MODELING AND SIMULATION OF PWM BASED STATCOM FOR REACTIVE POWER CONTROL

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Abstract—This dissertation is dedicated to Modeling and Simulation of STATic synchronous COMPensator (STATCOM) for Reactive Power Control. Among Flexible AC Transmission System (FACTS) controllers, the STATCOM has shown feasibility in terms of cost effectiveness in a wide range of problem solving abilities from transmission to distribution levels. The Modular Multilevel Cascaded Converters (MMCCs) with separated Direct Current (DC) capacitors is the most feasible topology for use as a power converter in the STATCOM applications. To be able to operate in a high voltage application, a large number of DC capacitors are utilized in a MMCC based STATCOM. All DC capacitor voltages must be balanced in order to avoid overvoltage on any particular link. MMCC based on Single Delta Bridge Cells (SDBCs) to a STATCOM, particularly for reactive-power control. SDBC is categorized by cascade connection of multiple single phase H-bridge (or full bridge) converter cells per leg, hence simplifying flexible circuit design and low voltage steps. Modeling and Simulation of a 100V 5kVA Pulse Width Modulated (PWM) STATCOM based on the SDBC using MATLAB/Simulink, with focus on the operating principle and performance. Simulation results show that it can control positive sequence reactive power, negative sequence reactive power and also low frequency active power.

Index Terms—STATCOM, multilevel converters, MMCC, reactive power, positive –sequence reactive power, negative-sequence reactive power.

I. INTRODUCTION

The Family of MMCC is expected as one of the next-generation power converters suitable for high-voltage or medium-voltage applications without line-frequency transformers [1] – [21]. From power-circuit and converter-cell configurations, it can be classified into the following [2]:

1) Single Star Bridge Cells (SSBCs)
2) Single Delta Bridge Cells (SDBC)
3) Double Star Chopper Cells (DSCCs)
4) Double Star Bridge Cells (DSBC)

The term “bridge cell” is a single-phase H-bridge (or full bridge) converter, and the “chopper cell” is a bidirectional chopper consisting of a dc capacitor and two insulated-gate bipolar transistors. SSBC is a STATic Synchronous COMpenstator (STATCOM) for voltage regulation [11], [13] and battery energy storage systems [14], [15]. However, without significantly increasing the converter-cell count, the SSBC-based STATCOM cannot draw any negative sequence reactive power because it has no circulating current. The SDBC, DSCC and DSBC are suitable for STATCOM for negative sequence reactive power control because they have the circulating current(s) that flow inside. Converter-cell count required for the DSCC is four times of that for the SSBC.

The authors of this paper have described the DSCC acting as a STATCOM with focus on control and performance [20], [21]. Attention has been paid to STATCOMs based on the SDBC [8]-[10]. The SDBC seems to be a better choice than the DSCC from a practical point of view because the converter-cell count
required for the SDBC is only 1.7 (=√3) times of that for the SSBC [2]. The authors of this paper have described the SDBC acting as STATCOM with experimental verification using down scaled model of 100, 5 kVA. Experimental results verify that it can control not only positive-sequence reactive power but also negative sequence reactive power and low-frequency active power at the same time. However, no simulation verification has been made in the literature [1].

The aim of this paper is to provide modeling and simulation verification of an SDBC-based pulse width-modulated (PWM) STATCOM for reactive-power control. This paper proposes a control method that is characterized by forming a feedback loop of the circulating current among the delta-connected clusters, leading to stable dc-mean voltage control of all the dc capacitors. This paper models and followed by simulation verification using a downscaled model rated at 100 V and 5 kVA. Simulation results verify that it can control positive-sequence reactive power, negative sequence reactive power and low-frequency active power at the same time.

II. MMCC-SDBC CONFIGURATIONS

Fig. 1 shows two kinds of SDBC-based STATCOM. The SDBC is characterized by easily increasing the voltage and current ratings without using line frequency converter transformers.

