Design and simulation of cascaded H-bridge 5-level inverter for grid connection system based on multi-carrier PWM technique

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Abstract. Cascaded H-Bridge (CHB) multi-level inverter has become attractive in medium voltage and grid connection to improve power quality with high efficiency, and low switching losses. Voltage Oriented Control (VOC) regulates the injected power and the connection between the cascaded H-bridge inverter and the utility grid. In the modulation stage for the VOC, there are several techniques such as Space Vector Pulse Width Modulation (SVPWM), Multi-Carrier Pulse Width Modulation (MCPWM), Selective Harmonic Elimination (SHE) used to obtain gating pulses for the IGBTs switches. In this paper, a three-phase 5-level CHB inverter with a grid connection system is present and the technique of MCPWM is used. A comparative study between each method of (MCPWM) using MATLAB/ Simulink environment has been done on the Total Harmonic Distortion (THD) for inverter phase voltage and current with different injected reference current values. It is found that phase current THD is less with the Phase Shift PWM (PS-PWM) technique.

1. Introduction
In the last decades, the need to generate electrical power by using renewable resources such as photo-voltaic and wind turbines has increased since it is considered environmentally friendly and endless sources for electric power in the future[1,2].

Power electronic converters are used to connect these sources to the utility grid, known as inverters that convert DC power to AC power. However, the application of the utility grid is classified as a medium and high power, making the conventional two-level inverter unsuitable for this purpose. Moreover, due to the lack number of output voltage levels, more harmonic waves may be resulted [3,4]. Therefore, a Cascaded H-Bridge Multilevel Inverter (CHBMLI) is the best choice for grid connection and PV systems. Several advantages may be obtained, including high power quality, high voltage capability along with higher efficiency, low switching losses, and reduced magnetic interference [5-7].

The cascaded H-bridge multi-level inverter is easily designed and realized by fewer components compared with other multi-level inverters (diode clamped topology, flying capacitor topology, as figure 1
(a) shows 3-level diode clamped, while in (b) three-level flying capacitor. In contrast, (c) shows a single-phase 5-level CHB inverter[5].

![multi-level inverter topology](image)

**Figure 1.** One leg of multi-level inverter topology

This paper presents in section (2) a proposed topology for the multi-level inverter system using cascaded H-bridge. The multi-carrier modulation techniques that control the three-phase 5-level CHB inverter is used in grid connection with control strategy are covered in section (3); section (4) provides simulation results for each (MC-PWM) modulation method. Finally, section (5) summarizes the conclusion of the paper.

2. Proposed topology

The proposed three-phase grid connection system shown in figure 2 consists of six DC isolated sources, a 5-level cascaded H-bridge inverter, RL-filter, and a utility grid.

![grid connection system](image)

**Figure 2.** Grid connection system

Three-phase CHBMLI means three single CHBMLI are connected in (Y) form. Each phase consists of two full-bridges (each has a separate DC source) called a cell. In contrast, the bridge consists of four IGBTs switches with an anti-parallel diode; as previously shown in figure 1(c). IGBT is chosen as a power semiconductor switch since it has a more favorable feature, unlike other power semiconductor switches. The number of cells (K) that are used in a single-phase determines the specified output voltage level (L) [8,9].

\[ L = 2K + 1 \] (1)
The total output voltage level of each phase is the sum of the voltages that are generated by the cells, where each cell is capable of producing an output voltage level of -1V, 0, +1V, so the output voltage for a 5-level inverter is -2V, -1V, 0, +1V, +2V DC voltages [10].

3. Modulation and control strategy
3.1 Proposed modulation techniques
To obtain an output voltage with low distortion as smooth as sinusoidal waveform, it is important to design a modulation circuit to generate pulses (gating signals) that control the ON/OFF time (switching frequency) for the semiconductor switch [9]. The modulation techniques used in the multi-level inverter are:
- Space Vector Pulse Width Modulation (SVPWM).
- Multi-Carrier Pulse Width Modulation (MCPWM).
- Selective Harmonic Elimination (SHE)[11].
Multi-carrier modulation PWM comprises two common methods, which are widely used and can be classified as:
3.1.1. Phase Shift Carrier Modulation (PS-PWM)
Phase Shift Carrier Modulation (PS-PWM) is the most common method used in multi-level inverter due to its simple implementation and it has some advantages such as even power distribution and the output current has high quality waveform [12]. Moreover, based on comparing the sinusoidal reference signal with the triangle carrier signal, the amplitude modulation index can be defined as:

\[ m_a = \frac{A_m}{A_c} \]

Where: \( A_m \) is the peak-to-peak amplitude of the sinusoidal reference signal and \( A_c \) is the amplitude of triangle carrier signal [13].

