Research Article
Modified Grid-Connected CSI for Hybrid PV/Wind Power Generation System

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The principle of a power conditioning unit for hybrid PV/wind power generation system is proposed. The proposed power conditioner is based on the current source inverter (CSI) topology. All energy sources are connected in parallel with a DC-bus through the modified wave-shaping circuits. To achieve the unity power factor at the utility grid, the DC-link current can be controlled via the wave-shaping circuits with the sinusoidal PWM scheme. In this work, the carrier-based PWM scheme is also proposed to minimize the utility current THD. The power rating of the proposed system can be increased by connecting more PV/wind modules through their wave-shaping circuits in parallel with the other modules. The details of the operating principles, the system configurations, and the design considerations are described. The effectiveness of the proposed CSI is demonstrated by simulation results.

1. Introduction

The steadily increasing energy consumption for the conventional energy sources like a fossil-energy-based fuel has created much interest in the alternative energy sources. Many renewable energy sources are now developed and being widely used. These energy sources can be integrated to form a hybrid system which is an excellent option for distributed energy product. In general, the hybrid systems have better potential to provide higher quality and more reliable power than the single source systems. Recently, the solar and wind energy are the most commonly used renewable energy sources in a hybrid system due to the high efficiency and reliability to supply the continuous power to the load or the utility grid. The typical hybrid power generation system is shown in Figure 1(a). This system includes the energy sources, DC-DC converters, a DC-AC inverter, and the utility grid. All energy sources are connected in parallel to a common DC-AC inverter through their individual DC-DC converters.

Several configurations of hybrid PV/wind power generation systems, applying the various static converter topologies, have been proposed in the literatures [1, 2]. Previous approaches of the hybrid PV/wind power converters were mainly based on voltage source inverter (VSI) topology. One of the commonly used VSI for hybrid PV/wind is shown in Figure 1(b). In this topology, all energy sources are connected to a common DC-bus through the individual DC-DC boost converters. The DC-DC converters are responsible for tracking the maximum power of the wind and PV sources under all operating conditions. The outputs of both DC-DC converters are then connected to a single-phase DC-AC inverter. The DC-link voltage will be regulated by the DC-AC inverter with the current-regulated PWM control to achieve the unity power factor at the utility grid. Nowadays VSI has received a lot of attention but the high switching losses of the switching devices in both conversion stages are still a major drawback of this topology. To overcome this problem, several power converters based on the current source inverter (CSI) topology have been developed [3–8]. Compared with the VSI topology, CSI topology has the ability to boost the output voltage without an additional boost converter [4, 9]. Therefore, CSI is strongly suggested for the grid-connected systems which the magnitude of the DC input voltage is lower than the peak
of utility voltage. In addition, CSI generally features simple converter structure and reliable short-circuit protection. Furthermore, the application of CSI for hybrid PV/wind grid-connected system has not been reported in the previous publications.

In this paper, a modified grid-connected CSI for hybrid renewable energy systems consisting of PV and wind is proposed. The details of the operation principle and the system configuration are also discussed. The simulation setup has been carried out to verify the system performance of the proposed ideas under the different scenarios.

2. Operating Principles

2.1. Overview Concept of the Proposed System with DC-Link Current Sharing Technique. In this section, the overview of the proposed hybrid PV/wind power generation system as shown in Figure 2 can be introduced. The proposed system consists of two constant current sources \( i_{pv} \) and \( i_{wind} \), two current wave-shaping circuits (can be named as DC-DC chopper), an unfolding circuit, and a low-pass filter. Two constant current sources are connected in parallel to a common DC-bus through their own current wave-shaping circuits. Both wave shaping circuits, operating in the same switching frequency, are used to perform the PWM output currents \( i_1 \) and \( i_2 \) at a DC-bus. In order to supply active power to the utility grid, the DC-link current \( i_{dc} \) is controlled to be in phase with the utility voltage \( v_{ac} \). Therefore, the unity power factor can be achieved. The unfolding circuit is used to produce a unipolar pulse-width modulation (PWM) current \( i_{inv} \) by setting the direction of a PWM current \( i_{dc} \) at a DC link. At the last stage, low-pass filter is connected to eliminate the high-frequency harmonic components in a unipolar PWM current \( i_{inv} \) before injected to the utility grid.

