An Isolated Dual-Input Converter for Grid/PV Hybrid Power Systems

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***Abstract*—An isolated dual-input power converter for a grid/photovoltaic (PV) hybrid power indoor lighting system is proposed in this paper. The proposed converter can be operated in single power supply mode or hybrid power supply mode. While the available PV power is insufficient for the load demand, the proposed dual-input converter will automatically deliver the complement power from the grid. The power complementing is achieved by two independent control loops of the PV power and the grid power. Finally, a prototype for a 36W LED lighting module is constructed to verify the validity of the proposed converter. From the experimental results, it can be seen that a smooth 24V/1.5A output power for the LED lighting module can be provided even while the PV power is insufficient or unavailable.**

***Index Terms*—hybrid power system, dual-input converter, PV array**

I. INTRODUCTION

Renewable energy systems have attracted a lot of attention due to the global warming and fuel crisis [1]-[6]. It is seen that the power consumption of office lighting systems may take 20% to 60% of total energy consumption in daily life [7]. Among the renewable energy resources, PV power has been considered as a more stable and reliable power source [8]. In most of PV power systems, the battery storage device is required to provide smoother electricity. However, the costs of installing PV arrays and maintaining battery pack are still considerable for consumers. In recent studies, reducing the consumption of grid power by combining renewable resources is one of the major trends. To reduce the system cost and provide a stable power supply, several types of multi-input converters with renewable energy resources and grid power hybrid have been proposed [9]-[18]. The dependence on grid power can then be reduced and the output power quality is also remained.

Basically, these multi-input converters can be classified into three types of topology. In first type, a multi-winding transformer is used to integrate the multi input power sources with single core [12]-[14]. In second type of converter, a pulsating voltage source cell (PVSC) is used as the power coupling component [9],[15]-[18]. Because the inductor is the main component in the PVSC, the major design criteria of the PVSC-type converter are the continuity of inductor current and the copper loss of inductor winding. In the last type converter, a pulsating current source cell (PCSC) is adopted as the power coupling component [17],[18]. The copper loss is relatively much lower because the multi-input power sources are coupled by capacitors [18].

