Two-Switch Partial Shading Compensator Using Resonant-Inverter and Voltage Multiplier for Series-Connected Photovoltaic Modules

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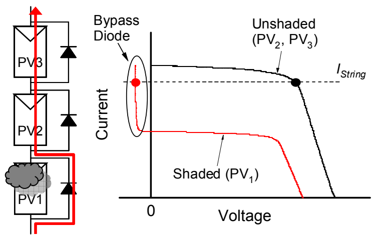
1. Introduction

In a photovoltaic (PV) string consisting of PV modules/sub-modules connected in series, partial shading is well known as not only triggering a significant reduction in power generation but also multiple maximum power points (MPPs), including one global MPP and local MPP(s), as shown in Fig. 1. The existence of multiple MPPs confuses and hinders the conventional MPP tracking (MPPT) algorithm to extract maximum power. Although advanced MPPT algorithms have been proposed, with which a global MPP can be found by sweeping operation voltage over a wide range and tracked even under partial-shaded conditions, a significant reduction in power generation.

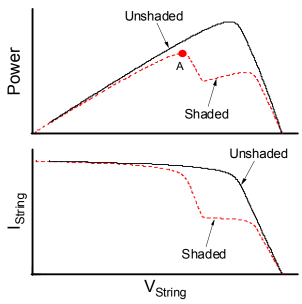
In general, most satellites are usually designed so that no module is shaded in nominal operation. However, if a system cannot be flexibly designed and does not allow enough clearance between a PV array and satellite body or observation instruments, some PV modules would be shaded, causing the issues mentioned above. Exploration rovers, which look like a swan having a pan-camera and PV modules as its head and wings, respectively, are a good example; PV modules mounted on a rover's body are very likely to be shaded by the pan-camera.

Various kinds of differential power processing (DPP) converters and voltage equalizers have been proposed and developed to address issues on partial shading in series-connected PV modules [1]–[4]. These converters transfer part of the generated power of non-shaded PV modules to shaded modules so that all the individual PV modules connected in series can operate at virtually the same voltage or even each MPP, precluding the partial shading issues. However, since conventional topologies are based on multiple individual dc-dc converters, the required switch count increases proportionally to the number of modules connected in series, increasing the complexity.

In this paper, a two-switch partial shading compensator using a series-resonant inverter (SRI) and voltage multiplier is proposed for series-connected PV modules. The two-switch configuration can dramatically simplify the circuitry compared to conventional compensators.



(a) Bypassed module and its characteristic.



(b) String characteristics.

Fig. 1. PV string under partial shading condition.

2. Proposed Two-Switch PV Compensator and its Major Benefits

The proposed PV compensator can be derived from the combination of a series-resonant inverter (SRI) and voltage multiplier, shown in Figs. 2(a) and (b), respectively. The example configuration of the proposed compensator for four modules (PV_1–PV_4) connected in series is shown in Fig. 3. The series-connected PV modules are tied to the input of the SRI,

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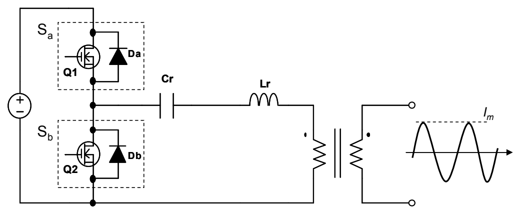
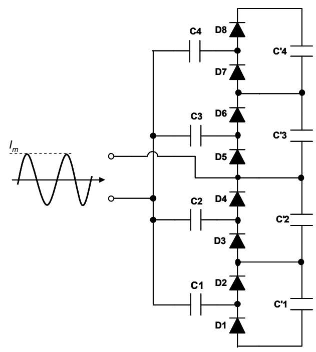
and the individual outputs of the voltage multiplier are connected to each PV module. The SRI is powered by the series connection of PV_1–PV_4 and produces sinusoidal current wave (i.e. at the transformer secondary winding). The voltage multiplier is driven by the sinusoidal wave generated by the SRI and theoretically produces uniform voltages for each output. The voltage multiplier preferentially supplies power to a module with the lowest voltage among PV_1–PV_4. In other words, the series connection of PV_1–PV_4 provides power for a module with the lowest voltage through the proposed compensator. In general, the operation voltage of a shaded module tends to be lower than that of unshaded modules when they are connected in series (see Fig. 1(a)). Therefore, the proposed compensator operates so that all the series-connected modules support and provide power for a shade module.

Only two switches are necessary for the proposed PV compensator, regardless of the number of modules connected in series. This means the circuitry can be significantly simplified compared to conventional compensators based on multiple dc-dc converters [1]–[4].

In addition, the proposed compensator is operable with open-loop control and voltages of PV modules are automatically nearly equalized, even at a fixed duty cycle and fixed frequency. This means the feedback loop and control circuit can be eliminated, further simplifying the circuitry; automatic voltage equalization mechanism is explained in the following section.



