Research Article

PV Power-Generation System with a Phase-Shift PWM Technique for High Step-Up Voltage Applications

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A PV power-generation system with a phase-shift pulse-width modulation (PWM) technique for high step-up voltage applications is proposed. The proposed power-generation system consists of two stages. In the input stage, all power switches of the full-bridge converter with phase-shift technique can be operated with zero-current switching (ZCS) at turn-on or turn-off transition. Hence, the switching losses of the power switches can be reduced. Then, in the DC output stage, a voltage-doubler circuit is used to boost a high dc-link bus voltage. To supply a utility power, a dc/ac inverter is connected to induce a sinusoidal source. In order to draw a maximum power from PV arrays source, a microcontroller is incorporated with the perturbation and observation method to implement maximum power point tracking (MPPT) algorithm and power regulating scheme. In this study, a full load power of 300 W prototype has been built. Experimental results are presented to verify the performance and feasibility of the proposed PV power-generation system.

1. Introduction

To overcome fossil energy shortage and reduce air pollution, the demand of renewable energy sources has been increased significantly. One of these sources is PV arrays energy, which is clean, quiet, and maintenance-free [1, 2]. In practice, the output voltage level of PV arrays is usually much lower than that of high dc-link bus voltage. This means that a front-end dc/dc converter is required to boost the low voltage of the PV arrays to a standard high dc-link bus voltage before being inverted into a 110 V ac (or 220 V ac) output. Thus, the dc/dc converter with a high step-up voltage ratio and high efficiency is usually demanded. Furthermore, to obtain maximum power from PV modules, tracking the maximum power point (MPP) of PV arrays is also an essential part of the PV power system, which is mostly realized by a microcontroller with a perturbation and observation method [3–5].

To achieve a high step-up voltage ratio, high efficiency, and galvanic isolation, a voltage-fed phase-shift full-bridge converter is used as a common solution [6–11]. However, it has several disadvantages, such as large input current ripple, large circulation current and high conduction losses of power switches. Compared with the voltage-fed phase-shift full-bridge converter, the current-fed phase-shift full-bridge converter has the clear advantages of lower input-current ripple and less conduction losses of power switches in the low-input high-output voltage conversion system. In this paper, a PV power-generation system with a current-fed phase-shift full-bridge converter for high step-up voltage applications is proposed, as shown in Figure 1. The proposed PV power-generation system has features as follows. (1) MPPT feature can be realized by a microcontroller with perturbation and observation method. (2) DC power from the PV arrays can induce a utility power via a dc/ac inverter. (3) Zero-current switching (ZCS) technology is implemented for all power switches (4) Electricity isolation is naturally obtained.

The operational principle of the proposed PV power-generation system is described in Section 2. The MPPT control scheme and protection circuit of the proposed PV power-generation system are described in Section 3. The design considerations of key components are described in Section 4. Experimental results obtained from a 300 W
2. Operational Principle

The circuit structure of the proposed PV power system is shown in Figure 1, in which it is composed of a current-fed phase-shift full-bridge converter, a voltage-doubler circuit, and a dc-ac inverter in cascade connection. By adopting a digital signal processor (DSP) control scheme with the perturbation and observation method [12–16], the proposed PV power system can draw power from the PV arrays source with MPPT features, and feed the drawn power to the voltage-doubler circuit. Then, the dc-ac inverter operated with sinusoidal pulse-width modulation (SPWM) control scheme will generate a utility power [17–20]. For convenience of illustration and analysis, the proposed PV power-generation system shown in Figure 1 is redrawn in Figure 2.

To facilitate the analysis of operation, Figure 3 shows the driving signal of switches \(M_1 \sim M_4\) and conceptual current and voltage waveforms of key components. Figure 4 shows the topological stages of the proposed power supply system during a switching cycle. To simplify the description of the operational modes, the following assumptions are made.

