Harmonic Current Compensation Using Constant DC-Capacitor Voltage-Control-Based Strategy of Three-Level Neutral-Point-Clamped Inverter-Based STATCOM with Reactive Power Control

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This paper proposes a constant dc-capacitor voltage-control (CDCVC)-based reactive power control strategy of a static synchronous compensator (STATCOM) with a three-level neutral-point-clamped (NPC) inverter, in which the source-side harmonic currents are also compensated. The CDCVC-based reactive power control strategy uses only a CDCVC, which is always used in the grid-connected inverters, STATCOMs etc. Calculation blocks of fundamental active, reactive, and harmonic components are not needed. Thus, the authors offer a simplified strategy for a source-side reactive power control with source-side harmonic current compensations. The authors offer a simplified strategy for a source-side active power control with source-side harmonic current compensations. The instantaneous power flowing into the STATCOM with a three-level NPC inverter is discussed in detail. The instantaneous power flow shows that using the CDCVC-based strategy for the STATCOM achieves sinusoidal source currents using the controlled source-side reactive power compensating the harmonic currents on the source side. A digital computer simulation is implemented to confirm the validity and high practicability of the CDCVC-based strategy. A reduced-scale prototype experimental model is constructed and tested. The simulation and experimental results demonstrate that sinusoidal source currents are obtained with the CDCVC-based strategy controlling the reactive power on the source side.

Keywords: neutral-point-clamped inverter, static synchronous compensator, constant dc-capacitor voltage control, reactive power control, harmonics compensation

1. Introduction

Static synchronous compensators (STATCOMs) are now on practical to solve the reactive power interferences. A three-level neutral-point-clamped (NPC) inverter, which was originally proposed by Prof. Nabae, et al., is widely used in industries. The three-level NPC inverter-based STATCOM can be directly connected to the 6,600-Vrms high-voltage distribution feeders. This is a great advantage of the three-level NPC inverter-based STATCOM. For the control strategy of the STATCOMs, the instantaneous active-reactive power theory originally proposed by Prof. Akagi, et al. is widely used. Most of this control algorithm is based on instantaneous active-reactive power theory and its extensions for the calculation of reference currents. A synchronous reference frame, decomposition in the time domain of the load currents and theory of instantaneous symmetrical component are also proposed. These reference current calculation methods require a large number of computation steps including transformation blocks. In single-phase three-wire distribution feeders, the present authors proposed a constant dc-capacitor voltage-control (CDCVC)-based strategy of the smart charger (SC) for electric vehicles (EVs) that can achieve sinusoidal and balanced source currents with a controlled reactive power on the source side.

This paper proposes a CDCVC-based reactive power control strategy for a three-level NPC inverter-based STATCOM, in which the source-side harmonic currents are also compensated. The CDCVC-based reactive power control strategy uses only a CDCVC, which is always used in the grid-connected inverters, STATCOMs etc. Calculation blocks of fundamental active, reactive, and harmonic components are not needed. The authors offer a simplified strategy for a source-side reactive power control with source-side harmonic current compensations. The instantaneous power flowing into the STATCOM with a three-level NPC inverter is discussed in detail. The instantaneous power flow shows that using the CDCVC-based strategy for the STATCOM achieves sinusoidal source currents using the controlled source-side reactive power compensating the harmonic currents on the source side. The simulation and experimental results demonstrate that sinusoidal source currents are obtained with the CDCVC-based strategy controlling the reactive power on the source side.
2. Constant DC-Capacitor Voltage-Control-Based Strategy for STATCOM

Figure 1 shows a circuit diagram of a three-level NPC inverter-based STATCOM with the proposed constant dc-capacitor voltage-control (CDCVC)-based reactive power control strategy. The proposed strategy uses only the CDCVC block, which is always used in the grid-connected inverters, STATCOMs etc. To claim the novelty, simplicity, and practicability of the proposed CDCVC-based reactive power control strategy, the authors, now, compare the proposed strategy to the reactive power control strategy with the instantaneous active-reactive power theory originally proposed by Prof. Akagi, et al. In Figure 1, three-phase terminal voltages \( v_{Ta}, v_{Tb}, \) and \( v_{Tc} \) are expressed as

\[
\begin{align*}
    v_{Tt} & = \sqrt{2} V_T \cos \omega t, \\
    v_{Tb} & = \sqrt{2} V_T \cos \left( \omega t - \frac{2}{3} \pi \right), \\
    v_{Tc} & = \sqrt{2} V_T \cos \left( \omega t + \frac{2}{3} \pi \right) \quad \text{................................(1)}
\end{align*}
\]