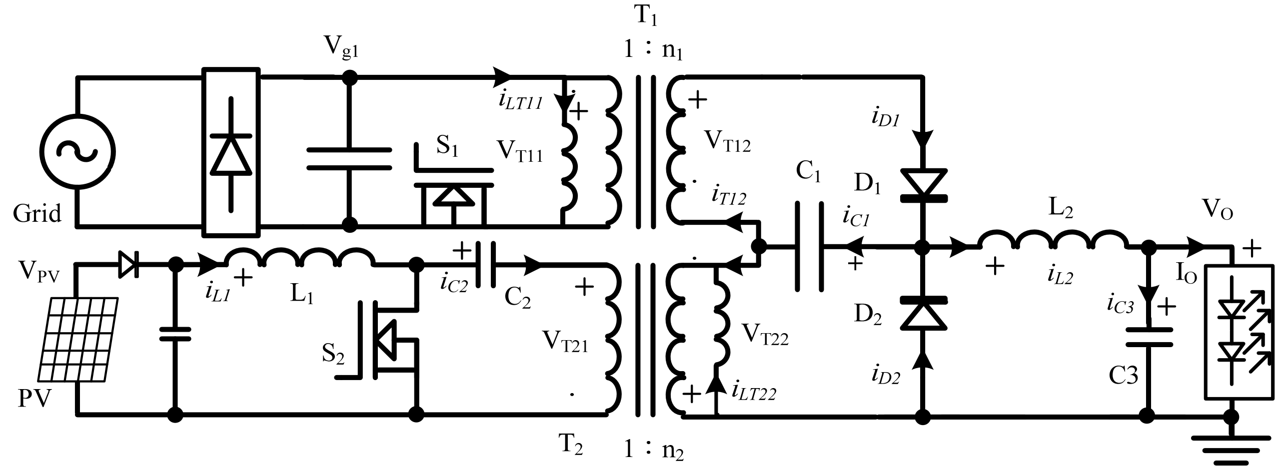

Figure 1. Grid/PV hybrid power system with proposed dual-input converter

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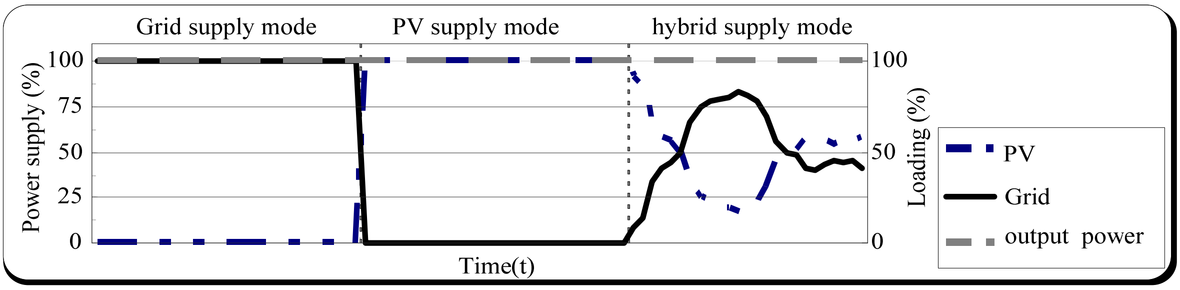


Figure 2. Power supply modes of the grid/PV hybrid power *system*

The circuit diagram of the grid/PV hybrid power system with proposed dual-input converter is shown in Fig. 1. The system can be operated in single power supply mode or hybrid power supply mode as shown in Fig. 2. While the PV power is unavailable, the converter would be operated in single power supply mode, namely, the grid supply mode. If the PV power can only provide part of the load, the converter will be operated in hybrid power supply mode for delivering the rest part of power from the grid to the load side. As a result, the commonly required battery pack in the stand-alone system can then be replaced by the grid to provide smooth electricity. The PV array installation capacity can also be reduced because additional capacity for presorting in the battery pack is not required. Therefore, resulted system installation and maintenance costs can both be reduced. It would be very helpful to encourage consumers to purchase a PV power system as an alternative electricity system.

II. OPERATION PRINCIPLE OF THE PRPOSED CONVERTER

For the proposed converter shown in Fig. 1, the active switch S_1 is adopted to control the power flow from the grid to the load through the coupling capacitor C_1. The other input terminal is connected to the PV array and the PV output power is controlled by the active switch S_2.

The PV power is delivered to the load side through the coupling capacitor C_1 as well. Once the available power from PV array is lower than the load demand, the proposed converter would deliver the complement power from the grid to the load side according to the feedback information about the load current. Based on the supplying power sources, there are three power supply modes of the proposed converter as shown in Fig. 2. First, if the PV power is unavailable, the converter is operated in the grid supply mode. Then the converter would be changed into the PV supply mode while the available PV power is higher than the load demand. Finally, if the PV power is available but not enough for the load, the converter would be operated in the third mode, namely the hybrid supply mode.

While the two sources are simultaneously delivering power, i.e. in the hybrid supply mode, there would be six operation modes in one switching cycle as shown in Fig. 3. The relative waveforms in one switching cycle are shown in Fig. 4. It can be seen that the two active switches are controlled with interleave phase shift technique to reduce the voltage and current ripple of the coupled capacitor. The corresponding operation principles are described as follows:

Mode1—($t_0 \leqq t<t_1$): In this operation mode, the switch S_1 and diode D_2 are turned off and switch S_2 and diode D_1 are turned on. The corresponding equivalent circuit is shown in Fig. 3(a). The pre-stored energy in the magnetizing inductance of the transformer T_1 is released to secondary side. The capacitor C_1 is charged with the difference (i_{LT12}-i_{L2}).