Fig. 1(a) shows a 22-kV/33-kV system with a grid transformer. Each cluster of the SDBC is connected in delta configuration via a single coupled inductor. The leakage inductance of the transformer works as ac-link inductors between the grid and the SDBC.

Fig. 1(b) shows a 6.6-kV system with no grid transformer. Each cluster of the SDBC is connected via three noncoupled inductors. The SDBC can be connected directly to the 6.6-kV grid because the noncoupled inductors work as ac-link inductors.

![Fig. 1 SDBC-based STATCOM. (a) 22-kV/33-kV system with a grid transformer. (b) 6.6-kV system with no grid transformer](image)

III. CIRCUIT CONFIGURATION OF THE SDBC

A. Circuit Configuration

Fig. 2 shows the detailed circuit configuration of the 100V 5kVA STATCOM used in MATLAB/Simulink. Each cluster of the SDBC consists of cascade connection of three bridge cells (i.e., single-phase full-bridge PWM converters), and the three clusters are connected in delta configuration via a single coupled inductor Ls.

The SDBC is connected to three-phase ac mains of 100V (line to line in rms) via a three-phase ac-link inductor Ls that corresponds to the leakage inductance of the grid transformer in Fig. 1(a). Here, \(v_{uv}, v_{vw}, \) and \(v_{wu}\) are the cluster voltages, \(i_{uv}, i_{vw}, \) and \(i_{wu}\) are the cluster currents, and \(p\) and \(q\) are the instantaneous active and reactive powers at the PCC.

The following relations exist between the compensating currents and the cluster currents. The compensating currents and the supply currents are the same in Fig. 3 because no load (arc furnace) is connected.

\[
i_u = i_{uv} - i_{wu} \\
i_v = i_{vw} - i_{uv} \\
i_w = i_{wu} - i_{vw}.
\]

(1)

![Fig. 2 Circuit configuration of the 100V 5kVA MMCC SDBC PWM STATCOM](image)
Let the circulating current flowing inside the delta-connected clusters be $i_Z$. It is defined as

$$i_Z = \frac{1}{3}(i_{uv} + i_{vu} + i_{wu})$$

(2)

**B. Simulation Parameters Used**

Table I summarizes the simulation parameters of the SDBC which will be used in simulation later on.

**TABLE I Simulation Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Capacity</td>
<td>5kVA</td>
</tr>
<tr>
<td>Rated Line to Line rms voltage</td>
<td>Vs 100V</td>
</tr>
<tr>
<td>Rated Line Frequency</td>
<td>$\omega / 2 \pi$ 50 Hz</td>
</tr>
<tr>
<td>Rated Line Current</td>
<td>I 29 A</td>
</tr>
<tr>
<td>Rated Cluster Current</td>
<td>$2I / \sqrt{3}$ 34 A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Description</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Capacitor of Bridge Cell</td>
<td>C 164 mF/0.9 F</td>
</tr>
<tr>
<td>DC Capacitor Voltage Reference</td>
<td>$V_C^*$ 60 V</td>
</tr>
<tr>
<td>Unit Capacitance Constant</td>
<td>H 53 ms/2.9 s</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>$f_c$ 2 kHz</td>
</tr>
<tr>
<td>Equivalent Switching frequency</td>
<td>6$f_c$ 12 kHz</td>
</tr>
<tr>
<td>AC Link inductor</td>
<td>$L_s$ 0.5 mH (8%*)</td>
</tr>
<tr>
<td>Coupled inductor</td>
<td>$L$ 27 mH (37%*)</td>
</tr>
</tbody>
</table>

*% inductance is on a three phase, 100V 5kVA and 50Hz base

Each carrier frequency of phase-shifted PWM for bridge cells was set as $f_C = 2$ kHz. The command of each dc-capacitor voltage was set as $V_C^*$ = 60 V.

The dc capacitor was set as either C = 16.4 mF (H = 53 ms) or C = 0.9 F (H = 2.9 s). The ac-link inductor and the coupled inductor were set as $L_s = 0.5$ mH (8%) and $L = 2.3$ mH (37%), respectively.