1. Boost inductor \(L_f\) is large enough so that the current flowing through it is constant over a switching period.

2. All of the switching devices and components are ideal.

Based on the above assumptions, the operational principle can be explained mode by mode as follows.

Mode 1 (Figure 4(a), \(t_0 \leq t < t_1\)). This mode begins when power switches \(M_1\) and \(M_4\) are turned on at time \(t_0\), and input current \(i_f\) starts to flow from the PV arrays through the transformer primary winding. At this operation, there will be a voltage across the secondary winding, which will turn on \(D_o1\). Then, the current in the secondary winding will flow through \(C_{o1}\) and the load. The equivalent circuit of Mode 1 is shown in Figure 4(a).

Mode 2 (Figure 4(b), \(t_1 \leq t < t_2\)). At time instant \(t_1\), \(M_2\) is turned on and \(M_1\) as well as \(M_4\) are still kept on but no current flows through \(M_1\). The input current \(i_f\) is freewheeling through power switches \(M_2\) and \(M_4\) and no current will flow through the transformer windings. Diodes \(D_{o1}\) and \(D_{o2}\) in secondary side of the transformer will be turned off, since all of transformer winding voltages are clamped to zero. The equivalent circuit of Mode 2 is shown in Figure 4(b).
Mode 3 (Figure 4(c), \( t_2 \leq t < t_3 \)). At time instant \( t_2 \), power switch \( M_1 \) is turned off at zero current due to the reason that there is no conducted current in the previous operating stage. That is, \( M_1 \) is operated with ZCS at turn-off transition. The power switches \( M_2 \) and \( M_4 \) are maintained on, and input current \( i_f \) is continuous free-wheeling through \( M_2 \) and \( M_4 \). The equivalent circuit of Mode 3 is shown in Figure 4(c).

Mode 4 (Figure 4(d), \( t_3 \leq t < t_4 \)). At time instant \( t_3 \), power switches \( M_2 \) and \( M_4 \) are still kept on. Power switch \( M_3 \) is turned on and operated with ZCS at turn-on transition, because transformer winding has no voltage. The equivalent circuit of Mode 4 is shown in Figure 4(d).

Mode 5 (Figure 4(e), \( t_4 \leq t < t_5 \)). At time instant \( t_4 \), power switches \( M_2 \) and \( M_3 \) are still kept on and \( M_4 \) is turned off. The input current \( i_f \) starts to revise flowing through the transformer primary winding. At this operation, there will be a revised voltage across the secondary winding of transformer which will turn on \( D_o2 \). Thus, the current in the secondary winding will flow through \( C_o2 \) and the load. The equivalent circuit of Mode 5 is shown in Figure 4(e).

Mode 6 (Figure 4(f), \( t_5 \leq t < t_6 \)). At time instant \( t_5 \), \( M_2 \) and \( M_3 \) are still kept on and \( M_1 \) is turned on. The input current \( i_f \) is free-wheeling through power switches \( M_1 \) and \( M_3 \) and no current will flow through the transformer windings. Diodes \( D_o1 \) and \( D_o2 \) in the transformer secondary will be turned off once again, since all of transformer winding voltages are clamped to zero. The equivalent circuit of Mode 6 is shown in Figure 4(f).

Mode 7 (Figure 4(g), \( t_6 \leq t < t_7 \)). At time instant \( t_6 \), \( M_1 \) and \( M_3 \) are still kept on and \( M_2 \) is turned off. Power switch \( M_1 \) is turned off under ZCS condition, due to the reason that there is no conducted current in the previous operating stage. The equivalent circuit of Mode 7 is shown in Figure 4(g).

Mode 8 (Figure 4(h), \( t_7 \leq t < t_8 \)). At time instant \( t_7 \), \( M_1 \) and \( M_3 \) are still kept on and \( M_4 \) is turned on and operated with ZCS at turn-on transition, because transformer winding has no voltage. The equivalent circuit of Mode 8 is shown in Figure 4(h). The proposed power system operation over one switching cycle is completed.