(a) Series-resonant inverter.



(b) Voltage multiplier.

Fig. 2. Key elements of the proposed PV compensator; (a) series-resonant inverter, (b) voltage multiplier.

3. Operation Analysis

3.1. Equivalent Circuit and Voltage Equalization Mechanism

Capacitors C_1–C_4 in the voltage mutlipler act as coupling capacitors that allow ac components only to flow through. Although PV_1–PV_4 are connected in series and are at different dc voltage levels, they can be separated and grounded thanks to the ac coupling of C_1–C_4, as shown in Fig. 4. The SRI is dipicted as an ac power source in this equivalent circuit. Since all the PV modules as well as each circuit consisting of C_i, $D_{(2i)}$, and $D_{(2i)}$ (i = 1…4) are connected in parallel, all the module voltages are automatically balanced. The balanced module voltages, V_{PVi}, are

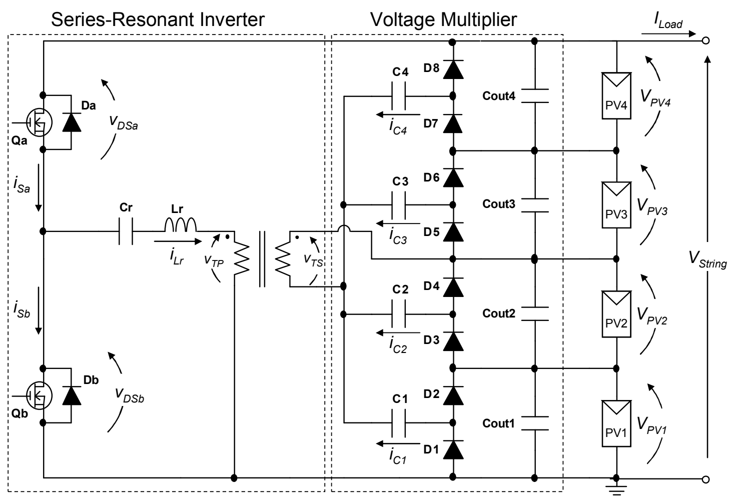


Fig. 3. Proposed two-switch PV compensator using series-resonant inverter and voltage multiplier for four PV modules connected in series.

espressed as

$$V_{PVi} = \frac{V_{String}}{N} - 2V_D \tag{1}$$

where V_{String} is the string voltage, V_D is the forward voltage drop of diodes, and N is the transformer turns ratio.

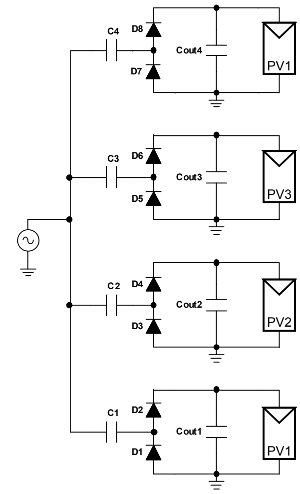


Fig. 4. Equivalent circuit.

3.2. Operation

Similar to conventional resonant inverters, the SRI in the proposed PV compensator is operated above the resonant angular frequency, ω_r, so that the series-resonant circuit represents inductive characteristic and zero voltage switching (ZVS) at turn-on transition is achieved:

$$\omega \geq \omega_r = \frac{1}{\sqrt{L_r C_r}}, \tag{2}$$

where ω is the angular switching frequency, L_r is the inductance of the resonant inductor L_r, and C_r is the capacitance of the resonant capacitor C_r.

Key operation waveforms and current flow directions when PV_1 is shaded and its voltage V_{PV1} is the lowest among V_{PV1}–V_{PV4} are shown in Figs. 5 and 6, respectively. Smoothing capacitors, C_{out1}–C_{out4}, are not illustrated in Fig. 6 for the sake of clarity. Switches Q_a and Q_b are alternately driven at a fixed duty cycle of slightly less than 50%.

In Mode 1, the current of the series-resonant circuit, i_{Lr}, is freewheeling through the anti-parallel diode, D_a. Meanwhile, C_1 in the voltage multiplier is being charged through D_2. The gating signal for Q_a, v_{GSa}, is applied in this mode before the direction of i_{Lr} is reversed. When i_{Lr} reaches zero, Q_a is turned on at zero voltage, achieving ZVS, and Mode 2 begins. All currents in the proposed voltage equalizer change sinusoidally. C_1 in the voltage multiplier starts to discharge through D_1. Before i_{Lr} decreases to zero, v_{GSa} is removed to turn off Q_a. When Q_a is turned off, the operation moves to the next mode. The next two modes, Modes 3 and 4, are symmetrical to Modes 1 and 2.

