A Novel Flyback-type Utility Interactive Inverter for AC Module Systems

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Abstract: In recent years, natural energy has attracted growing interest because of environmental concerns. Many studies have been focused on photovoltaic power generation systems because of the ease of use in urban areas. On the conventional system, many photovoltaic modules (PV modules) are connected in series in order to obtain the sufficient DC-bus voltage for generating AC output voltage at the inverter circuit. However, the total generation power on the PV modules sometimes decreases remarkably because of the shadows that partially cover the PV modules. In order to overcome this drawback, an AC module strategy is proposed. On this system, a small power DC-AC utility interactive inverter is mounted on each PV module individually and the inverter operates so as to generate the maximum power from the corresponding PV module. This paper presents a novel flyback-type utility interactive inverter circuit suitable for AC module systems. The feature of the proposed system are, (1) small in volume and light in weight, (2) stable AC current injection, (3) enabling a small DC capacitor. The effectiveness of the proposed system is clarified through the simulation and the experiments.

Key words: Photovoltaic generation, AC module, Flyback inverter, and Utility interactive inverter.

I. Introduction

In recent years, natural energy has attracted growing interest because of environmental concerns. Many studies have been focused on photovoltaic power generation systems because of the ease of use in urban areas. On the conventional system, many photovoltaic modules are connected in series in order to obtain the sufficient DC-bus voltage for generating an AC output voltage at the inverter circuit. However, it is difficult to avoid shadows created by neighboring buildings, electric poles, trees, and so on that partially cover the photovoltaic modules. Hence, the power generated from photovoltaic system decreases remarkably on the above condition [1]. In order to overcome this defect, an AC Module Strategy is proposed [2]. On this system, a small power DC-AC utility interactive inverter is mounted on each photovoltaic module individually as shown in Fig. 1 and the inverter operates so as to generate the maximum power from the corresponding photovoltaic module. The output terminal of the individual AC module inverters can be connected in parallel with each other to the utility line as shown in Fig. 2. Hence, the total output power is increased as the sum of output power on each AC module inverter. This means that the number of the parallel-connected inverter, which equivalent to the number of photovoltaic module, can be decided depending upon the dimension on which the photovoltaic modules can be installed. Hence, the flexibility of PV generation system is much improved. Another advantage of AC module concept is the decrease of manufacturing cost owing to mass production of same inverter.

The important issues on the AC module inverter are capability of parallel operation on AC side with low AC current distortion, smaller in volume, high efficiency, and low cost.

In order to satisfy above requirements for AC module

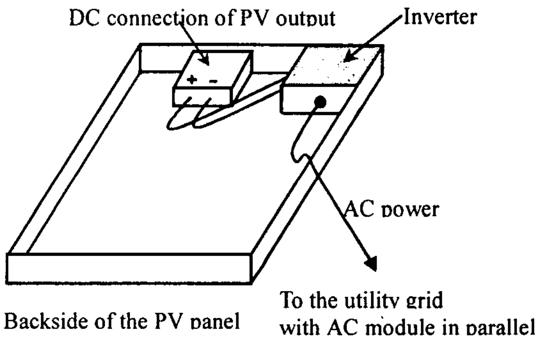


Figure 1. Exterior view of the AC module.

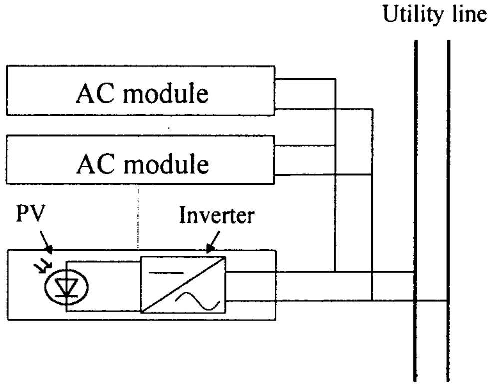


Figure 2. Parallel connection of multiple AC modules.

inverter, the authors present a novel flyback-type utility inverter based on the flyback operation theory. The advantage of the flyback operation is that the stable current injection into the utility line without using the inter-linkage inductor can be realized. Furthermore, volume of the DC input capacitor is dramatically reduced by the effect of a novel ripple reducing technique. The effectiveness of the proposed system is clarified through the simulation and the experiments.