3. Control Scheme of MPPT

The PV arrays are constructed by many series or parallel connected solar cells. Each solar cell is formed by a P-N junction semiconductor, which can produce currents by the photovoltaic effect. The typical V-I and output power characteristic curves of the PV arrays with different insolations are shown in Figure 5. For a specific isolation, there exists one operating point where the PV array can generate its maximum output power. In order to achieve the best energy utilization of the PV arrays, an MPPT algorithm must be integrated into the control strategy of the current-mode phase-shift full-bridge converter.

Figure 6 illustrates the flow chart of the MPPT algorithm. First of all, the terminal voltage \( V_{PV} \) and current \( I_{PV} \) of PV arrays are measured. The output power of PV arrays \( P_{PV} \) can be obtained from the product of \( V_{PV} \) and \( I_{PV} \).
Figure 4: Equivalent circuits of operating modes.

From the plot of $P_{PV}$ versus $V_{PV}$, as shown in Figure 7, two possible operating regions $A$ and $B$ for a given $P_{PV}$ except the maximum power point can be defined. The current operating point location can be determined by a perturbation in the PV output power. For instance, the output power and terminal voltage of PV arrays with a perturbation are found to be

$$P_{PV}(n-1) = P_2 < P_{PV}(n) = P_1,$$

$$V_{PV}(n-1) = V_2 > V_{PV}(n) = V_1,$$  \hfill (1)
Figure 5: PV arrays with different insolations: (a) V-I curves, and (b) output power and output voltage curves.

Figure 6: Flow chart of perturbation and observation method for MPPT algorithm.
Figure 7: PV output power curve with respect to the PV output voltage.

Figure 8: Conceptual control block diagram of the proposed PV power-generation system.

where parameters $n - 1$ and $n$ indicate the measured quantities before and after the perturbation, respectively. Equation (1) imply that this perturbation leads to an increased $P_{PV}$ and a decreased $V_{PV}$. From the program flow chart shown in Figure 6, it can be determined that the correct operating point of PV arrays is currently located in region $B$. Thus, to track the maximum power point for PV arrays, the next changing direction is to increase load, resulting in a reduction of $V_{PV}$. Hence, the operating point is moving from $B_2$ to $B_1$ in Figure 7. If the correct operating point of PV arrays is currently located in region $A$, then the next changing direction is to decrease load. Hence, the operating point will be moved from $A_2$ toward $A_1$. With this continuous process, the operating point of PV arrays can be moved toward the maximum power point for different temperature and insolation conditions. In this study, the MPPT algorithm mentioned above is realized on a single-chip microprocessor TMS320F240.

In order to regulate the output voltage of the proposed PV power-generation system and provide high-quality ac power to the load, the effective voltage and current feedback compensators are essential. By processing of feedback compensators, the voltage error signal $v_{e1}$ and current error signal $i_{e1}$ will be obtained. Then, the PWM1 compensator will
Figure 9: Protection circuits of the inverter: (a) overcurrent protection circuit, (b) overvoltage protection circuit, and (c) under voltage protection circuit.

generate driving signals of switches \((M_1 \sim M_4)\) to regulate the dc output voltage. The output voltage of inverter \(v_{dc}\) and its filter inductor current \(i_{ac}\) are sampled to generate driving signals of switches \((M_5 \sim M_8)\) and employed to realize a high steady and dynamic response sinusoidal voltage. The control strategies can be implemented by the TMS320F240 microcontroller to improve the system performance. The conceptual control block diagram of the proposed PV power-generation system is shown in Figure 8.

To achieve an optimal stability and safety for the proposed PV power-generation system, the functions of undervoltage, overvoltage protection, overcurrent protection, and overtemperature protection are required. Figures 9 and 10 show the key protection circuits of the proposed PV power-generation system. All of the protection signals are also realized on the TMS320F240 microcontroller, as shown in Figure 8.

