On-site detection of bypass circuit opening failure in photovoltaic array under power generation operation

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Abstract
To ensure the long-term reliability of photovoltaic systems (PVSs), periodical inspections are necessary. Despite the risk of severe temperature rise, bypass circuit open-circuit (BPC-OC) failure has attracted low research interest compared with other types of failure. This paper presents the pulsed light irradiation (PLI) method for robust BPC-OC failure detection that eliminates the need to switch off the power generation operation of the PVS. The proposed method detects the BPC-OC failure of the solar cell string by measuring the modulated current induced by local PLI. Electrical circuit simulations as well as indoor and outdoor experiments are performed to verify the performance of the proposed method. Results of the outdoor experiment show that the PLI method performs well in a real PVS under power generation operation. Finally, the advantages and disadvantages of the proposed method are summarized.

KEYWORDS
photovoltaics, power generation, solar energy

INTRODUCTION

The installation of photovoltaic systems (PVSs) for power generation has significantly increased, and the types of installation locations have become more diverse. In particular, an increased number of PVS installations are located close to residential areas; therefore, it is important to ensure the safety of PVSs. However, recently, several fire accidents have been reported that are caused by photovoltaic (PV) module failures.\(^{1,2}\) The establishment of PVS failure detection methods is therefore necessary to ensure the safety and long-term reliability of PVSs. Several types of PV module failures have been reported by investigating the failure rates during operation.\(^{3-9}\) Typical PV module failures are manifested by discolorations (yellowing or browning), delamination, glass breakages, hot spots, interconnect disconnections, cell cracks, bypass circuit (BPC) failures, etc.\(^{10-16}\) BPC failures are failures of the bypass function of the PV module, which is enabled by installing diodes, which are also called bypass diodes. With the exception of BPC open-circuit (BPC-OC) failures, these failures can be detected by visual inspection,\(^{17,18}\) infrared (IR) imaging technology,\(^{17-23}\) and photoluminescence\(^{24}\) in outdoor conditions.

In this study, we investigated an outdoor BPC-OC failure detection method, which has not yet been well established. A BPC is a protection circuit that prevents electrical power loss and severe local cell temperature rise, that is, hot spots in PV modules. A BPC-OC failure is a disconnection failure of the bypass diode itself or its solder joints in a junction box that is typically placed at the backside of the PV module. Hot spots...
cause degradations owing to continuous thermal cycles. Kato reported that the local temperature of a PV module reached several hundred degrees Celsius when a hot spot occurs in BPC-OC failure. The occurrence of such a high-temperature hot spot in PV modules would lead to the risk of a fire accident and related failures such as glass breakages, interconnect disconnections, and cell cracks increases that are due to high thermal cycle stress. Thus, PV modules should be inspected regularly for the early detection of BPC-OC failure.

Unlike BPC short-circuit (BPC-SC) failure, BPC-OC failures do not affect the power generation performance of the PVS in principle if partial shading on the PV module is not frequent, and if there is no highly resistive part in the solar cell string of the PV module. For this reason, less attention has been given to BPC-OC failures despite the above-mentioned risk, and few studies have been conducted on BPC-OC failures. The use of a current transmitter/detector with a light-shielding panel as a detection method for BPC-OC failures was introduced in a report by the International Energy Agency (IEA). In this method, the PVS operation needs to be shut down to connect the current transmitter to the terminals of the target string in the PV combiner box. Nevertheless, a considerable time is generally required to move the current detector along with the interconnect ribbons on the rear or front surface of each PV module. Recently, commercial bypass diode failure detectors have been developed.

Although these detectors determine whether BPC-OC failure has occurred in the target string, they cannot identify the specific PV module in which BPC-OC failure occurred. The detectors also need to be connected to the target string, meaning that the PVS operation must be shut down before the inspection.

In this study, we investigated the application of the pulsed light irradiation (PLI) method for BPC-OC failure detection without shutting down the PVS. A similar irradiation method has been employed for outdoor photoluminescence imaging; however, the objective was not to detect BPC-OC failures. First, the working principle of the PLI method for BPC-OC failure detection is explained in detail. Then, the working principle is verified using circuit simulation based on a mathematical model and indoor experiment with a single PV module. Finally, the feasibility of the proposed method is demonstrated by performing outdoor experiments using a real PVS during power generation operation.