In Figure 2(b), the waveforms of \( i_{1}, i_{2}, i_{dc} \), and \( i_{inv} \) in the block diagram in Figure 2(a) are shown. According to Kirchhoff’s current law (KCL), it can be seen that the PWM current at a DC-bus \( i_{dc} \) is the sum of output currents from the two wave-shaping circuits \( i_1 \) and \( i_2 \), respectively. Hence, the instantaneous DC-link current \( i_{dc} \) can be determined by \( i_{dc} = i_1 + i_2 \). In addition, the magnitude of \( i_{dc} \) can be found by summing the magnitude of \( i_1 \) and \( i_2 \) (\( i_{dc} = I_{pv} + I_{wind} \)), respectively. As a result, the magnitude of \( i_{dc} \) can be independently controlled by two constant current sources \( i_{pv} \) and \( i_{wind} \) respectively.

2.2. Circuit Configuration and Control Strategy. Figure 3(a) shows the circuit topology of the proposed grid-connected CSI for hybrid PV/wind power generation. The circuit diagram differs from that of a VSI in Figure 1(b) by the absence of a DC-link capacitor \( C_f \). The proposed circuit is composed of two wave-shaping circuits, a thyristor-based H-bridge inverter, and \( CL \) low-pass filter. Input renewable energy sources, PV and wind, are connected to a common DC-bus through their own wave-shaping circuits. The proposed system control scheme is also illustrated in Figure 3(b).
On the DC-side of the inverter, the DC chokes $L_{pv}$ and $L_{wind}$ are required to provide the smooth and continuous DC currents $i_{pv}$ and $i_{wind}$, respectively. Chopper switches $S_{pv}$ and $S_{wind}$ can be controlled to shape the constant input DC current $i_{pv}$ and $i_{wind}$ to be the PWM currents $i_1$ and $i_2$, respectively, at a DC-bus. To achieve the unity power factor at the utility grid, the utility current $i_{inv}$ is required to be sinusoidal and in phase with the utility voltage $v_{ac}$. Thus the voltage $v_{ac}$ will be rectified to establish a full-wave rectified sinusoidal signal $v_m$, where $K_1$ is an absolute gain. In the same time, the maximum power point tracker (MPPT) can be used for tracking the maximum power of PV and wind by multiplying the reference signal $v_m$ with the MPPT reference of each energy source $i_{pv}$ and $i_{wind}$ to produce the modulating signal $v_{m,pv}$ and $v_{m,wind}$, respectively. In PV array, an MPPT algorithm is used to determine the optimal operating point $i_{pv}$. The optimal current $i_{pv}$ is calculated and tracked from measured valued of PV voltage $v_{pv}$ and PV current $i_{pv}$. Similarly, for the wind turbine, the extracted power of the wind turbine $P_{cal}$ and wind speed $\omega_m$ are measured. The optimal point $i_{wind}$ can be provided by the MPPT controller. In both energy sources, $K_{pv}$ and $K_{wind}$ are the constant gain of the MPPT controller of PV and wind, respectively.

To obtain the control signal of chopper switches $v_{S_{pv}}$ and $v_{S_{wind}}$, the modulating signals $v_{m,pv}$ and $v_{m,wind}$ are compared with a triangular-shaped carrier waveform $v_c$ of the switching frequency $f_{sw}$. The instantaneous DC-link current $i_{dc}$ can be obtained by the summation of $i_1$ and $i_2$. The H-bridge inverter operates in synchronism with the utility grid and is controlled to provide a unipolar PWM current $i_{inv}$. The zero-crossing circuit is used to generate the control signal of H-bridge inverter $v_{T1}, v_{T2}, v_{T3}$, and $v_{T4}$. Switches $T_1$ and $T_4$ are turned on in the positive half-cycle of the grid voltage $v_{ac}$, whereas $T_2$ and $T_3$ are turned on in the negative half cycle. It can be observed that the inverter current $i_{inv}$ is obtained by unfolding the DC-link current $i_{dc}$. At the last stage, $C_f$ and $L_f$ form the low-pass filter which attenuates the high frequency components in the inverter output current $i_{inv}$.