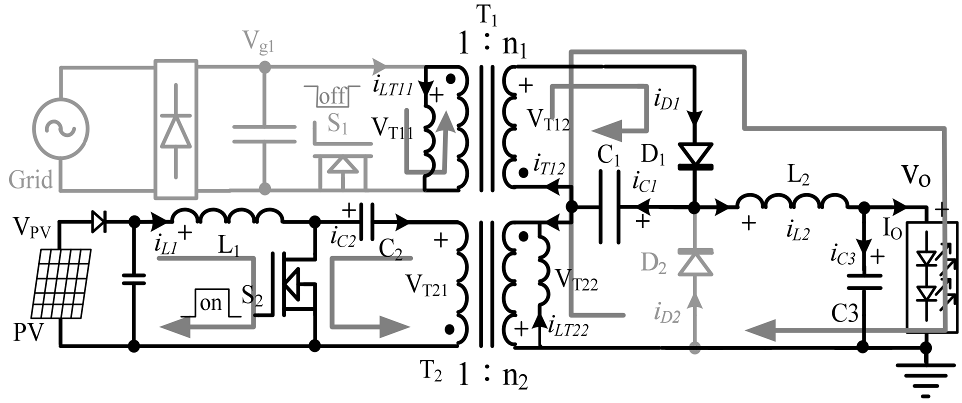
Mode2—($t_1 \leqq t<t_2$): In the second mode, the magnetizing current of T_1 to the secondary side, i.e. i_{LT12}, is lower than the inductor i_{L2} and the coupled capacitor C_1 would turn into being discharged by the difference between these two currents. The corresponding equivalent circuit is shown in Fig. 3(b). The magnetizing current i_{LT11} is continuously decreased and will become zero at the end of this mode.

*Mode3—($t_2 \leqq t<t_3$):*In the mode, the magnetizing current of T_1 at the secondary side is zero and the diode D_1 is turn into off. The corresponding equivalent circuit is shown in Fig. 3(c).

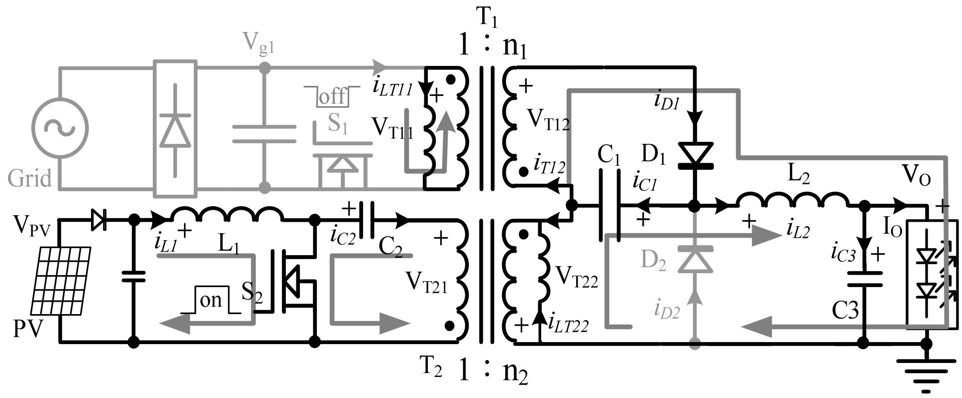
Mode4—($t_3 \leqq t<t_4$): The active switch S_2 is turned off at $t=t_3$ and then the converter would be operated in mode 4, as shown in Fig. 3(d). The diode D_2 is turned on for the pre-stored energy in inductor L_1 to charge the capacitors C_2 and C_1.

*Mode5—($t_4 \leqq t<t_5$):*In this mode, the active switch S_2 is still turned off and the corresponding equivalent circuit is shown in Fig. 3(e). The diode D_2 is still turned on because the inductor current i_{L2} is larger than the difference between the magnetizing current i_{LT22} and the inductor current transferred to secondary side i_{L1}/n_2. Therefore, the coupled capacitor C_1 would be discharged by the current difference i_{LT22}-i_{L1}/n_2.