2 | PULSED LIGHT IRRADIATION METHOD

Figure 1 shows a schematic of the working principle of the PLI method for BPC-OC failure detection. In this study, the pair of a BPC and a solar cell string connected in parallel in the PV module is referred to as a “cluster.” Each cluster has one BPC, which is composed of a bypass diode and connecting wires. Solar cells in the same cluster are connected in series, and current flowing through the cluster is hence determined by current flowing through the cell with the lowest light-induced current. Therefore, if the photocurrent in one cell is modulated, the current flowing in all other cells in the same cluster, which are referred to as the “control cluster,” is modulated.

Figure 1(A) shows a coil and a pulsed-light generator (PLG). The coil acts as a magnetic sensor as it induces current from a nonstatic magnetic field. The PLG consists of a light-shielding box and an infrared light emitting diode (LED) that emits light with a wavelength corresponding to the band gap of the solar cell to be inspected. In the LED light-on (LED on) condition, a magnetic flux is produced owing to current flow through the control cluster. In the LED light-off (LED off) condition, the magnetic flux disappears because the light-shielding solar cell prevents current flow. Magnetic flux variation occurs in the control cluster owing to modulated current flow as a result of switching on and off the LED as a pulse wave. The coil placed above the interconnect ribbons of the series-connected cells detects the magnetic flux variation due to the induced current. That is, when a PLG is placed on a PV module under power generation operation with a maximum power point (MPP) tracking scheme, the operating point of the control cluster can be switched between the quasi open-circuit condition (LED off) and MPP (LED on) condition and vice versa; the operating point switch of the control cluster can be detected by the coil.

Figure 1(B,C) shows the detection method for BPC-OC failure using a PLG and a light-shielding plate. Cluster 1 is the control cluster where the PLG is placed. Cluster 2, in which the light-shielding plate is shading some of the solar cells, is referred to as the “test cluster.” Figure 1(B) shows the current flow path in the PV module when the BPC of the test cluster is normal, that is, there is no failure. In this case, the current flows through the BPC of the test cluster (cluster 2) because the bypass diode works as expected to prevent current flowing through the cell string. The coil placed in the control cluster detects magnetic flux fluctuations due to modulation as the current of the control cluster (cluster 1) is modulated by the PLG. However, Figure 1(C) shows the current path in the PV module when the BPC of the test cluster has open-circuit failure. In this case, the test cluster prevents current from flowing through the cell string of the control cluster even when the LED is turned on because the resistance of the cell string of the test cluster is too high to allow current flow; this limits the current flowing through the other clusters that are connected in series with the test cluster. Thus, the coil in the control cluster does not detect magnetic flux variation regardless of LED irradiation. Consequently, this method can be employed to detect BPC-OC failure in the test cluster by measuring the magnetic flux variation in...
FIGURE 1  Working principle of pulsed light irradiation (PLI) method: (A) coil and pulsed-light generator; (B) current flow path without BPC-OC failure; (C) current flow path with BPC-OC failure.
the control cluster. By only moving the light-shielding plate to a neighboring cluster (eg, from cluster 2 to cluster 3), the BPC-OC failure of a neighboring cluster can be inspected. With this method, the light-shielding plate needs to have a sufficiently large light-shielding area to bypass the current that flows in the solar cell string of the test cluster. When applying this method to a multi-wire solar cell or a solar cell with a large number of busbars, it may be difficult to measure the magnetic flux on the solar cell because the current flowing through the finger electrodes or busbars is too low. Therefore, in this case, the magnetic flux should be measured on a cross-connector at the short edge of the module where the full module current is flowing.

