magnetic field and stores energy in the magnetic field. The inductively stored energy and the rated power for SMES devices can be expressed as follows:

\[ E = \frac{1}{2} LI^2 \]  

(5.1)

\[ P = \frac{dE}{dt} = LI \frac{dI}{dt} = VI \]  

(5.2)

where \( L \) is the inductance of the coil, \( I \) is the DC current flowing through the coil and \( V \) is the voltage across the coil. When DC current flows through the SMES coil, it is either charged or discharged depending upon the polarity of the applied voltage. When zero voltage is applied, the SMES coil is in standby mode, maintaining constant DC current.

### 5.4 INTEGRATION OF SMES WITH A STATCOM

SMES can be added to a FACTS controller as shown in Figure 5.3 to significantly improve the control actions of FACTS.

![Figure 5.3 Integration of SMES with a STATCOM](image)
The integration of a FACTS device with SMES can provide independent real and reactive power absorption/injection into/from the grid. If a transmission line experiences significant power transfer variations in a short time notice, a combination of FACTS and SMES can be installed to relieve the loaded transmission line.

5.4.1 Active and Reactive Power Control

In the case of a STATCOM/ESS as shown in Figure 5.4, the number of operating modes is extended to four. These modes are namely, inductive with DC charge, inductive with DC discharge, capacitive with DC charge and capacitive with DC discharge. Due to the nature of ESS, the STATCOM/ESS cannot be operated infinitely in one of the four modes because of the storage device charge/discharge cycle; therefore, these modes represent a transient-state operation.

Figure 5.5 shows the transient-state operational characteristics of the STATCOM/ESS output. Under steady-state, the output voltage of the traditional STATCOM spreads $V_{in}$ along the path shown in dashed lines. To control the reactive power generation or absorption, the STATCOM must keep the voltage at the DC bus capacitor at a required level and constant amplitude of the output voltage of the controller ($V_{inv}$). This is achieved by making $V_{inv}$ lag or lead the AC system voltage $V_{ac}$ by a small angle ($\alpha$) during reactive power injection and during reactive power absorption.
The STATCOM with reactive power injection capability enable the voltage to be rapidly controlled, but without active power capabilities, the rotor oscillations are not completely damped by the STATCOM. When an SMES coil is added to the STATCOM, both the voltage and rotor oscillations are quickly damped. In order to provide capacitive or inductive compensation, the controller must absorb or inject a small amount of active power from or to the AC system by using the DC capacitor. The limit values of $\alpha$, can be determined by the reactive power ratings of the STATCOM.
Figure 5.5  STATCOM/ESS output characteristics

In the case of a STATCOM/ESS, the output voltage can take any value within the circle as shown in Figure 5.5 during a time that is dependent both on the energy of the storage device and on the charge/discharge capacity of the STATCOM/ESS. The voltage at the DC capacitor can be controlled by using the interface of the energy storage device, i.e. by compensating reactive power. The active power injection or absorption can be controlled by leading or lagging the output voltage $V_{\text{inv}}$ by an angle $\alpha_2$ with respect to the AC system voltage ($V_{\text{ac}}$). The limit values of $\alpha_2$ can be determined by the active power ratings of the STATCOM/ESS. Hence active and reactive power compensation can be independently controlled, which enhances the device performance.

5.4.2  Control Scheme of STATCOM/SMES

The proposed internal control block as shown in Figure 5.6 generates the switching signals for the different thyristors of the VSC of the STATCOM and the DC-DC chopper. The proposed control scheme coordinates the control subsystems of the chopper and the VSC of the STATCOM. The control of the inverter is of the decoupled type according
to components of active and reactive power. This control has independent inputs of the reference signals of the current $I_{qr}$ and $I_{pr}$ injected in the connection bus. From these reference signals, the internal control determines the amplitude and phase ratings of the voltage at the VSC of the STATCOM with respect to the voltage at the AC system.

The duty cycle $D$ of the chopper is estimated ($D^*_{est}$) from the active power ratings that the STATCOM should inject ($V_{ac} \cdot I_{pr}$), from the voltage at the DC bus ($V_{dc}$) and from the current stored into the superconducting coil $I_{smes}$, as it is shown in Figure 5.6. $D^*_{est}$ is adjusted through a closed loop control whose function is to eliminate the voltage error between the calculated and the real voltage ratings at the DC bus.

