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Correlation between Reverse Voltage Characteristics and Bypass Diode Operation with Different Shading Conditions for c-Si Photovoltaic Module Package

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Abstract—A photovoltaic (PV) system generates electricity by installing a solar energy array; therefore, the photovoltaic system can be easily exposed to external factors, which include environmental factors such as temperature, humidity, and radiation. These factors—as well as shading, in particular—lead to power degradation. When there is an output loss in the solar cell of a PV module package, the output loss is partly controlled by the bypass diode. As solar cells become highly efficient, the characteristics of series resistance and parallel resistance improve, and the characteristics of reverse voltage change. A bypass diode is connected in parallel to the string that is connected in series to the PV module. Ideally, the bypass diode operates when the voltage is -0.6[V] around. This study examines the bypass diode operating time for different types of crystalline solar cells. It compares the reverse voltage characteristics between the single solar cell and polycrystalline solar cell. Special modules were produced for the experiment. The shading rate of the solar cell in the specially made solar energy module was raised by 5% each time to confirm that the bypass diode was operating. The operation of the bypass diode is affected not only by the reverse voltage but also by the forward bias. This tendency was verified as the number of strings increased.

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***Index Terms*—Solar cell, PV module package, bypass diode, hot spot**

I. INTRODUCTION

PVs generates electricity by exposing depletion layer of the PN structure in light. PV module consists of serially connected solar cell which has low voltage characteristics. The generation performance and reliability of a PV module is affected by situations such as micro cracks, mismatches between solar cells, and shading [1, 2].

A PV module is a structure with solar cells in series. If a hot spot occurs, decrease the I_{sc} of generated solar cell [3, 4]. In this case, the generation not only by a solar cell, but also by the entire string is degraded. During this time, the bypass diode is operational [5, 6, 14].

Recently, interest in photovoltaic generation has increased. Many studies are being conducted to increase the output including bypass diode turn-on by shading [5, 7, 8]. However, most of the studies only simulate the degradation of the output by studying the shading ratio, the relationship between shading and resistance, and the output owing to the existence of a bypass diode [7, 9, 10].

The efficiency of the PV module did not improve as much as the efficiency of solar cells because of an increase in CTM (cell-to-module) loss [2]. In addition, using a high-efficiency solar cell, the parallel resistance R_{sh} became higher, and the bypass diode on the solar cell operated more effectively. This occurred as a result of a small area of shading or reduced mismatch between solar cells.

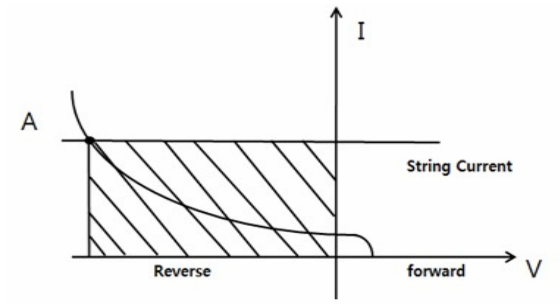


Fig. 1. Output loss of solar cell power

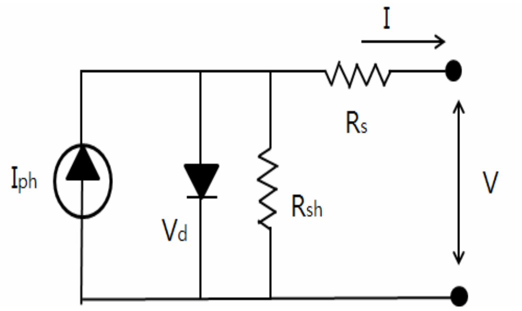


Fig. 2. Equivalent circuit of solar cell

II. Characteristics of Solar Cell Reverse Voltage

1. Power Loss of Solar Cell by Reverse Voltage

PV generation needs solar cells in series to get the necessary capacity because solar cells have low voltage characteristics. Connecting solar cells in series could result in high voltage; however, the current is constant. If the current is not constant, the total current is determined according to the lower current. In this case, a solar cell that has lower current would initiate reverse voltage, and eventually degradation would occur. In addition, hot spots may occur on the solar cell [10, 13]. Decrease the output of one part of the solar cells, decrease total output of PV module. At this time, bypass diode operates to minimize this damage.