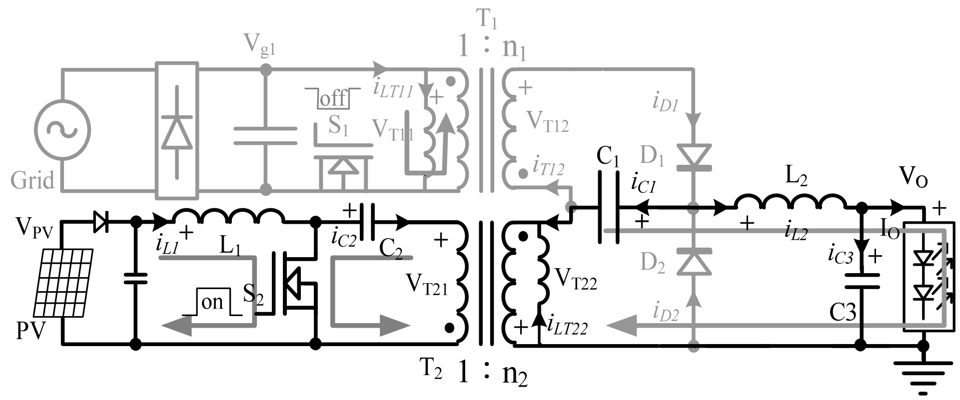
Mode6—($t_5 \leqq t<t_6$): In the mode, the diode D_2 is turn into off, the active switch S_1 is turned on at $t=t_5$, then the operation mode of this converter would change into mode 6 as shown in Fig. 3(f). The capacitor current i_{C1} is equal the inductor current i_{L2}. In this mode, the energy on the magnetizing inductance of transformer T_1 would be increased again by the grid source. This operation mode would be ended while the active switch S_1 is turned off and then the operation mode would be recycled to mode 1.



