Abstract—Voltage Source Converters (VSC) have been widely utilized to provide instantaneous reactive power support to power systems, an application referred to as Static synchronous Compensators (StatCom). Integration of energy storage (ES) into a StatCom makes it possible for the StatCom to provide a certain amount of active power as well as reactive power support. The possible benefit of the additional active power support of a StatCom can be power oscillation damping capability, mitigation of phase-jump related disturbance, etc. Direct connection of ES device to the dc link of the VSC incurs unnecessary high voltage rating of the VSC due to the considerable voltage swing associated with the ES device. This paper proposes a thyristor converter topology as the interface between the ES device and the VSC dc link. With the proposed interface, the dc voltage of the VSC can be kept constant and thus lower the VSC rating and cost.

Keywords - StatCom; voltage source converter; VSC; energy storage; dc link; interface; active power support.

I. INTRODUCTION

Static synchronous Compensators (StatCom) have been widely utilized to enhance power system voltage stability and to increase the power transfer capacity due to its instantaneous reactive power support capability. Possible integration of energy storage into StatCom has been considered in recent years. It has been reported that improved performance in power oscillation damping can be achieved by integration of energy storage to a StatCom [1]-[3]. It has also been shown that a StatCom with active power compensation can mitigate disturbances, regarding both phase jump and magnitude fluctuation, created by sudden load changes in the connected network [4].

Integration of energy storage requires no change in the main circuit. With some modification of the control system, a StatCom is capable of providing a certain amount of active power as well as reactive power. The reduction in reactive power supply is small due to the quadratic relation between the active and reactive power. Depending on the power and energy level and the application requirements, the energy storage can be batteries, large conventional capacitor banks, or supercapacitors.

Large amounts of energy delivery and the recharging processes afterwards cause considerable voltage swings in the energy storage devices, especially for capacitors and supercapacitors. Even the voltage swing in batteries can be considerable. For instance, the charging voltage of Ni-Cd batteries is normally approximately 50% higher than the final discharging voltage [5].

The voltage stress on the voltage source converter (VSC) components can be very high if the energy storage devices are connected directly to the converter dc link. As a result, the VSC voltage rating has to be increased. For a VSC to deliver power to the network, a minimum dc side voltage must be maintained. If energy storage devices with a certain voltage swing are connected directly on the dc side, the final discharging voltage should be no lower than the minimum dc link voltage. Hence, the VSC voltage rating must be chosen as the charging voltage of the energy storage, which is considerably higher than the minimum required voltage. However, the VSC can be rated at the minimum required dc link voltage if the dc side voltage is kept constant during the charging and discharging processes. This can only be achieved with an interface between the energy storage and the VSC dc link. Topologies for low and medium voltage applications have been reported in literature. They are mainly IGBT based bi-directional dc/dc converters either with a single leg [6]-[9] or with three legs [10], [11].

In this paper, a topology based on dual thyristor converter for interfacing high-power energy storage with the dc link of a high-voltage VSC will be proposed. The high voltage and current handling capability and low cost features of thyristors make this topology attractive for high-power applications. The dual thyristor converter itself is not new. However, the application as an energy storage interface is a new concept. The proposed topology is suitable for applications where a Stat-
Com is required to deliver a moderate amount of active power (e.g., 20% of the rated power) in addition to the reactive power support.

II. THE DUAL THYRISTOR CONVERTER INTERFACE

A. The Topology

The proposed dual thyristor converter interface topology is depicted in Fig. 1. The thyristor converter is connected via transformer $T_2$ to the low-voltage side of the VSC transformer $T_1$. The dc side of the thyristor converter consists of an inductor and a capacitor $C_2$, which can be quite small. Capacitor $C_2$ is in series with the energy storage device ES and the whole branch is then connected in parallel with the dc-side capacitor ($C_1$) of the VSC. The dual thyristor converter consists of two standard three-phase thyristor bridges connected in antiparallel, as shown in Fig. 2. This enables a power flow in either direction and facilitates the charging and discharging of the energy storage devices. Since a 4-quadrant operation in the current-voltage plane can be achieved with this topology, it is possible to charge the energy storage devices to a voltage level higher than the steady-state dc side voltage of the VSC.

B. Dc Side Voltage and Power Flow

The output voltage of the thyristor converter is controlled such that the dc voltage of the VSC is always kept constant. In other words, the thyristor converter should always provide a voltage across capacitor $C_2$ that is the difference between the dc-side voltage of the VSC and the terminal voltage of the ES.