![Figure 5.6  Internal control block of the VSI and DC-DC chopper](image)

The external control as shown in Figure 5.7 determines the active and reactive power exchange with the system. The output signals of this control block, $I_{qr}$ and $I_{pr}$ are used as inputs for the internal control
block as shown in Figure 5.6. This control has the responsibility of minimizing the magnitude and duration of system disturbances by regulating the output terminal voltage of the STATCOM and by damping power oscillation. The external control block is to maintain the system frequency above the acceptable minimum level during the disturbance.

The external control block regulates the voltage at the STATCOM bus through the control of the reactive component of the output current. The AC voltage measurement system is modeled as a low-pass filter with a gain $K_m$ and a time delay $T_m$. A phase-lag compensator is used to improve the performance of the voltage regulation system. In order to allow the terminal voltage of the STATCOM to vary in proportion with the compensating current a voltage regulation droop $R_d$ and a proportional gain $K$ are also included.

$$\frac{K_m}{T_m s + 1}$$

$$\frac{K}{T_2 s + 1}$$

$$\frac{I_{q\text{max}}}{I_{q\text{min}}}$$

$$\frac{I_{p\text{max}}}{I_{p\text{min}}}$$

$$\frac{I_{q\text{min}}}{I_{q\text{max}}}$$

$$\frac{(T_1 s + 1)}{T_2 s + 1}$$

$$\frac{(T_3 s + 1)}{T_4 s + 1}$$

$$\frac{K f}{R_p}$$

$$\frac{K f}{R_p}$$

$$\Delta V$$

$$\Delta I_p$$

$$\Delta f$$

$$V_{ae}$$

$$V_r$$

$$f$$

$$f_r$$

Figure 5.7  External control block of the STATCOM/SMES system

Power oscillation damping can be carried out by the modulation of the $I_{qr}$ or $I_{pr}$ current, or by the modulation of the two of them. However, the most effective control action for power oscillation damping
and controlling the system frequency is by exchanging active power with
the utility system. Power oscillation damping by the modulation of the
active output current is possible only with a STATCOM/SMES
combination. In this case, the reference of the active component of the
output current of the STATCOM/SMES is directly derived from $\phi I_p$.

A phase-lag compensator is used to enhance the performance of
the frequency control system. Thus, the active power exchange between the
STATCOM/SMES device and the electric system is controlled, forcing the
STATCOM to absorb active power when the generators accelerate, or to
supply active power when they decelerate. Similar to a DC capacitor of
traditional VSC STATCOM the SMES device must be partially charged at
a specific rating to allow power to be absorbed or injected from or into the
grid at any time. This results in change of positive and negative powers in
the circuit.

5.4.3 ESS-Chopper Topology

As the SMES coil is a current source device, another electronics
interface is needed to attach the coil to a VSC for exchange of power.
This interface is called a DC-DC chopper. It maintains the adequate
voltage across the coil terminals, applying the $V_{dc}$ during the charging
mode and reversing the voltage. During the power exchange the chopper
provides freewheeling path to the coil current even when no power
exchange is needed. The chopper controls the DC current and voltage
levels by varying the inverter DC output voltage as required across the
SMES coil terminal. The basic chopper topology is presented in Figure 5.8,
while the equivalent circuits during charging and discharging modes are
given in Figures 5.9 and 5.10 respectively. The value of coil current is
governed by the following differential equations:
The SMES coil is charged or discharged by making the voltage across the coil positive or negative. The coil absorbs power from the AC system and acts as a load during one half cycle when the VSC voltage is positive. During the next half cycle, the coil operates as a generator sending power back into the AC systems when the VSC voltage is made negative. When the SMES coil is on standby, independent of storage level, the current is constant, and the average voltage across the SMES coil is zero. A bypass switch shown in Figure 5.1 is used to reduce energy losses when the coil is on standby. The switch is also used for bypassing DC coil current disconnecting the converter from the circuit if cooling is needed.