**C. MATLAB/SIMULINK Model Development**

As shown in Fig 4(a) to 4(d), MATLAB/SIMULINK R2010a used to Model a Circuit configuration of 100V 5kVA MMCC SDBC PWM STATCOM and MATLAB/SIMULINK developed models shown in Fig 4(a) to 4(d).
Fig. 4(a) MATLAB/SIMULINK Modeling of Circuit configuration of 100V 5kVA MMCC SDBC PWM STATCOM

Fig. 4(b) MATLAB/SIMULINK Modeling of u-phase H-Bridges circuit

Fig. 4(c) MATLAB/SIMULINK Modeling of v-phase H-Bridges circuit
IV. CONTROL METHODS OF MMCC-SDBC BASED PWM STATCOM

Fig. 5 shows the MATLAB/SIMULINK Model-block diagram of the dc-capacitor voltage control. Voltage control of the nine floating dc capacitors in Fig. 2 can be divided into the following:

1) cluster-balancing control;
2) circulating-current control;
3) individual-balancing control.

A. Cluster-Balancing Control

Fig. 5(a) shows the MATLAB/SIMULINK Model-block diagram of the cluster-balancing control. The voltage major loop forces the average voltage of each cluster, namely, \( \overline{V_{Cu}} \), \( \overline{V_{Cv}} \), and \( \overline{V_{Cw}} \), to follow the average voltage of the three clusters \( \overline{V_C} \) where they are defined as

\[
\begin{align*}
\overline{V_{Cu}} &= \frac{1}{3} \sum_{j=1}^{3} V_{Cju}, \\
\overline{V_{Cv}} &= \frac{1}{3} \sum_{j=1}^{3} V_{Cvj}, \\
\overline{V_{Cw}} &= \frac{1}{3} \sum_{j=1}^{3} V_{Cwj}, \\
\overline{V_C} &= \frac{\overline{V_{Cu}} + \overline{V_{Cv}} + \overline{V_{Cw}}}{3}
\end{align*}
\]

Here, \( \overline{V_{Cu}} \), \( \overline{V_{Cv}} \), \( \overline{V_{Cw}} \), and \( \overline{V_C} \) are instantaneous values containing both ac and dc components. It is desirable to extract only the dc components (i.e., \( (\overline{V_{Cu}})_d \), \( (\overline{V_{Cv}})_d \), \( (\overline{V_{Cw}})_d \) and \( (\overline{V_C})_d \)) because the existence of the ac components deteriorates the controllability.
The last method is adopted in this project. Note that 
\[ \sin(\omega t + \pi/6) \]
and \( V_{uv} \) are in phase. When \( (V_{C} \_dc) > (V_{Cu} \_dc) \), the product of \( V_{uv} \) and \( i_Z \) forms positive active power. As a result, an amount of active power flows into the \( u \)-phase cluster, thus leading to increasing \( (V_{Cu} \_dc) \). On the other hand, the product of \( V_{uv} \) and \( i_Z \) forms negative active power. Therefore, the sum of the voltage commands is equal to zero. This means that no interference occurs between the individual balancing control and the circulating-current control.

### Circulating-Current Control

Fig. 5(b) shows the MATLAB/SIMULINK Model-block diagram of the circulating-current control. The current minor loop forces \( i_Z \) to follow its command, producing the voltage command \( V^*_A \) that is common to the three clusters.

### Individual-Balancing Control

Fig. 5(c) shows the MATLAB/SIMULINK Model-block diagram of the individual balancing control. It forms an active power between the ac voltage of each bridge cell and the corresponding cluster current. The voltage commands \( V^*_{ju} \), \( V^*_{jv} \), and \( V^*_{jw} \) are given by

\[
V^*_{ju} = K_4 (\bar{V}_{Cu} - V_{Cju}) i_{uv} \\
V^*_{jv} = K_4 (\bar{V}_{Cv} - V_{Cjv}) i_{vw} \\
V^*_{jw} = K_4 (\bar{V}_{Cw} - V_{Cjw}) i_{wv}
\]