Fig. 1 shows the I–V characteristic curve of a solar cell, where the output decreases owing to shading. In Fig. 1, I_{sc} of the solar cell decreases output and is lower than the I_{sc} of the string. Reverse voltage occurs around point A, where the graph crosses the string current line in the reverse-bias area. As a result, output decrease occurs as a loss of heat or in another form, as shown in Fig. 1.

2. Reverse Voltage Model Considering Partial Shading

Studies of output decrease of solar cells have been introduced variously. There were many researches to reduce output decrease by changing the string structure and studies of output change by resistance. Recently there are theoretical approaches and simulation by Bishop Equation with avalanche effect [10]. Solar cells have PN-junction characteristics, when the sunlight or any other light is incident upon solar cells, photocurrent is generated by photovoltaic effect. Fig. 2 shows an equivalent circuit of the solar cell.

The current in the equivalent circuit of the solar cell could be determined as follows:

$$I_{ph} = I + I_d + I_{sh} \quad (1)$$

Reworking Eq. (1) for the output current,

$$I = I_{ph} - I_d - I_{sh} \quad (2)$$

I_{ph} is the photocurrent, and I_d shows diode current, so

$$I = I_{ph} - I_0\left[exp\left(\frac{qV}{nkT}\right) - 1\right] - I_{sh} \quad (3)$$

A common solar cell has a series resistance (R_s) and parallel resistance (R_{sh}). It could be represented as

$$I = I_{ph} - I_0\left[exp\left(\frac{qV}{nkT}\right) - 1\right] - \frac{V + R_s I}{R_{sh}} \quad (4)$$

I_0 in Eq. (4) is reverse saturation current, n is solar cell's ideal coefficient, k is Boltzmann constant and T is atmospheric temperature.

I–V characteristic curve of a solar cell includes forward , reverse, and breakdown voltages.

Part A of the forward voltage in Fig. 3 could be calculated using Eq. (4). Parts B and C of the reverse voltage are then calculated using Eq. (5). The reverse current is comprised of the leakage current and breakdown current.

Reverse current = leakage current + breakdown current.

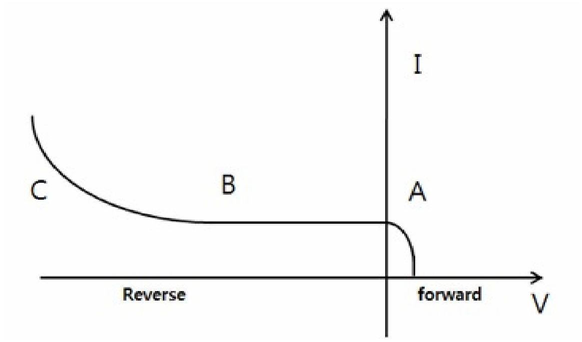


Fig. 3. I–V characteristics of a solar cell

$$= I_0\left[exp\left(\frac{qV}{nkT}\right)-1\right]+\alpha V+\beta \quad (5)$$

Leakage current could be calculated using diode equation and breakdown current as a linear function of voltage. The breakdown current in fact depends on the shading ratio. It is therefore suggested for the first time as Eq. (6).

$$Reverse\,Current = I_0\left[exp\left(\frac{qV}{nkT}\gamma\right)-1\right]+$$
$$\alpha V+\beta+I_{ph}\frac{100-Shading\,ratio}{100} \quad (6)$$

Calculation of I_{ph}, photo current, considering shading ratio depends on its ratio. In Eq. (6). α, β, and γ are modification coefficients; and I0 is the reverse saturation current. β is obtained from the experiment to compensate for the breakdown current. Constants in simulation are calculated approximately by reconciling the experimental results with different shading ratio of a solar cell.

