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Discussion on module-based hot-spot suppression in a PV generation system

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Abstract. This paper presents a novel control system for the hot-spot detection and suppression in a photovoltaic (PV) generation system. In this novel system, a distributed structure of a PV string is employed by installing a buck-boost converter to each module. Following this structure, a systematic control strategy is proposed for the module-based hot-spot detection. Moreover, the safe operation is adopted to suppress the prolonged high temperature when the hot-spot is detected. On the other hand, the normal modules can work at their maximum power point tracking (MPPT), respectively. On this occasion, the PV string could be smart because every module could function in their optimal state which is determined to their respective conditions. In order to validate this novel control system, the experiments have been carried out in a laboratory prototype. The verified results show that the PV generation system can operate safely at module level by using this novel control system.

1. Introduction

The classical hot-spot phenomena usually exist in the c-Silicon PV generation system when under partial shading conditions (PSCs) [1]-[4]. The partially shaded PV modules are usually heated up homogenously due to the minor reverse current when those modules function in the reverse bias. More importantly, it has been reported recently that one kind of typical hot-spot phenomena which usually resulting from the low-resistance defects (LRDs) may lead to more severe destruction to the malfunction modules within a short period of time [5]-[7]. For monitoring and suppression of this typical phenomenon, the mechanism of which has been analysed in conjunction with the working modes of the PV modules range from the open circuit to the short circuit. According to the feature of LRDs induced hot-spots, we proposed a hybrid control method to detect and suppress this hot-spot phenomenon. The hybrid method involves the transient scan process to allow the online detection during power generation. Besides, if these hot-spots are detected, the heat-avoided control strategy is adopted to ensure the safe operation by shifting the operation from the maximum power point to the safe area, thus the high temperature can be controlled to the normal state.

In prior work [8], we have investigated this issue on the basis of a PV string. Unfortunately, during the experimental trials, we found that it is very difficult to figure out the malfunction modules by means of our control method. In addition, the safe operation will lead to comparatively large amount of power loss, which is related to the length of a PV string. Therefore, the newly developed technique is not suitable to be employed in the large-scale installed system at its current form. As a result, this article presents a novel research in order to deal with these critical problems. In particular, we propose a novel control system in conjunction with the distributed structure of a PV string.

2. Theoretical analysis

In this section, the review of our prior work and new control system are mainly introduced.

2.1. Review of prior work

In order to easier comprehend the formation of LRDs induced hot-spot phenomenon, the simplified model of defective cell is shown in figure 1. The letter X represents the shadow ratio in theory, such that the maximum current that can be generated by this cell turns to be $(1-X) I_{SC}$, here, I_{SC} is the short circuit current. Moreover, it can be seen that compared with the normal cell, the defective cell will produce a new current path with low resistance, the fundamental mechanism of which is recognized as multilevel trap-assisted tunnelling effect (TAT) [9]-[10]. Thus, so long as the shaded defective cell is under reverse bias, and the main circuit current I_{PV} is greater than $(1-X) I_{SC}$, meaning that the reverse current I_{LR} will flow through the PN junction easily due to the presence of LRDs.
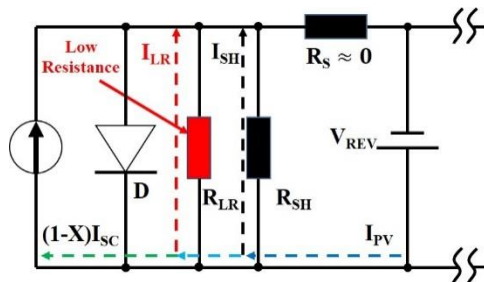

Figure 1. The simplified model of the defective cell
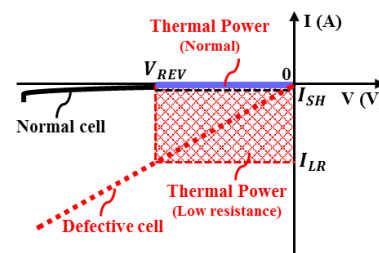

