

Voltage Equalizing of Solar Modules for Shadowing Compensation

Hurng-Liahng Jou^{*}, Kuen-Der Wu[†], Jinn-Chang Wu^{**}, Cheng-Huan Chung^{*}, and Ding-Feng Huang^{*}

^{*,†}Department of Electrical Engineering, National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan

^{**}Department of Microelectronics Engineering, National Kaohsiung Marine University, Kaohsiung, Taiwan

Abstract

This paper proposes a shadowing compensation method for the solar modules of grid-connected photovoltaic generation systems. The shadowing compensator (SC) implemented by the proposed shadowing compensation method is used only for the solar modules that can be shaded by predictable sources of shading. The proposed SC can simplify both the power circuit and the control circuit as well as improve power efficiency and utilizes a voltage equalizer configured by a modified multi-winding fly-back converter. The proposed SC harvests energy from the entire solar cell array to compensate for the shaded sub-modules of the solar cell array, producing near-identical voltages of all shaded and un-shaded sub-modules in the solar cell array. This setup prevents the formation of multiple peaks in the P-V curve under shaded conditions. Hardware prototypes are developed for the SCs implemented by the conventional and modified multi-winding fly-back converters, and their performance is verified through testing. The experimental results show that both SCs can overcome the multiple peaks in the P-V curve. The proposed SC is superior to the SC implemented by the conventional multi-winding fly-back converter.

Key words: Photovoltaic generation system, Shadowing compensator, Solar cell array

I. INTRODUCTION

For the I-V (current-voltage) curves of solar modules, a lower temperature corresponds to a higher open-circuit voltage, and a higher irradiance corresponds to a greater solar current [1]. For the P-V (power-voltage) curves of solar modules, a higher irradiance corresponds to a greater maximum power point and a greater output power [2]. A solar module has a unique maximum power point for different irradiance levels and different operating temperatures.

Given that individual solar cells produce a very small output voltage, solar modules utilizes serially connected solar cells to produce energy. A solar cell array comprises many solar modules. The output characteristics of a solar cell array are influenced by irradiance and operating temperature. A mismatch of solar modules may occur in practical situations, resulting in different I-V curves for individual sub-modules

in a solar module. The factors causing a mismatch include imperfections in the manufacturing processes, age, and improper interconnections and shadows [3]. In general, mismatches in a solar module that are caused by the manufacturing processes are generally negligible and can be eliminated in the manufacturing processes. However, mismatches caused by circumstantial conditions, such as cloud cover, the orientation of the sun, sand dust, or the shadows of buildings and trees, are uncontrollable. Therefore, mismatches among sub-modules in a solar cell array caused by circumstantial conditions are unavoidable in practical applications [4]. Figure 1 shows the I-V curves of a solar module. The output current is nearly constant when the voltage is less than the corner voltage and is reduced when the voltage is higher than the corner voltage. As shown in Fig. 1, the output current of the solar module increases as the irradiance increases, and the corner voltage increases as the temperature decreases. Accordingly, the output current of a shaded solar cell is reduced by decreasing irradiation, and the corner voltage is slightly increased by decreasing the temperature. A solar module contains several solar cells connected in series, all of which must have the same current. A shaded solar cell can cause the following two scenarios: (1) a scenario wherein the output current of the solar module is

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[†]Corresponding Author: jinnwu@mail.nkmu.edu.tw

Tel: +886-7-3917141, Fax: +886-7-3645589, National Kaohsiung University of Applied Sciences

^{*}Dept. of Electrical Eng., Nat'l Kaohsiung Univ. of Applied Sci., Taiwan

^{**}Dept. of Microelectronics Eng., Nat'l Kaohsiung Marine Univ., Taiwan

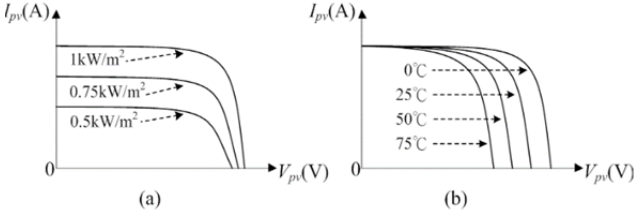


Fig. 1. I–V curves of a solar module. (a) Different irradiance levels. (b) Different temperatures.