Let assume that the three-phase load currents \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) include harmonic currents. The three-phase load currents \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) are expressed as

\[
\begin{align*}
    i_{La} & = \sqrt{2} I_{L1} \cos (\omega t - \phi_1), \\
    i_{Lb} & = \sqrt{2} I_{L1} \cos \left( \omega t - \frac{2}{3} \pi - \phi_1 \right), \\
    i_{Lc} & = \sqrt{2} I_{L1} \cos \left( \omega t + \frac{2}{3} \pi - \phi_1 \right) \quad \text{................................(2)}
\end{align*}
\]

When the terminal voltages \( v_{Ta}, v_{Tb}, \) and \( v_{Tc} \), and the load currents \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) are transformed into \( \alpha-\beta \) coordinates, the instantaneous active power \( p \) and instantaneous reactive power \( q \) are given by

\[
\begin{pmatrix}
    p \\
    q
\end{pmatrix} =
\begin{pmatrix}
    v_{Ta} & v_{Tb} \\
    -v_{Tb} & v_{Ta}
\end{pmatrix}
\begin{pmatrix}
    i_{La} \\
    i_{Lb}
\end{pmatrix} \quad \text{................................(3)}
\]

From (3), the three-phase load currents on \( \alpha-\beta \) coordinates are decomposed as

\[
\begin{align*}
    i_{La} & = \frac{v_{Ta}}{v_{Ta}^2 + v_{Tb}^2} \hat{p} + \frac{v_{Tb}}{v_{Ta}^2 + v_{Tb}^2} \hat{q}, \\
    i_{Lb} & = -\frac{v_{Tb}}{v_{Ta}^2 + v_{Tb}^2} \hat{p} + \frac{v_{Ta}}{v_{Ta}^2 + v_{Tb}^2} \hat{q}, \\
    i_{Lc} & = \frac{v_{Ta}^2 + v_{Tb}^2}{v_{Ta}^2 + v_{Tb}^2} \hat{p} - \frac{v_{Tb}}{v_{Ta}^2 + v_{Tb}^2} \hat{q},
\end{align*}
\]
the dc component of the three-phase source currents that contains the fundamental components, and \( \tilde{\mathbf{p}} \) and \( \tilde{\mathbf{q}} \) are originated in the harmonic components in (2). In (4), controlling the dc component \( \tilde{\mathbf{q}} \) on the source side with \( \mathbf{p} \) achieves the reactive power control on the source side.

Figure 2 shows a control circuit diagram for STATCOMs. Figure 2(a) shows a block diagram of the instantaneous active-reactive power theory-based reactive power control strategy. Figure 2(b) shows a block diagram of the proposed CDCVC-based reactive power control strategy, which is the part enclosed by the dotted line in Figure 1. The authors, thus, claim that the simplified source-side reactive power control strategy is offered.

The basic principle of the proposed CDCVC-based reactive power control strategy is, now, discussed in detail. When the harmonic currents of the three-phase load currents \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) are compensated on the source side by the STATCOM with the proposed CDCVC-based reactive power control strategy, the three-phase source currents \( i_{Sa}, i_{Sb}, \) and \( i_{Sc} \) are sinusoidal with a controlled reactive power. Three-phase source currents, therefore, can be expressed as

\[
i_{Ga} = \sqrt{2} I_s \cos(\omega t - \phi) = \sqrt{2} I_p \cos(\omega t + K \sin(\omega t)),
\]
\[
i_{Gb} = \sqrt{2} I_s \cos(\omega t - \frac{2}{3} \pi - \phi) = \sqrt{2} I_p \left( \cos(\omega t - \frac{2}{3} \pi) + K \sin(\omega t - \frac{2}{3} \pi) \right),
\]
\[
i_{Gc} = \sqrt{2} I_s \cos(\omega t + \frac{2}{3} \pi - \phi) = \sqrt{2} I_p \left( \cos(\omega t + \frac{2}{3} \pi) - K \sin(\omega t + \frac{2}{3} \pi) \right),
\]

where \( I_p = I_s \cos \phi \) and \( K = \tan[\cos^{-1}(\text{power factor (PF)})].\)

