Differential Power Processing Converter with Electrical Diagnosis Capability for Photovoltaic Panels

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1. Introduction

Partial shading on a photovoltaic (PV) panel comprising multiple substrings connected in series is well known to trigger not only significantly reduced power generation but also multiple maximum power points (MPPs), including a global MPP and local MPP(s). For instance, 10% equivalent area of partial shading on a PV panel reportedly result in 30% reduction in power generation of the PV panel as a whole [1]. Characteristics of a PV panel and substrings under partial shading are shown in Fig. 1. A shaded substring, PV3, that is less capable of generating current is bypassed by a bypass diode connected in parallel. Hence, the bypassed substring no longer contributes to power generation, and an extractable maximum power significantly decreases. In addition, the existence of local MPP(s) likely confuses ordinary MPP tracking algorithms.

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 kind of differential power processing (DPP) converters, also known as voltage equalizers, have been proposed and developed to address partial shading issues [2]–[6]. These DPP converters transfer a fraction of the generated power of unshaded PV substrings to shaded ones so that all the substring characteristics are virtually unified, thus precluding the partial shading issues. Meanwhile, power generation of PV panels substantially decreases when a part of panel deteriorates due to damage, uneven aging, and radiation. Therefore, PV panels should be desirably diagnosed to detect degradation even in exploration rovers. In recent years, an electrical diagnosis technique capable of an autonomous diagnosis, such as ac impedance measurement, is considered as a promising solution.

This paper proposes a DPP converter for PV panels to address partial shading issues and an electrical diagnosis technique using the proposed DPP converter.

2. Proposed DPP converter

2.1. Circuit description and voltage conversion ratio

The proposed DPP converter for three substrings is shown in Fig. 1. Equalization currents are directly supplied to shaded substrings from the panel through the DPP converter. Furthermore, equalization currents can be regulated by PWM control manipulating duty cycle d of the switch Q_2. All the substring voltages of V_{PVi} (i = 1…3) are assumed to

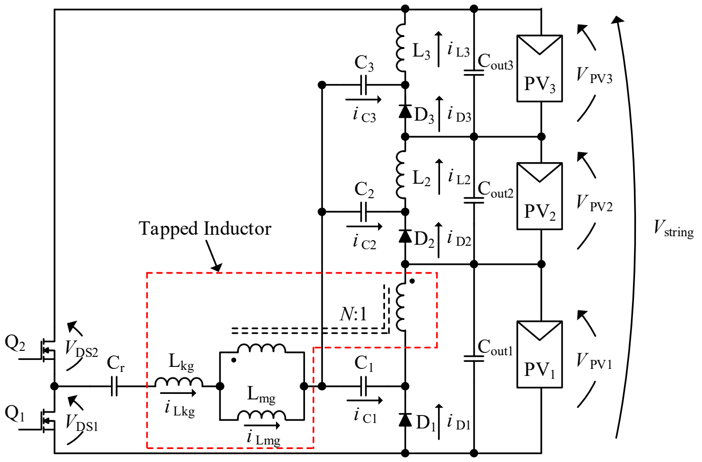

Fig. 1. Proposed DPP converter.

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be equal as V_{PV}. V_{PV} is expressed as

$$V_{PV} = \frac{d}{N+1} V_{string} \qquad (1)$$

where d is the duty cycle, N is the turn ratio of the tapped inductor, and V_{string} is the panel voltage. The proposed DPP converter can also be used for PV panels comprising an arbitrary number of substrings by adjusting N.

2.2. AC impedance measurement using the DPP converter

A control block diagram and notional ac impedance measurement using the proposed DPP converter are illustrated in Figs. 2(a) and (b), respectively. The proposed DPP converter operates with the sinusoidally perturbated duty cycle Δd superimposed on d to supply ac currents to each PV substring. Then the ac currents and ac voltages of substring are measured, to obtain ac impedance.

AC impedance is measured over wide frequency ranges, and consequently, Nyquist plot of a PV substring can be obtained as shown in Fig. 3(a). As depicted in Fig. 3(b), an equivalent circuit of a PV substring consists of three passive elements, a series resistance R_s, a parallel resistance R_p, a diffusion capacitance C_d, a diode D, and a constant current source. In addition, the parameters of the passive elements generally vary with degradation. The Nyquist plot yields each parameter of the passive elements, hence contributing to the panel diagnosis.

