A Novel PFC Circuit for Reduced Switching Loss
Bidirectional AC/DC Converter PWM Strategy with Feedforward Control for Grid-Tied Microgrid Systems

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Abstract-In this paper, a buck half-bridge DC-DC converter is used as a single-stage power factor correction (PFC) converter for feeding a bidirectional AC/DC converter. A simplified pulse width modulation (PWM) strategy is used for the bidirectional ac/dc single phase converter in a microgrid system. Then, the operation mechanism of the novel simplified PWM is clearly explained. The number of switchings of the simplified PWM strategy is one fourth that of the unipolar PWM and bipolar PWM. Based on the novel simplified PWM strategy, a feasible feedforward control scheme is developed to achieve better rectifier mode and inverter mode performance compared with the conventional dual-loop control scheme. The simplified PWM strategy with the feedforward control scheme has lower total harmonic distortion than the bipolar PWM and higher efficiency than both unipolar and bipolar PWMs. Furthermore, the simplified PWM operated in the inverter mode also has larger available fundamental output voltage $V_{dc}$ than both the unipolar and bipolar PWMs. The proposed PFC converter improves the value of the output DC voltage of bidirectional AC/DC converter. The simulations are carried out in MATLAB/Simulink environment.

Keywords: Bidirectional ac/dc converter, simplified pulse width modulation (PWM) strategy, total harmonic distortion (THD), PFC.

1. Introduction

The single-phase ac/dc pulse width modulation (PWM) converter is widely used in many applications such as adjustable-speed drives, switch-mode power supplies, and uninterruptible power supplies. The single-phase ac/dc PWM converters [1]–[11] are usually employed as the utility interface in a grid-tied renewable resource system, as shown in Fig. 1. To utilize the distributed energy resources (DERs) efficiently and retain power system stability, the bidirectional ac/dc converter plays an important role in the renewable energy system. When DERs have enough power, the energy from the dc bus can be easily transferred into the ac grid through the bidirectional ac/dc converter. In contrast, when the DER power does not have enough energy to provide electricity to the load in the dc bus, the bidirectional ac/dc converters can simultaneously and quickly change the power flow direction (PFD) from ac grid to dc grid and give enough power to the dc load and energy storage system. There are many requirements for ac/dc PWM converters as utility interface in a grid-tied system; for instance, providing power factor correction functions [4], [5], [7], low distortion line currents [1], [3], [7], high-quality dc output voltage [2], [9], and bidirectional power flow capability [8], [10], [11], [25]. Moreover, PWM converters are also suitable for modular system design and system reconfiguration. In this paper, a novel PWM control strategy with feedforward control scheme of a bidirectional single-phase ac/dc converter is presented.

![Fig. 1 Distribution energy system](image-url)
achieve better quality output. However, the switching loss in the HPWM is still the same as that of the UPWM [16]. The hysteresis switching method utilizes hysteresis in comparing the actual voltage and/or current to the reference. Although the hysteresis switching method has the advantages of simplicity and robustness [3], [20]–[24], the converters’ switching frequency depends largely on the load parameters, and consequently, the harmonic ripples are not optimal. Hysteresis control methods [3], [20]–[24] with constant switching frequency have recently been presented. Those are usually based on the voltage and/or current error zero-crossing time to achieve a constant switching frequency. However, the capacitor ripple voltage and inductor ripple current are assumed to be ignored and the implemented inductor and/or capacitor are not very practical. The switching frequency jitter [3] problem would occur during the inverter dead-time control (i.e., dead time effects) in the hysteresis modulation.

Fig. 2 Application of a bidirectional single-phase ac/dc converter in the renewable energy system

The simplified PWM requires only one active switch to change status during the switching period. In contrast, the conventional UPWM and/or BPWM require four active switches to change statuses during the switching period. There is no switching frequency jitter problem [3], [19]–[21] compared to hysteresis control methods in the simplified PWM strategy. A novel feedforward control scheme is also developed so that both the rectifier and inverter mode can be operated in a good manner. It is worth mentioning that the proposed feedforward control scheme is also suitable for the conventional UPWM and BPWM to provide fast output voltage response as well as improve input current shaping.

One problem associated with many existing drive systems with frequent regeneration is that the size of the dc link capacitor is often very large in order to limit the link voltage. Normally, a large capacitor bank of thousands of micro-Farad is required. The large capacitor bank not only increases the size and weight of the converter equipment, but also the equipment cost. If a braking resistor is used to dissipate the regenerative energy, the overall efficiency of the drive system becomes low. In order to reduce the link capacitor, a bidirectional switched-mode rectifier can be used so that regenerative energy can be absorbed by the supply instead of being stored in large capacitor bank or dissipated in a braking resistor. With the bidirectional feature, the switched mode converter concept originally developed for switched mode power supplies can now be employed in electronic drive systems.