II. Circuit Configuration and Operation Principle

Fig. 3 shows the circuit configuration of the proposed inverter circuit. The circuit consists of two main switches; Q_1 and Q_2, a flyback transformer, T_1, AC switch, Q_{AC1} and Q_{AC2}, active DC power smoothing circuit, and CL filter. Switching frequency of the main switches, Q_1 and Q_2, are 200-500kHz, but that of the AC switches, Q_{AC1} and Q_{AC2} are 50/60 Hz, which is synchronized with the utility line voltage. Hence, the volume of the flyback transformer is reduced and the switching loss on the AC switches is minimized. As the magnetizing current of the flyback transformer is on discontinuous operation, then main switches perform the ZCS turn on operation. Hence, the turn-on loss on the main switch is also decreased. As a result, conversion efficiency is increased.

Fig. 4(a) and (b) show the equivalent circuit and the operation waveforms on which the output current flows on positive direction. Fig. 5(a) and (b) show the same ones on which the output current flows on negative direction. In Fig. 4, main switch, Q_1, operates at 500kHz whereas another main switch, Q_2, turns off. The AC switch, Q_{AC1}, is kept to turn on during this interval. In Fig. 5, main switch, Q_2, operates at 500kHz whereas another main switch, Q_1, turns off. The AC switch, Q_{AC2}, is kept to turn on during this interval.

The operation modes in Fig. 4 are as follows,

(a) Mode 1:

Main switch, Q1, turns on and magnetizing current, i_1, of the transformer increases linearly, and the peak value

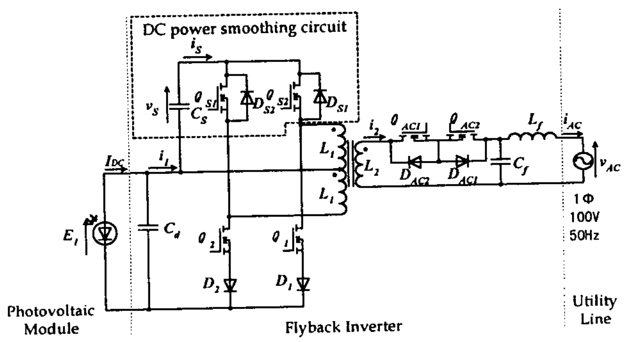
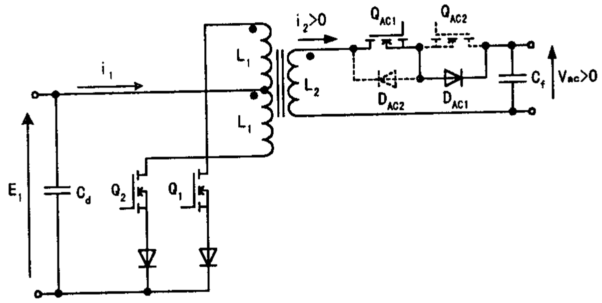


Figure 3. Circuit configuration of the proposed system.

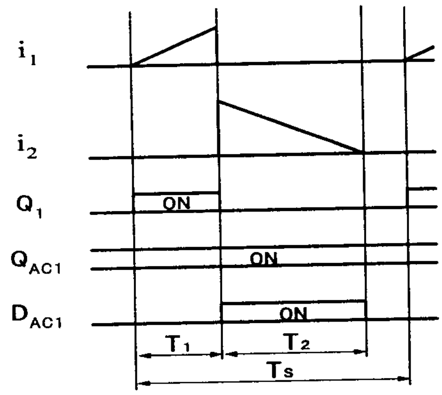
is expressed as,

$$I_1 = \frac{E_1 T_1}{L_1} \tag{1}$$

where, E_1: input voltage, L_1:self inductance of primary

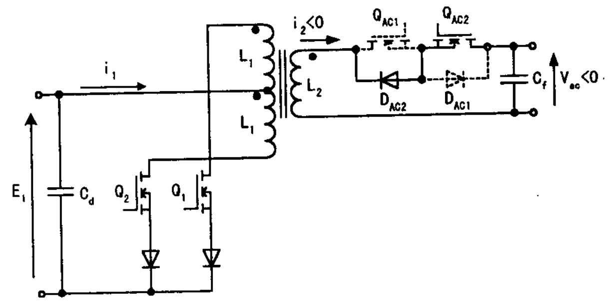


(a) equivalent circuit.

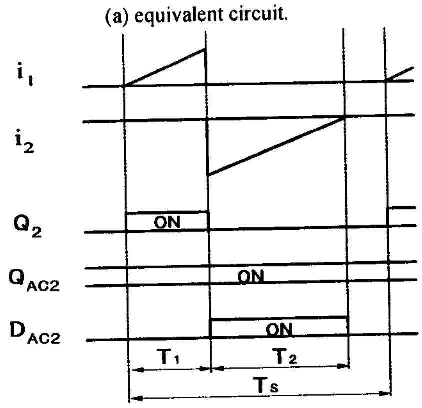


(b) operation waveforms.