The advantages of this method are as follows: (a) it is not necessary to stop the power generation of the PVS, (b) it is not necessary to connect any electronic device to the circuit of the PVS, (c) inspections can be carried out regardless of the PVS scale, that is, the number of clusters, and (d) inspections can be carried out regardless of the PV cell size or the number of cells in the PV module. Furthermore, by using a robot running on the PV array as the light-shielding device, the inspection time can be significantly reduced. Figure 2 shows a light-shielding robot under development. The robot creates a shaded area over most of the cluster and plays the role of a light-shielding plate. In a preliminary test, a PV module consisting of 6-in solar cells (54 cells, three clusters) was successfully inspected in approximately 6 seconds using the proposed PLI method with this prototype robot.

The proposed PLI method has the following advantages: (a) more robust detection is possible without being affected by fluctuations in the solar radiation and external magnetic field, (b) sliding the large-area light-shielding plate from one cluster to the other throughout the PV array is the simplest approach, and it is compatible with a fast robotic inspection, ensuring safe inspection, that is, low risk of high solar cell temperature.

Other than the proposed PLI method, several other simple BPC-OC failure inspection methods are possible. As the first example, if a magneto-impedance sensor or anisotropic magneto-resistive sensor that can detect a static magnetic field is used instead of a coil, BPC-OC failures can be detected by the same method without generating a pulsed current. However, in this case, both magnetic sensors tend to measure signals inaccurately when the external magnetic field is relatively strong and when the solar irradiance fluctuation is rapid. For the coil current induced by the PLI method, the use of the coil with a band pass filter circuit ensures a more robust detection of BPC-OC failures. As the second example, by placing the PLG in the test cluster and measuring the magnetic field in the other cluster with the magnetic sensor, BPC-OC failures can also be detected. In this case, the light-shielding plate is not necessary. However, a large-area PLG is required for a safe BPC-OC failure detection. If the light-shielding area by the PLG is too small (eg, a single solar cell) and the test cluster has a BPC-OC failure, a high current flows into the solar cells under the PLG, resulting in the hot spot. Therefore, this simpler method requires a large-area PLG to lower the risk of damaging the tested solar cells by the rapid increase of the solar cell temperature; however, such a large-area PLG requires a large-capacity battery, making on-site inspection difficult. Moreover, it is difficult to mount such a PLG on the robot. Compared with those simpler methods, the proposed PLI method has the following advantages: (a) more robust detection is possible without being affected by fluctuations in the solar radiation and external magnetic field, (b) sliding the large-area light-shielding plate from one cluster to the other throughout the PV array is the simplest approach, and it is compatible with a fast robotic inspection, ensuring safe inspection, that is, low risk of high solar cell temperature.

BPC-SC failure can also be detected by applying the proposed method. For BPC-SC failure detection, the PLG and magnetic sensor are placed in the same cluster (test cluster), and the PV array must be an open circuit or shut down during power generation operation, and the PV array must be exposed to sunlight. In this setup, when the BPC of the test cluster has a short-circuit failure, the magnetic sensor detects the signal induced by the PLG. Conversely, when the BPC is normal, the magnetic sensor does not detect the signal. However, it is known that BPC-SC failure can be easily detected using IR imaging technology because solar cells in a cluster that has BPC-SC failure have temperatures that are several degree Celsius higher than other solar cells.

3 | SIMULATION

To verify the working principle of the proposed method, the circuit simulation was carried out using the free software LTSpice from Linear Technology™. Two cases were simulated,
namely the single-module case and the multi-module case. In the single-module case, the simulation model consists of only one PV module, whereas in the multi-module case, the simulation model consists of eight PV modules connected in series to simulate conditions that are close to those of real PVSs.

### 3.1 Single-module case

Figure 3 shows the simulation model of the single-module case. As illustrated in a dotted speech bubble, each solar cell is modeled by an equivalent circuit, that is, a single-diode model based on the physical properties of the monocrystalline silicon. The simulation parameters of the PV module under standard test condition (STC) and bypass diode are summarized in Table 1. Using these parameters, it was confirmed that the simulation model reproduces the same performance as a real PV module in an indoor experiment. The PLI method was used for two solar cells in cluster 1, whereas light shielding was employed for two solar cells in cluster 2; thus, cluster 1 and cluster 2 are the control cluster and the test cluster, respectively. The photocurrent of solar cells under STC, $I_{ph}$, is 2.53 A, and that of solar cells during light shielding, $I_{phs}$, is assumed to be 5% of $I_{ph}$. Thus, the photocurrent of