The RMS value \( I_p \) of the active currents in each phase on the source side in (5) is given by

\[
I_p = I_{L1} \cos \phi_1.
\]

Note that this \( I_p \) equals the RMS value of the active currents \( I_p = I_{L1} \cos \phi_1 \) on the load side. Thus, it is concluded that the CDCVC of the STATCOM in Figure 1 can calculate the fundamental active current of the load currents \( i_{La}, i_{Lb}, \) and \( i_{Lc} \) in three-phase circuits. In the control circuit block of Figure 1, the dc-capacitor voltages \( V_{C1} \) and \( V_{C2} \) are detected. Then, the
The difference between the detected dc-capacitor voltage $v_{C1} + v_{C2}$ and the reference value $V_{DC}$ of the dc-capacitor voltage is amplified by the proportional-integral (PI) controller. A moving-average low-pass filter (LPF) is used to remove the $6\omega$ angular frequency component, where $\omega$ is the angular frequency of the terminal voltages $v_{Ta}$, $v_{Tb}$, and $v_{Tc}$. Then, the RMS value $I_p$ of the active currents in each phase is obtained. With the control gain $K$, the RMS value of the fundamental reactive currents on the source side is calculated, where this control gain $K$ can control the reactive power on the source side. Figure 3 shows a per-phase phasor diagram for the terminal voltage $V_{T}$, the source current $i_S$, and the load current $I_L$. From Figure 3, controlling the control gain $K$ can control the source-side reactive power. The line-to-line voltages $v_{ab}$ and $v_{bc}$ are detected, and then, an electrical angle $\theta_b$ is generated using a three-phase phase-locked-loop (PLL) (15). Using this $\theta_b$, $I_p$, and $K_I$, the source currents $i_{S1}$, $i_{S2}$, and $i_{S3}$ with the controlled reactive power in $a$-$b$-$c$ coordinates are calculated. Subtracting the calculated $i_{S1}$, $i_{S2}$, and $i_{S3}$ from the detected load currents $i_{La}$, $i_{Lb}$, and $i_{Lc}$ gives the reference values $i_{Ca}$, $i_{Cb}$, and $i_{Cc}$ of the STATCOM. The reference values $i_{Ca}$, $i_{Cb}$, and $i_{Cc}$ in $a$-$b$-$c$ coordinates are given by

$$i_{Ca} = i_{La} - i_{Sa},$$

$$i_{Cb} = i_{Lb} - i_{Sb},$$

$$i_{Cc} = i_{Lc} - i_{Sc}.$$  \hspace{1cm} (10)

The PI controllers in $d$-$q$ coordinates are used to control the output currents $i_{Ca}$, $i_{Cb}$, and $i_{Cc}$. Thus, the differences between the reference values $i_{Ca}^*, i_{Cb}^*$, and $i_{Cc}^*$ and the detected values $i_{Ca}$, $i_{Cb}$, and $i_{Cc}$ in $a$-$b$-$c$ coordinates are transformed into $i_{Ca}^*$ and $i_{Cc}^*$, respectively. $i_{Ca}$ and $i_{Cc}$ are amplified by the PI controllers in $d$-$q$ coordinates. The amplified differences are retransformed into $a$-$b$-$c$ coordinates. It is well known that two dc-capacitor voltages $v_{C1}$ and $v_{C2}$ are unbalanced (16).

Prof. H. Akagi et al. proposed a voltage-balancing control with the 6th-order zero-sequence voltage $\cos(6\theta_b + \phi)$ for a three-level NPC inverter (16). The basic principle of the proposed voltage-balancing control was discussed in detail. The experimental results demonstrated that adding $\cos(6\theta_b + \phi)$ to the reference values of the three-phase output voltages well balanced two dc-capacitor voltages, where $\phi = 1.4$ rad. In this paper, the 6th-order zero-sequence voltage is, thus, added to the reference values of the three-phase output voltages $v_{B1}$, $v_{B2}$, and $v_{B3}$ in Figure 1. For more detail, see the literature (17). The 6th-order zero-sequence voltage is added to the three-phase reference voltages $v_{B1}$, $v_{B2}$, and $v_{B3}$ (16). A sinetriangle intercept technique is used to generate the gate signals for twelve insulated-gate bipolar transistors (IGBTs).