limited by the shaded solar cell; or (2) a scenario wherein a reverse-biased voltage occurs across the shaded solar cell when the output current of the solar module is not reduced. In the first scenario, the maximum power point of the un-shaded solar cell is missed, and the output power of solar module is reduced. In the second scenario, the shaded solar cell is regarded as a load and therefore consumes real power. The consumed real power results in a hotspot that damages the shaded solar cells. In general, a solar module is divided into several (2–3) sub-modules connected in a series. An anti-diode is connected in parallel to a sub-module to bypass a sub-module wherein all or a number of the solar cells are shaded [5], [6]. Regardless of whether they are shaded or un-shaded, the solar cells of the bypassed sub-module do not produce power. The output voltage and output power of the solar string are then reduced. Accordingly, the P–V curve of the solar cell array displays multiple peaks when shadowing occurs: one global maximum point and one or several local maximum power points [6].

Maximum power point tracking (MPPT) is crucial for harvesting the output power of solar cell arrays. Many MPPT methods have been proposed to track the maximum power point of a solar cell array in a grid-connected photovoltaic generation system. However, conventional MPPT methods have difficulty in finding the global maximum power point [7]–[10] when part of the solar cell array is shaded. Many advanced MPPT methods [11]–[14] have been proposed to find the global maximum power point on a P–V curve with multiple peaks. Given that the shaded solar cells are bypassed or the output current of the solar cell array is limited by the shaded solar cells, the solar cell array does not output the true maximum output power generated by all solar modules in the solar cell array even when the global peak is tracked. Many power technologies have been established for grid-connected photovoltaic generation systems. MPPT methods for grid-connected photovoltaic generation systems can be classified as follows depending on the topology of the power circuit: central MPPT [14], [15], distributed MPPT [15], [17], or central MPPT with power-electronic compensators [3], [18]–[21].

This paper discusses the central MPPT with a power-electronic compensator to solve the shadowing problems of solar cell arrays. The concept of shadowing compensators (SC) based on power electronics is the same as

that for the voltage equalizer of a battery set. The shaded solar cell still operates and outputs a small amount of power, and the partial output power of all solar cells is converted by the SC to supplement the gap for the output powers between un-shaded and shaded solar cells. A power electronics-based SC was proposed to resolve the problem of shaded solar modules, which use many power electronic switches and an energy-stored inductor [3]. A fly-back DC–DC power converter was used to compensate for the shaded solar module [20]. A bidirectional buck-boost converter was installed between two serially connected solar modules to equalize their voltages [21]. However, this power electronics-based SC should be applied to each solar module in a solar cell array, thereby complicating both the power circuit and the control circuit as well as increasing the power loss.

This paper proposes a SC for a grid-connected photovoltaic generation system. The proposed SC uses a voltage equalizer to compensate for the shaded solar module and is implemented by a modified multi-winding fly-back DC–DC converter. The power source for the proposed SC is the output power of the entire string of solar modules. The proposed SC supplies compensating power to the shaded sub-modules to maintain their voltages at nearly the same level as the voltages of the un-shaded sub-modules. Therefore, the shaded sub-modules can still generate power after the compensation by the proposed SC. Consequently, multi-peaks are avoided, and the photovoltaic generation system generates a greater power than that without the use of the proposed SC. In addition, the shaded sub-modules can still generate, rather than bypass, the output power. To simplify the power and control circuits, the proposed SC is used only for the sub-modules of the solar cell array shaded by the shadow sources that can be predicted. Hardware prototypes are developed for the SCs implemented by the conventional and modified multi-winding fly-back converters; these prototypes are tested to verify their performance.

II. OPERATING PRINCIPLE

In general, the output power and output voltage of the solar module at the maximum power point are mainly affected by the irradiation and operating temperature, respectively. Given that shadows significantly decrease the irradiation and slightly decrease the operating temperature, shadows can decrease the output current while only negligibly changing the output voltage at the maximum power point. In practice, shaded solar cells can still generate power, but the generated power depends on the degree of shadowing. A bypass diode is connected to each solar sub-module to by-pass a shaded sub-module, and all solar cells in the bypassed sub-module are disabled. Thus, the voltage of the bypassed sub-module is only the voltage drop of a bypass diode. Consequently, the

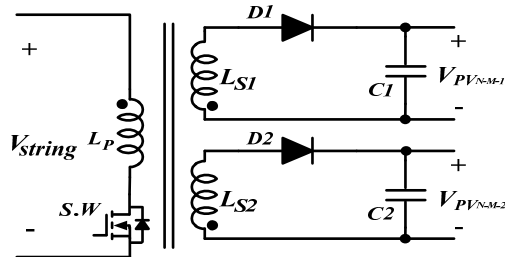


Fig. 2. Circuit configuration of the SC implemented by the conventional multi-winding fly-back converter.

output power of the shaded sub-modules is lost, thereby reducing the output power of the photovoltaic generation system.

