REDUCED SWITCHING LOSS AC/DC/AC CONVERTER WITH FEED FORWARD CONTROL

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Abstract—This paper presents a novel simplified pulse width modulation (PWM) strategy for the bidirectional ac/dc single phase converter in a micro grid system. Then, the operation mechanism of the novel simplified PWM is clearly explained. The number of switching's of the proposed simplified PWM strategy is one fourth that of the conventional unipolar PWM and bipolar PWM. Based on the novel simplified PWM strategy, a feasible feed forward control scheme is developed to achieve better rectifier mode and inverter mode performance compared with the conventional dual loop control scheme. The proposed simplified PWM strategy with the proposed feed forward control scheme has lower total harmonic distortion than the bipolar PWM and higher efficiency than both unipolar and bipolar PWMs. Furthermore, the proposed simplified PWM operated in the inverter mode also has larger available fundamental output voltage $v_{ab}$ than both the unipolar and bipolar PWMs.

I. 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 uninterrupted power supplies. The single-phase ac/dc PWM converters 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 system 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 low distortion line currents high-quality dc output voltage and bidirectional power flow capability. Moreover, PWM converters are also suitable for modular system design and system reconfiguration. In this paper, a novel PWM control strategy with feed forward control scheme of a bidirectional single-phase ac/dc converter is presented. In the existing PWM control strategies of a single-phase ac/dc converter, the converter switches are operated at higher frequency than the ac line frequency so that the switching harmonics can be easily removed by the filter. The ac line current waveform can be more sinusoidal at the expense of switching losses. Until now several PWM strategies have been utilized in a single-phase ac/dc converter such as bipolar PWM (BPWM), unipolar PWM (UPWM), HPWM, and Hysteresis switching. UPWM results in a smaller ripple in the dc side current and significantly lower ac side harmonic content.
compared to the BPWM. The UPWM effectively doubles the switching frequency in the ac voltage waveform harmonic spectrum allowing the switching harmonics to be easily removed by the passive filter. The HPWM utilizes two of the four switches modulated at high frequency and utilizes the other two switches commutated at the (low) output frequency to reduce the switching frequency and achieve better quality output. However, the switching loss in the HPWM is still the same as that of the UPWM. The hysteresis switching method utilizes hysteresis in comparing the actual voltage and/or

![Diagram](image)

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

Current to the reference. Although the hysteresis switching method has the advantages of simplicity and robustness, the converters’ switching frequency depends largely on the load parameters, and consequently, the harmonic ripples are not optimal. Hysteresis control methods 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 problem would occur during the inverter dead-time control (i.e., dead time effects) in the hysteresis modulation. The proposed 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 compared to hysteresis control methods in the proposed simplified PWM strategy. A novel feed forward 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 feed forward control scheme is also suitable for the conventional UPWM and BPWM to provide fast output voltage response as well as improve input current shaping. The remainder of this paper is organized as follows. Section II presents the proposed simplified PWM strategy operating principle. Comparison of the BPWM, UPWM, and the proposed simplified PWM operated in a single-phase bidirectional ac/dc converter is given for illustration. Based on the proposed simplified PWM strategy, a feed forward control scheme is proposed in Section III. Section IV provides simulation and experimental results for validating the proposed theory. Conclusions are offered in section V.

II. OPERATION PRINCIPLE OF THE PROPOSED 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 bi-directionally 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.

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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 proposed 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 proposed simplified PWM strategy reduces the switching losses and also provides high conversion efficiency. The switching statuses of the proposed 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.

### B. 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 $v_s > 0$, the operating circuits of Statuses A and B listed in Table I of the proposed 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

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

![Fig. 3. Operation circuit of the proposed simplified PWM operated in the rectifier mode under (a) Status A and (b) Status B, while $v_s > 0$ and $i_L > 0$](image-url)
Fig. 4. Operation circuit of the proposed simplified PWM operated in the rectifier mode under Status E, while $V_s > 0$ and $I_L > 0$

One can see that while $I_S > 0$, the inductor current is increasing in both Statuses A and B, and the voltage across the inductor is $V_L$. Therefore, in this condition, the inductor current is in the charging 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:

$$v_s - L \frac{di_L}{dt} - V_{dc} = 0.$$ (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. Consider the ac grid voltage source during the negative half cycle $V_s < 0$ in Fig. 2. The operating circuits of Statuses C and D of the proposed 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

$$v_s - L \frac{di_L}{dt} = 0.$$ (3)

Fig. 5. Operation circuit of the proposed simplified PWM operated in the rectifier mode under (a) Status C and (b) Status D, while $V_s < 0$ and $I_L < 0$

Fig. 6. Operation circuit of the proposed simplified PWM operated in the rectifier mode under Status E, while $V_s < 0$ and $I_L < 0$

Fig. 7. Operation circuit of the proposed simplified PWM operated in the inverter mode under (a) Status F and (b) Status G, while $V_s > 0$ and $I_L < 0$.