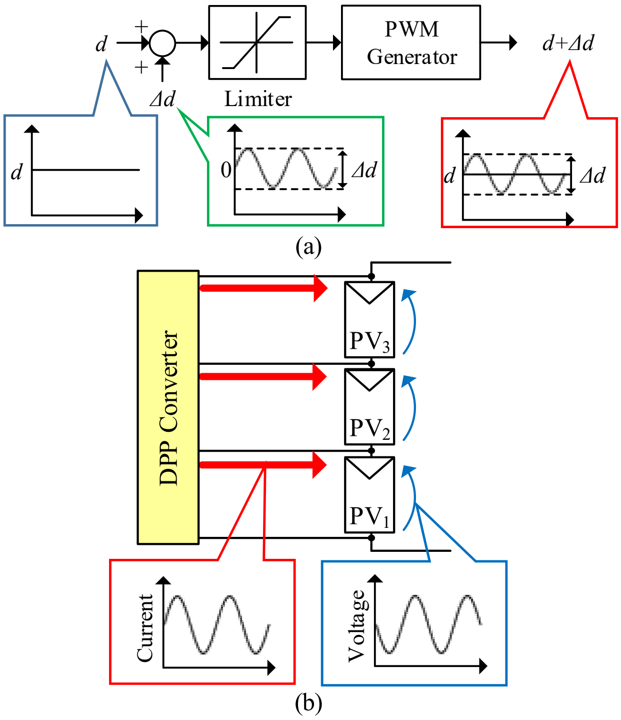

Fig. 2. (a) Control block diagram. (b) Notional ac impedance measurement using the DPP converter.

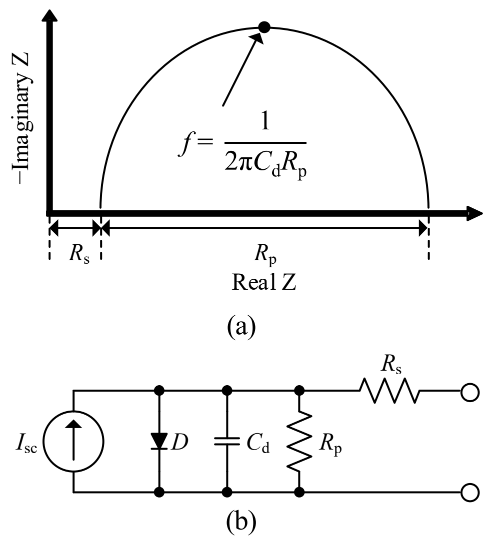

Fig. 3. (a) Typical Nyquist plot and (b) An equivalent circuit of a PV substring.

3. Experimental results

3.1. Experimental equalization test emulating the partial shading condition

An experimental equalization test using solar array simulators (E4361A, Keysight Technologies) was performed emulating PV_1-shaded condition. Individual PV substring characteristics used for the experiment are shown in Fig. 4(a). The prototype of the proposed DPP converter was operated with a fixed d = 0.2. A bypass diode was connected in parallel with each substring to compare panel characteristics with/without equalization. The panel characteristics were manually swept using an electronic load.

The measured panel characteristics with/without the DPP converter are compared in Fig. 4(b). Without the proposed DPP converter, two MPPs were observed, and the maximum power was 122 W at V_{string} = 37.6 V. With the proposed DPP converter, the local MPP disappeared and the maximum power increased to 138 W at V_{string} = 34.2 V, corresponding to 13.1% improvement.

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The experimental result demonstrated the efficacy of the proposed DPP converter.

3.2. Experimental ac impedance measurement using a PV substring emulator

To facilitate the experiment in the laboratory, a PV substring emulator that is an electrical circuit based on an equivalent circuit of a PV substring [see Fig. 3(b)] was prepared. As can be seen in Fig. 5(a), the PV substring emulator consists of two resistance, a capacitor, a diode, and a constant current source.

The experimental setup to measure ac impedance using the proposed DPP converter is depicted in Fig. 5. PV_2 and PV_3 were removed, and the external power supply was used as the input voltage V_{in}. To draw a current from the substring emulator, an electronic load was connected in parallel with the substring emulator. The Ac currents and ac voltages of the substring emulator were measured using the frequency response analyzer (FRA). The bias voltage corresponding to an operation voltage of the PV substring emulator was set to be 12.4 V. The prototype of the proposed DPP converter was operated with $d = 0.3$, $\Delta d = 0.2$, and $V_{in} = 36$ V, respectively. As a reference, the values of R_s, R_p, and C_d were also measured using the FRA alone without the proposed DPP converter.

The measured Nyquist plots using the FRA with/without the proposed DPP converter are compared in Fig. 6. Each Nyquist plot was very similar to Fig. 3(a). Parameters of the passive elements were calculated from the measured Nyquist plots, as shown in Table 1. The calculated values with the proposed DPP converter were good agreement with those without the DPP