A multi-winding fly-back converter was used to equalize battery voltages in a battery set [22]. This concept was applied to equalize the voltages of solar modules in a grid-connected photovoltaic generation system and was verified by computer simulations [23]. The number of secondary windings depends on the number of sub-modules in a solar module. Fig. 2 depicts the circuit configuration of the conventional multi-winding fly-back converter used to implement the SC. The converter comprises a primary winding and two secondary windings. The turn ratio of the primary winding to the secondary winding is 30:3. The primary winding of the transformer is connected to the output of the solar string. Each secondary winding is connected to a sub-module of the solar modular through a diode. The energy is stored in the transformer. This energy is transferred to the secondary windings when the power electronic switch is turned on, and it automatically charges the shaded sub-modules when the power electronic switch is turned off. By setting an appropriate turn ratio between the primary and secondary windings of the transformer, the voltage of a shaded sub-module is maintained at nearly the same level as that of an un-shaded sub-module. Therefore, the voltages of all sub-modules in the solar cell array are the same regardless of whether the sub-modules are shaded or not. In this way, both shaded and un-shaded solar cells still output power, as no anti-diodes of the sub-module are conducted. The P-V curve of the solar cell array has only one maximum power point, thereby eliminating the problem of multiple peaks. Therefore, conventional MPPT methods can be used to track the maximum power point. In addition, this SC increases both the output voltage and output power of the solar cell array in the presence of shadows.

In a solar cell array of the photovoltaic generation system, each solar string has H solar modules, and each solar module has G sub-modules. The solar cell array is configured by a string with M solar modules connected in series, and each solar module has K sub-modules. The output voltage of each string, V_{string} , is the summation of the output voltages of the M solar modules. The output power of each secondary winding of the fly-back converter can be expressed as

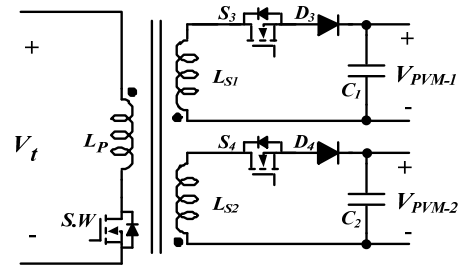


Fig. 3. Circuit configuration of the proposed SC implemented by the modified multi-winding fly-back converter.

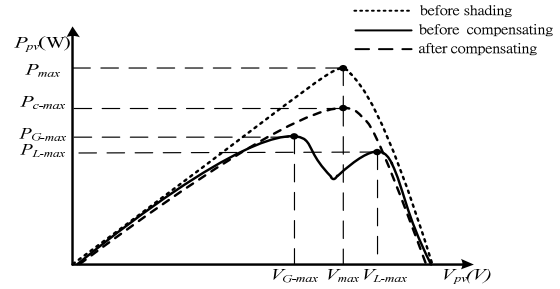


Fig. 4. P-V curves before and after shading.

$$P_C = \frac{V_{string}}{HG} I_C \quad (1)$$

where I_C is the compensation current in the secondary winding of the transformer.

In theory, only the winding of the conventional multi-winding fly-back converter connected to the sub-module with the lowest voltage can be conducted. However, every secondary winding of the multi-winding fly-back converter will be conducted because the flux and voltage drops of the diodes are unequal in practice. This phenomenon results in additional power loss. To solve this problem, a SC equipped with a modified multi-winding fly-back converter (Fig. 3) is proposed. As shown in Fig. 3, an additional power electronic switch is added in each secondary winding. This power electronic switch is turned on only when the voltage of the connected sub-module is lower than that of the other sub-modules. Accordingly, the secondary windings connected to the un-shaded sub-modules will not conduct to avoid additional loss.