III. Experimental Results and Considerations

1. Experimental Conditions

Two types of solar cell were used to study the reverse voltage characteristics of solar cell. One is high-efficiency single crystalline (c-Si) solar cell from Shinsung Solar Energy and the other from KPE's high-efficiency multi c-Si solar cell.

Fig. 4. Fabricated PV module for the experiment

I-V characteristics of the solar cells were obtained using jig in a simulator. Shading ratio is then changed for both single c-Si solar cell and multi c-Si. Source meter was used to examine the reverse voltage characteristics.

Operation point of the bypass diode with different reverse voltage characteristics of a solar cell is measured from the module fabricated for the test shown in Fig. 4. To maintain the uniformity of the specimens, I_{sc} of solar cell is traced based on the same production date and sorting condition.

In particular, photovoltaic modules with 5 × 6 cell array structure were fabricated for both single c-Si and multi c-Si.

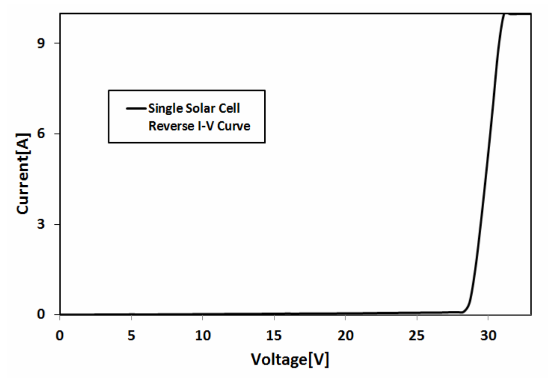
2. Experiment and Measurement

Keithley Source Meter 2430 was used to determine the reverse-voltage characteristics of the modules. The pulse measuring interval is 0.001[sec], and the current range of 0–10 [A] under the condition of 100% darkness to avoid any external light source. The test results are then as follows:

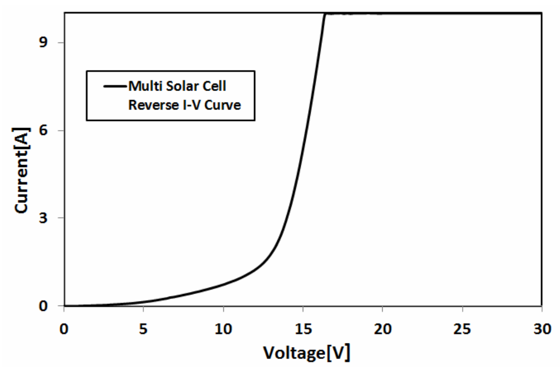
Reverse I–V curve for each type of c-Si solar cells are shown in Fig. 5. The incline of a single c-Si cell is steeper than that of a multi c-Si cell. Because solar cell generates photocurrent through a PN junction formed through doping process [12], the resistance characteristics of depletion layer of each cell could be identified.

The reverse-voltage characteristics of each cell considering shading ratio were measured with an increment of shading ratio by 25% at a time shown in Figs. 6 and 7

With the same c-Si PV module, the reverse voltage of



(a) Reverse I–V characteristics of single c-solar cell



(b) Reverse I–V characteristics of multi-c solar cell

Fig. 5. Reverse *I-V* characteristics of crystalline Si and multi crystalline solar cells

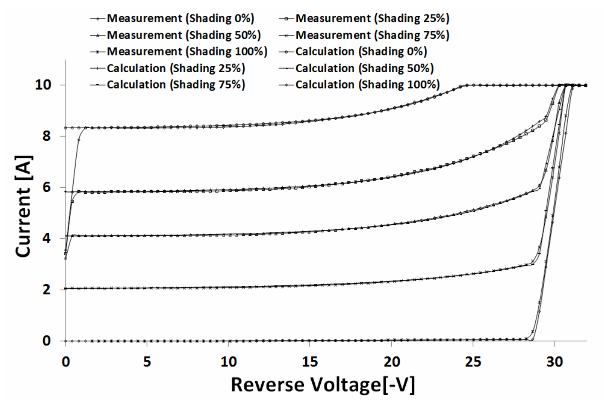


Fig. 6. Reverse I-V characteristics of single c-Si solar cell by shading ratio

a single c-Si solar cell is higher than that of the multi c-Si solar cell with a little shading, as. This means that, in the case of a single c-Si solar cell, the bypass diode could operate in a little shading condition compared with multi c-Si solar cell.