The principle of the PWM scheme for the proposed CSI is illustrated in Figure 4. For the proposed modulation scheme, two modulating waves $v_{m,pv}$ and $v_{m,wind}$ are required. Both modulating waves are of the same frequency and synchronize with the utility grid but the magnitudes $V_{m,pv}$ and $V_{m,wind}$ are different. The modulating waves $v_{m,pv}$ and $v_{m,wind}$ are compared with a common triangular carrier wave $v_c$, generating two gating signals $v_{S_{pv}}$ and $v_{S_{wind}}$ for chopper switches $S_{pv}$ and $S_{wind}$, respectively. It should be noted that the fundamental-frequency component of the inverter current $i_{inv}$ can be expressed as $i_{inv1}$ as shown in Figure 4.

2.3. Inverter Mode of Operation. In order to understand the operation details of the proposed grid-connected CSI in Figure 3(a), the equivalent circuit is illustrated in Figure 5. This circuit can be subdivided into two configurations, the input DC-side and the output AC-side, respectively.

For a simplify analysis in each interval of the circuit, the following conditions are assumed.

(I) The input voltage sources $v_{pv}$ and $v_{wind}$ and DC chokes $L_{pv}$ and $L_{wind}$ can be considered and modeled...
2.3.1. DC-Side Operation. For the one switching period, the operation of the converter in the DC-side can be divided into two stages. The equivalent circuit for each stage is shown in Figure 6 and its key waveforms are depicted in Figure 4. Assuming that the modulating signals for energy sources can be defined as \( v_{m,pv} = v_{m,wind} = v_m \). The operation processes of the DC-side are specified as follows.

**Stage 1** \((v_m < v_{cr})\). When \( v_m < v_{cr} \), chopper switches \( S_{pv} \) and \( S_{wind} \) are on, chopper diodes \( D_{pv} \) and \( D_{wind} \) are off, the input DC currents \( I_{pv} \) and \( I_{wind} \) flow through \( S_{pv} \) and \( S_{wind} \), respectively. The current \( I_{pv} \) and \( I_{wind} \) cannot flow through the diodes \( D_{pv} \) and \( D_{wind} \), leading to \( i_1 = i_2 = 0 \). According to KCL, the DC-link current \( i_{dc} \) can be considered as consisting of the sum of diode currents \( i_1 \) and \( i_2 \). That is,

\[
i_{dc}(t) = 0.
\]  

**Stage 2** \((v_m > v_{cr})\). When \( v_m > v_{cr} \), chopper switches \( S_{pv} \) and \( S_{wind} \) are off, chopper diodes \( D_{pv} \) and \( D_{wind} \) are on, the input DC currents \( I_{pv} \) and \( I_{wind} \) flow to the load through \( D_{pv} \) and \( D_{wind} \), respectively, resulting in \( i_1 = I_{pv} \) and \( i_2 = I_{wind} \). Similar to the first stage, the DC-link current \( i_{dc} \) is obtained as

\[
i_{dc}(t) = I_{pv} + I_{wind}.
\]  

The DC-link current \( i_{dc} \) for all stages can be rewritten in term of the switching states as follows:

\[
i_{dc}(t) = I_{pv} \left[ 1 - d_{pv} \right] + I_{wind} \left[ 1 - d_{wind} \right],
\]  

where \( d_{pv} \) and \( d_{wind} \) are the switching states of the chopper switches \( S_{pv} \) and \( S_{wind} \), respectively. The switching states \( d_{pv} = 1 \) and \( d_{wind} = 1 \) if \( v_m < v_{cr} \) (in stage 1); otherwise 0 (in stage 2).

2.3.2. AC-Side Operation. In Figure 7, the equivalent circuit in the AC-side is shown. The AC utility voltage can be expressed by \( v_{ac} = V_{ac} \cdot \sin(\omega t) \), where \( V_{ac} \) is the peak of utility voltage. The operation of this side consists of two stages during the switching cycle. The operation can be described as follows.