Fig. 4 shows the P-V curves of a solar cell array before and after part of the solar cell array is shaded. Before part of the solar cell array is shaded, the P-V curve is smooth, involving only one maximum power point. The multi-peaks appear on the P-V curve when part of the solar cell array is shaded because the relative anti-diodes are conducted or the currents of the un-shaded solar cells are limited. Thus, the output power of the photovoltaic generation system is reduced. If the SC is applied, the shaded sub-modules can maintain the same voltages as the un-shaded sub-modules. Therefore, the shaded sub-modules can still operate to output less power, and the relative anti-diodes are not conducted. In addition, the currents of the un-shaded solar cells are not

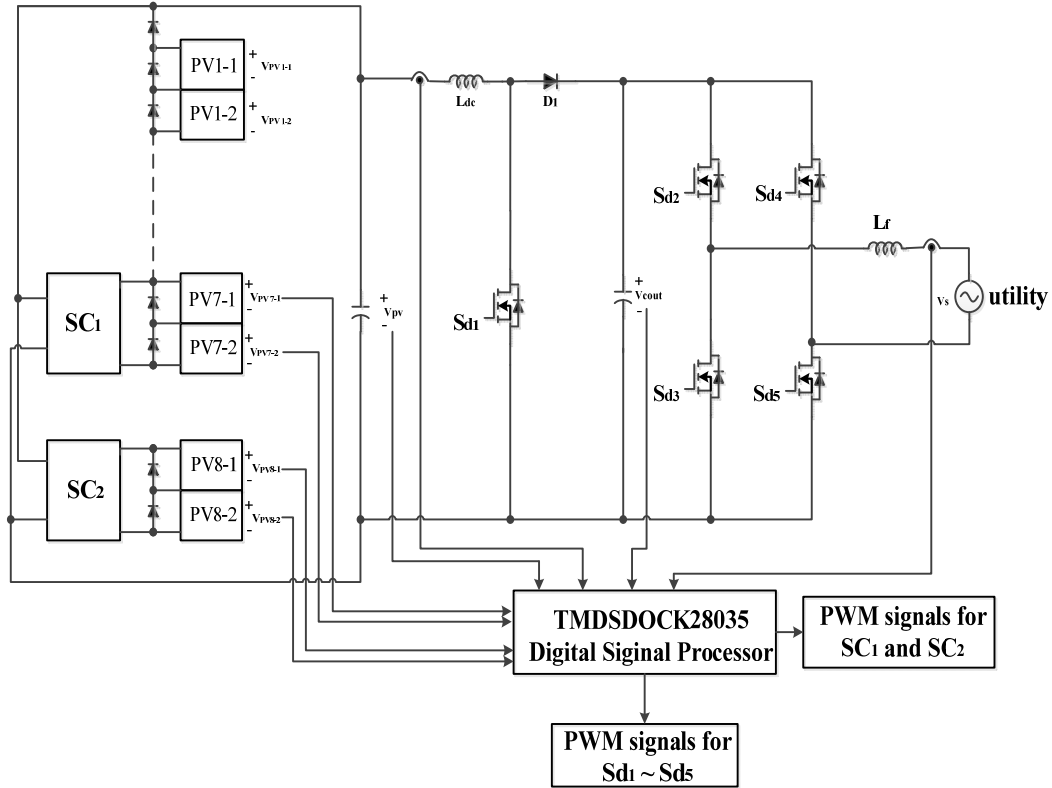


Fig. 5. Circuit topology of the photovoltaic generation system.

limited, and the un-shaded solar cells can output their maximum power. In this way, the P–V curve is smooth and has only one maximum power point even though part of the solar cell array is shaded. Consequently, the multi-peaks are avoided, and the photovoltaic generation system can generate greater power than that without the use of the proposed SC even if the advanced MPPT, which can accurately track the global maximum power point, is used.

SCs are typically applied to every solar module in a solar string [3], [18]–[21]. Thus, the grid-connected photovoltaic generation system has a complex power circuit, particularly for SCs based on a multi-winding fly-back converter. In addition, installing more SCs will result in additional power loss. Therefore, the application of conventional SCs to every solar module in a solar string leads to complex power and control circuits, thereby decreasing power efficiency. A solar cell array is installed in a pre-ordained location. Thus, the possible sources of shading, such as buildings and trees, can be predicted, so the degree of shading for a solar module in the solar cell array can be evaluated. To simplify both the power and control circuits, the proposed SC is used only for the solar modules that can be shaded by the predicted sources of shading. In addition, the power efficiency is also improved because the number of SCs is reduced, further promoting the practical use of the proposed SC.