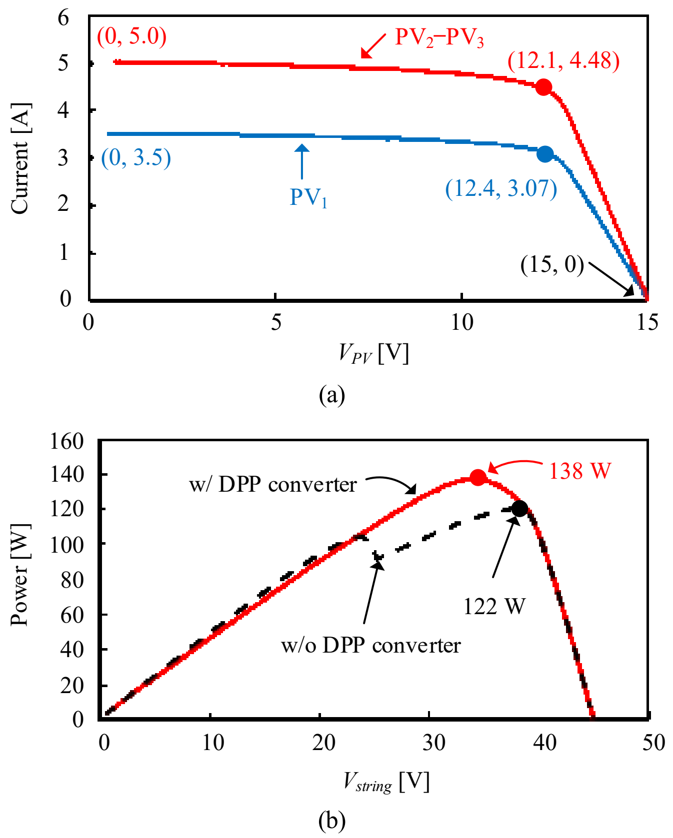

Fig. 4. Experimental results of the equalization test: (a) individual PV substring $I-V$ charactristics, (b) panel characteristics with/without DPP converter.

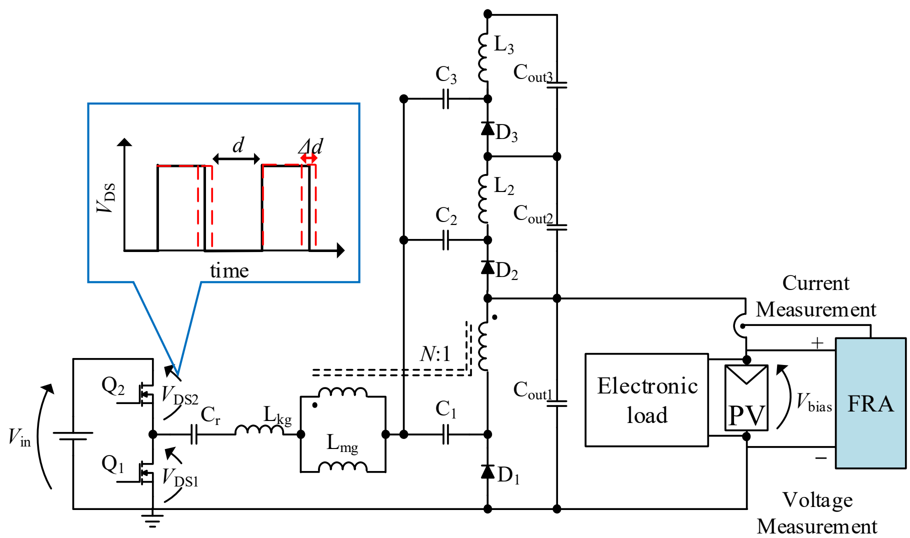

Fig. 5. Experimental setup for ac impedance measurement.

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converter, corresponding to errors less than 12.3%. The result demonstrated the efficacy of the proposed electrical diagnosis technique.

Table 1. Parameters of passive elements.

Element	Without DPP converter	With DPP converter	Error
R_s	51.2 mΩ	57.5 mΩ	12.3%
R_p	3.11 Ω	2.94 Ω	5.49%
C_d	974 nF	984 nF	1.05%

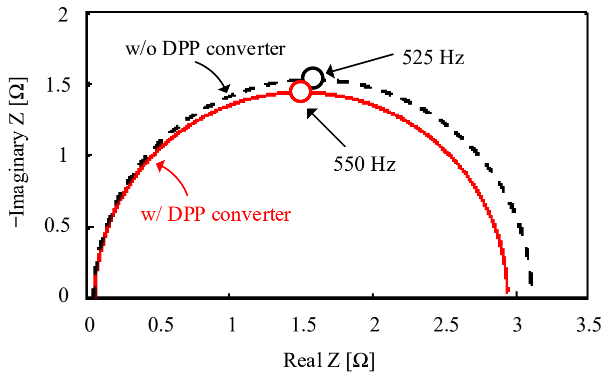

Fig. 6. Measured Nyquit plots using the FRA with/without the proposed DPP converter.

4. Conclusions

The novel DPP converter and the electrical diagnosis technique using the DPP converter for a PV panel have been proposed in this paper. The principle of the electrical diagnosis technique using the DPP converter was explained, and the operation analysis of the proposed DPP converter was performed.

The experimental equalization test using the prototype of the proposed DPP converter was performed for three substrings connected in series emulating the partial shading condition. With the proposed DPP converter, a local MPP successfully disappeared, and the extractable maximum power increased. The results demonstrated the proposed DPP converter precluded the partial shading issues. Meanwhile, the experimental ac impedance measurement using the PV substring emulator was also performed with the proposed DPP converter. The result demonstrated the efficacy of ac impedance measurement using the proposed DPP converter.

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