The average voltage of the SMES coil is related to the STATCOM output DC voltage with the following equation. Equation (5.5) and Equation (5.6) exhibits the relationships within the chopper.

\[ V_{\text{coil}} = [1-2d]V_{dc} \]  

\[ L_{\text{SMES}} \frac{di_{\text{SMES}}}{dt} = V_{\text{ch}} V_c \quad \text{charging} \]  

\[ L_{\text{SMES}} \frac{di_{\text{SMES}}}{dt} = -\bar{V}_{\text{ch}} V_c \quad \text{discharging} \]

Figure 5.8 DC-DC chopper topology
\[ I_{dc} = [1-2d]I_{coil} \]  \hspace{1cm} (5.6)

where \( V_{\text{coil}} \) is the average voltage across the SMES coil, \( I_{\text{coil}} \) is the coil current, \( V_{dc} \) is the DC link capacitor voltage, \( d \) is the GTO conduction time over the period of switching cycle or duty cycle. These relationships can be interpreted as follows:

<table>
<thead>
<tr>
<th>Condition</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>( d &gt; 0.5 )</td>
<td>Coil is charging</td>
</tr>
<tr>
<td>( d &lt; 0.5 )</td>
<td>Coil is discharging</td>
</tr>
<tr>
<td>( d = 0.5 )</td>
<td>Coil is on standby</td>
</tr>
</tbody>
</table>

A 2-level one phase chopper as shown in Figure 5.9 is operated according to the four sub topologies shown in Figure 5.10. The SMES coil is charged (\( V_{\text{smes}} > 0 \)) when sub topologies I, III and IV are active, and it is discharged (\( V_{\text{smes}} < 0 \)) when sub topologies II, III and IV are active.

![Figure 5.9 2-level two-quadrant DC-DC chopper](image)
The current in SMES coil during charging and discharging is

\[
L \frac{d_i}{dt} = V_{\text{charge}} V_c \tag{5.7}
\]

\[
L \frac{d_i}{dt} = -V_{\text{discharge}} V_c \tag{5.8}
\]

where \( V_c = V_{ca} - V_{cb} \), \( V_{\text{charge}} \) and \( V_{\text{discharge}} \) are Boolean Variable governing the state of the switches in the chopper, \( V_c \text{ discharge} \) is the complementary of \( V_{\text{discharge}} \). Table 5.1 and Table 5.2 display the switching sequences of the chopper circuit during charging and discharging modes respectively.
Table 5.1  Chopper switching signals sequence during charging mode

<table>
<thead>
<tr>
<th>S_{chopper1}</th>
<th>S_{chopper2}</th>
<th>V_{charge}</th>
<th>V_{SMES}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>V_c</td>
</tr>
</tbody>
</table>

Table 5.2  Chopper switching signals sequence during discharging mode

<table>
<thead>
<tr>
<th>S_{chopper1}</th>
<th>S_{chopper2}</th>
<th>V_{charge}</th>
<th>V_{SMES}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-V_c</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

\[ S_{\text{Chopper}} = S_{\text{chopper}} (V_{dc \text{ ref}} - V_{dc}) \]  \tag{5.9}

where \( V_{dc} = V_{dc1} + V_{dc2} \). This restores the reference DC voltage. If \( S_{\text{chopper}} > 0 \), then \( V_{dc} < V_{dc \text{ ref}} \), this implies the discharging mode of SMES coil to recover DC voltage. If \( S_{\text{chopper}} < 0 \), then \( V_{dc} > V_{dc \text{ ref}} \) which makes the chopper to draw current from the DC to charge SMES coil and reduces the DC voltage.