| Table 1 | Simulation parameters and simulated module performance for the single-module case |
|---------|----------------------------------------------------------------------------------|
| **Simulation parameters** | |
| Number of cells in the module | 36 |
| Number of cells per bypass diode | 18 |
| Module temperature °C | 25 |
| Irradiance W/m² | 1000 |
| Series resistance $R_s$ mΩ | 6.94 |
| Parallel resistance $R_{sh}$ Ω | 750 |
| Photocurrent $I_{ph}$ A | 2.53 |
| Saturation current of diode (Solar cell) pA | 30.56 |
| Saturation current of diode (Bypass diode) mA | 0.1 |
| **Diode parameters in the solar cell** | |
| Emission coefficient | 0.91 |
| Series resistance mΩ | 8.89 |
| High-injection knee current A | 0 |
| **Simulated module performance at STC** | |
| Short-circuit current A | 2.41 |
| Open-circuit voltage V | 20.0 |
| Fill factor | 0.787 |

**FIGURE 3** Circuit simulation model of the single-module case

**FIGURE 4** Simulation results of the single-module case: (A) I-V curves without BPC-OC failure; (B) I-V curves with BPC-OC failure
solar cells with PLI was modulated from $I_{\text{ph}}$ (LED on) to $I_{\text{phs}}$ (LED off), and the current-voltage (I-V) characteristics of the PV module for each condition were calculated. It should be noted that the emitted LED irradiation must be equivalent to 1 sun to realize the amplitude of the current modulation. BPC-OC failure was modeled by turning off the switch connected in series with the bypass diode of the test cluster (cluster 2). The I-V characteristics were calculated by varying the value of the variable resistance.

Figure 4 shows the simulated I-V curves when the LED is turned on and off. The reference I-V curve under STC is also plotted (dotted line). Figure 4(A) shows the I-V curves without BPC-OC failure; the current difference between the two I-V curves (i.e., LED on and LED off) at the MPP, $\Delta I$ is 2.29 A. In contrast, Figure 4(B) shows that with BPC-OC failure, $\Delta I$ becomes 0 A. The difference in the value of $\Delta I$ (with and without BPC-OC failure) can be observed as the magnetic flux fluctuation on the tested cluster (cluster 1) and hence can be detected by the coil.

### 3.2 Multi-module case

To simulate more realistic cases that are close to those of real PVSs, circuit simulations of the multi-module case were performed.

**TABLE 2** Simulation parameters and simulated module performance for the multi-module case

| Simulation parameters                  | Value |
|----------------------------------------|-------|
| Number of cells in the module          | 54    |
| Number of cells per bypass diode       | 18    |
| Module temperature °C                  | 25    |
| Irradiance W/m²                        | 1000  |
| Series resistance $R_s$ mΩ             | 0.236 |
| Parallel resistance $R_{sh}$ Ω         | 80.9  |
| Photocurrent $I_{ph}$ A                | 8.51  |
| Saturation current of diode (Solar cell) pA | 20.6  |
| Saturation current of diode (Bypass diode) mA | 0.1   |

**Diode parameters in the solar cell**

| Parameter                           | Value |
|-------------------------------------|-------|
| Emission coefficient                | 0.83  |
| Series resistance mΩ                | 5.32  |
| High-injection knee current A       | 0     |

**Simulated module performance at STC**

| Parameter            | Value |
|----------------------|-------|
| Short-circuit current A | 8.51  |
| Open-circuit voltage V      | 29.6  |
| Fill factor            | 0.757 |
performed using the simulation model shown in Figure 5, each of which consists of eight PV modules connected in series. Each PV module consists of three clusters (three BPCs and 54 solar cells). The parameters of the simulation, such as the module specification and the module performance under STC, are summarized in Table 2. The parameters of the bypass diode are the same as those listed in Table 1. PLI was employed in one solar cell in cluster 1 (control cluster), whereas light shielding was used in all solar cells in cluster 2 and cluster 3 (test clusters). BPC-OC failure was modeled by turning off the switch connected in series with the bypass diode of cluster 3.