The following equation is obtained from above equation:

\[
\sum_{j=1}^{3} V^*_{ju} + \sum_{j=1}^{3} V^*_{jv} + \sum_{j=1}^{3} V^*_{jw} = 0
\]

### Active-power, Reactive-Power, and Overall Voltage Controls

Fig. 6 shows the MATLAB/SIMULINK Model-block diagram of the active-power, reactive power, and overall voltage controls, in which \( p^* \) and \( q^* \) represent the power commands of \( p \) and \( q \) at the PCC. The dc component of \( q^* \) is adjusted to control positive-sequence reactive power keeping the relation of \( p^* = 0 \). On the other hand, a couple of second-order components (100 Hz) with the same amplitude but a phase difference of 90° are superimposed on \( p^* \) and \( q^* \), respectively, to control negative-sequence reactive power. A low-frequency component is superimposed on \( p^* \) to control active power, keeping the relation of \( q^* = 0 \). The line-to-line voltage commands \( V^*_{uv} \), \( V^*_{vw} \), and \( V^*_{wu} \) are determined by decoupled current control of the compensating currents. A voltage major loop intended for compensating the converter loss is formed as shown in Fig. 6 which forces \( (V_{C} \_dc) \) to follow its command \( V^*_C \).
V. SIMULATION RESULTS AND DISCUSSIONS

In the present work, 100-V 5-kVA downscaled model considered for the Modeling and Simulation of PWM STATCOM for Reactive Power Control. The following section explains the results obtained in the simulation.

Fig. 8 to 11 show the Simulation waveforms obtained from the 100-V 5-kVA downscaled model. All the Simulation waveforms were taken in a personal computer (PC) through the MATLAB/Simulink R2010a with different sampling frequencies.

Figs. 8, 9 and 11 had a sampling frequency of 100 kHz, and Fig. 10 had a sampling frequency of 20 kHz.

A. Negative-Sequence Reactive-Power Control

The instantaneous active and reactive power commands in the three-phase circuit $p^*$ and $q^*$ are given by

\[
p^* = 5 \cos(2\omega t + \frac{5\pi}{6}) [kW]
\]

\[
q^* = 5 \sin(2\omega t + \frac{5\pi}{6}) [kVAR]
\]  

where the initial phase was set as $\phi = 5\pi/6$ so that the amplitude of $i_w$ has its maximal value.

Equation (6) and block diagram of instantaneous active and reactive power controls, and overall voltage control give $i_d^*$ and $i_q^*$ as follows:

\[
i_d^* = 5 \cos(2\omega t + \frac{5\pi}{6}) [A]
\]

\[
i_q^* = 5 \sin(2\omega t + \frac{5\pi}{6}) [A]
\]  

where the dc component of $i_q$ coming from the overall voltage control is excluded from above equation.

Applying the inverse d–q transformation produces $i_u^*$, $i_v^*$, and $i_w^*$ as

\[
i_u^* = 41 \sin(\omega t - \frac{\pi}{6}) [A]
\]

\[
i_v^* = 41 \sin(\omega t + \frac{\pi}{2}) [A]
\]

\[
i_w^* = 41 \sin(\omega t - \frac{5\pi}{6}) [A]
\]  

It is obvious from above equation that $i_u^*$ leads $i_w^*$ by 120° and $i_v^*$ by 240°, thus resulting in drawing the negative-sequence reactive power from the ac mains.

Fig. 8 shows the Simulation waveforms when the rated negative-sequence reactive power of 5 kVAR was controlled. The cluster voltage $V_{uv}$ is a seven-level PWM waveform with a voltage step of 60 V ($=V_c$).
containing much less harmonic voltages as well as much less common-mode voltages than traditional two-level voltage-source PWM converters. Since the carrier frequency of each chopper cell is 2 kHz, the equivalent switching frequency of the cluster is 12 kHz (2 kHz x 6). The compensating currents \(i_u\), \(i_v\), and \(i_w\) agree well with their current commands.