\[
L \frac{d}{dt} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L \\ \omega L & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} - \begin{bmatrix} V_{cd} \\ V_{cq} \end{bmatrix} \]  \tag{5.10}

\[ \omega = \frac{d\theta}{dt} \]  \tag{5.11}
\[
\begin{bmatrix}
V_{cdref} \\
V_{qref}
\end{bmatrix}
= 
\begin{bmatrix}
V_{sd} + \omega LI_{qref} - L \frac{d}{dt} I_{def} \\
V_{sq} - \omega LI_{qref} - L \frac{d}{dt} I_{qref}
\end{bmatrix}
\] (5.12)

\[
V_{Cref} = \sqrt{V_{cdref}^2 + V_{qref}^2}
\] (5.13)

\[
\delta = \tan^{-1}\left[ \frac{V_{qref}}{V_{cdref}} \right]
\] (5.14)

\[
V_{dc}(t) = \frac{1}{c} \int_{-\tau}^{t} i_{dc}(t) dt
\] (5.15)

In case of the analysis of the chopper system no transformations are involved. As the chopper behaves as an ideal controllable voltage source the effects of the current harmonics are neglected.

**Figure 5.11 Chopper equivalent circuit**

In the equivalent circuit shown in Figure 5.11, the chopper voltages are as follows:

\[
V_{storage} = LdI/dt \text{ chopper} + V_{chopper}
\] (5.16)

\[
V_{chopper} = V_{storage} - \Delta V_{drop}
\] (5.17)
The voltage drop can be compensated using a P controller

\[ V_{\text{chopper}} = V_{\text{storage}} - L \Delta I / \Delta t_{\text{chopper}} \]  \hspace{1cm} (5.18)

\[ = V_{\text{storage}} - K_L \Delta I_{\text{chopper}} \]  \hspace{1cm} (5.19)

where \( K_L \) is the gain of the controller.

Using energy balance theorem

\[ P_{\text{chopper}} = P_{\text{dclink}} + P_{\text{losses}} + P_{\text{inVout}} \]  \hspace{1cm} (5.20)

\[ P_{\text{dclink}} = V_{\text{storage}} I_{\text{chopper}} - P_{\text{inVout}} - P_{\text{losses}} \]  \hspace{1cm} (5.21)

The PI controllers determine the \( I_{qr} \) and \( I_{pr} \) currents by using the difference between the measured dc link voltage and reference value, and the difference between terminal voltage and reference value, respectively. The reference signal for VSC is determined by converting \( V_d \) and \( V_q \) voltages which are determined by the difference between \( I_{qr} \) and \( I_{pr} \) currents and their measured values. The PWM signal is generated for electronic switching by comparing the reference signal which is converted to three-phase sinusoidal wave with the triangular carrier signal. The \( V_{\text{dc}} \) is kept constant throughout by the 6-pulse PWM converter.

5.4.4 Interface between ESS and the DC Link of the VSC

The DC link bus is the bridge between the ESS and the VSC. The DC link system can be modeled as shown in Figure 5.12. For a traditional STATCOM configuration, the DC link capacitor is necessary for an unbalanced system operation and harmonic absorption. For STATCOM with ESS, the DC link capacitor is to reduce the DC
current ripple from/into the ESS and therefore a smaller DC-link capacitor could be used. By controlling the firing of the chopper switching the relationship between the storage quantity and the corresponding quantity on the DC side of the VSC can be controlled. In SMES, energy is stored in a large lossless inductor.

![Figure 5.12 DC link regulator](image)

The size of the energy storage device on the DC side of the shunt converter can be calculated as

\[
E_{\text{shunt}} = S_{\text{load}} \cos \phi \Delta T
\]  

(5.22)

where, \( S_{\text{load}} \) is the rating of the protected load in MVA, \( \cos \phi \) is the power factor of the protected load and \( \Delta T \) is the duration of the disturbance in secs. \( E_{\text{shunt}} \) is the energy stored in KJ. Without ESS connected to the DC side of the converter, the active power at steady state must be zero. But in practice, some active power is drawn from AC network to compensate for the losses at the transformer and values. The active and reactive power measured at the AC bus is given as

\[
P = \frac{3}{2} \frac{V_L V_f}{X_L} \sin \delta
\]  

(5.23)
The phase shift angle $\delta$ can be adjusted by the feedback control to a small positive value. If $\delta$ is changed then $V_{\text{inv}}$ can be changed.