Fig. 5 shows the circuit topology of the photovoltaic generation system with the proposed SC, which includes a solar cell array, a boost DC–DC converter, and a

grid-connected full-bridge DC–AC inverter. Eight solar modules are connected in series in a solar string. Only PV7 and PV8 modules may be shaded in this solar string. The boost DC–DC power converter boosts the output voltage of the solar cell array to match the DC bus voltage of the DC–AC inverter and perform the function of MPPT. The general MPPT method can be implemented in the boost DC–DC power converter. The DC–AC inverter converts the DC power from the boost DC–DC power converter to an AC power injecting into the utility. The controller is similar to that presented in [24].

Fig. 6 shows the flowchart for controlling the proposed SC. Each string has H solar modules, and each solar module has G sub-modules. V_{PVM-K} is the voltage of the K^{th} sub-module in the M^{th} solar module that may be shaded, and V_{ave} is the average voltage of sub-modules in the string. The number of solar modules, H , in a solar string and the number of sub-modules of each module, G , are preset. Then the output voltage of the solar string, V_{string} , and the voltage of the sub-module, V_{PVM-K} , are detected, and V_{ave} is then calculated. V_{PVM-K} is subtracted from V_{ave} . The power electronic switch in the primary winding is switched by pulse-width modulation (PWM) signal, and the power electronic switch in the secondary winding connected to the K^{th} sub-module is still turned on if the subtracted result is larger than the set voltage (0.5 V in this paper), which indicates that the K^{th} sub-module is shaded. Otherwise, the power electronic switch in the primary winding is turned off, and the SC is disabled.

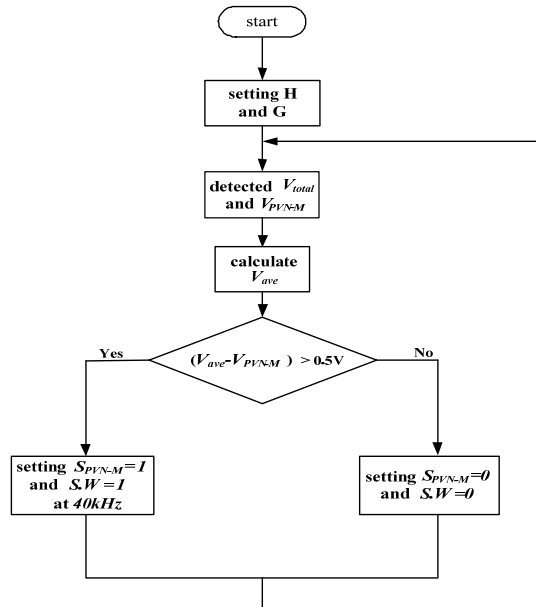


Fig. 6. Flowchart of the proposed compensator.

The control is then returned to detect V_{string} and V_{PVM-K} . This control loop is repeated such that the proposed SC is operated only when specific sub-modules are shaded, thereby avoiding the power loss of the conventional SC under the un-shaded condition.

The control of the fly-back power converter is open-loop control, and the PWM has a constant duty. If the fly-back power converter is operated in continuous conduction mode (CCM), then the duty of the PWM can be expressed as

$$D = \frac{NV_o}{V_{string} + NV_o} \quad (2)$$

where N is the turn ratio between the primary and secondary windings. V_o is the desired output voltage of the fly-back power converter and can be expressed as

$$V_o = \frac{V_{string}}{HG} \quad (3)$$

The proposed SC controls the fly-back power converter to be a voltage source to output a constant voltage equal to the voltage of the un-shaded sub-module. Given that the corner voltage for the shaded sub-module will be slightly increased because of the reduced irradiation and temperature, the shaded sub-module will still be operated at the constant current region shown in Fig. 1. Thus, the compensation current of the fly-back power converter can be expressed as

$$I_c = I_{nom} - I_{shaded} \quad (4)$$

where I_{nom} and I_{shaded} are the currents of un-shaded and shaded sub-modules, respectively.

In most conventional SCs, each solar module in a solar string requires a SC, and the voltage of each solar module should be detected to diagnose whether a shaded condition exists. The proposed SCs are applied only to the solar modules that are predicted to be shaded, such that only V_{PVM-K} and V_{string} should be detected. Although an additional power electronic switch is added in each secondary winding

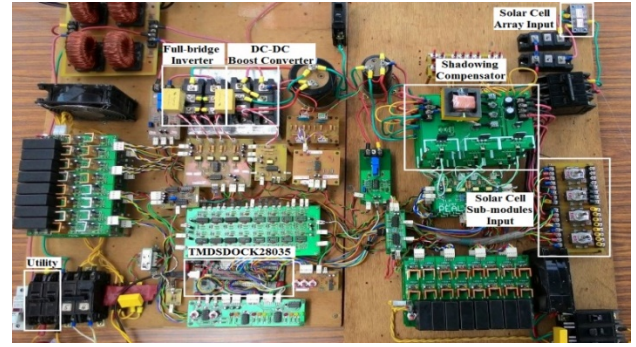


Fig. 7. Photo of the prototype.