Figure 4. Equivalent circuit and operation waveforms on the positive output current condition.



(a) equivalent circuit.



(b) operation waveforms.

Figure 5. Equivalent circuit and operation waveforms on the positive output current condition.

winding, T_1:On time of Q_1

(b) Mode 2:

The magnetizing current is flowing out from the secondary winding of the transformer and it flows to utility line via AC switch, S_{AC1}, and diode,D_{AC1}. The secondary current, i_2, is expressed as,

$$i_2 = I_2 - \frac{V_{AC}}{L_2} t. \qquad (2)$$

$$I_2 = I_1 \sqrt{\frac{L_1}{L_2}} \qquad (3)$$

where, L_2: self inductance of the secondary winding, V_{AC}: utility line voltage, I_2: peak current of i_2.

When the current, i_2, decreased to zero, the diode, D_{AC1}, turns off on ZCS switching manner.

(c) Mode 3:

No current flows on both the primary and secondary winding on the transformer.

Here, the averaged current on the secondary windings is expressed as,

$$\bar{i}_2 = \frac{1}{T_S} \int^{T_2} i_2 dt = \frac{E_1{}^2 T_1{}^2}{2 L_1 T_S V_{AC}}. \qquad (4)$$

where, $T_2 = \frac{L_2 I_2}{V_{AC}}$, T_S: Switching interval.

It is assumed that the utility line voltage, V_{AC}, is expressed as sinusoidal waveform, and the turn-on time of Q_1 is controlled to be in proportion to the utility voltage V_{AC}.

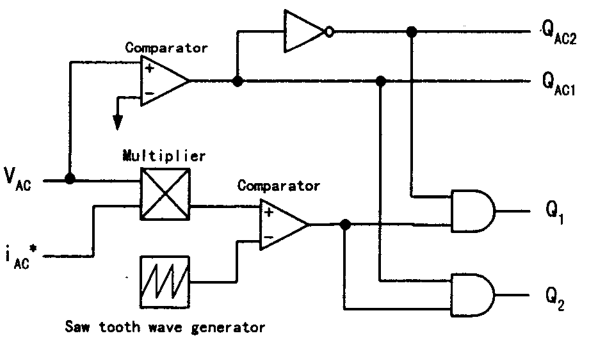


Figure 6. Control block diagram.

Table 1. Circuit parameters

DC Voltage	E_1	35V
Input capapacitor	C_d	10uF
Snubber capapacitor	C_S	50uF
AC filter inductor	L_f	100uH
AC filter capacitor	C_f	0.6uF
Self inductance of flyback transformer	L_1,L_2	1uH
	L_3	25uH

$$V_{AC} = V \sin \omega t \qquad (5)$$

$$T_1 = k T_S \sin \omega t \qquad (6)$$

where, $0<k<1$.

Substituting (5) and (6) into (4), the AC output current i_{AC} is expressed as,

$$\bar{i}_{AC} = \frac{k E_1{}^2 T_S}{2 L_1} \sin \omega t \qquad (7)$$

Same equation is derived on the condition in Fig.3.

From the above discussion, it is clear that the output current is controlled to sinusoidal. Hence, the current control loop in the inverter controller and inter-linkage inductor can be rejected those are necessary for the conventional voltage-source utility interactive inverter system. In another words, the proposed utility inverter can inject the AC current into the utility line.

Fig. 6 shows the control block diagram of the proposed inverter system. This very simple control circuit is effective to the reduction of the production cost of the inverter system.

III. Simulation and Experimental Results

Table 1 shows the circuit parameters. In order to grasp the operation of the inverter clearly, constant DC voltage source is used instead of photovoltaic modules. The switching frequency of the mains switches is set to 500kHz.

Fig. 7 shows the simulated waveforms of the proposed inverter. It is clear that the peak value of the primary winding current, i_1, forms the rectified sinusoidal waveform and that of secondary winding current, i_2, forms the sinusoidal waveform. Hence, the output current, i_{AC}, is in conformity with the utility voltage waveform V_{AC}.

Fig. 8 shows the operation waveforms during one switching period. During the period of Q_1 (or Q_2) are turned on, the primary current increases linearly and it reaches to the peak value. When the main switches are turned off, the primary current is transferred to the secondary winding and decreases linearly. It is also clear that the discontinuous current mode operation is performed.