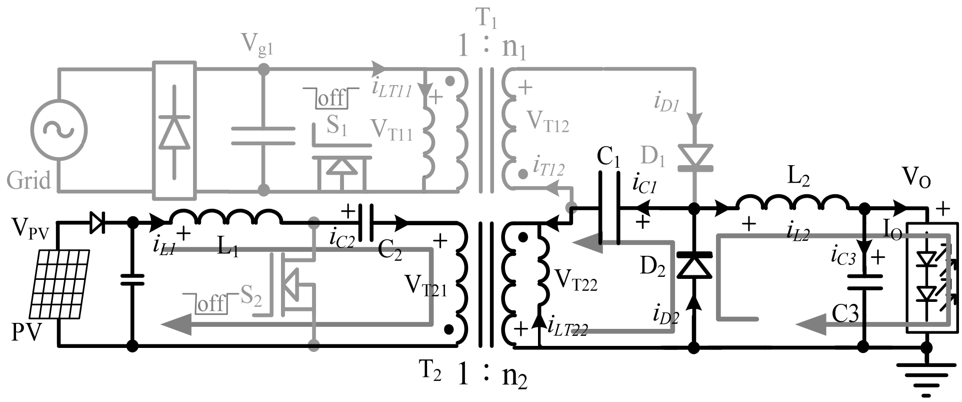
(a) Mode 1



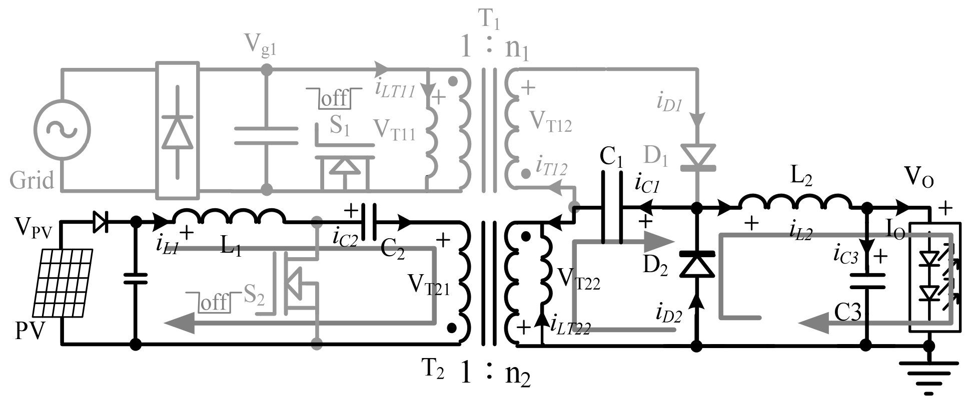
(b) Mode 2



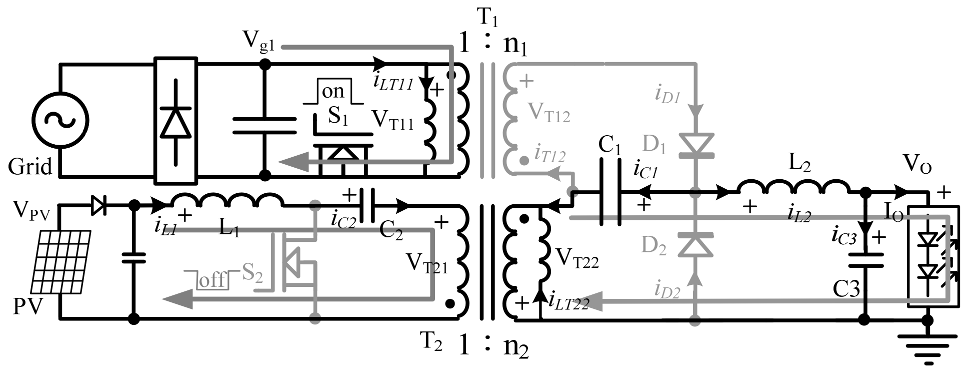
(c) Mode 3



(d) Mode 4



(e) Mode 5



(f) Mode 6

Figure 3. Equivalent circuits of the proposed converter in different operation modes

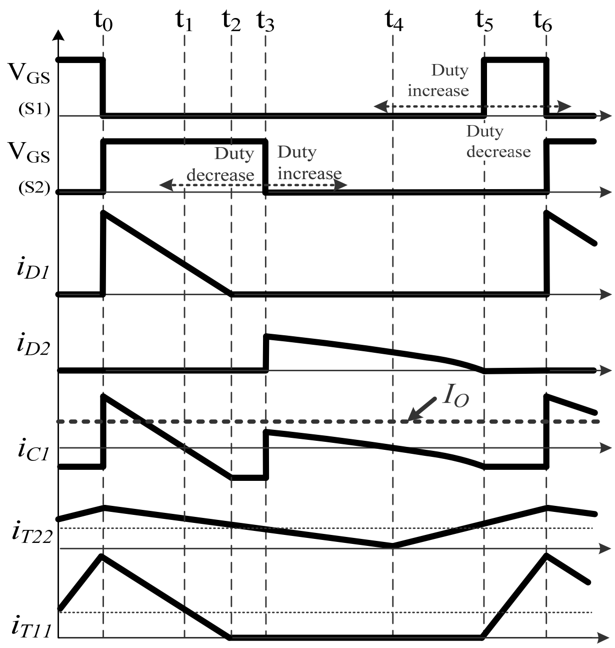


Figure 4. Relative waveforms in one switching cycle

III. Power Complement Controller

From section II, it is seen that the power drawn from the grid is controlled by the active switch S_1 and firstly buffered in the coupling capacitor. Then, it would be transmitted to the load side through the inductor L_2. The other input power, i.e. the PV power, is controlled by the active switch S_2. The power processes are similar to an isolated Cuk converter. The PV power would be delivered to the load side through the transformer T_2 and coupling capacitor C_1. Obviously, the two power flows are both unidirectional and transferred to the load side individually. Therefore, the two active switches can be independently used to control the power from each input source. To achieve automatically delivering the complement power part from the grid to provide smooth electricity for the load, a power complement controller for the proposed converter is shown in Fig. 5. It is seen that the power complement controller is composed of two independent control loops for grid power and PV power respectively.

Usually, a maximum power point tracking (MPPT) would be adopted to fully utilize the renewable PV power. Hence, the gating signal of the active switch S_2 is provided according to the adopted MPPT strategy. The MPPT strategy is out of the scope of this study and would not be further described. Basically, either one of the well-known current-controlled type MPPT strategies can be directly applied to this controller. And the gating signal of the active switch S_1 is then decided according to the amount of the complement power for the load. In this paper, a well-known hill-climbing searching MPPT strategy is adopted in the prototype lighting system. For the control loop of PV power, the PV current is regulated to the current command for extracting maximum PV power.