Figure 6 shows the simulated I-V curves when the LED is turned on and off. Figure 6(A) shows that without BPC-OC failure, \( \Delta I \) is 7.57 A; however, with BPC-OC failure, \( \Delta I \) is 0 A, as shown in Figure 6(B). The difference in the value of \( \Delta I \) with and without BPC-OC failure is large enough to be detected.

In the above simulation, it is assumed that the solar irradiance is 1 sun (1000 W/m\(^2\)). Next, \( \Delta I \) was examined at lower values of solar irradiance. The condition when the solar irradiance varies from 50 to 500 W/m\(^2\) was given by varying \( I_{ph} \) from 5% to 50% of its value at 1 sun. \( I_{phs} \) is constant regardless of the values of \( I_{ph} \) (\( I_{phs} = 5\% \) of its value at 1 sun). The LED emits sufficient irradiance such that the current generated by the solar cell under the PLG is equal to or larger than \( I_{ph} \). Other simulation parameters remain the same as those in the above simulation. Figure 7 shows \( \Delta I \) without BPC-OC failure, indicating that \( \Delta I \) decreases as the solar irradiance decreases. \( \Delta I \) becomes zero at 50 W/m\(^2\), where \( I_{ph} \) is equivalent to \( I_{phs} \).

As \( \Delta I \) is indirectly measured by the coil as magnetic flux fluctuation \( \Delta B \), if \( \Delta I \) is too small, it cannot be detected by the coil. Therefore, the lower limit of solar irradiance allowed by the sensitivity of the coil to be used was determined. Assuming that the interconnect ribbon is sufficiently longer than the coil, the following relationship between \( \Delta I \) and \( \Delta I \) is derived based on the Biot-Savart law:

\[
\Delta B = \frac{\mu_0 \Delta I}{2\pi a}
\]

where \( \mu_0 \) and \( a \) represent the vacuum permeability and the distance between the interconnect ribbon and the coil, respectively.

The lower limit of the current difference \( \Delta I_{lim} \) that can be detected by the coil was calculated based on the following assumptions. (a) The coil is placed on the glass of the PV module (above the interconnect ribbon). (b) The relative permeability of the sealing material and glass of the PV module is 1, and the total thickness of the sealing material and glass is 3 mm, that is, \( a = 3 \) mm. (c) The lower limit of \( \Delta B \) that can be accurately detected by the coil is 4.5 \( \mu \)T, which is 4.5 times higher than the minimum detectable value of the coil. The resultant \( \Delta I_{lim} \) is 0.067 A. From Figure 7, it is estimated that BPC-OC failure can be accurately detected by the coil when the solar irradiation is larger than 111 W/m\(^2\).

### 4 Indoor Experiment (Single-Module Case)

Indoor experiments were conducted to verify the simulation results. Figure 8 shows photographs of the indoor experiment. Figure 8(A) shows the PV module used in the experiment. The module consists of 36 solar cells and two BPCs; the solar cell is a half-size 5-in Si solar cell. The BPC-OC failure mode was initiated by turning on a switch that is connected in series with the bypass diode of cluster 2, similar to the approach used during simulation. Figure 8(B) shows a photograph of the PLG. The PLG consists of LEDs, a coil, and a pyranometer. The eight infrared LEDs (peak emission wavelength: 940 nm) mounted on the PLG emit a 1000 W/m\(^2\) irradiance. The PLG can generate PLI at 5 kHz as well as continuous irradiation. Figure 8(C) shows the experimental setup of a room-type solar simulator. The setup consists of a PV module, a light-shielding plate, a PLG, an electronic load device, and a current probe.

First, the reference I-V characteristic of the PV module without PLG was measured under a 1000 W/m\(^2\) uniform irradiance condition using an I-V curve tracer. Next, the PLG was used with two solar cells in cluster 1 (control cluster), and the light-shielding plate was used with two solar cells in cluster 2 (test cluster). Then, the I-V characteristics of the PV module were measured with and without BPC-OC failure when the LED is turned on (continuous irradiation) and off. Finally, the current wave (time variation) of the PV module and the voltage wave of the coil were measured using an oscilloscope under PLI condition in which the PV module was connected to an electronic load device that operates the PV

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**Figure 7** Influence of solar irradiance on \( \Delta I \) of the PV module without BPC-OC failure. \( \Delta I_{lim} \) is the lower limit of \( \Delta I \) that can be detected by the coil used in the experiment.
module at MPP. Figure 8(D) shows the position of the coil; the coil was placed on the glass surface of the PV module in the control cluster.