2. OPERATION PRINCIPLE OF THE SIMPLIFIED PWM STRATEGY

A bidirectional single-phase ac/dc converter is usually utilized as the interface between DERs and the ac grid system to deliver power flows bidirectionally and maintains good ac current shaping and dc voltage regulation, as shown in Fig. 2. Good current shaping can avoid harmonic pollution in an ac grid system, and good dc voltage regulation can provide a high-quality dc load.

<table>
<thead>
<tr>
<th>Status</th>
<th>$T_{a_r}$</th>
<th>$T_{a_f}$</th>
<th>$T_{b_r}$</th>
<th>$T_{b_f}$</th>
<th>Inductor status</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>$v_L &gt; 0$</td>
</tr>
<tr>
<td>B</td>
<td>OFF</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>$v_L &lt; 0$</td>
</tr>
<tr>
<td>C</td>
<td>ON</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>$v_L &lt; 0$</td>
</tr>
<tr>
<td>D</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>ON</td>
<td>$v_L &gt; 0$</td>
</tr>
<tr>
<td>E</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>OFF</td>
<td>$v_L &lt; 0$</td>
</tr>
</tbody>
</table>

To achieve bidirectional power flows in a renewable energy system, a PWM strategy may be applied for the single-phase full-bridge converter to accomplish current shaping at the ac side and voltage regulation at the dc side. Generally, BPWM and UPWM strategies are often utilized in a single-phase ac/dc converter. In this paper, a novel simplified PWM strategy is proposed. The simplified PWM only changes one active switch status in the switching period to achieve both charging and discharging of the ac side inductor current. Therefore, the simplified PWM strategy reduces the switching losses and also provides high conversion efficiency. The switching statuses of the simplified PWM are listed in Tables I and II for rectifier mode and inverter mode operation, respectively. Both the rectifier and inverter mode operations of the simplified PWM strategies are explained in this section as follows.

A. Rectifier Mode

Consider the single-phase system shown in Fig. 2 and assume the ac grid system internal impedance is highly inductive and, therefore, represented by $L$. The equivalent series resistance of $L$ is neglected. Consider the converter is operated in the rectifier mode. While ac
grid voltage source is operating in the positive half-cycle $vs > 0$, the operating circuits of Statuses A and B listed in Table I of the simplified PWM are shown in Fig. 3(a) and (b), respectively. Using Kirchhoff’s voltage law in the circuit operation shown in Fig. 3(a) and (b), the voltage relationship can be obtained as follows:

$$v_s - L \frac{d}{dt} i_L = 0. \quad (1)$$

The inductor voltage is $v_s - V_{dc}$, which decreases the inductor current. Therefore, in this condition, the inductor current is in the discharging state.

Consider the ac grid voltage source during the negative half cycle $vs < 0$ in Fig. 2. The operating circuits of Statuses C and D of the simplified PWM are shown in Fig. 5(a) and (b), respectively. Using Kirchhoff’s voltage law in the circuit operation shown in Fig. 5, the voltage relationship can be obtained as follows:

$$v_s - L \frac{d}{dt} i_L = 0. \quad (2)$$

The inductor voltage is $v_s - V_{dc}$, which decreases the inductor current. Therefore, in this condition, the inductor current is in the discharging state.

One can see that while the ac grid voltage source is operating in the negative half-cycle $vs < 0$, the inductor current is decreasing in both Statuses C and D. Therefore, in this condition, the inductor current is in discharging state.

While the converter is in Status E, as shown in Fig. 4, all of the switches are turned OFF. Using Kirchhoff’s voltage law in the circuit operation shown in Fig. 4, the voltage relationship can be obtained as follows:

$$v_s - L \frac{d}{dt} i_L - V_{dc} = 0.$$
The inductor voltage is \( v_s + V_{dc} \), which increases the inductor current. Therefore, in this condition, the inductor current is in the charging state.

In summary, while ac grid voltage source is operating in the positive half-cycle \( v_s > 0 \), both Statuses A and B increase the inductor current and Status E decreases the inductor current to achieve ac current shaping and dc voltage regulation. While the ac grid voltage source is operating in the negative half-cycle \( v_s < 0 \), both Statuses C and D decrease the inductor current and Status E increases the inductor current to accomplish ac current shaping and dc voltage regulation. Regardless whether the ac grid voltage source is operating in the positive half-cycle \( v_s > 0 \) or negative half-cycle \( v_s < 0 \), the converter inductor current can be increased or decreased properly in the simplified PWM operated in the rectifier mode.