Figure 2. Thermal power produced at reverse bias

The thermal power produced at reverse bias is shown in figure 2. It can be seen that when under the same reverse voltage V_{REV}, the normal cell induced thermal power is limited to a low level. Whereas, on the other hand, the thermal power produced by defective cell is positively proportional to the square of the reverse current I_{LR} (or voltage V_{REV}). Therefore, it indicates that LRDs induced hot-spot phenomenon is much more severe that the classical one. It is also proved that if the system is in absence of any alarm or protection, the defective module will endure the prolonged high temperature.
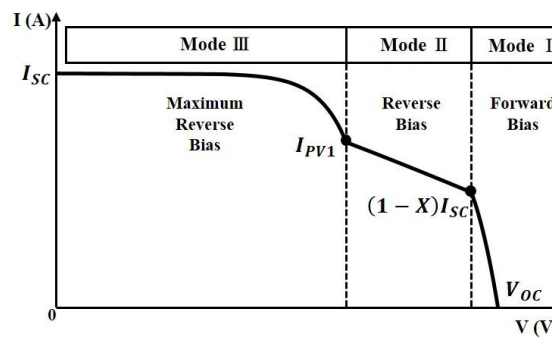

Figure 3. Schematic working modes of defective module

Figure 3 presents the detailed working modes of the system according to the magnitude of the current ranging from the open circuit to short circuit. In this case, we analysed that the module works at reverse bias in the Mode II and III for maximum power point tracking (MPPT) will produce nonzero thermal power corresponding to the simplified model. In contrast, in the Mode I, the module works at forward bias where the reverse current is prevented to zero, that is, the system is permitted to operate safely. Therefore, the conjunction between Mode I and II is treated as a safe point to suppress the undesirable thermal power.

2.2. New control system

2.2.1. Configuration of the control system. Based on the prior work, we propose a new control system to realize the aim at module-level hot-spot detection and suppression.
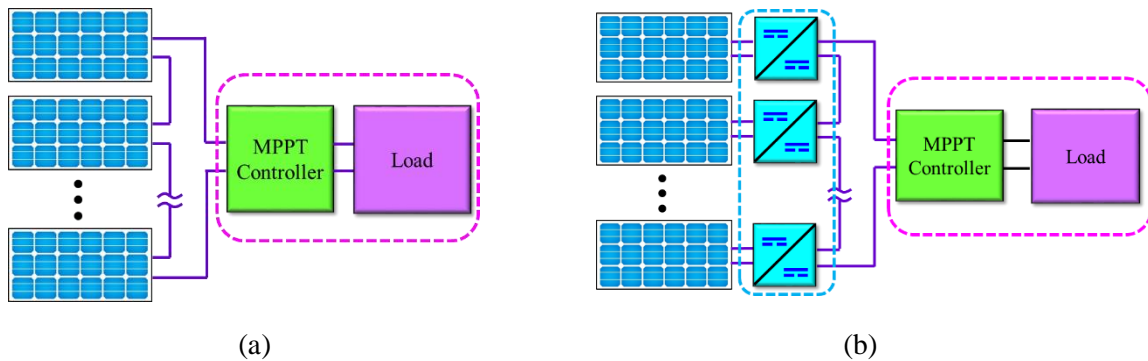

(a)   (b)

Figure 4. Schematic diagram of a standalone PV system,

(a) the conventional system, (b) the proposed system.