For cascaded H-bridge multi-level inverter, the carrier signals of different cells (which are equal in amplitude and frequency) are phase shifted by \( \frac{360^\circ}{n} \), where \( n \) is the number of cells in each phase [14] and will be \( 90^\circ \) for 5-level CHB inverter, as shown in figure 3.

![Figure 3. PS-PWM](image)

3.1.2. Level Shift Pulse Width Modulation (LS-PWM)
In the level Shift Pulse Width Modulation (LS-PWM), all carrier signals are equal in amplitude, frequency, and phase but dispositioned vertically relative to the ZERO reference line. For 5-level CHB inverter, it needs \( (m-1) \) carrier signals for \( m \) output voltage levels resulting in four carrier signals, two of them are above the ZERO reference, and the other two signals are below the ZERO reference, the amplitude modulation index is defined as[3,15]:

\[ m_a = \frac{A_m}{(m-1)A_c} \]

Level shift pulse width modulation can be classified into three main techniques:
• Phase Disposition (PD): in this category of (LP-PWM), all carrier signals are in phase with each other, as shown in figure 4 (a).

• Phase Opposition Disposition (POD): in this technique, the carrier signals above the ZERO reference line are shifted by 180° out of phase with those signals under ZERO-line. Figure 4 (b) shows the carrier signals positioning to the ZERO-line and the sinusoidal reference signal.

• Alternative Phase Opposition Disposition (APOD): in this technique, each carrier signal is dispositioned 180° out of phase with its neighbor carrier, as shown in figure 4 (c)[10].

![Figure 4. LS-PWM technique PD, POD, APOD](image)

3.2. Voltage Oriented Control (VOC)

Voltage Oriented Control is the most common control scheme in the grid connection application that consists of the modular stage that regulates the interaction between the CHB and the utility grid [16]. Figure 5 shows the block diagram for the grid connection system with VOC.

![Figure 5. Voltage oriented control diagram](image)

![Figure 6. Space phasor diagram of VOC](image)

In VOC, the quantities of the three-phase system are converted to the stationary alpha-beta reference frame, this is similar to field oriented control for an electrical machine [17]:

\[
\begin{bmatrix}
    f_{\alpha} \\
    f_{\beta}
\end{bmatrix}
= \frac{2}{3}
\begin{bmatrix}
    1 & -\frac{1}{2} & -\frac{1}{2} \\
    -\frac{1}{2} & \sqrt{3}/2 & -\sqrt{3}/2 \\
    -\frac{1}{2} & -\sqrt{3}/2 & \sqrt{3}/2
\end{bmatrix}
\begin{bmatrix}
    f_u \\
    f_v \\
    f_w
\end{bmatrix}
\]
These new quantities will convert to DC components in the rotating d-q frame because it is easier to deal with DC component as follows:

\[
\begin{bmatrix}
    f_d \\
    f_q
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta & \sin \theta \\
    -\sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    f_a \\
    f_b
\end{bmatrix}
\]  
(5)

Where \( f \) can be current or voltage.