$$V_{\text{inv}} = \text{Constant} / V_{\text{dc}} \quad (5.25)$$

If $V_{\text{inv}} = V_{\text{ac}}$ then $\delta = 0$. Assuming AC bus bar voltage as a co-sinusoidal function and DC voltage is stiff, Fourier analysis of the converter phase voltage is

$$V_{f}(\phi - N(t)) = \frac{2}{\pi} V_{\text{dc}} \sum_{m=1}^{\infty} \frac{(-1)^{m} \cos \left( \frac{n(\omega t - \delta)}{n} \right)}{n}$$  

$$V_{f}(1) = \frac{2}{\pi} V_{\text{dc}} \quad (5.27)$$

where $V_{f}(1)$ is the fundamental frequency component of the VSC output voltage. DC capacitor size can be characterized as a time constant ($\tau$)

$$\tau = \frac{1}{2} C V_{\text{dc}}^{2} N / S_{N} \quad (5.28)$$

where $\frac{1}{2} CV_{\text{dc}}^{2} N$ is the stored energy at rated DC voltage when VSC current is zero and $S_{N}$ is the nominal apparent power of the converter. The purpose of inter phase inductors is to allow balanced current sharing for each chopper phase. It reduces the current ripples produced by the chopper in order to guarantee the ESS working life.
5.5 CONVERTER CONTROL FOR ACTIVE POWER EXCHANGE

Figure 5.13 depicts the connection scheme of a 24-pulse VSI with four 6-pulse elementary VSIs. The four inverters are shunt-connected in the DC side and series-connected in the AC side through coupling transformers. By combining two 24-pulse VSIs, phase-shifted 7.5° from each other, an equivalent 48-pulse inverter can be created, thus avoiding the use of large banks of capacitors for harmonics filtering. The output voltage waveform of the 48-pulse VSI is a staircase approximation of a sine wave and not a perfect sine wave. However, the multi-pulse converter supplies an almost sinusoidal current to the AC system, the current being smoothed through the tie-reactance of the coupling transformer. As a result, the net three-phase instantaneous power (VA) at the output terminal of the VSC fluctuates slightly, making the 48-pulse inverter satisfactory for high power utility applications.

Figure 5.13 24-pulse VSI
The interaction of the VSI with the AC system is shown in Figure 5.14 (a). The phasor diagram for fundamental frequency operation shown in Figure 5.14 (b) shows the active and reactive power flow exchanged by the STATCOM output terminal for each phase can be expressed through Equations (5.29) and (5.30) respectively;

The real and reactive powers are represented by

\[ P = 3V_s \frac{V_{an}\delta}{\omega L} \]  \hspace{1cm} (5.29)

\[ Q = 3V_s \frac{V_{cos}\delta - V_s}{\omega L} \]  \hspace{1cm} (5.30)

Using the above equations, the magnitude and phase angle of VSC voltage \( V_{VSC} \), the steady state control of active and reactive power is possible. However the dynamic control of VSC cannot be explained. From these equations, it can be concluded that the reactive power exchange between the inverter and the AC system can be controlled fundamentally.
by varying the amplitude of the three-phase output voltage. That is because practical phase-shift ratings are within ±10° so that the impact of this variable in Equation (5.29) is lower than ±1.5%. In a similar way, the active power exchange between the inverter and the AC system can be controlled basically by varying the phase-shift α. This is due to the fact that the impact of inverter voltage variations with respect to AC voltage is not higher than 5%.

For the following set of equations, it is assumed that the inverter behaves like an ideal controllable voltage source, neglecting the effects of the current harmonics. The capacitor filter is neglected in the analysis, since the filter current represents a small portion of the inverter’s current. The VI characteristics of the system can then be represented as shown in Figure 5.15.