The conventional structure of a PV string is shown in figure 4(a). Especially, it can be seen in figure 4(b), the distributed structure of a PV string is adopted. In addition, the Two-Switch Buck-Boost (TSBB) converter in figure 5 is employed after each module.
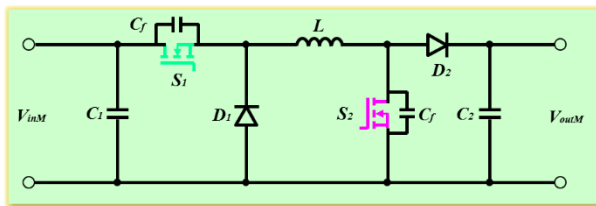

Figure 5. Schematic diagram of a TSBB converter

Table 1. Operation modes of TSBB

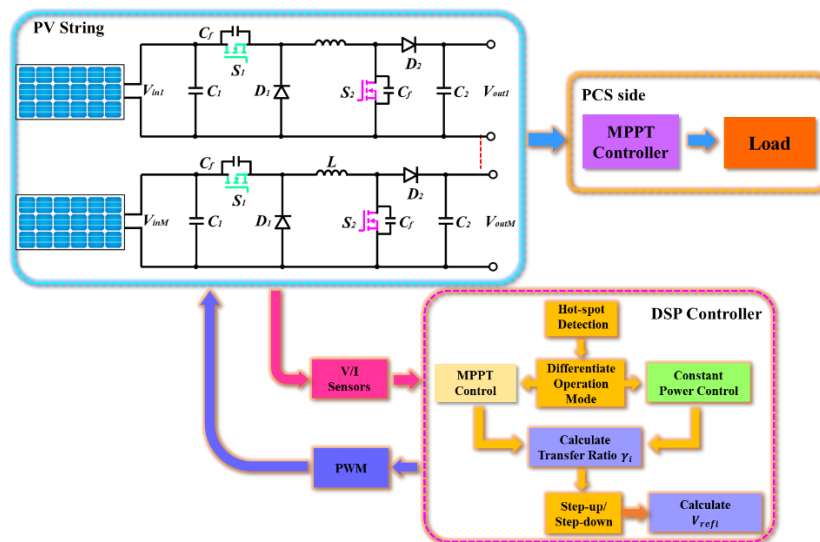| Mode	S1	S2
Buck	Switching	Off
Boost	On	Switching
Buck-Boost	Switching	Switching

Figure 6. Schematic block diagram of control system

The normalized operation modes of TSBB is shown in Table 1, it is well recognized that due to feature of this converter, the wide operational range can be provided. As a result, we selected this converter for this research. Moreover, the block diagram of the control system is given in figure 6. It mainly consists of a PV string, a DSP controller, and the Power conditioning system (PCS). The DSP control-

ler plays a role in data fetch, data analysis, and PWM generation. Especially, the data analysis includes hot-spot detection, operation modes determination, and parameter calculation.

2.2.2. Control scheme. In order to comprehensively explain the control process in detail, we mainly discussed two main situations involving hot-spot suppression and normal operation. Supposing that a PV string consists of (m+n) modules, especially the hot-spot phenomenon occurs in m modules. The rest of n modules are normal modules. In the case of the hot-spot suppression, once the hot-spot is detected, the constant power control is recommended, and the safe operation power can be saved simultaneously. Thus, the malfunctioning modules can operate at their constant power control by shifting the operational point from the MPP to a safe point, respectively. Similarly, on the other hand, in the case of normal modules, the optimal control is employed in this research. This control permits the normal modules work at MPPT to maximize the output energy by scan process, irrespective of other modules, or conditions. In summary, this systematic control scheme can provide the adaptive operation for each module.