Fig. 9 shows the output current waveforms on the experimental setup. The output current is controlled to sinusoidal waveform except the zero-crossing distortion. This distortion is caused by the pulse width error on the gate drive circuit. However, it will be possible to correct it by using the high-speed gate drive circuit or by adding the auxiliary current feedback control loop.

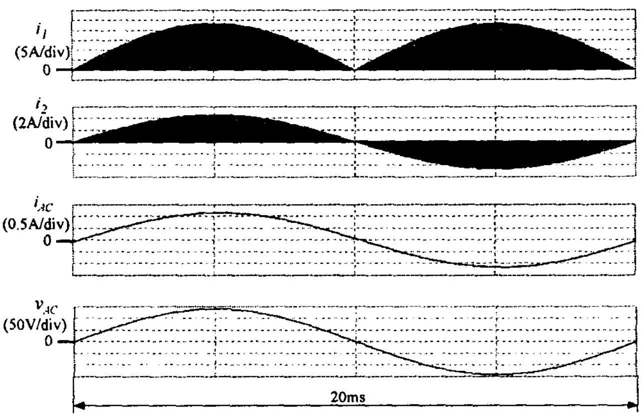


Figure 7. Simulated waveforms.

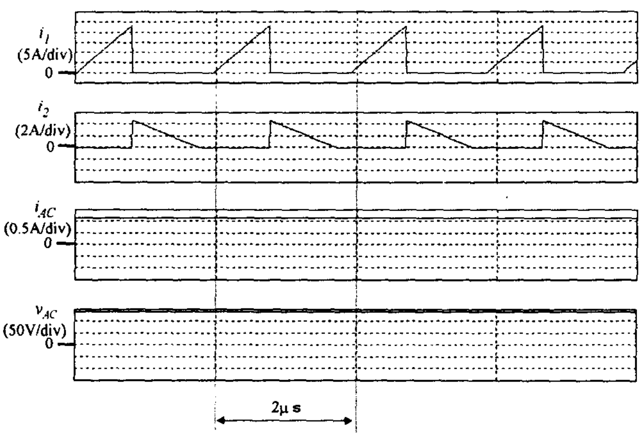


Figure 8. Simulated results of the switching waveforms.

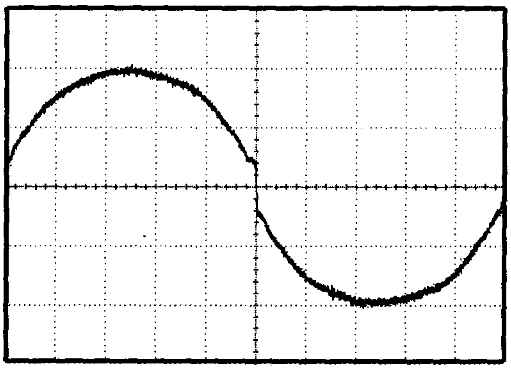


Figure 9. Experimental result of the output current waveform.

IV. DC Ripple Voltage Reduction

On the single-phase utility inverter circuit, large amount of ripple voltage with twice the utility frequency appears on the DC-bus voltage. This ripple voltage results in the distortion on the output current. In order to reduce the ripple voltage, a chemical capacitor having large capacitance has been used. However, those of the chemical capacitor affect volume and lifetime of the inverter.

In order to solve these drawbacks, a DC power smoothing circuit that can reduce the ripple current on the DC-bus is proposed. The circuit configuration is same with the conventional DC-active-clamp snubber circuit whereas the control signal for the active-switch is deferent. The circuit, which is denoted by the dotted line in Fig.3, consists of active snubber switches, Q_{S1} and Q_{S2} and snubber capacitor, Cs.

Fig. 10 shows the operational principle of the DC-ripple voltage reduction. The current i_{AC}* and i_{DC}* denote the control command of AC output current and averaged DC input current, respectively. The operation is classified into two modes as follows,

Mode I ($i_{AC}^* < i_{DC}^*$)

Main switch, Q_1 (or Q_2), is turned on at t_a, and magnetizing current, i_1, increases linearly. When i_1 reaches to i_{DC}^* at t_b, main switch is turned off. The magnetizing current, i_1, charges the energy into snubber capacitor C_S through D_{S1} (or D_{S2}), and i_1 decreases linearly. AC switch, Q_{AC1} (or Q_{AC2}), is turned on at t_c, and the secondary current i_2 flows out into AC output side and i_2 decreased linearly to zero at t_d.