Figure 9 shows the measured I-V characteristics corresponding to Figure 4. Figure 9(A) shows the I-V curves without BPC-OC failure; $\Delta I$ is 2.13 A. Figure 9(B) shows the I-V curves with BPC-OC failure; $\Delta I$ is 0 A. Table 3 shows a comparison of the simulation and experimental results of the current and voltage at the MPP in each condition. The experimental results show good agreement with the simulation results. This simulation assumed ideal semiconductor properties, and thus, the current and voltage values are slightly higher than the experimental results. If a more advanced parameter identification method is applied, the error between the simulation and the experimental results can be reduced. However, this error does not affect the verification of the principle of the proposed method.

Figure 10 shows the measured current wave of the PV module and the measured voltage wave of the coil under PLI conditions. Figure 10(A) shows the waves without BPC-OC failure, indicating that the coil voltage varied in accordance with LED on and LED off. However, Figure 10(B) shows the waves with BPC-OC failure, and it can be observed that the coil voltage is nearly flat. This apparent difference in the coil voltage enables the detection of BPC-OC failure.

### 5 | OUTDOOR EXPERIMENT (MULTI-MODULE CASE)

This section describes BPC-OC failure detection carried out using the PLI method during the operation of the PVS. Figure 11 shows the experimental setup, which consists of a PLG and a light-shielding plate. The PLG in this experiment is the same as that used in the indoor experiment. A signal conversion circuit mounted on the PLG was used to calculate $\Delta B$ from the measured voltage wave of the coil. The detectable range of $\Delta B$ is 0-4.5 $\mu$T. The detectable frequency of the coil voltage wave was tuned using a frequency filter circuit to match the frequency induced by the PLI. The coil was placed on the glass of the PV module, similar to the indoor experiment. A pyranometer mounted on the PLG was used to measure the solar irradiance. The PLG was maintained in the LED on condition when it was placed on the solar cell of the PV module to ensure that the temperature of the solar cell does not rise owing to partial shading.

$\Delta B$ and the solar irradiance were measured for 5 minutes using the test modules with and without BPC-OC failure. The test modules consist of three clusters (42 solar cells and three BPCs), and the solar cell is a typical 5-in Si solar cell with two busbars. The BPC functions of the test modules were confirmed before they were connected in the PV array. The test module with and without BPC-OC failure was connected in the PV array, and $\Delta B$ and the solar irradiance were measured by the PLI method. The PV array is composed of a power conditioner with a single-module string in which 10 PV modules are connected in series. The power generation operation of the PV array was not turned off during the entire measurement process, and the power conditioner thus kept the MPP tracking functioning. The light-shielding plate covered all of the solar cells of the target PV module, that is, it covered three clusters with three BPCs. In this case, the PLI method detects BPC-OC failure if at least one of the BPCs of the three clusters is in open-circuit failure. In other words, if at least one cluster with BPC-OC failure is in the shaded clusters, the coil signal displays $\Delta B \approx 0$. The rear-side temperature of the test modules was observed during the light-shielding process using an infrared camera. The temperature of the test module with BPC-OC failure increased up to $\sim$70°C (ambient temperature + 36°C) 5 minutes after light shielding. In contrast, the temperature of the test module without BPC-OC failure decreased owing to light shielding. The risk of temperature rise in the PV module with BPC-OC failure due to light shielding can be reduced by decreasing the duration of light shielding.