In stationary \( \alpha, \beta \) frame, the active power \( P \) and the reactive power \( Q \) can be calculated according to the following equations:

\[
P = \frac{3}{2} \left( v_a i_\alpha + v_\beta i_\beta \right)
\]  
(6)

\[
Q = \frac{3}{2} \left( v_a i_\beta - v_\beta i_\alpha \right)
\]  
(7)

Where \( v_a \) and \( v_\beta \) are voltages in the stationary \( \alpha-\beta \) frame

\( i_\alpha \) and \( i_\beta \) are currents in the stationary \( \alpha-\beta \) frame

Using space phasor \( wt = d\theta/dt \), whereas \( wt \) is the angular frequency of the grid voltage, and the active power \( P \) is directly related to the \( i_d \). In contrast, the reactive power \( Q \) is related to the \( i_q \) according to equations (8) and (9), respectively.

\[
P = \frac{3}{2} \left( v_a i_d + v_q i_q \right) = \frac{3v_d i_d}{2}
\]  
(8)

\[
Q = \frac{3}{2} \left( v_a i_q - v_q i_d \right) = \frac{3v_q i_q}{2}
\]  
(9)

Where \( v_d \) and \( v_q \) are voltages in the rotating d-q frame

\( i_d \) and \( i_q \) are currents in the rotating d-q frame

However, it is noticed that when the rotating reference frame is synchronized with the grid voltage, \( v_q \) becomes zero to inject the current with the unity power factor [18]. Figure 6 shows the stationary and the rotating frames of VOC.

The \( i_d \) and \( i_q \) will be sent to the PI controller to obtain reference voltages \( (V_{ref_d}, V_{ref_q}) \) which is converted to \( \alpha-\beta \) coordinate \( (V_{ref_\alpha}, V_{ref_\beta}) \) by using equation (10) and then to UVW system \( (V_{ref_U}, V_{ref_V}, V_{ref_W}) \) using equation (11). The resulting voltages will use as reference signals for the modulation stage to get the gating signals for the IGBTs[17].

\[
\begin{bmatrix}
    V_{ref_\alpha} \\
    V_{ref_\beta}
\end{bmatrix} =
\begin{bmatrix}
    \cos \theta & -\sin \theta \\
    \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
    V_{ref_d} \\
    V_{ref_q}
\end{bmatrix}
\]  
(10)

\[
\begin{bmatrix}
    V_{ref_u} \\
    V_{ref_v} \\
    V_{ref_w}
\end{bmatrix} =
\begin{bmatrix}
    1 & 0 \\
    \frac{1}{2} & \frac{\sqrt{3}}{2} \\
    \frac{1}{2} & -\frac{\sqrt{3}}{2}
\end{bmatrix}
\begin{bmatrix}
    V_{ref_\alpha} \\
    V_{ref_\beta}
\end{bmatrix}
\]  
(11)

The phase angle \( (\theta) \) can be obtained by using Phase Lock Loop (PLL) as shown in figure 7, in which the measured voltages from the grid \( (V_u, V_v, \text{and } V_w) \) are transformed to rotating frame \( V_d \) and \( V_q \) as in equation...
(4) and (5) respectively \( V_q \) controlled by PI controller which employs as loop filter. Its output will be the grid frequency \( (\omega) \), which is integrated to obtain the output phase angle \( (\theta) \) [19].

![Figure 7. Block diagram for PLL.](image)

### 4. Simulation results

A 5-level CHB inverter grid connection system is simulated using MATLAB/Simulink environment. The simulated results obtained for phase voltage for the inverter and the grid voltage are synchronized in frequency and phase angle, as shown in figure 8(a). Also, the inverter current is in phase with the grid phase voltage, as shown in figure 8(b), which means the power is injected with the unity power factor. Therefore, at the same simulation parameters, as listed in table 1, carrier shift modulation techniques are studied by using Fast Fourier Transform (FFT) analysis.

![Figure 8. Grid voltage with inverter voltage and with inverter current in phase (u)](image)

| Table 1. Electrical parameters values of CHB inverter grid connection system |
|-----------------------------|------------------|
| Parameters                  | Value            |
| CHB DC source               | 200 V            |
| Switching frequency         | 5000 Hz          |
| Grid phase to phase voltage | 380 V            |
| Grid fundamental frequency  | 50 Hz            |
| Filter inductance           | 0.5 mH           |
| Filter resistance           | 5 mΩ             |
| Reference current           | 100 A            |

Figure 9(a) illustrates the modulation circuit in the Phase Shift (PS-PWM) technique that provides a train of pulses control the ON/OFF time for each IGBT to get the inverter output voltage by comparing between reference sinusoidal voltage obtained from current control loop for the VOC and tringle carrier generator in the modulation stage. It is observed from figure 9(b) that the modulation index is 0.8 according to the amplitudes of the reference voltage (0.8) and tringle signal that equal to 1 by using equation (2).
Figure 9. The circuit block diagram and the waveforms for PS-PWM in phase (u)

The Total Harmonic Distortion (THD) for phase (u) of the inverter current and voltage is presented in figure 10 by using the PS-PWM technique. It can be seen that the THD for the inverter current is 1.21%, while the THD of the inverter phase (u) voltage is 39.36% as shown in figure 10(a) and figure 10(b) respectively.