Mode II ($i_{AC}^* > i_{DC}^*$)

Main switch, Q_1 (or Q_2), is turn on at t_e, and magnetizing current, i_1, increases linearly. When i_1 reaches to i_{DC}^* at t_f, the main switch is turned off and snubber switch, Q_{S1} (or Q_{S2}), is turned on. The snubber capacitor discharges its energy and i_1 continues to increase. When i_1 reaches to i_{AC}^* at t_g, Q_{S1} (or Q_{S2}) is turned off and Q_{AC1} (or Q_{AC2}) is turned on, and the secondary current i_2 flows out into AC output side and i_2 is decreased linearly to zero at t_h.

From above mentioned operation, the following effects can be obtained.

(a) DC input current has a constant peak value with triangular waveform. This means that low-frequency component on the DC input current is kept to constant value.

(b) On mode I, the DC input energy is larger than that for the AC output energy and hence the residual energy is stored into the snubber capacitor. On the contrary, on mode II, the DC input energy is less than the AC output energy and hence insufficient energy is supplied from the snubber capacitor. Consequently, the energy that causes the low-frequency ripple voltage is transferred into the snubber capacitor and the voltage on the DC capacitor is kept constant.

(c) Even when the capacitance of C_S is small, energy transfer can be executed whereas the voltage fluctuation on C_S is increased. Hence, both capacitance of C_d and C_S can be minimized without increasing the ripple voltage on the DC input. Generally, the total capacitance of C_d and Cs is reduced to around 1/50 of the one on the conventional circuit.

Fig. 11 shows simulation waveforms when the DC power smoothing circuit is activated. It is clear that the input current I_{DC} is kept constant but voltage, V_{CS}, on the snubber capacitor fluctuates. The output current waveform is also remained sinusoidal. This circuit topology and corresponding control circuit are very simple and hence the volume and production cost for this circuit can remarkably be reduced.

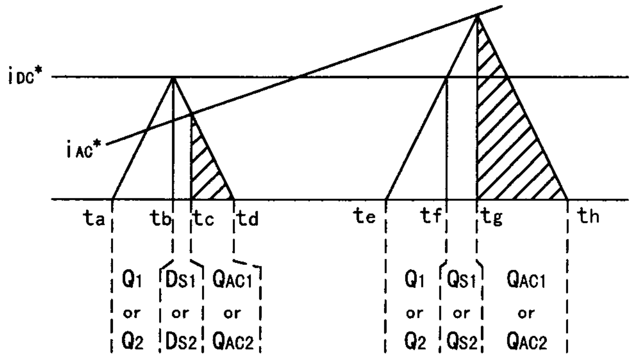


Figure 10. Operation principle of the DC voltage ripple reduction.

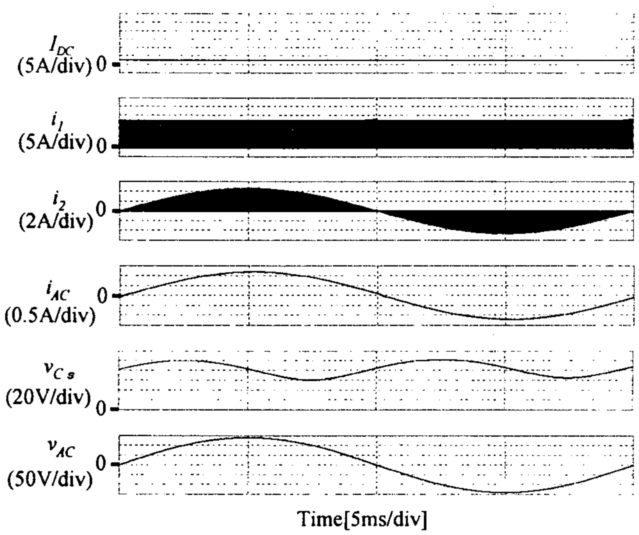


Figure 11. Simulated waveforms in the case that the DC voltage ripple reduction is activated.

V. Conclusions

A novel photovoltaic inverter circuit suitable for AC module system is presented. By utilizing the high-frequency flyback action of the transformer, AC current injection with low harmonic distortion into the utility line is realized. Furthermore, DC power smoothing circuit that can not only diminish the low-frequency ripple voltage but also decrease the total capacitance on the DC input side is presented. It can be shown that chemical capacitor on the DC input side will be swapped to film capacitor with small capacitance.

Hence, the problems of lifetime and volume of the AC module inverter system can be solved.

The effectiveness of this system are confirmed thorough the simulation and experimental results.

Acknowledgment

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