TABLE I
MAJOR PARAMETERS USED IN THE EXPERIMENTS

Maximum output power(P_{mp})	75W
Voltage of maximum output power(V_{mp})	16.8V
Current of maximum output power(I_{mp})	4.5A
Open voltage(V_{OC})	21.7V
Short current(I_{SC})	5A

of the proposed SC, both the power and control circuits are still simplified. Moreover, the power efficiency is improved because the additional power loss in the conventional fly-back power converter is avoided.

II. EXPERIMENTAL RESULTS

A prototype is developed for the photovoltaic generation system with the proposed SC to verify the proposed SC. The circuit topology is the same that in Fig. 5. Fig. 7 depicts the prototype used in the experiments. The solar module used in this paper is F-MSN-75W-R-02. The parameters for the F-MSN-75W-R-02 are shown in Table I. The F-MSN-75W-R-02 module has two sub-modules. These solar modules have been in use for more than 10 years. Thus, the generated power of each solar module is severely decreased because of aging.

Fig. 8 presents the experimental results for the secondary winding of the conventional multi-winding fly-back converter where only one sub-module is shaded. The figure shows that the diodes of both windings are conducted. However, the windings have different currents. Thus, the conventional multi-winding fly-back converter will generate an additional compensation current for the un-shaded sub-module, resulting in additional power loss. Figure 9 shows the experimental results for the secondary winding of the modified multi-winding fly-back converter where only one sub-module is shaded. As shown, only the winding connected to the shaded sub-module is conducted. Thus, the additional compensation current and the additional power loss for the un-shaded sub-module in the conventional multi-winding fly-back converter are avoided.

Modules 7 and 8 in the experiments may be shaded, and only two SCs are applied to these two modules. Two

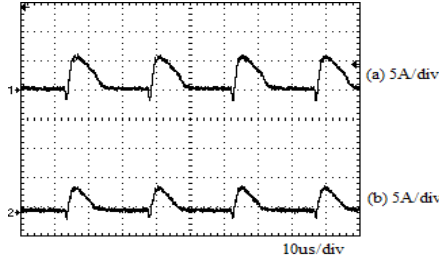


Fig. 8. Experimental results for the secondary winding of the conventional multi-winding fly-back converter. (a) Current of the winding 1. (b) Current of the winding 2.

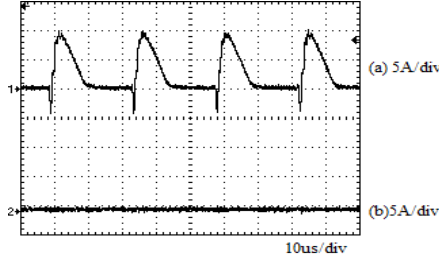


Fig. 9. Experimental results for the secondary winding of the modified multi-winding fly-back converter. (a) Current of the winding 1. (b) Current of the winding 2.

TABLE II

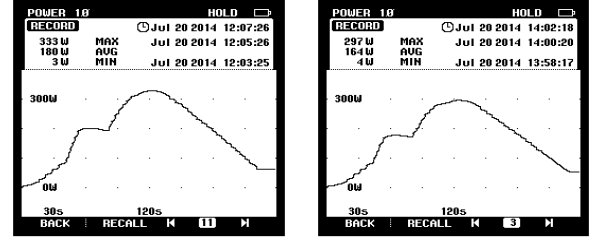
EXPERIMENTAL RESULTS BEFORE AND AFTER COMPENSATION

Case	Shaded module or sub-module	After compensation by the modified fly-back power converter				Input power of the boost converter
		Un-shaded		Shaded		
		Irra	T °C	Irra	T °C	
1	#PV8-1 #PV8-2	885	52.6	295	45.1	353
2	#PV7-1 #PV8-1	720	51.5	130	44.4	297