Figure 12 shows the measured $\Delta B$ and solar irradiance (measured for 5 minutes). In this experiment, the minimum solar irradiance was 319 W/m$^2$, which is sufficiently larger than the calculated lower limit of the solar irradiance (111 W/m$^2$). Figure 12(A) shows the result without BPC-OC failure. $\Delta B$ was constant at the maximum detectable range of $\Delta B$ (4.5 $\mu$T) regardless of the solar irradiance. Figure 12(B) shows the result with BPC-OC failure. $\Delta B$ was approximately 0 $\mu$T regardless of the solar irradiance. Figure 12(C) shows the relationship between $\Delta B$ and the solar irradiance; the figure shows that $\Delta B$ varies depending on whether or not BPC-OC failure occurred. These results agree with simulation results, indicating that this method can be employed to detect BPC-OC failure without the influence of solar irradiance variation and power conditioners. In addition, the results indicate that the proposed method can measure $\Delta B$ within a few seconds; thus, a duration of 5 minutes for light shielding is unnecessarily long.

### 6 | CONCLUSIONS

In this study, an on-site inspection method for BPC-OC failures was investigated by performing electrical circuit simulations as well as indoor and outdoor experiments. The simulation results show that the proposed PLI method can detect BPC-OC failure of a PV module in a PV array under power generation operation. Furthermore, BPC-OC failures are detectable even when the solar radiation condition varies during inspection if the solar radiation is higher than approximately 100 W/m$^2$. The I-V characteristics of the PV
module (with and without BPC-OC failure) that was measured during the indoor experiment showed good agreement with the simulation results. The indoor experiment also revealed that the magnetic field induced by the current wave modulated by PLI can be measured using a coil placed above

**FIGURE 8** Photographs of the indoor experiment: (A) PV module; (B) PLG; (C) experimental setup of the solar simulator; (D) distance between the coil and the PV module

**FIGURE 9** Experimental results of the indoor experiment: (A) I-V curves without BPC-OC failure; (B) I-V curves with BPC-OC failure

**TABLE 3** Comparison of simulated and measured results (current and voltage at the MPP) in the single-module case

|                  | BPC-OC failure | Voltage [V] (@ MPP) | Current [A] (@ MPP) |
|------------------|----------------|---------------------|--------------------|
| Simulation w/o   | ON             | 9.76                | 2.41               |
|                  | OFF            | 23.3                | 0.12               |
| w/               | ON             | 23.6                | 0.13               |
|                  | OFF            | 23.1                | 0.13               |
| Experiment w/o   | ON             | 6.21                | 2.18               |
|                  | OFF            | 16.0                | 0.05               |
| w/               | ON             | 14.5                | 0.05               |
|                  | OFF            | 14.7                | 0.05               |
the PV module, enabling the detection of BPC-OC failure by monitoring variations in the magnetic-field characteristics. Furthermore, in an outdoor experiment to detect the BPC-OC failure of a PV module in a real PV array, it was confirmed that the proposed method successfully detected the PV module with BPC-OC failure.

The proposed method has the following advantages: It enables the on-site inspection of BPC-OC failures in a PV array without shutting down the PVS and without connecting additional electronic devices such as transmitters and I-V tracers to the PVS. The inspection is robust to the time variations of solar irradiation and possibly to external magnetic-field disturbances as well as to the number of clusters in the PV array. The method uses a low-cost inspection system, which consists of inexpensive parts and
materials. The PLI method can efficiently identify the PV module with BPC-OC failure in the module string within seconds when combined with a commercial bypass diode failure detector that can identify the module string, including BPC-OC failures (although this requires system shutdown).

The proposed method also has some disadvantages. The proposed method requires time and effort if it is used for a large-scale PVS in which many PV modules are arrayed. Furthermore, it is difficult to place the PLG and perform fast movement of the light-shielding plate manually. There is also the risk of an increase in temperature for the solar cell under the light-shielding plate; therefore, fast movement of the light-shielding plate is required, and further research should be conducted to investigate this risk. These disadvantages can be mitigated by employing light-shielding robots or tools. An example robot being developed by the authors is briefly introduced.

In this study, we investigated only PV modules and PV arrays that do not have other types of failures, such as interconnect disconnections and severely cracked solar cells. It is recommended that future research should focus on the detection of a combination of multiple failures using the proposed method, as well as the effect of the type of power conditioner and PV array configuration.

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