**Stage 1** \((v_{ac} > 0)\). When \( v_{ac} > 0 \), the inverter switches \( T_1 \) and \( T_4 \) are on, \( T_2 \) and \( T_3 \) are off, the input DC current \( I_{dc} \) flows to the grid through \( T_1 \) and \( T_4 \), respectively. Then the AC utility current \( I_{ac} \) equals to \( I_{dc} \).

**Stage 2** \((v_{ac} < 0)\). The inverter switches \( T_1 \) and \( T_4 \) are off, \( T_2 \) and \( T_3 \) are on, when \( v_{ac} < 0 \). The DC current \( I_{dc} \) flows to the grid through \( T_2 \) and \( T_3 \), respectively, resulting in the utility current \( I_{ac} \) to be equal to \(-I_{dc}\).
Therefore, the utility current $i_{ac}$ can be defined as

$$i_{ac}(t) = \begin{cases} i_{dc}(t); & \sin(\omega t) \geq 0 \\ -i_{dc}(t); & \sin(\omega t) < 0. \end{cases}$$

(4)

Thus,

$$i_{dc}(t) = \frac{1}{2} \left( m_{pv} I_{pv} + m_{wind} I_{wind} \right) \cdot \sin(\omega t)$$

$$+ \sum_{k=1}^{\infty} \frac{I_{pv}}{\pi k} \cdot \sin[k \pi m_{pv} \sin(\omega t)] \cdot \cos(k \omega t)$$

$$+ \sum_{k=1}^{\infty} \frac{I_{wind}}{\pi k} \cdot \sin[k \pi m_{wind} \sin(\omega t)] \cdot \cos(k \omega t).$$

(7)

According to (4) the inverter output current $i_{inv}$ can be obtained by the operating of the unfolding circuit. Hence, the inverter output current $i_{inv}$ can be expressed in terms of its harmonic components as

$$i_{inv}(t) = \frac{1}{2} \left( m_{pv} I_{pv} + m_{wind} I_{wind} \right) \cdot \sin(\omega t)$$

$$+ \sum_{k=1}^{\infty} \frac{I_{pv}}{\pi k} \cdot \sin[k \pi m_{pv} \sin(\omega t)] \cdot \cos(k \omega t)$$

$$+ \sum_{k=1}^{\infty} \frac{I_{wind}}{\pi k} \cdot \sin[k \pi m_{wind} \sin(\omega t)] \cdot \cos(k \omega t).$$

(8)

Under the conditions of $I_{pv} = I_{wind}$ and $m_{pv} \neq m_{wind}$, the waveform of the inverter output current $i_{inv}$ and its harmonic contents in (8) can be shown in Figure 8. It can be observed that the waveform of the inverter current $i_{inv}$ is close to a unipolar PWM waveform. We can consider at the conditions of $I_{pv} = I_{wind} = I$ and $m_{pv} = m_{wind} = m$, the current $i_{inv}$ simplified as follows:

$$i_{inv}(t) = mI \cdot \sin(\omega t)$$

$$+ \sum_{k=1}^{\infty} \frac{2I}{\pi k} \cdot \sin[k \pi m \sin(\omega t)] \cdot \cos(k \omega t).$$

(9)

From this result, the PWM inverter current $i_{inv}$ can be shown in Figure 9(a). This waveform is similar to a unipolar PWM waveform. Figure 9(b) shows the harmonic spectrum of the inverter current $i_{inv}$. It can be seen that the current has
harmonics at the multiples of the switching frequency, that is, at $f_{sw}$, $2f_{sw}$, and so on. The harmonics of significant magnitudes also appear in the side bands of the switching frequency and its multiples.