![Fig. 3. Per-phase phasor diagram for the terminal voltage $V_T$, the source current $i_S$, and the load current $I_L$.](image)

### Table 1. Circuit constants for Figure 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td>Source inductor</td>
<td>$L_a$</td>
<td>0.8 mH</td>
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<td>Switching inductor</td>
<td>$L_{S}$</td>
<td>12.8 mH</td>
</tr>
<tr>
<td>Filter capacitor</td>
<td>$L_p$</td>
<td>44.8 mH</td>
</tr>
<tr>
<td>Reference dc-capacitor voltage</td>
<td>$V_{dc}$</td>
<td>400 Vdc</td>
</tr>
<tr>
<td>DC capacitor</td>
<td>$C_1$</td>
<td>14300 µF</td>
</tr>
<tr>
<td>DC capacitor</td>
<td>$C_2$</td>
<td>14300 µF</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>$f_{sw}$</td>
<td>17 kHz</td>
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</tbody>
</table>

![Fig. 4. Simulation waveforms for Figure 1 with the control gain $K = \tan(\cos^{-1}(PF)) = 0$ as shown in Figure 3.](image)

### 3. Simulation Results

Digital computer simulation is implemented to confirm the validity and high practicability of the proposed CDVCV-based reactive power control strategy using PSIM software. The three-phase load currents $i_{La}$, $i_{Lb}$, and $i_{Lc}$ include the 5th- and 7th-order harmonic currents in following simulation results. The ratings of three-phase source voltages are 200 Vrms and 60 Hz. The rated three-phase load is 10 kVA. Therefore, the RMS value of the fundamental components of the load currents is 28.7 Arms. The 5th-order components of 5.7 Arms, which is 20% as compared to the RMS value of fundamental component, and the 7th-order components of 4.1 Arms, which is 14.3%, are also included in the load currents $i_{La}$, $i_{Lb}$, and $i_{Lc}$. Thus, total harmonic distortion (THD) values of $i_{La}$, $i_{Lb}$, and $i_{Lc}$ are 24.6%. The PF between the terminal voltages and load currents is 0.70. Table 1 shows circuit constants for Figure 1, which were used in the following simulation results.

Figure 4 shows simulation results for Figure 1 with the control gain $K = \tan(\cos^{-1}(PF)) = 0$ as shown in Figure 3. $v_{T}$, $v_{B1}$, $v_{B2}$, and $v_{B3}$ are the terminal voltage waveforms and $i_{Sa}$, $i_{Sb}$, and $i_{Sc}$ are the source current waveforms. $i_{La}$, $i_{Lb}$, and $i_{Lc}$ are the load current waveforms; $i_{Ca}$, $i_{Cb}$, and $i_{Cc}$ are the compensation current waveforms of the STATCOM with the three-level NPC inverter; and $v_{C1}$ and $v_{C2}$ are the dc-capacitor voltage waveforms. Although the load currents $i_{La}$, $i_{Lb}$, and $i_{Lc}$ are distorted with the PF of 0.70, the source currents $i_{Sa}$, $i_{Sb}$, and $i_{Sc}$ are sinusoidal with the PF of 1.00. The THD values of $i_{Sa}$, $i_{Sb}$, and $i_{Sc}$ are 5.8%, 5.9%, and 5.8%, respectively. The dc-capacitor voltages $v_{C1}$ and $v_{C2}$ are well balanced with the method proposed in (17). The ripples of $v_{C1}$ and $v_{C2}$ are ±
of the proposed control method, which uses only CDCVC for the STATCOM. Figure 7 shows a block diagram of the constructed prototype experimental model. The ratings of three-phase source voltage are 200 Vrms and 60 Hz. Three-phase load consists of three-phase diode rectifier and Y-connected inductor. The rated three-phase load is 6.7 kVA. The PF between the terminal voltages and load currents is 0.60, and THD values of $i_{a}$, $i_{b}$, and $i_{c}$ are 13.6%. Table 2 shows circuit constants for Figure 7, which were used in the following experimental results. The detected line-to-line voltages $v_{ab}$, $v_{bc}$, and $v_{ca}$ are the terminal voltage waveforms and $i_{a}$, $i_{b}$, and $i_{c}$ are the source current waveforms. $i_{a}$, $i_{b}$, and $i_{c}$ are load current waveforms; $i_{a}$, $i_{b}$, and $i_{c}$ are the compensation current waveforms of the STATCOM with the NPC inverter, and $v_{c1}$ and $v_{c2}$ are the dc-capacitor voltage waveforms. Although the load currents $i_{a}$, $i_{b}$, and $i_{c}$ are distorted with the PF of 0.60, the source currents $i_{a}$, $i_{b}$, and $i_{c}$ are sinusoidal with the PF of 0.90. The THD values of $i_{a}$, $i_{b}$, and $i_{c}$ are 9.0%, 9.0%, and 8.9%, respectively. The dc-capacitor voltages $v_{c1}$ and $v_{c2}$ are well balanced with the method proposed in (17). Thus, the CDCVC-based strategy for the STATCOM with a three-level NPC inverter achieves not only the source-side harmonic current compensations but also reactive power control with the proposed CDCVC-based reactive power control strategy. The experimental results of Figure 8 and Figure 9 are in good agreement with the simulation results of Figure 4 and Figure 5.

