Multi-Level Inverter Based STATCOM for High Power Applications with Improved Power Quality using Fuzzy Logic

U. VENKATESWARA RAO¹, B. PRAVEEN KUMAR²

¹PG Scholar, Narasaraopeta Engineering College, India, E-mail: venkateswararao@ouindia.org.
²Assistant Professor, Narasaraopeta Engineering College, India, E-mail: id.praveen6646@gmail.com.

Abstract: In this paper, a simple STATCOM scheme using a cascaded two-level inverter-based multilevel inverter is proposed. The topology consists of two standard two-level inverters connected in cascade through open-end windings of a three-phase transformer. The dc-link voltages of the inverters are regulated at different levels to obtain four-level operation. The simulation study carried out in MATLAB/SIMULINK to predict the performance of the proposed scheme under balanced and unbalanced supply-voltage conditions. Further, stability behavior of the topology is investigated. The dynamic model is developed and transfer functions are derived. The system behavior is analyzed for various operating conditions.

Keywords: Flexible AC Transmission Systems (FACTS), Static Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), Power Quality (PQ) and Thyristor Switched Capacitor (TSC).

I. INTRODUCTION

The application of flexible ac transmission systems (FACTS) controllers, such as static compensator (STATCOM) and static synchronous series compensator (SSSC), are increasing in power systems. This is due to their ability to stabilize the transmission systems and to improve power quality (PQ) in distribution systems. STATCOM is popularly accepted as a reliable reactive power controller replacing conventional var compensators, such as the thyristor switched capacitor (TSC) and thyristor-controlled reactor (TCR). This device provides reactive power compensation, active power oscillation damping, flicker attenuation, voltage regulation, etc. [1]. Generally, in high-power applications, var compensation is achieved using multilevel inverters [2]. These inverters consist of a large number of dc sources which are usually realized by capacitors. Hence, the converters draw a small amount of active power to maintain dc voltage of capacitors and to compensate the losses in the converter. However, due to mismatch in conduction and switching losses of the switching devices, the capacitors voltages are unbalanced. Balancing these voltages is a major research challenge in multilevel inverters. Various control schemes using different topologies are reported in [3]–[7]. Among the three conventional multilevel inverter topologies, cascade H-bridge is the most popular for static var compensation [5], [6]. However, the aforementioned topology requires a large number of dc capacitors. The control of individual dc-link voltage of the capacitors is difficult. Static var compensation by cascading conventional multilevel/two level inverters is an attractive solution for high-power applications.

The topology consists of standard multilevel/two level inverters connected in cascade through open-end windings of a three-phase transformer. Such topologies are popular in high-power drives [8]. One of the advantages of this topology is that by maintaining asymmetric voltages at the dc links of the inverters, the number of levels in the output voltage waveform can be increased. This improves PQ [8]. Therefore, overall control is simple compared to conventional multilevel inverters. Various var compensation schemes based on this topology are reported in [10]–[12]. In [10], a three-level inverter and two-level inverter are connected on either side of the transformer low-voltage winding. The dc-link voltages are maintained by separate converters. In [11], three-level operation is obtained by using standard two-level inverters. The dc-link voltage balance between the inverters is affected by the reactive power supplied to the grid. In this paper, a static var compensation scheme is proposed for a cascaded two-level inverter-based multilevel inverter. The topology uses standard two-level inverters to achieve multilevel operation. The dc-link voltages of the inverters are regulated at asymmetrical levels to obtain four-level operation. To verify the efficacy of the proposed control strategy, the simulation study is carried out for balanced and unbalanced supply-voltage conditions.