2.5. Carrier-Based PWM Scheme. In order to reduce the harmonic distortion in the inverter output current $i_{inv}$, a carrier-based PWM scheme can be proposed. In general, this scheme can be classified into two categories: phase-shifted and level-shifted modulations. In this paper, a phase-shifted modulation is only studied and applied to the proposed hybrid PV/wind power systems. Normally, the hybrid PV/wind system may be connected in parallel more than two energy sources. The $n$ energy sources require $n$ triangular carrier signals. For the phase-shifted multicarrier modulation, the carrier waves for each module $v_{cr,pv}$ and $v_{cr,wind}$ are of same amplitude and frequency, but there is a phase shift $\phi_{cr}$ between any the adjacent carrier waves, given by

$$\phi_{cr} = \frac{360^\circ}{n}.$$  \hspace{1cm} (10)

For the proposed hybrid PV/wind system as shown in the Figure 3(a), there are two energy sources for system. The modulating signals $v_{m,pv}$ and $v_{m,wind}$ have the same frequency but the amplitude is different depending on the MPPT signals of each module. According to (10), the phase shift $\phi_{cr}$ between each carrier wave $v_{cr,pv}$ and $v_{cr,wind}$ is $180^\circ$. The gate signals $v_{S,pv}$ and $v_{S,wind}$ are generated by comparing the modulating wave $v_{m,pv}$ and $v_{m,wind}$ with the carrier waves $v_{cr,pv}$ and $v_{cr,wind}$, respectively. The principle of the proposed phase-shifted modulation for the hybrid PV/wind system can be shown in Figure 10. The inverter operates under the conditions of $I_{pv} = I_{wind} = I$ and $m_{pv} = m_{wind} = m$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.png}
\caption{PWM output current waveform $i_{inv}$ and harmonic content of the proposed circuit operating at $m_{pv} \neq m_{wind}$, $I_{pv} = I_{wind}$, $f_{line} = 50$ Hz and $f_{sw} = 1$ kHz.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure9.png}
\caption{PWM output current waveform $i_{inv}$ and harmonic content of the proposed circuit operating at $m_{pv} = m_{wind}$, $I_{pv} = I_{wind}$, $f_{line} = 50$ Hz, and $f_{sw} = 1$ kHz.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{The steady-state waveforms of the proposed phase-shifted PWM multicarrier modulation.}
\end{figure}
I voltage sources are used in the DC-side of the inverter, which make the input
3.1. Input DC Choke Design.
Large inductors \( L \) are chosen. A detailed analysis is not considered in this paper. The circuit
parameters are shown in Table 1. The PV and wind energy is not studied in this paper. The circuit
setup has been designed and carried out with PSIM. It should be noted that the MPPT operating for PV
and wind sources \( v_{\text{pv}} \) and \( v_{\text{wind}} \), respectively.

The inverter PWM current \( i_{\text{inv}} \) can be expressed in terms of Fourier series as [3]

\[
i_{\text{inv}}(t) = m I \cdot \sin(\omega t) + \sum_{\text{even}, k} \frac{2m}{\pi k} \sin[k \pi m \sin(\omega t)] \cdot \cos(k \omega t).
\]  

(11)

The inverter output current waveform \( i_{\text{inv}} \) based on phase-shifted multicarrier modulation is shown in Figure 11(a), and its spectrum is also illustrated in Figure 11(b). The operating conditions are \( I_{\text{pv}} = I_{\text{wind}} = 1 \), \( m_{\text{pv}} = m_{\text{wind}} = 0.8 \), \( f_{\text{line}} = 50 \) Hz, and \( f_{\text{sw}} = 1 \) kHz. The inverter current has harmonics and sidebands at the multiple of the twice switching frequency, that is, \( 2f_{\text{sw}} \), \( 4f_{\text{sw}} \), and so on. It is clear that the current waveform is formed by five current steps: \( 2I \), \( I \), \( 0 \), \( -I \), and \( -2I \), resulting in a further reduction in THD.

3. Design Consideration

3.1. Input DC Choke Design. Large inductors \( L_{\text{pv}} \) and \( L_{\text{wind}} \) are used in the DC-side of the inverter, which make the input voltage sources \( v_{\text{pv}} \) and \( v_{\text{wind}} \) appear as the constant DC current sources \( I_{\text{pv}} \) and \( I_{\text{wind}} \). When the chopper switch is turned on, the inductor current rises and the energy is stored in the inductor. If switch is turned off, the energy stored in the inductor is transferred to the AC-side through the diode and the inductor current falls. To design the value of this inductor, the inductor stored energy must be considered. When the switch is turned on, the energy stored in the inductor is

\[
E_L = \frac{1}{2} L I^2 = P_{\text{dc}} T_{\text{on}},
\]  