4. Design Considerations of Power Switches

Most power converters have power components that operate at temperatures that are high enough to cause burns
if handled improperly. The power dissipation in power switches normally increases with the internal temperature, and the losses become excessively high even at temperatures of 200°C. Component manufacturers typically will guarantee the maximum values of component parameters such as onstate conduction voltages, switching frequencies, and switching losses at a specified maximum temperature, which varies from one type of component to another and is often at 125°C. Therefore, a system intended to have high reliability would be designed for a worse-case junction temperature in power switches of 20–40°C below 125°C. In order to reduce temperatures of the power switches for the proposed PV power-generation system, the small heat sinks are usually recommended.

The proposed PV power-generation system consists of a phase-shift full-bridge converter, a voltage-doubler circuit, and a full-bridge inverter, as shown in Figure 1. To design the

4.1. Selection of the Power Switches (M₁ ~ M₄). For the current-fed full-bridge phase-shift converter, the voltage

Figure 10: Over-temperature protection circuit of the proposed PV power-generation system.

Figure 11: Measured gate signal waveforms of the power switches (M₁ ~ M₄).

Figure 12: Measured voltage and current waveforms of the power switch M₁.

Figure 13: Measured voltage and current waveforms of the power switch M₄.
4.3. Selection of the Rectifier Diodes

MOSFETs with low \( R_{ds(on)} \) can usually keep low conduction losses and temperatures, but they usually have high parasitic capacitance and require a larger die size. In this design, the power switches are IRF530N with a drain-source breakdown voltage of 400 V, drain current of 15 A, and a channel resistance of 0.064 \( \Omega \).

4.2. Selection of the Power Switches

For the dc/ac inverter, the voltage stress imposed on power switches \( (M_5 \sim M_8) \) is \( V_{ds(max)} = V_{PV} + V_{Li} = 40 \) V. When power switches are turned on, the maximum switching current \( i_{ds(peak)} \) is equal to the current \( i_{ds(peak)} \). Thus, the maximum switching current \( i_{ds(peak)} = 10 \) A. Selection of power switches involves a tradeoff between conduction losses and switching losses. MOSFETs with low \( R_{ds(on)} \) can usually keep low conduction losses and temperatures, but they usually have high parasitic capacitance and require a larger die size. In this design, the power switches are IRF530N with a drain-source breakdown voltage of 100 V, drain current of 15 A, and a channel resistance of 0.064 \( \Omega \).

To verify the performance of the proposed PV power-generation system, a 300 W prototype power system was built. Its specifications are listed as follows:

(1) input voltages: \( V_{PV} = 15 \sim 20 \) \( V_{dc} \),
(2) dC output voltage: \( V_{dc} = 230 \) \( V_{dc} \),
(3) output AC voltage: \( V_{ac} = 110 \) \( V_{ac} \), 60 Hz,
(4) output power: \( P_{out,max} = 300 \) W,
(5) switching frequency: \( f_s = 50 \) kHz \( (M_1 \sim M_4) \),
(6) switching frequency: \( f_{ac} = 20 \) kHz \( (M_5 \sim M_8) \).

Figure 11 shows measured gate signal waveforms of power switches \( (M_1 \sim M_4) \). Figures 12 and 13 show measured drain-source voltage and current waveforms of the power switches \( M_1 \) and \( M_4 \) to illustrate a ZCS feature at turn-on or turn-off transition, respectively. In Figures 12 and 13, ringing condition appeared in voltage and current waveforms of power switches are caused by the parasitic elements of the switching devices and the transformer. Figure 14 shows measured primary and secondary voltage waveforms of the transformer. Figure 15 shows measured output voltage, current, and power waveforms of PV arrays.