II. CASCADED TWO-LEVEL INVERTER-BASED MULTILEVEL STATCOM

Fig. 1 shows the power system model considered in this paper [13]. Fig. 2 shows the circuit topology of the cascaded two-level inverter-based multilevel STATCOM using standard two-level inverters. The inverters are connected on the low-voltage (LV) side of the transformer and the high-voltage (HV) side is connected to the grid. The dc-link voltages of the inverters are maintained constant and modulation indices are controlled to achieve the required objective. The proposed control scheme is derived from the ac side of the equivalent circuit which is shown in Fig. 3. In the figure, $v_1$, $v_2$, and $v_3$ are the source voltages referred to LV side of the
transformer, \( r_a r_b \) and \( r_c \) are the resistances which represent the losses in the transformer and two inverters, and are leakage inductances of transformer windings, \( L_a, L_b \) and \( L_c \). \( e_{a1}, e_{b1}, e_{c1}, e_{a2}, e_{b2}, e_{c2} \) are the output voltages of inverters 1 and 2, respectively. Are the leakage resistances of dc-link capacitors \( C_1 \) and \( C_2 \), respectively.

\[
\begin{bmatrix}
\frac{dv_a}{dt} \\
\frac{dv_b}{dt} \\
\frac{dv_c}{dt}
\end{bmatrix} = \begin{bmatrix}
0 & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
e_a \\\ne_b \\\ne_c
\end{bmatrix} + \frac{1}{L} \begin{bmatrix}
v_a - (v_{a1} - v_{a2}) \\
v_b - (v_{b1} - v_{b2}) \\
v_c - (v_{c1} - v_{c2})
\end{bmatrix}
\]

(1)

Eq.(1) represents the mathematical model of the cascaded two-level inverter-based multilevel STATCOM in the stationary reference frame. This model is transformed to the synchronously rotating reference frame [14]. The d–q axes reference voltage components of the converter \( e_d \) and \( e_q \) are controlled as

\[
e_d^* = -x_1 + \omega L i_d' + v_d'
\]

\[
e_q^* = -x_2 - \omega L i_d' + v_q'
\]

(2) (3)

Where is the \( v_{d1}' \)-axis voltage component of the ac source \( i_d' \) and \( i_q' \) are d–q axes current components of the cascaded inverter, respectively. The synchronously rotating frame is aligned with source voltage vector so that the q-component of the source voltage \( v_q' \) is made zero. The control parameters and are controlled as follows:

\[
x_1 = \left(k_{p1} + k_{i1}\right) (v_d' - i_d)
\]

\[
x_2 = \left(k_{p2} + k_{i2}\right) (v_q' - i_q).
\]

(4) (5)

\[
\hat{\omega} = \left(k_{p3} - \frac{h_m}{\Omega} \right) \left| V_{d1}' + V_{d2}' - (V_{d1} + V_{d2}) \right|
\]

(6)

These reference voltages, the inverter supplies the desired reactive current and draws required active current to regulate total dc-link voltage \( v_{d1} + v_{d2} \). However, this will not ensure that individual dc-link voltages are controlled at their respective reference values as shown in Fig.5. Hence, additional control is required to regulate individual dc-link voltages of the inverters. The resulting voltage of the cascaded converter can be given as \( e_1 \), where and . The active power transfer between the source and inverter depends on \( \delta \) and is usually small in the inverters supplying var to the grid [1]. Hence, \( \delta \) can be assumed to be proportional to . Therefore, the q-axis reference voltage component of inverter-2 \( e_{q2}^* \) is derived to control the dc-link voltage of inverter-2 as

\[
e_{q2}^* = \left(k_{p4} + k_{i4}\right) \left(V_{d2}' - v_{d2}\right).
\]

(7)

The q-axis reference voltage component of inverter-1 is obtained as

\[
e_{q1}^* = e_{q1}' - e_{q2}^*.
\]

(8)

The dc-link voltage of inverter-2 \( V_{d2} \) is controlled at 0.366 times the dc-link voltage of inverter-1 \( V_{d1} \) [9]. It results in
Multi-Level Inverter Based STATCOM for High Power Applications with Improved Power Quality using Fuzzy Logic

four-level operation in the output voltage and improves the harmonic spectrum. Expressing dc-link voltages of inverter-1 and inverter-2 in terms of total dc-link voltage, as

\[
\begin{align*}
V_{dc1} &= 0.732V_{dc} \\
V_{dc2} &= 0.268V_{dc}.
\end{align*}
\]  

(9)

Since the dc-link voltages of the two inverters are regulated, the Reference d-axis voltage component is divided in between the two inverters in proportion to their respective dc-link voltage as

\[
e_{d1} = 0.732e_{d2} \\
e_{d2} = 0.268e_{d2}.
\]  

(10)

Fig.5. Fuzzy logic controller.