B. Inverter Mode

The switching combination of the simplified PWM operated in the inverter mode is listed in Table II. When the converter is operated in the inverter mode, the actual inductor current is in the reverse direction compared to the ac grid voltage. Consider the ac grid voltage source is operating in the positive half-cycle \( v_s > 0 \); the input current is in the reverse direction \( i_L < 0 \). Both Statuses F and G give inductor L positive voltage to charge the inductor current. The corresponding circuit operation of Statuses F and G is shown in Fig. 7. Status H gives inductor L negative voltage to discharge the inductor current, as shown in Fig. 8.

While the ac grid voltage source is operating in the negative half-cycle \( v_s < 0 \), the input current is in the reverse direction \( i_L > 0 \). Both Statuses I and J give inductor L negative voltage to discharge the inductor current. The corresponding circuit operation of Statuses I and J is shown in Fig. 9. Status K gives inductor L positive voltage to charge the inductor current, as shown in Fig. 10. Regardless of whether the ac grid voltage source is operating in the positive half-cycle \( v_s > 0 \) or the negative half-cycle \( v_s < 0 \), the converter inductor current can be increased or decreased properly to achieve ac current shaping and dc voltage regulation in the simplified PWM operated in the inverter mode.

According to the previous discussion, the ac grid line current of a single-phase ac/dc PWM converter could be increased and decreased easily in both rectifier and inverter mode to achieve bidirectional power flows and proper line current shaping and voltage regulation in the simplified PWM strategy.
results in the most efficient loading of the supply. A load distribution system. A load with a power factor of 1.0
All current flow causes losses both in the supply and
necessary to provide a magnetizing field required by
power is known as reactive power which unfortunately is
When the power factor is less than one the ‘missing’
losses in the supply system and a higher bill for the
consumer. A comparatively small improvement in power
factor can bring about a significant reduction in losses
since losses are proportional to the square of the current.
When the power factor is less than one the ‘missing’
power is known as reactive power which unfortunately is
necessary to provide a magnetizing field required by
motors and other inductive loads to perform their desired
functions. Reactive power can also be interpreted as
wattless, magnetizing or wasted power and it represents
an extra burden on the electricity supply system and on
the consumer’s bill. A poor power factor is usually the result of
a significant phase difference between the
voltage and current at the load terminals, or it can be due
to a high harmonic content or a distorted current
waveform. A poor power factor is generally the result of
an inductive load such as an induction motor, a power
transformer, a ballast in a luminaire, a welding set or an
induction furnace. A distorted current waveform can be
the result of a rectifier, an inverter, a variable speed
drive, a switched mode power supply, discharge lighting
or other electronic loads. A poor power factor due to
inductive loads can be improved by the addition of power
factor correction equipment, but a poor power factor due
to a distorted current waveform requires a change in
equipment design or the addition of harmonic filters.
Some inverters are quoted as having a power factor of
better than 0.95 when, in reality, the true power factor is
between 0.5 and 0.75. The figure of 0.95 is based on the
cosine of the angle between the voltage and current but
does not take into account that the current waveform is
discontinuous and therefore contributes to increased
losses. An inductive load requires a magnetic field to
operate and in creating such a magnetic field causes the
current to be out of phase with the voltage (the current
lags the voltage). Power factor correction is the process of
compensating for the lagging current by creating a
leading current by connecting capacitors to the supply. A
sufficient capacitance is connected so that the power
factor is adjusted to be as close to unity as possible. The
basic configuration of power factor correction circuit is
shown in figure.

Fig. 10 Operation circuit of the simplified PWM
operated in the inverter mode under Status K, while
$v_s < 0$ and $i_L > 0$.

3. PROPOSED POWER FACTOR
CORRECTION CIRCUIT

POWER FACTOR is the ratio between the useful
(true) power (kW) to the total (apparent) power (kVA)
consumed by an item of a.c. electrical equipment or a
complete electrical installation. It is a measure of how
efficiently electrical power is converted into useful work
output. The ideal power factor is unity, or one.