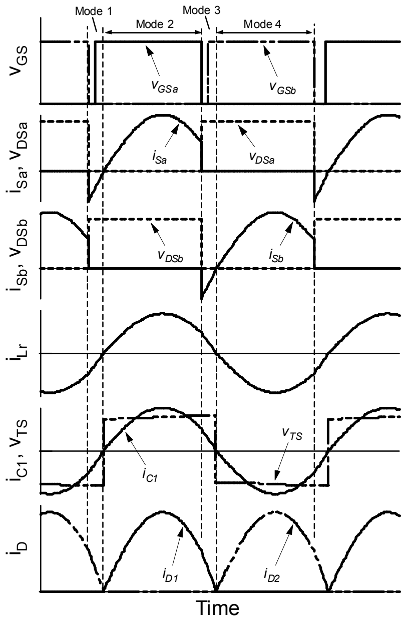
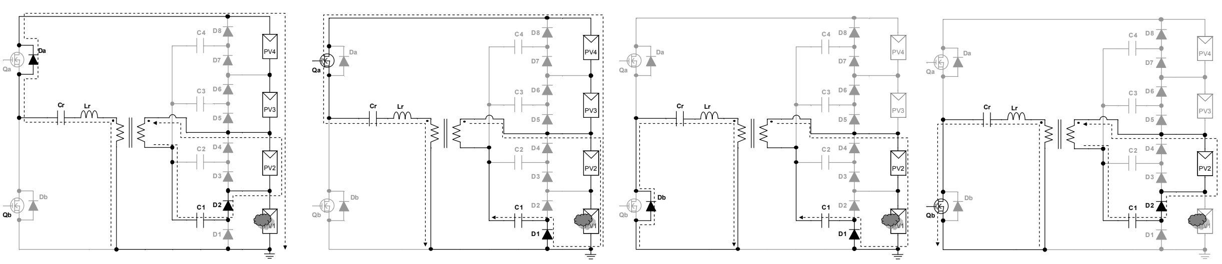


Fig. 5. Key waveforms when PV_1 is shaded.

As shown in Fig. 6, only D_1, D_2, and C_1 that are connected to the shaded module of PV_1 are in operation. This operation can



(a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4.

Fig. 6. Current flow directions when PV_1 is shaded.

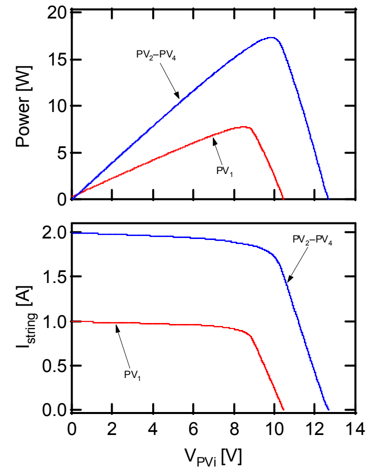
be extended to a general case; currents in the voltage multiplier flow through capacitors and diodes that are connected to shaded modules.

3. EXPERIMENTAL RESULTS

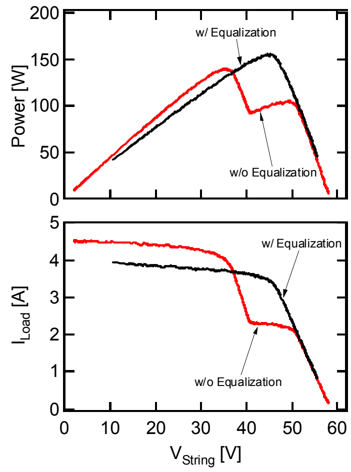
A prototype that can supply 25 W for each shaded module was built for four PV modules connected in series. The prototype was operated at a fixed switching frequency (85 kHz).

An experimental test was performed emulating the partially-shaded condition that only PV_1 is shaded. Four Solar Array Simulators (E4350B, Agilent Technology) were used to emulate the shaded conditions, as shown in Fig. 7(a).

The measured I-V and P-V characteristics of the string with and without the PV compensator are compared in Fig. 7(b). Two MPPs (global and local) were observed in the case without the compensator (i.e. with bypass diodes). With the compensator, conversely, the local MPP successfully disappeared and extractable maximum power dramatically increased, demonstrating the efficacy of the proposed partial shading compensator.



(a) Individual module characteristics used for the experiment.



(b) Measured string characteristics with and without the PV compensator.

Fig. 7. Experimental results.

4. CONCLUSIONS

A two-switch partial shading compensator for series-connected PV modules has been proposed in this paper. The two-switch configuration can significantly simplify the circuitry compared with conventional DPP converters or voltage equalizers requiring multiple switches proportional to the number of modules connected in series.

An experimental equalization test was performed for four PV modules connected in series, emulating only one module was shaded. With the compensator, the local MPP disappeared and the extractable maximum power considerably increased compared with that without equalization, demonstrating the efficacy of the proposed compensator.

References

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