3. Experimental results
The practical feasibility of this novel control system validated in a laboratory prototype shown in figure 7 by experiments that two-series connected PV modules are presented in this section.
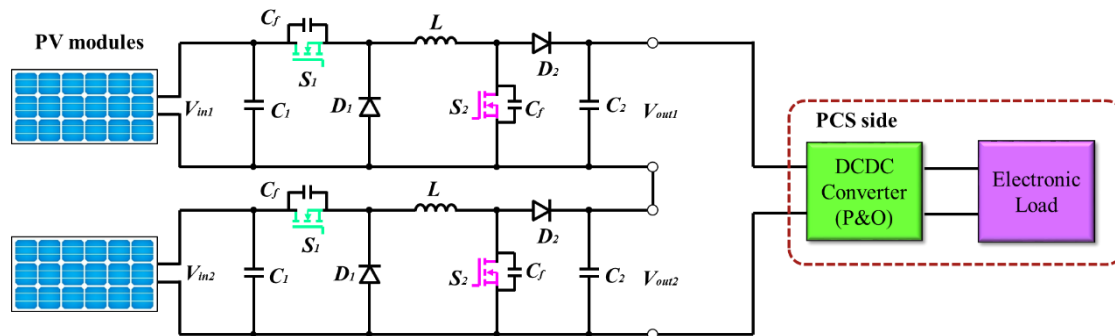

Figure 7. Configurations of the experimental trial.

4. Conditions
Before carrying out the experiments, it is necessary to determine the parameters of this control system. The specification of PV modules is shown in table 2, whereas the parameters of TSBB and experimental conditions are given in table 3 and 4, respectively.

Table 2. Specification of PV modules

Parameter	Value
Maximum output	50[W]
Open-circuit voltage	20.5[V]
Short-circuit current	3.35[A]
Optimal operating voltage	16.4[V]
Optimal operating current	3.05[A]

Table 3. Specification of TSBB

Parameter	Value
Filter C_1	4.7[μF]
Filter C_2	1000[μF]
Filter C_f	0.1[μF]
Inductance	7.5[mH]

Table 4. Specification of experimental conditions

Parameter	Value
Irradiance	650[W/m²]
Temperature of Module	40.3[°C]

5. Results

The steady waveforms acquired from the experiments are shown in figure 8. In this experimental trial, the scan period is set to 200 ms, whereas the duration between detection is set to 30 s.
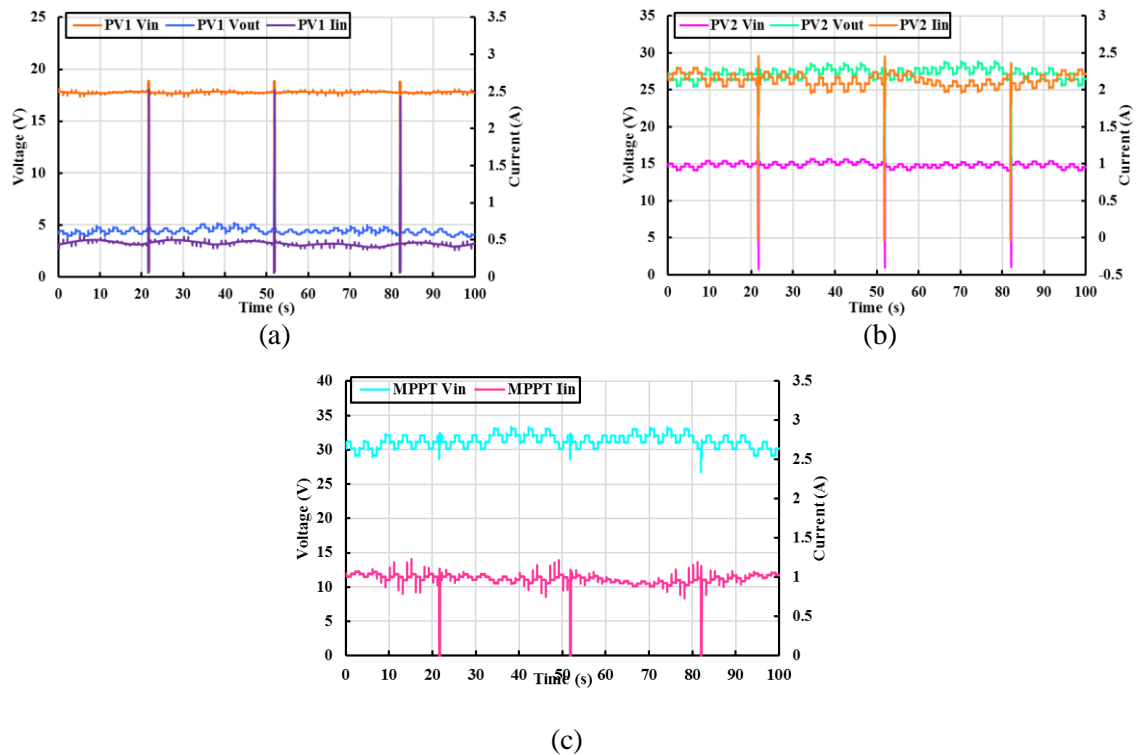