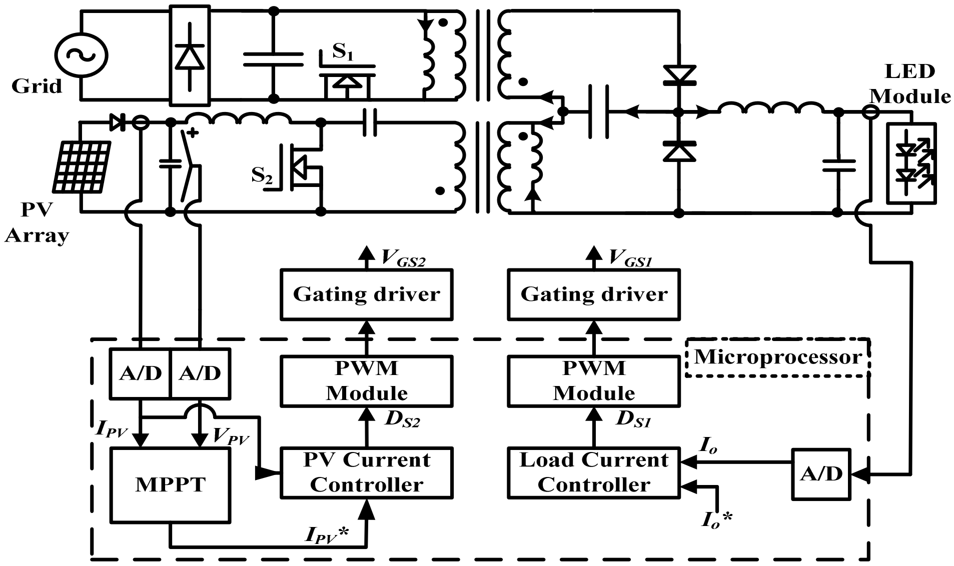


Figure 5. Power complement controller diagram

The active switch S_2 is driven by gating signal V_{GS2} to control the input current from PV array. For the control loop of grid power, the main object is to deliver the complement power for remaining smooth current to the LED lighting module. Therefore, the load current I_o is fed back and needs to be regulated to the load current command I_o^* which is decided by the normal operating current of LED module. Then the active switch S_1 will be driven by the gating signal V_{GS1} to control the input grid power for complementing the power demand.

IV. Experiment Results

To evaluate the performance and validity of proposed converter, a prototype with a 45W PV array for a 36W LED lighting module is constructed as shown in Fig. 6. The controlled is implemented by a microprocessor, HT46R23, and relative electrical parameters are shown in Table I. The input current from PV array and load current are sampled by hall sensors. Fig. 7 shows the waveforms of the grid input current, PV input power and the load condition. In Fig. 7(a), it can be seen that firstly the load demand is only provided by the grid because the PV power is unavailable. Then, the PV power is started to provide its maximum power, but the available PV power is still not enough for the load.

Therefore, the converter is automatically changed into hybrid supply mode for delivering the complement power from the grid. Once, the maximum PV power is higher than the load demand, there is no complement power required from grid. As a result, the output power for the LED module as shown in Fig. 7(b) can then be well-controlled at 36W/24V/1.5A. Fig. 8 shows the waveforms of the capacitor C_1 while the converter is operated in hybrid supply mode with 50% PV power and 50% grid power. It can be seen that the current ripple and peak current are reduced because of adopting the interleave phase shift technique. Fig. 9 shows the efficiency of the proposed converter in single power supply mode with PV power or Grid power input. The efficiency in hybrid power supply mode is measured and shown in Fig. 10, and the definition of the efficiency η is given as following:

$$\eta = \frac{P_O}{P_{PV} + P_{Grid}} \tag{1}$$

Table I. Parameters of Prototype System

Input	-	V_{Grid}=110VACrms, 60 Hz $V_{MPPT} \approx 45$ V, $I_{MPPT} \approx 1$ A
Output	-	V_O=24 V, I_O=1.5 A
Frequency	-	38.4 kHz
Ferrite core	-	EI-33
Transformer Component	-	L_{T1P}/L_{T1S}=425μH / 35.8μH $A_{gip} \approx$ 0.29 mm N_{T2P}/N_{T2S}=32N / 16N
Inductance Component	-	L_1=460μH L_2=525μH
Capacitor Component	-	C_1=6μF C_2=1μF C_3=220μF