Case	Shaded module or sub-module	After compensation by the conventional fly-back power converter				Input power of the boost converter
		Un-shaded		Shaded		
		Irra	T °C	Irra	T °C	
1	#PV8-1 #PV8-2	895	57.9	305	47.9	350
2	#PV7-1 #PV8-1	730	52.9	140	44.4	294

Case	Shaded module or sub-module	Before compensation				Input power of the boost converter
		Un-shaded		Shaded		
		Irra	T °C	Irra	T °C	
1	#PV8-1 #PV8-2	900	59.3	310	48.3	333
2	#PV7-1 #PV8-1	740	49.6	150	43.4	297

#: shaded module or sub-module, Irra: irradiance, T: temperature



(a)

(b)

Fig. 10. P-V curve at the input of the boost DC-DC converter before compensation, (a) case 1, (b) case2

shadowing scenarios verify the compensation performance of the proposed SC. Table II shows the experimental conditions and results for these two cases. In case 1, the shadowing scenario is that a module is completely shaded. In this case, module 8 is shaded, and only the SC applied to module 8 is operated. In case 2, one sub-module each in modules 7 and 8 is shaded. In this case, sub-modules 7-1 and 8-1 are shaded, and the SCs of modules 7 and 8 are operated. The climatic condition cannot be maintained as identical in each experiment. Therefore, their irradiance and temperature differ slightly.

Fig. 10 shows the P-V curve at the input of the boost DC-DC converter before compensation. As shown in Fig. 10, the P-V curve of both cases has two peak power points. The global maximum power point (333 W) of case 1 is greater than that (297W) of case 2 because of the greater irradiance in case 1.

Fig. 11 shows the P-V curve at the input of the boost DC-DC converter after the compensation by the conventional multi-winding fly-back converter. The figure shows that the P-V curves of both cases are smooth and contain only one peak power point. In case 1, the peak power point after the compensation by the conventional fly-back converter is larger than the global maximum power point prior to the compensation, although the irradiance in Fig. 11(a) is lower than that in Fig. 10(a). This phenomenon verifies that the conventional fly-back converter can smooth the P-V curve and harvest more energy from the grid-connected photovoltaic generation system under this shaded condition. In case 2, the peak power point (294 W) after the compensation by the conventional fly-back converter is lower than the global maximum power point (297 W) prior to the compensation. This phenomenon occurs because the irradiance in Fig. 11(b) is lower than that in Fig. 10(b). The two un-shaded sub-modules incur additional power loss because of the use of the conventional fly-back converter.

Fig. 12 shows the P-V curve at the input of the boost DC-DC converter after the compensation by the modified multi-winding fly-back converter. Table 2 shows that the irradiances of both cases are lower than that in Fig. 10. Figure 12 shows that the P-V curve of both cases are smooth and contain only one peak power point. In case 1, the peak power

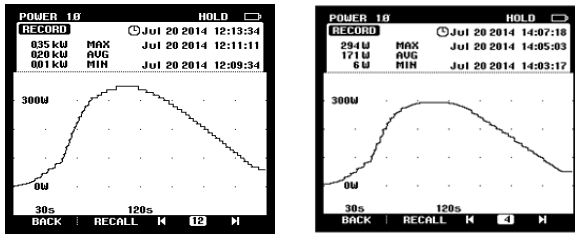


Fig. 11. P-V curve at the input of the boost DC-DC converter after the compensation by the conventional multi-winding fly-back converter. (a) Case 1. (b) Case 2.

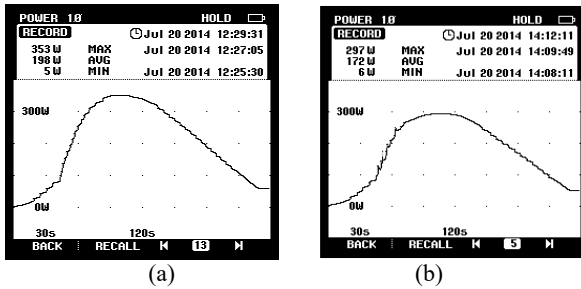


Fig. 12. P-V curve at the input of the boost DC-DC converter after the compensation by the modified multi-winding fly-back converter. (a) Case 1. (b) Case 2.

point (353 W) after the compensation by the modified fly-back converter is larger than the global maximum power point (333 W) prior to the compensation, although the irradiance in Fig. 12(a) is lower than that in Fig. 10(a). Moreover, the peak power point (353 W) after the compensation by the modified fly-back converter is also larger than the maximum power point (350 W) after the compensation by the conventional fly-back converter in case 1, although the irradiance in Fig. 12(a) is lower than that in Fig. 11(a). In case 2, the peak power point (297 W) after the compensation by the modified fly-back converter is the same as the global maximum power point (297 W) prior to the compensation, although the irradiance in Fig. 12(b) is lower than that in Fig. 10(b). Furthermore, the peak power point (297 W) after the compensation by the modified fly-back converter is larger than the maximum power point (294 W) after the compensation by the conventional fly-back converter, although the irradiance in Fig. 12(b) is lower than that in Fig. 11(b) in case 2.