III. SIMULATION RESULTS

The system configuration is considered for simulation. The simulation study is carried out using MATLAB/SIMULINK. The system parameters are given in Table I.

<table>
<thead>
<tr>
<th>Table I: Simulation System Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
</tr>
<tr>
<td>Transformer voltage rating</td>
</tr>
<tr>
<td>AC supply frequency, f</td>
</tr>
<tr>
<td>Inverter-1 dc-link voltage, V_{dc1}</td>
</tr>
<tr>
<td>Inverter-2 dc-link voltage, V_{dc2}</td>
</tr>
<tr>
<td>Transformer leakage reactance, X_l</td>
</tr>
<tr>
<td>Transformer resistance, R</td>
</tr>
<tr>
<td>DC link capacitances, C_1, C_2</td>
</tr>
<tr>
<td>Switching frequency</td>
</tr>
</tbody>
</table>

A. Reactive Power Control

In this case, reactive power is directly injected into the grid by setting the reference reactive current component at a particular value. Initially, Isse t at 0.5p.u. At 2.0 s, is changed to 0.5 p.u. Fig. 6(a) shows the source voltage and converter current of the phase. Fig. 6(b) shows the dc-link voltages of two inverters. From the figure, it can be seen that the dc-link voltages of the inverters are regulated at their respective reference values when the STATCOM mode is changed from capacitive to inductive. Moreover, the dc-link voltage of inverter 2 attains its reference value faster compared to that of inverter 1 as discussed in Section II.

B. Load Compensation

In this case, the STATCOM compensates the reactive power of the load. Initially, STATCOM is supplying a current of 0.5p.u. At 2.0 s, the load current is increased so that STATCOM supplies its rated current of 1 p.u. Fig. 7(a) shows source voltage and converter current, while Fig. 7(b) shows the dc-link voltages of two inverters. The dc-link voltages are maintained at their respective reference values when the operating conditions are changed.

C. Operation During the Fault Condition

In this case, a single-phase-to-ground fault is created at 1.2s, on the phase of the HV side of the 33/11-kV transformer. The fault is cleared after 200 ms. Fig. 8(a) shows voltages across the LV side of the 33/11-kV transformer. Fig. 8(b) and (c) shows the d-q axes components of negative-sequence current of the converter. These currents are regulated at zero during the fault condition.

Case 1:

![Fig. 6(a) the source voltage and converter current of the phase, (b) the dc-link voltages of two inverters.](image)

Case 2:

![Fig. 7. (a) source voltage and converter current, while (b) the dc-link voltages of two inverters.](image)
DC-link voltage balance is one of the major issues in cascaded inverter-based STATCOMs. In this paper, a simple var compensating scheme is proposed for a cascaded two-level inverter-based multilevel inverter. The scheme ensures regulation of dc-link voltages of inverters at asymmetrical levels and reactive power compensation. The performance of the scheme is validated by simulation under balanced and unbalanced voltage conditions. Further, the cause for instability when there is a change in reference current is investigate with fuzzy logic controller. The dynamic model is developed and transfer functions are derived. System behavior is analyzed for various operating conditions. From the analysis, it is inferred that the system is a non minimum phase type, that is, poles of the transfer function always lie on the left half of the s-plane. However, zeros shift to the Right half of the s-plane for certain operating conditions. For such a system, oscillatory instability for high controller gains exists.

V. REFERENCES

Fig. 8(a) shows voltages across the LV side of the 33/11-kV transformer. Fig 8(b) and (c) shows the d-q axes component of negative-sequence current of the converter.
Multi-Level Inverter Based STATCOM for High Power Applications with Improved Power Quality using Fuzzy Logic