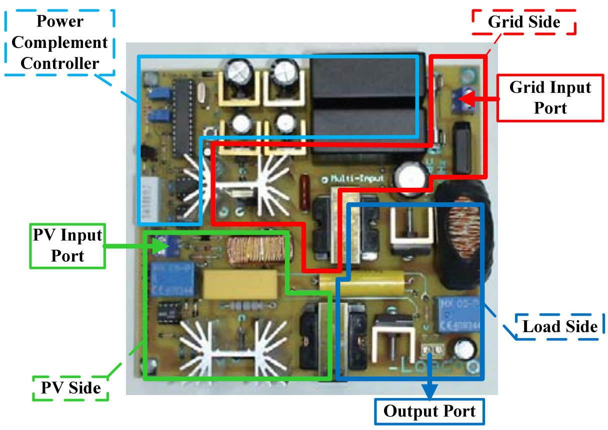
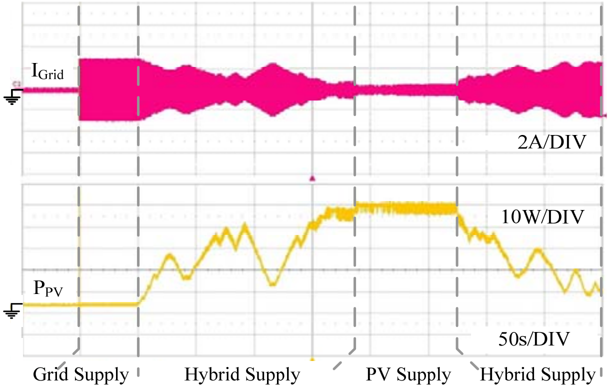
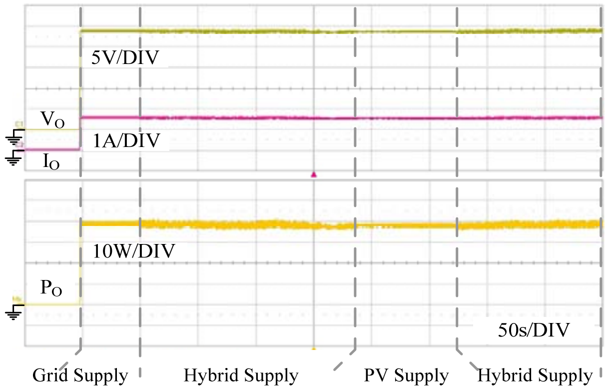


Figure 6. Prototype of proposed dual-input power converter



(a) grid input current I_{GRID}



(b) output voltage V_o, output current I_o and output power P_o

Figure 7. Measured waveforms in hybrid power supply mode

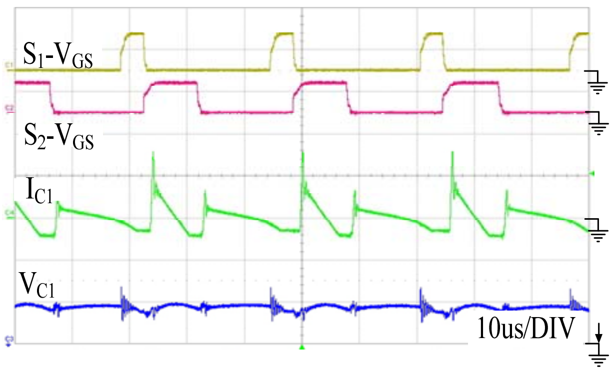


Figure 8. Waveforms in different supply modes ($V_{GS1\&GS2}$: 20V/DIV, V_{C1}: 5V/DIV, I_{C1}:4A/DIV)

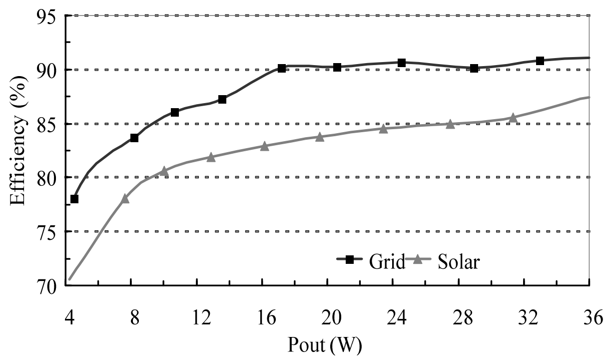


Figure 9. Measured Efficiency of the proposed converter in single power supply modes