Table II and Figs. 10–12 show that the output power of the solar cell array compensated by the proposed SC is higher than that compensated by the SC implemented by the conventional the multi-winding fly-back power converter even when the irradiance for the proposed SC is smaller than that for the SC implemented by the conventional the multi-winding fly-back power converter. Therefore, the experimental results verify that the modified multi-winding fly-back converter can smooth the P-V curve and harvest more energy of the grid-connected photovoltaic generation system. In addition, the proposed SC implemented by the

modified fly-back converter can increase the output power of the solar cell array and assist the solar cell array to generate more power.

III. CONCLUSIONS

A SC is proposed for the grid-connected photovoltaic generation system. The proposed SC uses a voltage equalizer implemented by a modified multi-winding fly-back converter. The proposed SC compensates for shaded solar cells in the sub-module by equalizing the voltages of the sub-modules, thereby avoiding multiple peaks in the P-V curve for the solar cell array.

The possible sources of shading, such as buildings and trees, are predicted before a grid-connected photovoltaic generation system is installed. Thus, a solar module in the solar cell array that can be shaded by sources of shading can be predicted. Therefore, the proposed SC is used only for the shaded solar sub-module rather than for all solar sub-modules in the solar cell array. The proposed SC has the advantages of a simple power circuit, high efficiency, a low cost, ease of control, increased power generation, and high reliability.

Hardware prototypes are developed for the SCs implemented by the conventional and modified multi-winding fly-back converters, and these prototypes are tested to verify their performance. The experimental results show that both SCs can solve the problem of multiple peaks in the P-V curve and harvest more energy. Nonetheless, the proposed SC implemented by the modified multi-winding fly-back converter is superior to the SC implemented by the conventional multi-winding fly-back converter because it can harvest a greater amount of energy.

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Hurng-Liahng Jou was born in Taiwan in 1959. He received his B.S.E.E. degree from Chung Yuan University, Jongli, Taiwan, in 1982 and his M.S.E.E. and Ph.D.E.E. degrees from the National Cheng Kung University, Tainan, Taiwan, in 1984 and 1991, respectively. He is currently a Professor in the Department of Electrical Engineering of the National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan. His major interests are power electronics applications and power quality improvement techniques.



Kuen-Der Wu was born in Tainan, Taiwan in 1954. He received his B.S.E.E. degree from Tamkang University, Taipei, Taiwan, in 1977 and his M.S.E.E. degree from the National Cheng Kung University, Tainan, Taiwan, in 1980. He is currently an Associate Professor in the Department of Electrical Engineering of the National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan. His major interests are power-electronics applications and power quality improvement techniques.



Jinn-Chang Wu was born in Tainan, Taiwan in 1968. He graduated from the National Kaohsiung Institute of Technology, Kaohsiung, Taiwan in 1988 and received his M.S.E.E. and Ph.D.E.E. degrees from the National Cheng Kung University, Tainan, Taiwan in 1992 and 2000. He is currently a professor at the Department of Electrical Engineering of the National Kaohsiung University of Applied Sciences, Taiwan. His research interests are power quality and power electronics applications.



Cheng-Huan Chung was born in Kaohsiung, Taiwan in 1989. He received his B.S.E.E. and M.S.E.E. degrees from the National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan, in 2012 and 2014, respectively. He is currently an Assistant Developer in the Institute of Nuclear Energy Research Atomic Energy Council, Taiwan, Taoyuan, Taiwan. His major interests are power electronics applications.



Ding-Feng Huang was born in Taichung, Taiwan, in 1991. He received his B.S.E.E. and M.S.E.E. degrees from the National Kaohsiung University of Applied Sciences, Kaohsiung, Taiwan, in 2014 and 2016, respectively. He is currently an Assistant Developer in National Chung-Shan Institute of Science & Technology, Taoyuan, Taiwan. His major interest includes power electronics applications.