(a)

(b)

(c)

Figure 8. Waveforms acquired from experimental trial, (a) constant power control (hot-spot suppression), (b) optimal control, (c) PCS side (MPPT controller)
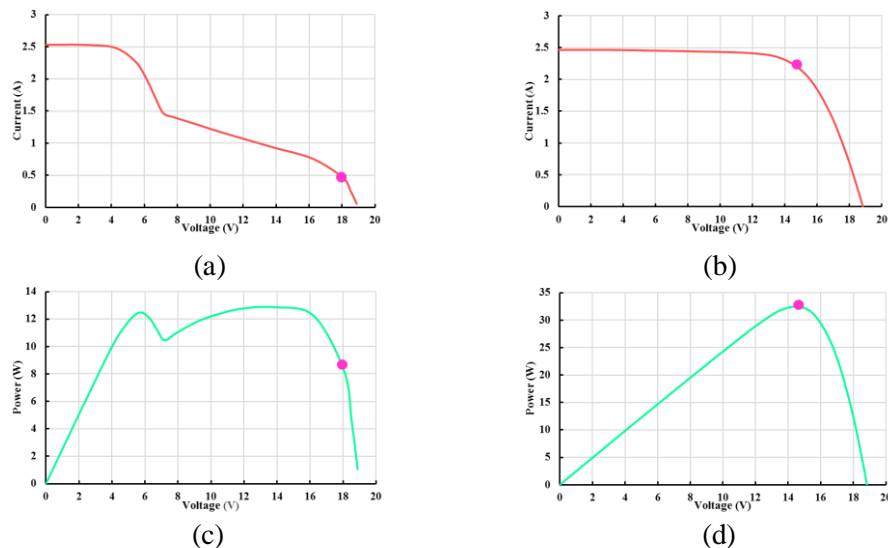

(a)

(b)

(c)

(d)

Figure 9. I(P)-V curves acquired from real-time scan process,
(a) and (c) are PV1, (b) and (d) are PV2.

It can be seen in figure 8 (a), the PV module 1 operates at constant power control when the defective cell is shadowed (e.g. a 3/4 shadow for one cell). The input voltage is approximately limited to the safe operation voltage which can be referred in figure 9 (a) and (c), in this case, the malfunctioning module is working at mode I (forward bias). In addition, the output voltage is working at MPPT with respect to the PCS operation. In figure 8 (b), the PV module 2 operates at its MPPT, which can be seen

in figure 9 (b) and (d). Besides, the PCS side is always working at its MPPT for the maximum output. According to this experimental trial, we found that the distributed structure of a PV string has a potential to provide the hot-spot detection at the module level, more significantly, different operation for each module to make sure that the string is working at the optimal state.

6. Conclusion
We proposed a novel control system for hot-spot detection and suppression by employing the distributed TSBB converters. The main feature of this system is summarized as follows.
- Online hot-spot detection at module level,
- Independent safe operation of the malfunction module in a PV string is permitted.

From the experimental trial, in the case of hot-spot suppression, the PV 1 operates at the Buck mode, which may lead to low conversion efficiency. It is a trade-off problem to be considered that how to achieve a reasonable balance between the safe operation and high efficiency. As a result, to improve the conversion efficiency of the converter will be our future work.

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