Three-phase quantities are written in rotating reference frame for its simplicity and easiness in deriving the transfer functions needed for control system synthesis. Vector representations of instantaneous three-phase variables, orthogonal co-ordinates and rotating reference are demonstrated in Figure 5.15. A balanced three phase voltages (V₁, V₂, V₃) can be aligned on a stationary two axis (d-q) coordinate system and the d-q axis components can be given as

\[ V_{qs} = V_1 - V_2 \cos 60 - V_3 \cos 60 \]  
\[ = V_1 - V_2/2 - V_3/2 \]  
\[ V_{ds} = 0 + V_2 \cos 30 - V_3 \cos 30 \]  
\[ = V_2 \sqrt{3}/2 - V_3 \sqrt{3}/2 \]
The transformation matrix is

\[
\begin{bmatrix}
V_{ds} \\
V_{qs} \\
V_{os}
\end{bmatrix} = \begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \sqrt{3}/2 & -\sqrt{3}/2 \\
\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix}
\] (5.35)

With this three phase to two phase transformation as shown in Figure 5.11 the instantaneous powers in both coordinate systems must remain the same.

\[P_{dq} = P_{123} \] (5.36)

To obtain this condition the transformation matrix is multiplied by \(\sqrt{2}/3\).
In the above three phase to two phase stationary reference frame, the sinusoidal voltages $V_{qs}$ and $V_{ds}$ are time varying parameters. Due to this, the system model is complex and system response is very slow. To overcome this disadvantage, Paul C. Krause (1986) proposed a transformation from stationary to a fictitious rotary reference frame. With this model, the system response is very fast.

$$\omega_f = \frac{d\theta_f}{dt} \quad (5.41)$$

where, $\omega_f$ is the angular speed of orthogonal axis $d_f$ and $q_f$, and $\theta_f$ is the angular displacement.
\[
\begin{bmatrix}
V_{qf} \\
V_{df}
\end{bmatrix}
= \begin{bmatrix}
\cos \theta_f & -\sin \theta_f \\
\sin \theta_f & \cos \theta_f
\end{bmatrix}
\begin{bmatrix}
V_{qs} \\
V_{ds}
\end{bmatrix}
\] (5.42)

Using Park’s transformation

\[
T_2 = \begin{bmatrix}
\cos \theta_f & -\sin \theta_f \\
\sin \theta_f & \cos \theta_f
\end{bmatrix}
\] (5.43)

\[
T_2^{-1} = \begin{bmatrix}
\cos \theta_f & \sin \theta_f \\
-\sin \theta_f & \cos \theta_f
\end{bmatrix}
\] (5.44)

\[T_1 T_1 = T_{T1} \quad T_1 = \text{identity matrix}\]

\[T_2 T_2 = T_{T2} \quad T_2 = \text{identity matrix}\]

Using dynamic equations for each phase, for Decoupled Current Control,

\[
\begin{bmatrix}
V_1 \\
V_2 \\
V_3
\end{bmatrix}
= L \frac{d}{dt} \begin{bmatrix}
i_1 \\
i_2 \\
i_3
\end{bmatrix} + R \begin{bmatrix}
i_1 \\
i_2 \\
i_3
\end{bmatrix} + \begin{bmatrix}
V_{ao} \\
V_{bo} \\
V_{co}
\end{bmatrix}
\] (5.44)

\[
\begin{bmatrix}
V_{qf} \\
V_{df}
\end{bmatrix}
= \omega_f L \begin{bmatrix}
0 & 1 \\
-10 & 0
\end{bmatrix} \begin{bmatrix}
i_{qf} \\
i_{df}
\end{bmatrix} + L \frac{d}{dt} \begin{bmatrix}
i_{qf} \\
i_{df}
\end{bmatrix} + R \begin{bmatrix}
i_{qf} \\
i_{df}
\end{bmatrix} + \begin{bmatrix}
V_{c qf} \\
V_{c df}
\end{bmatrix}
\] (5.45)

where \( \omega_f = \frac{d \theta_f}{dt} \) (5.46)

\[V_{qf} = L \frac{di_{qf}}{dt} + \omega_f L i_{df} + R i_{qf} + V_{c qf} \] (5.47)
\[ V_{df} = L \frac{di_{df}}{dt} + \omega_f L_i_{qf} + R_i_{df} + V_{c_{df}} \] (5.48)

These equations represent the dynamic dq model of the VSC in a reference frame rotating at an angular speed of \( \omega_f \). In this model \( \omega_f, i_{df}, i_{qf} \) and \( V_{df} \) are state variables and \( V_{c_{df}} \) and \( V_{c_{qf}} \) are the inputs. Since the current components are not decoupled the dynamics of these components interfere with each other. By active power compensation, it is possible to reduce the bus voltage magnitude deviation and the phase jump. In case the active load is 3-phase symmetric, load current measurement is more straightforward than load power measurement. The measured load current is transformed into the dq plane using the angle from the PLL and the active current (q component) is taken as the reference for the active power compensation.