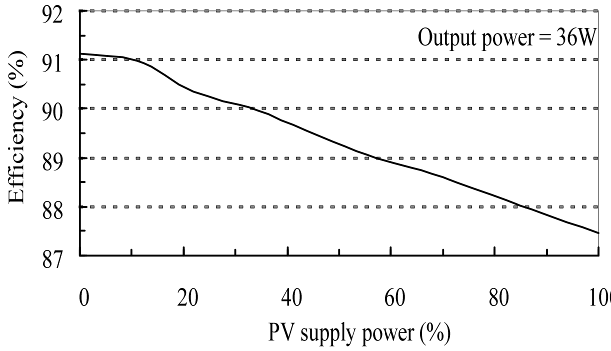


Figure 10. Measured Efficiency of the proposed converter in hybrid power supply mode

The comparison of system cost between stand-alone PV power system and the proposed hybrid power system is shown in Table II. For a 36W office lighting power system with 85% efficiency works 8 hours a day, the minimum required power capacity is 340Wh. However, the rated power of PV array is only available in 2~3 hours a day [19]. The minimum PV array installed capacity for a 36W stand-alone power system is 120W. Compared with the stand-alone system, the required capacity of PV array in the proposed system is only 36W. Moreover, the energy storage device is not required neither. It is seen that the installing and maintenance cost can then be greatly reduced.

Table II. THE POWER SUPPLY SYSTEM COST COMPARISON (8HOURS/DAY AT 36W)

	Stand-Alone PV System	Proposed system
Loading	36W	36W
PV Array	120W	36W
Battery bank	720Wh	—
Cost	High	Low

V. CONCLUSION

This paper proposed an isolated dual-input power converter for grid/PV hybrid power conversion systems which can be operated in single power supply mode or hybrid power supply mode. The power complement controller composed of two independent control loops for the grid and the PV power. Once the available PV power is insufficient for the load demand, the power flow from the grid would automatically be controlled to complement the output power. Finally, a prototype for a 36W LED lighting module is constructed to evaluate the validity and performance of the proposed converter. From the experimental results, it is seen that even while the PV power is unstable, the proposed converter can provide a smooth 24V/1.5A output power for the LED module.

a prototype with a 45W PV array for a 36W LED lighting module is constructed as shown in Fig. 6.

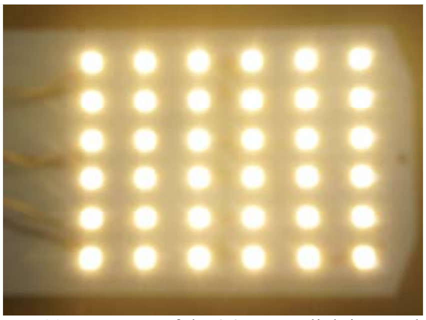


Figure 11. Prototype of the 36W LED lighting module

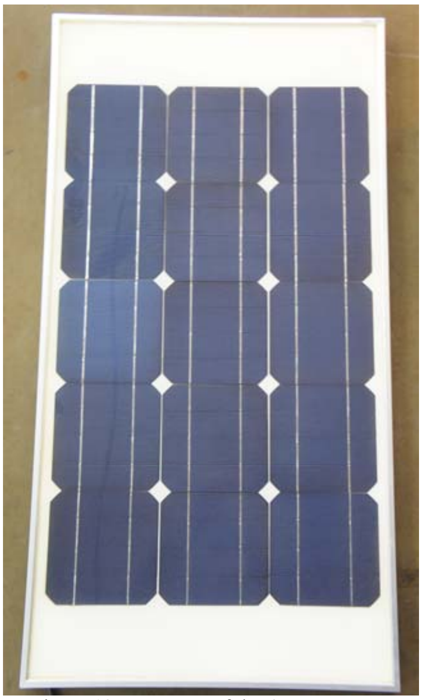


Figure 12. Prototype of the 45W PV array

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