(12)

where \( L \) = choke inductance, \( P_{\text{dc}} \) = average input power at DC-side, \( T \) = switching period, \( T_{\text{on}} = T/2 \) = turn-on time, and \( I \) = average input current. The choke inductance can be expressed as

\[
L = \frac{P_{\text{ac}}}{\eta I f_{\text{sw}}},
\]  

(13)

where \( \eta \) = converter efficiency, \( P_{\text{ac}} = \eta \cdot P_{\text{dc}} \) = average output power at AC-side, and \( f_{\text{sw}} \) = switching frequency.

3.2. Output Low-Pass Filter Design. In order to reduce the high-frequency harmonics in the PWM output current \( i_{\text{inv}} \) of the grid-connected inverter, a low-pass filter is needed. Passive low-pass filters are normally used as \( L \), \( C \), \( L \), and \( L \) filters. In this paper, a simple \( C \) low-pass filter is chosen. A detailed analysis is not considered in this paper.

Following the design procedure of [10], the inductor \( L_f \) and capacitor \( C_f \) can be found through the following equations:

\[
L_f = \frac{V_{\text{ac}}}{P_{\text{ac}} 2\pi f_{\text{sw}}},
\]

\[
C_f = \frac{0.33}{2\pi f_{\text{sw}} L_f},
\]

(14)

where \( V_{\text{ac}} \) is the amplitude of the grid voltage \( v_{\text{ac}} \).

4. Results and Discussion

To verify the proposed grid-connected CSI for hybrid PV/wind system with a simple current-sharing technique, the simulation setup has been designed and carried out with PSIM. It should be noted that the MPPT operating for PV and wind energy is not studied in this paper. The circuit parameters are shown in Table 1. The PV and wind energy sources \( v_{\text{pv}} \) and \( v_{\text{wind}} \) and input DC chokes \( L_{\text{pv}} \) and \( L_{\text{wind}} \) are modeled by DC current sources \( I_{\text{pv}} \) and \( I_{\text{wind}} \), respectively.

Figure 12 confirms the principle of PWM strategy for the proposed CSI operating under the condition of \( m_{\text{pv}} = 0.9 \) and \( m_{\text{wind}} = 0.4 \). The gate signals for all switches in CSI \( v_{\text{S,pv}}, \)

Table 1: Simulation parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output-rated power ( P_{\text{ac}} )</td>
<td>1000 W</td>
</tr>
<tr>
<td>PV source current ( I_{\text{pv}} )</td>
<td>5 A</td>
</tr>
<tr>
<td>PV source current ( I_{\text{wind}} )</td>
<td>5 A</td>
</tr>
<tr>
<td>Utility grid voltage ( V_{\text{ac}} )</td>
<td>220 V</td>
</tr>
<tr>
<td>Utility grid frequency ( f_{\text{sw}} )</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Chopper switching frequency ( f_{\text{sw}} )</td>
<td>3 kHz</td>
</tr>
<tr>
<td>Input inductor for PV converter ( L_{\text{pv}} )</td>
<td>13 mH</td>
</tr>
<tr>
<td>Input inductor for wind converter ( L_{\text{wind}} )</td>
<td>13 mH</td>
</tr>
<tr>
<td>Low-pass filter inductor ( L_f )</td>
<td>4 mH</td>
</tr>
<tr>
<td>Low-pass filter capacitor ( C_f )</td>
<td>2 ( \mu ) F</td>
</tr>
</tbody>
</table>
Figure 12: PWM switching strategy (top to bottom) $v_{m,pv}$, $v_{m,wind}$, $v_{cr}$, $v_{S,pv}$, $v_{S,wind}$, $v_{T1}$, $v_{T4}$, $v_{T2}$, and $v_{T3}$.