**5.6 SIMULATION OF POWER SYSTEM RESPONSE TO ACTIVE POWER COMPENSATION**

To illustrate the significant impact of STATCOM/ESS on cyclic loads, simulation studies are carried out and the results are presented in the following sections. The power consumption of cyclic loads varies with certain periods. A particle accelerator is a typical cyclic load consuming pulsating reactive and active power with varying power factor. Fast magnetization and demagnetization of the main magnets require short rise and fall times of the power during each power cycle. A cyclic load model used in this study is shown in Figure 5.16 to show the dynamic performance of the STATCOM with a SMES coil.
Although the voltage magnitude disturbance at the PCC is mainly caused by the pulsating reactive power, the active load power also plays a role. The pulsating active power will be mainly exchanged between the cyclic load and the converter, while the network only needs to supply the average active power to the load.

The load model of a particle accelerator main magnet supplied from a 48-pulse VSC is simulated in Matlab/ Simulink environment. The first load is initially synchronised with the grid. The second load is switched on after 0.5 sec. The load total capacity is 395 MVA. The accelerator consumes cyclic active and reactive power. Fast magnetization of the main magnet requires a short rise time of the load current. When the acceleration is finished, the main magnet should be demagnetized quickly, requiring a short fall time of the current. In the control system of the cyclic load implemented in Matlab the outer loop controls the load current and gives the references of the converter output DC voltage. The inner load voltage control loop controls the converter output voltage and delivers the command of the converter firing angle $\alpha$. 

![Cyclic load model diagram](image)
To obtain the sinusoidal voltage with low harmonic content the STATCOM is modelled with a 3-level 48-pulse VSC is build. Four 3-level 12-pulse converters are connected in series at the primary side of the coupling transformer to form equivalent 48-pulse voltage source converter, as shown in Figure 5.17. Two ordinary three-phase transformers have their secondary windings connected in delta and the other two in ungrounded star. The transformers connections and the necessary firing pulse logics are modelled to get the 48-pulse operations.

![Figure 5.17 48-pulse voltage source inverter](image_url)

The 48-pulse VSC can be used in high voltage, high power application without the need for any ac filters due to its very low THD content on the AC side. The output voltage have normal harmonics $n = 48k+1$, where $k = 0,1,2,...$ etc. This converter is used in STATCOM VSC block by replacing the DC source with energy storage device and connecting it with bus through appropriate interfacing inductor. Two 24-pulse GTO-converters, phase-shifted by $7.5^\circ$ from each other, can provide the full 48-pulse converter operation. Using a symmetrical shift criterion, the $7.5^\circ$ are provided in the following way: phase-shift winding...
with $-3.75^\circ$ on the two coupling transformers of one 24-pulse converter and $+3.75^\circ$ on the other two transformers of the second 24-pulse converter.

### 5.6.1 Integration of ESS with STATCOM

STATCOM circuit integrated with a capacitor bank, a battery and SMES as shown in Figure 5.18 is simulated and a comparison of the performance with and without STATCOM is made with the simulated results. The simulations have been performed in Matlab to verify the proposed compensation strategy circuit. The reliability and stability is very low for this method.

![Figure 5.18 STATCOM integration with SMES](image)

The dynamics of the integration of a STATCOM, and 100 MJ SMES coil (100 MW peak power and 24 kV DC interface) is modelled and simulated. The STATCOM is modelled with two 48-pulse voltage source inverters. The voltage source inverters are connected to the AC system through two coupling transformers, and linked to a 10 mF DC capacitor in the DC side. The DC link capacitor establishes equilibrium between the instantaneous output and input power of the inverter.
5.6.2 Simulation Results

Figure 5.19 to Figure 5.24 shows the simulation results obtained for the system compensated with STATCOM/SMES connected at the sending end, midpoint and the received ends of the system considered with cyclic loads.