The waveform of \(i_u\) can be considered as a sinusoidal waveform with a fundamental component of 50Hz. The total harmonic distortion value of \(i_u\) is low. The \(u\)-phase cluster acts as an inductor because \(i_{uv}\) lags \(V_{uv}\) by 90°.

On the other hand, the \(v\)- and \(w\)-phase clusters act as a capacitor because \(i_{vw}\) leads \(V_{vw}\) by 90°. The \(u\)-phase cluster acts as an inductor because \(i_{uv}\) lags \(V_{uv}\) by 90°.

The dc-capacitor voltages \(V_{C1u}\), \(V_{C1v}\), and \(V_{C1w}\) contain both dc and ac components, in which the voltage control regulates the dc component at 60 V. The ac component consists of a second-order (100 Hz) frequency component.

B. Active-Power and Reactive-Power Controls

Flicker compensation of arc furnaces requires to control positive-sequence reactive power, negative-sequence reactive power, and low-frequency active power at the same time.

Fig. 9 shows the Simulation waveforms when a positive-sequence capacitive reactive power of 1.7 kVAr, a negative-sequence reactive power of 1.7 kVAr, and a 10-Hz active power of 1.7 kW were simultaneously controlled with a condition of \(C = 16.4 \text{ mF}\). As an example, \(p^*\) and \(q^*\) are given by

\[
p^* = 1.7 \sin\left(\frac{\alpha t}{5}\right) + 1.7 \cos\left(2\omega t + \frac{5\pi}{6}\right)[kW] \tag{9}
\]

\[
q^* = 1.7 \sin\left(2\omega t + \frac{5\pi}{6}\right) - 1.7[kVA]
\]

Fig. 9 is one-third of that in Fig. 8 because the negative sequence reactive power in Fig. 8 is reduced to one-third of that in Fig. 8.
C. Low-Frequency Active-Power Control

To control a 1-Hz instantaneous active power of 5 kW, \( p^* \) and \( q^* \) are given by

\[
\begin{align*}
p^* &= 5 \sin \left( \frac{\omega t}{50} \right) [kW] \\
q^* &= 0 [kVAr]
\end{align*}
\]

(10)

Fig. 10 shows the Simulation waveforms in which each of the dc capacitors was replaced with \( C = 0.9 \text{ F} \) (\( H = 2.9 \text{ s} \)). Both compensating and cluster currents form 1-Hz envelopes as shown in Fig. 10, in which the amplitude of the cluster currents was \( 1/\sqrt{3} \) of that of the compensating currents. Carefully looking into Fig. 10 reveals that the amplitudes of both cluster and compensating currents when \( p^* > 0 \) are larger than that of the currents when \( p^* < 0 \) due to the converter loss.

The relation of \( i_Z = 0 \) always exists because no negative-sequence reactive power was controlled. The dc-capacitor voltages \( V_{C1u}, V_{C1v}, \) and \( V_{C1w} \) contain both 1- and 100-Hz components in which the former is much larger than the latter.

D. Transient-State Performance

It is clear from Fig. 11 that the STATCOM can achieve fast negative-sequence reactive-power control without delay time. However, the waveforms of \( V_{C1u}, V_{C1v}, \) and \( V_{C1w} \) show that a maximal voltage difference of 12V (20%) occurs during the transient state. To increase the capacitance of each dc capacitor is required to decrease the voltage difference during the transient period.

VI. CONCLUSION

This paper has discussed Modeling and Simulation of PWM based STATCOM using an MMCC-SDBC for Reactive Power Control, with focus on operating principle and performance, the simulation results obtained from the 100V 5kVA downscaled model has led to the following conclusions.

1) The SDBC has a capability to control negative-sequence reactive power with the help of the circulating current among the delta-connected clusters.
2) Positive-sequence reactive power, negative-sequence reactive power, and low-frequency active power can be controlled simultaneously.

These conclusions suggest that the SDBC is applicable to a STATCOM for Reactive Power Compensation.

VII. REFERENCES