The power flow during a discharging process has the following pattern. When power $P_{ES}$ is delivered from the energy storage devices, the current passes through the thyristor converter. Meanwhile, the thyristor converter has to charge capacitor $C_2$ to keep the VSC dc side voltage. This incurs certain active power output from the thyristor converter. This part of power is sent through the VSC and then comes back to the thyristor converter. In other words, it is circulating through the VSC and the thyristor converter. The amount of the circulating power depends on the final discharging voltage of the energy storage devices and peaks at the instant when the voltage of the ES is the lowest. The peak value of the circulating power is determined by

$$P_{cl} = \frac{U_d - U_f}{U_f} P_{ES},$$

where $U_d$ is the VSC dc side voltage and $U_f$ is the final discharging voltage of the ES.

A lower final discharging voltage requires a higher voltage boost across $C_2$ and a higher discharging current, resulting in a higher circulating power.

The power flows with a similar pattern during the recharging process but with the opposite direction.

The dc side voltage and the power flow pattern can be illustrated through the results of the simulation with the power system simulation software – PSCAD. The specifications of the simulated system are listed in Table I. The energy storage device employed was conventional capacitor bank. The VSC was assumed to deliver 20 MW active power to the energy-consumption-load connected at the point of common coupling (PCC). The ES capacitor was discharged for 0.5 seconds from 0.2 s to 0.7 s and was re-charged afterwards slowly.
TABLE I
SPECIFICATIONS OF THE SYSTEM PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSC Rated power</td>
<td>100 MVA</td>
</tr>
<tr>
<td>VSC Rated current</td>
<td>1.5 kA (rms)</td>
</tr>
<tr>
<td>Rated ac voltage</td>
<td>38.5 kV (line-line, rms)</td>
</tr>
<tr>
<td>VSC dc side voltage</td>
<td>75 kV</td>
</tr>
<tr>
<td>Phase reactor inductance $L_v$</td>
<td>7.07 mH (0.15 pu)</td>
</tr>
<tr>
<td>Active power to be delivered</td>
<td>20 MW</td>
</tr>
<tr>
<td>Active power delivery period</td>
<td>0.5 s</td>
</tr>
</tbody>
</table>

Fig. 3 shows the dc side voltage of the VSC, the voltage of the ES and the voltage across $C_2$.

The power flow for the complete discharging/charging cycle is shown in Fig. 4. The energy storage capacitor was delivering 20 MW during the discharging period. There was a portion of active power circulating through the VSC and the thyristor converter. The peak of the circulating power was approximately 13 MW. The thyristor converter dc current is shown in Fig. 5.

### III. CONVERTER RATING

Even with the addition of the circulating active power, the VSC power rating does not increase proportionally since the circulating active power is in quadrature with the reactive power. However, with direct connection of the ES to the dc link, the power rating increases in proportion to the increase of the voltage rating. A rough comparison of the VSC rating can be made through a simple example.

Assume a 100 MVA VSC is supposed to provide additional 20 MW active power with the integration of energy storage on the dc side. The voltage swing of the energy storage device is 50%, i.e., the charging voltage $U_{chg}$ is 50% higher than the final discharging voltage $U_f$. The new rating of the VSC will be compared for the two cases.

In case of direct connection, the final charging voltage should be no lower than the minimum required VSC dc side voltage $U_{d_{min}}$. In order to provide required active power, the VSC voltage rating $U_{d_{1}}$ has to be increased by 50% and so does the power rating, i.e.
\[ U_{f_1} = U_{d_{\min}} \]
\[ U_{d_1} = U_{\text{chg}_1} = 1.5U_{d_{\min}} \]
\[ S_1 = \frac{U_{d_1}}{U_{d_{\min}}}S_{\text{base}} = 150 \text{ MVA} \]

where \( S_{\text{base}} = 100 \text{ MVA} \) is the original VSC power rating.

With the proposed topology, however, the following holds:
\[ U_{\text{chg}_2} = U_{d_{\min}} \]
\[ U_{d_2} = U_{\text{chg}_2} = 1.5U_{f_2} \]
\[ P_{d_{\min}} = 0.5P_{\text{ES}} \]

The VSC power rating is determined by:
\[ S_2 = \sqrt{S_{\text{base}}^2 + (P_{\text{ES}} + P_d)^2} = 104 \text{ MVA} \]

The rating of the thyristor converter depends on the peak of the circulating power, which is 10 MVA in this example.

The VSC voltage ratings in relation to the ES voltage swing for these two cases can be illustrated by Fig. 6.

Considering that thyristor converters are much cheaper than VSCs of the same rating, the proposed topology is economical and attractive. Detailed cost estimation will be presented in another paper.

IV. CONCLUSION

In applications where a StatCom is required to deliver a moderate amount of active power in addition to the reactive power support, the energy storage devices on the dc side create considerable voltage swings. A direct connection results in a significant increase in the VSC rating and cost. A dual thyristor converter topology is proposed for the interface between the energy storage devices and the VSC dc link. The high power handling capability and low cost features of thyristors make the topology an economical and attractive solution.

REFERENCES