5. Conclusion

This paper has proposed a CDCVC-based reactive power control strategy of a STATCOM with a three-level NPC inverter, in which the source-side harmonic currents are also compensated. The CDCVC-based reactive power control strategy uses only a CDCVC, which is always used in the grid-connected inverters, STATCOMs etc. Calculation blocks of fundamental active, reactive, and harmonic components are not needed. The authors offer a simplified strategy for the source-side reactive power control with the source-side harmonic current compensations. The instantaneous power flowing into the STATCOM with a three-level NPC inverter has been discussed in detail. The instantaneous

![Fig. 5. Simulation waveforms for Figure 1 with the control gain $K = \tan(\cos^{-1}(PF)) = 0.484$ as shown in Figure 3](image)

![Fig. 6. Theoretical values and simulated values between the control gain $K = \tan(\cos^{-1}(PF))$ and the source-side PF](image)
Constant DC-Capacitor Voltage-Control-Based Strategy for STATCOM (Ayumu Tokiwa et al.)

Fig. 7. Brock diagram of constructed experimental model for STATCOM with three-level NPC inverter in Figure 1

Table 2. Circuit constants for Figure 7

<table>
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<th>Symbol</th>
<th>Value</th>
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<td>Switching inductor</td>
<td>$L_f$</td>
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<tr>
<td>Filter capacitor</td>
<td>$C_f$</td>
<td>6.0 µF</td>
</tr>
<tr>
<td>Reference dc-capacitor voltage</td>
<td>$V_{DC}$</td>
<td>400 Vdc</td>
</tr>
<tr>
<td>DC capacitor</td>
<td>$C_1, C_2$</td>
<td>11200 µF</td>
</tr>
<tr>
<td>Unit capacitance constant</td>
<td>$H$</td>
<td>44.8 ms</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>$f_{sw}$</td>
<td>7.2 kHz</td>
</tr>
<tr>
<td>Inductor</td>
<td>$L$</td>
<td>20 mH</td>
</tr>
<tr>
<td>DC-side resistor of three-phase diode rectifier</td>
<td>$R_d$</td>
<td>16.7 Ω</td>
</tr>
<tr>
<td>AC-side inductor of three-phase diode rectifier</td>
<td>$L_c$</td>
<td>1.2 mH</td>
</tr>
</tbody>
</table>

Fig. 8. Experimental waveforms for Figure 7 with the control gain $K = \tan\{\cos^{-1}(PF)\} = 0$ as shown in Figure 3

controlled source-side reactive power compensating the harmonic currents on the source side. A digital computer simulation has been implemented to confirm the validity and high practicability of the CDCVC-based strategy. A reduced-scale prototype experimental model has been constructed and tested. The simulation and experimental results have demonstrated that the sinusoidal source currents are obtained with the CDCVC-based strategy controlling the reactive power on the source side.

In this paper, balanced load conditions have been considered to demonstrate the validity and high practicability of the proposed CDCVC-based harmonic current compensation strategy with reactive power control. The compensation
performance of the proposed CDCVC-based strategy of the three-level NPC inverter-based STATCOM under unbalanced load conditions is a next issue for further study. This will be reported in another article.

References


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