**Figure 5.19** Active power at sending end with and without compensation

**Figure 5.20** Reactive power at sending end with and without compensation
Figure 5.21  Active power at receiving end with and without compensation

Figure 5.22  Reactive power at receiving end with and without compensation

Figure 5.23  Active power at mid point with and without compensation
Various algorithms have been reported in the past, on how to install/place FACTS devices to protect a sensitive load (De loiveira et al. 2000). Considerable researches have been done in the power system to find the optimal locations of FACTS devices. Capacitor banks can be sited at the midpoint of the transmission line, which has been proven in Kimbark (1998) as the optimum location for shunt capacitor compensation. This conclusion is extended to STATCOM in the proposed work and its location at sending end, midpoint and receiving end is analyzed. The location of the STATCOM device depends on the application for which it is installed. For improving HVDC link performance and bus voltage regulation, shunt FACTS devices are installed at the endpoints of transmission lines. However for increasing the power transfer capability of long transmission lines midpoint STATCOM is the best location (Mathur and Varma 2002). Hence the impact of midpoint STATCOM compensated line on the performance of cyclic loads is analyzed using Matlab. The real and reactive power responses of the compensator to cyclic loads are
compared for different locations. Power flow is analyzed by connecting STATCOM/ESS at different locations starting from sending end and loads are varied by a factor $\lambda$, until singular point of power flow linearization is reached. Three locations are identified and their power flow improvements obtained through simulation are shown in the following sections. The simulation results show that STATCOM with SMES provides effective voltage support at the bus to which it is connected to.

![Figure 5.25 Optimal location of STATCOM for active power compensation](image)

In the studied test system the location of the STATCOM at the midpoint is more appropriate because the effect of power flow control is the highest at this point. The location of the STATCOM is based on quantitative benefits evaluation. The location of STATCOM is generally chosen to be the location in the system which needs reactive power. To place a STATCOM at any load bus reduces the reactive power flow through the lines, thus, reducing line current and also the $I^2R$ losses. But when located at midpoint the active power is enhanced more as shown in Figure 5.25. The active power in the system without STATCOM is
0.3 (P.U). The active power is improved to 0.43 (P.U) when it is located at midpoint.

Similarly from Figure 5.26 it is proved that the reactive power gets reduced to 0.07 (P.U) when the STATCOM is located at the midpoint. It is concluded that the optimal location of STATCOM integrated with energy storage device in a power system network is midpoint.

![Figure 5.26 Optimal location of STATCOM for reactive power compensation](image)

When the STATCOM/ESS is connected at the midpoint we can observe that the real power is improved and shows the significant enhancement of the load ability margin of the power system. The midpoint has the weakest profile and maximum loading point or bifurcation point where Jacobian matrix becomes singular at $\lambda = 11.1614$. With STATCOM at midpoint, bifurcation for the system occurs at a higher load value than for the system, without STATCOM and with STATCOM at other locations.
Cyclic loads may create severe disturbances in the network. Simulations have shown that a STATCOM can provide fast reactive power support and thus can stabilize the bus voltage. Integration of energy storage with a STATCOM can further mitigate the voltage magnitude disturbance and provide active power support. Adding energy storage can reduce the MVA rating requirements of the STATCOM operating alone. The reactive power injected to the system is dependent on the STATCOM terminal voltage where as the SMES is ordered according to the variation of the real power flow in the system. SMES controlled is independent of the STATCOM controller.

The location where the compensator with SMES is connected is important for improvement of overall system dynamic performance. When connected at the midpoint the real power is improved and the load ability margin. The midpoint sitting of STATCOM also facilitates the independent control of reactive power at both the ends of the transmission line. For a given voltage limit, the midpoint sitting controls a larger reactive power because each side of the STATCOM device addresses only half the line impedance and not the full line impedance as in the case of the transmission line receiving end sitting and sending end sitting. The simulation study shows that a STATCOM with real power capability can improve the real power and enhance load stability margin, damp the power system oscillations more effectively and stabilize the system faster if the STATCOM-SMES controller is located at the midpoint rather than other places.