4.3. Selection of the Rectifier Diodes \( (D_{o1}, D_{o2}) \).

In the voltage-doubler circuit, the voltage stress imposed on rectifier diodes \( D_{o1} \) and \( D_{o2} \) is \( V_{di} = (N_p/N_o)(V_{in}/2) = 115 \) V. When rectifier diode \( D_{o1} \) or \( D_{o2} \) is conducting, the maximum diode current \( i_{ds(max)} = (N_p/N_o)I_{in(max)} = 0.9 \) A. Thus, an MUR420 ultrafast diode which has a maximum recurrent peak reverse voltage of 200 V, maximum average forward rectified current of 4 A, and forward voltage drop \( (V_F = 0.89 \) V) is selected.

5. Experimental Results

To verify the performance of the proposed PV power-generation system, a 300 W prototype power system was built. Its specifications are listed as follows:

(1) input voltages: \( V_{PV} = 15 \sim 20 \) \( V_{dc} \),
(2) dC output voltage: \( V_{dc} = 230 \) \( V_{dc} \),
(3) output AC voltage: \( V_{ac} = 110 \) \( V_{ac} \), 60 Hz,
(4) output power: \( P_{out,max} = 300 \) W,
(5) switching frequency: \( f_s = 50 \) kHz \( (M_1 \sim M_4) \),
(6) switching frequency: \( f_{ac} = 20 \) kHz \( (M_5 \sim M_8) \).

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Overvoltage protection

\[ V_{dc}: 5 \text{ V/div}, \quad v_{ac}: 200 \text{ V/div}, \quad i_{ac}: 5 \text{ A/div}, \quad i_{ac, ref}: 2 \text{ V/div}, \quad \text{time: 100 ms/div} \]

(a)

Undervoltage protection

\[ V_{dc}: 5 \text{ V/div}, \quad v_{ac}: 200 \text{ V/div}, \quad i_{ac}: 5 \text{ A/div}, \quad i_{ac, ref}: 2 \text{ V/div}, \quad \text{time: 200 ms/div} \]

(b)

Overcurrent protection

\[ I_{dc}: 5 \text{ V/div}, \quad i_{ac}: 5 \text{ A/div}, \quad \text{time: 500 ms/div} \]

(c)

Figure 17: Measured waveforms for circuit protection functions: (a) over-voltage protection, (b) under-voltage protection, and (c) over-current protection.

In this paper, a PV power-generation system for high step-up voltage applications is proposed. All power switches of the full-bridge converter with phase-shift PWM technique have a ZCS feature at turn-on or turn-off transition. Hence, the switching losses of the power switches can be reduced. In order to draw maximum power from the PV arrays source, a simple perturbation and observation method is incorporated to realize maximum power conversion. Then, the dc-link bus is used by a dc/ac inverter, which can induce a sinusoidal source to supply utility power. To adopt a cost effective of the proposed power supply system, the MPPT algorithms and protected circuits consist of a digital signal processor (DSP) and analog circuits to implement MPPT and protect system. Thus, the control circuit of the proposed PV power-generation system is compact and programmable. Experimental results have been verified that the proposed PV power-generation system is relatively suitable for high step-up voltage applications.

6. Conclusions

In this paper, a PV power-generation system for high step-up voltage applications is proposed. All power switches of the full-bridge converter with phase-shift PWM technique have a ZCS feature at turn-on or turn-off transition. Hence, the switching losses of the power switches can be reduced. In order to draw maximum power from the PV arrays source, a simple perturbation and observation method is incorporated to realize maximum power conversion. Then, the dc-link bus is used by a dc/ac inverter, which can induce a sinusoidal source to supply utility power. To adopt a cost effective of the proposed power supply system, the MPPT algorithms and protected circuits consist of a digital signal processor (DSP) and analog circuits to implement MPPT and protect system. Thus, the control circuit of the proposed PV power-generation system is compact and programmable. Experimental results have been verified that the proposed PV power-generation system is relatively suitable for high step-up voltage applications.

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