All current flow causes losses both in the supply and
distribution system. A load with a power factor of 1.0
results in the most efficient loading of the supply. A load
with a power factor of, say, 0.8, results in much higher
losses in the supply system and a higher bill for the
consumer. A comparatively small improvement in power
factor can bring about a significant reduction in losses
since losses are proportional to the square of the current.
When the power factor is less than one the ‘missing’
power is known as reactive power which unfortunately is
necessary to provide a magnetizing field required by
motors and other inductive loads to perform their desired
functions. Reactive power can also be interpreted as
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leading current by connecting capacitors to the supply. A
sufficient capacitance is connected so that the power
factor is adjusted to be as close to unity as possible. The
basic configuration of power factor correction circuit is
shown in figure.

Fig. 11 General Configuration of Power Factor
Correction Circuit

4. FEEDFORWARD CONTROL SCHEME
FOR BIDIRECTIONAL AC/DC CONVERTER

Based on the simplified PWM, a novel feedforward
control scheme is presented in this section. For a
convenient explanation, the converter operated in the
rectifier mode is discussed first. The rectifier mode
switching combination is listed in Table I. One can
choose operation Statuses A and E during the condition
$v_s > 0$, and Statuses C and E during the condition $v_s < 0$.
It should be noted that the selection of Status A or B for
increasing inductor current and Status C or D for
decreasing inductor current is all allowable in the
simplified PWM strategy.

To derive the state-space averaged equation for the
simplified PWM strategy, the duty ratio $D_{on}$ is defined as
$D_{on} = t_{on}/T$, where $t_{on}$ is the time duration when the
switch is turned ON, i.e., $S_{on} = 1$, and $T$ is the time
period of triangular waveform. The duty ratio $D_{off}$ is defined as
$D_{off} = 1 - D_{on}$, which is the duty ratio when the
switch is turned OFF. While the ac grid voltage
source is operating in the positive half-cycle $v_s > 0$, the
switching duty ratio of Status A is defined as $D_{on}$
and that of Status E is defined as $D_{off}$. The corresponding
circuit equations of Statuses A and E were obtained in (1)
and (2), respectively. By introducing the state-space
averaged technique and volt–second balance theory, the
state-space averaged equation is derived as follows:

$$v_s - (1 - D_{on}) V_{dc} = 0.$$  

When the converter is operated in the steady state, the dc
voltage is equal to the desired command $V_{dc} = V_{dc}$; (12)
can also be expressed in the following form:

$$D_{on} = \left(1 - \frac{V_{on}}{V_{dc}}\right).$$

While the ac grid voltage source is operating in the
negative half-cycle $v_s < 0$, the duty ratios corresponding
to Statuses E and C are $D_{on}$ and $D_{off}$, respectively. The corresponding circuit equations for Statuses E and C were obtained in (4) and (3), respectively. By introducing the state-space averaged technique and volt-second balance theory, the state-space averaged equation is derived as follows, while the ac grid voltage source is operating in the negative half-cycle $v_s < 0$:

$$v_s + D_{on}V_{dc} = 0$$

Similarly, when the converter is operated in the steady state, the output voltage is equal to the desired command $V_{dc} = V_{dc}$. Equation (14) can be expressed in the following form:

$$D_{on} = -\frac{v_s}{V_{dc}}$$

According to the PWM properties, the switching duty ratio can be expressed in terms of the control signal $v_{cont}$ and the peak value $\hat{v}_{tri}$ of the triangular waveform

$$D_{on} = \frac{v_{cont}}{\hat{v}_{tri}}$$

Substituting (13) and (15) into (16), the switching duty ratios in both conditions $v_s > 0$ and $v_s < 0$ are derived

$$v_{cont} = \left\{ \begin{array}{ll}
\left(1 - \frac{v_s}{V_{dc}}\right)\hat{v}_{tri}, & \text{if } v_s > 0 \\
-\frac{v_s}{V_{dc}}\hat{v}_{tri}, & \text{if } v_s < 0
\end{array} \right.$$
6. CONCLUSION

The proposed PFC converter further improves the DC voltage of bidirectional AC/DC converter. This paper presented a simplified PWM strategy using a feedforward control scheme in the bidirectional single-phase ac/dc converter. The simplified PWM strategy only requires changing one active switch status in the switching period instead of changing four active switch statuses as required in the UPWM and BPWM strategies. The efficiency of an ac/dc converter operated in the simplified PWM strategy is higher than that in the UPWM and BPWM strategies. And its efficiency increased further when we used the proposed PFC converter with bidirectional AC/DC converter.

REFERENCES


[7] A. Abrishamifar, A. A. Ahmad, and M. Mohamadian, “Fixed switching frequency sliding mode control for


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