Fig. 8. Operation circuit of the proposed simplified PWM operated in the inverter mode under Status H, while $V_s > 0$ and $I_L < 0$.

One can see that while the ac grid voltage source is operating in the negative half-cycle $V_s < 0$, the inductor current is decreasing in both Statuses C and
D. The voltage across the inductor L is \( V_S \). Therefore, in this condition, the inductor current is in the discharging state.

While the converter is in Status E, as shown in Fig. 6, all of the switches are turned OFF. Using Kirchhoff’s voltage law in the circuit operation shown in Fig. 6, the voltage relationship can be obtained as follows:

\[
v_S - L \frac{d}{dt} i_L + V_{dc} = 0. \tag{4}
\]

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 proposed simplified PWM operated in the rectifier mode.

C. Inverter Mode:

The switching combination of the proposed 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. 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 proposed 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 proposed simplified PWM strategy.
losses are less than that for the conventional BPWM and UPWM strategies. Consider the converter is operated in the sinusoidal PWM using triangular carrier waveform with frequency 40 kHz and the cumulative number of switching’s includes all status changes for four active switches in the BPWM, UPWM, and the proposed simplified PWM, shown in Fig. 16. From Fig. 16, it can be seen that the number of switching’s in the novel simplified PWM strategy is only one-fourth that of the conventional UPWM and BPWM.

III. PROPOSED FEED FORWARD CONTROL SCHEME

Based on the proposed simplified PWM, a novel feed forward 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 proposed simplified PWM strategy.

To derive the state-space averaged equation for the proposed simplified PWM strategy, the duty ratio \( D_{on} \) is defined as \( D_{on} = \frac{T_{on}}{T} \), where \( T_{on} \) is the time duration when the switch is turned ON, i.e., \( T_{on} = 1 \), 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

\[ v_s - (1 - D_{on}) V_{dc} = 0. \] (12)

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:

\[ D_{on} = \left(1 - \frac{v_s}{V_{dc}^*}\right). \] (13)

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 \( v_s < 0 \):

\[ v_s + D_{on} V_{dc} = 0. \] (14)

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:

\[ D_{on} = -\frac{v_s}{V_{dc}^*}. \] (15)

According to the PWM properties, the switching duty ratio can be expressed in terms of the control signal \( V_{cont}^* \) and the peak value \( V_{tri}^* \) of the triangular waveform

\[ D_{on} = \frac{V_{cont}^*}{V_{tri}^*}. \] (16)

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

\[
\begin{align*}
\nu_{cont}' &= \begin{cases} 
\frac{1 - v_s}{V_{dc}^*} V_{tri}, & \text{if } v_s > 0 \\
\frac{v_s}{V_{dc}^*} V_{tri}, & \text{if } v_s < 0.
\end{cases} 
\end{align*}
\] (17)
Because the control signal $V_{cont}$ is proportional to $D_{on}$, one can regard the calculated signal $V^*_{cont}$ in (17) as the duty ratio feed forward control signal $v_{ff}$ to add into the dual-loop feedback control signal $v_{fb}$. The feed forward control signal $v_{ff}$ can enhance the control ability to provide fast output voltage response as well as improve current shaping. Thus, the developed control scheme for the proposed simplified PWM is presented in Fig. 20. The detailed switching signal generator function is also shown in Fig. 21. The switching signal generator requires signals $S_{on}$, the grid voltage sign ($v_s$), and PFD combined with Tables I and II to generate switching signals $T_{a+}, T_{a-}, T_{b+}, T_{b-}$. It is worth mentioning that the proposed feed forward control scheme is suitable for both the proposed simplified PWM strategy and the conventional BPWM and UPWM strategies.

IV. RESULTS

Fig. 25. Simulation results with pure sinusoidal ac grid voltage (a) $V_s$ and $i_L$, (b) $v_{cont}$, (c) $v_{ff}$, and (d) $v_{fb}$ using the feedforward control scheme in the proposed simplified PWM strategy operated in the inverter mode.

Fig. 23. Simulation results with pure sinusoidal ac grid voltage (a) $V_s$ and $i_L$, (b) $v_{cont}$, (c) $v_{ff}$, and (d) $v_{fb}$ using the feedforward control scheme in the proposed simplified PWM strategy operated in the rectifier mode.

V. CONCLUSION

This paper presented a novel simplified PWM strategy using a feed forward control scheme in the bidirectional single-phase ac/dc converter. The proposed 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 proposed simplified PWM strategy is higher than that in the UPWM and BPWM strategies. Based on the proposed feed forward control scheme, both ac current shaping and dc voltage regulation are achieved in both the rectifier and inverter operating modes. In addition, the proposed simplified PWM operated in the inverter mode has larger available fundamental output voltage $V_{AB}$ than both BPWM and UPWM. The simulation results verify the validity of the proposed PWM strategy and control scheme.
REFERENCES