Figure 10. THD in PS-PWM

The Phase Disposition PWM system illustrated in figure 11(a) is realized by comparing four individual carriers (which all in phase with each another) with the reference voltage that will be changed for the three phases legs depending on its phase angle. However, it can be seen that the modulation index is 0.8 by using equation (3), as shown in figure 11(b).

Figure 11. The circuit block diagram and the waveforms for PD-PWM in phase (u)

Figure 12 illustrates the total harmonic distortion for phase (u) of the inverter current and voltage. The THD for the inverter current is shown to be 2.71%, as illustrated in figure 12(a) and THD for the inverter phase (u) voltage is 39.60% as in figure 12(b).
Figure 12. THD in PD-PWM

Figure 13(a) shows the Phase Opposition Disposition (POD) modulation structure. It illustrates that the lower carriers are 180° degrees out of phase with the upper carrier signal; figure 13(b) shows the modulation index is 0.8 by using equation (3).

Figure 13. The circuit block diagram and the waveforms for POD-PWM in phase (u)

The total harmonic distortion for phase (u) of the inverter current and voltage is illustrated in figure 14, where the THD for the inverter current is 6.44% as in figure 14(a), and THD for the inverter phase (u) voltage is 39.30% as in figure 14(b).

Figure 14. THD for POD-PWM

An Alternative Phase Opposition Disposition (APOD) modulation topology (each carrier signal is dispositioned 180° out of phase with its neighbor carrier) is presented in figure 15(a). It is clear that the modulation index is 0.8 by using equation (3) as shown in figure 15(b).
Figure 15. The circuit block diagram and the waveforms for APOD-PWM in phase (u)

The total harmonic distortion in this technique for phase (u) of the inverter current is 4.80% and THD for the inverter voltage is 39.46% as shown in Table 2.

Table 2. THD of carrier shift methods

| Injected current (A) | PS-PWM | PD-PWM | POD-PWM | APOD-PWM |
|----------------------|--------|--------|---------|----------|
|                      | Inverter current THD | Inverter voltage THD | Inverter current THD | Inverter voltage THD | Inverter current THD | Inverter voltage THD | Inverter current THD | Inverter voltage THD |
| 100                  | 1.21%  | 39.60% | 2.71%   | 39.60%   | 6.44%   | 39.30%   | 4.80%   | 39.46%   |
| 125                  | 0.97%  | 39.30% | 2.17%   | 39.56%   | 5.15%   | 39.25%   | 3.86%   | 39.41%   |
| 150                  | 0.81%  | 39.29% | 1.81%   | 39.53%   | 4.29%   | 39.25%   | 3.23%   | 39.37%   |
| 175                  | 0.70%  | 39.26% | 1.55%   | 39.47%   | 3.68%   | 39.22%   | 2.78%   | 39.34%   |
| 200                  | 0.61%  | 39.18% | 1.35%   | 39.44%   | 3.22%   | 39.16%   | 2.44%   | 39.28%   |

5. Conclusion
This paper involves a study and analysis for a three-phase 5-level cascaded H-bridge inverter for grid connection with unity power factor. The system controlled by traditional voltage-oriented control. Carrier shift techniques are used in modulation stage and simulated by MATLAB/Simulink environment. The application of Fast Fourier Transform (FFT) analysis for THD in these techniques shows that the total harmonic distortion for the inverter current by using Phase Shift Pulse Width Modulation (PS-PWM) is small compared with other existing methods. It means that high-quality output current and even high-power distribution are obtained; therefore, this technique is suitable for grid connection.

6. References
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