Figure 13: Operation of the system under the conditions of $m_{pv} = m_{wind}$, $I_{pv} = I_{wind}$, $f_{line} = 50$ Hz and $f_{sw} = 3$ kHz (top to bottom) $i_1$, $i_2$, $i_{dc}$, $i_{inv}$, $v_{ac}$, and $i_{ac}$. 
Figures 13, 14 and 15 show the simulated waveform for the proposed CSI, operating under the different conditions, (a) \( m_{\text{pv}} = m_{\text{wind}} \) and \( I_{\text{pv}} = I_{\text{wind}} \); (b) \( m_{\text{pv}} = m_{\text{wind}} \) and \( I_{\text{pv}} < I_{\text{wind}} \); (c) \( m_{\text{pv}} > m_{\text{wind}} \) and \( I_{\text{pv}} < I_{\text{wind}} \). The following can be observed.

(a) The two different currents \( i_1 \) and \( i_2 \) can be combined to produce the current \( i_{\text{dc}} \) at a DC-bus.

(b) The amplitude of \( i_{\text{dc}} \) can be determined by \( I_{\text{DC}} = I_{\text{pv}} + I_{\text{wind}} \). The magnitude of \( i_1 \) and \( i_2 \) can be independently controlled by the output power of each energy source.

(c) The unfolding circuit has two complementary switch pairs (\( T_1, T_4 \) and \( T_2, T_3 \)) switching at line frequency 50 Hz. The unipolar PWM current \( i_{\text{inv}} \) is performed by unfolding the DC-link current \( i_{\text{dc}} \).
Figure 16: Operation of the system under the conditions of $m_{pv} > m_{wind}$, $I_{pv} < I_{wind}$, $f_{line} = 50$ Hz and $f_{sw} = 20$ kHz (top to bottom) $i_1$, $i_2$, $i_{dc}$, $i_{inv}$, and $i_{ac}$.

(d) The waveform of the grid current $i_{ac}$ is close to sinusoidal with low THD. The low amount of harmonic distortion is due to the elimination of high-order harmonic contents by the filtering effect of $CL$ low-pass filter.

Figure 17: Simulated waveforms of the hybrid PV/wind system with phase-shifted PWM operating under the conditions of $m_{pv} = m_{wind}$, $I_{pv} = I_{wind}$, $f_{line} = 50$ Hz and $f_{sw} = 20$ kHz (top to bottom) $i_1$, $i_2$, $i_{dc}$, $i_{inv}$, $v_{ac}$, and $i_{ac}$.

Figure 16 shows the simulated waveforms for the proposed CSI, operating at higher switching frequency. It can be observed that the proposed converter can produce a smooth AC current at the utility grid with low harmonic components. The waveforms of the proposed grid-connected CSI for hybrid PV/wind system with phase-shifted multicarrier modulation are shown in Figure 17. It can be noted that the inverter output current waveform $i_{inv}$ is formed with five current levels.

In higher power applications, the increasing of output power rating of a hybrid PV/wind power generation system is required. It can be achieved by connecting more PV/wind
Figure 18: Extension energy sources for increasing the output power of the proposed hybrid PV/wind system.

Figure 19: Simulated waveforms of the multimodules hybrid PV/wind system with phase-shifted PWM operating under the conditions of \( m_{pv1} = m_{wind} = m_{pv2}, I_{pv1} = I_{wind} = I_{pv2}, f_{line} = 50 \text{ Hz} \) and \( f_{sw} = 20 \text{ kHz} \) (top to bottom) \( i_1, i_2, i_3, i_{dc}, v_{ac}, \text{ and } i_{ac} \).

modules in parallel with the other modules through their own DC-DC chopper to a common DC-bus. The configuration of multimodules PV/wind system with all modules connected in parallel is shown in Figure 18. The waveforms of the converter can be shown in Figure 19.

5. Conclusion

A grid-connected inverter for hybrid PV/wind power generation system was proposed. The proposed inverter was based on the current source inverter (CSI) topology. A number of issues were investigated, including the simple current sharing technique, the inverter configuration, operating principle, PWM strategy technique, PWM current analysis, and design consideration. The emphasis of this paper was on the new power converter scheme, where the operating analysis was discussed in details. The proficiency of the proposed inverter was accessed through the computer simulation under the different operation conditions. The performance of the proposed CSI was confirmed by the simulation results.

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References


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