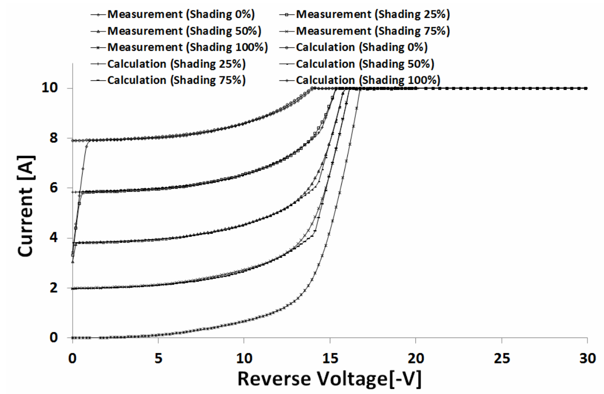


Fig. 7. Reverse I-V characteristics of multi c-Si solar cell by shading ratio

IV. Experimental Results and Analysis

We increased the shading ratio by 5% at a time, and experimented with 60-unit solar cells composed of two modules consisting of 30 units each.

The turn-on point of the bypass diode considers not only reverse voltage also forward bias. Therefore, we experimented with increasing the shading area and increasing the number of strings.

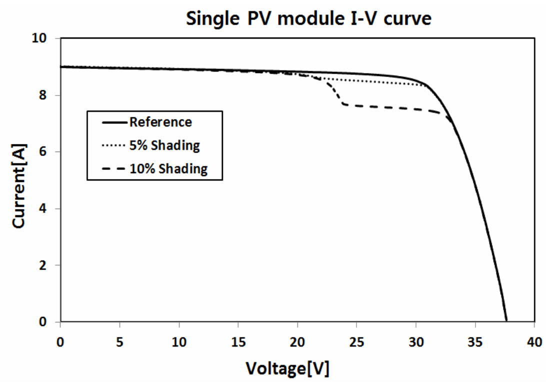
From the comparison of experimental results for each of the single c-Si solar cells and multi c-Si solar cells, we confirmed that different types of solar cells have different turn-on points for their bypass diodes.

Fig. 8 shows measurements of the string that connects 15 units, as we increased the shading area by 5%.

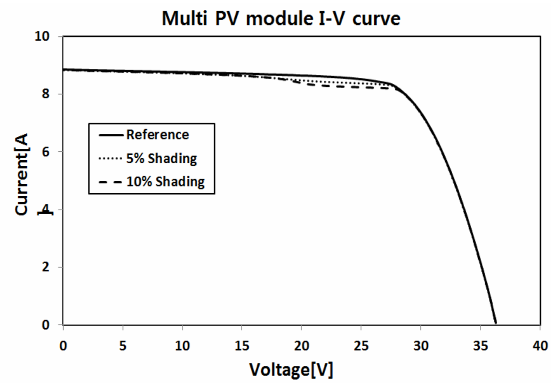
When we increased the shading ratio by 10%, in the case of a single c-Si solar cell, the breakdown point incline was steep. The bypass diode therefore operated, but it did not operate in the multi c-Si solar cell.

Fig. 9 shows the experiment that confirms whether the bypass diode is operational when the forward bias voltage is large. The bypass diode operates in a little shading on the PV module because of the reverse-bias characteristics in the single c-Si solar cell. Fig. 9 shows the measurements of the string that connects 60 units with an increase in the shading area of one unit.

In Fig. 8(a), the bypass diode operates when the shading ratio is 10%. However, as shown in Fig. 9(a), when the number of single c-Si solar cell strings increases, the bypass diode does not operate even when the shading ratio is 10%. On the other hand, from Fig. 8(b) and (b), the multi c-Si solar cell did not operate

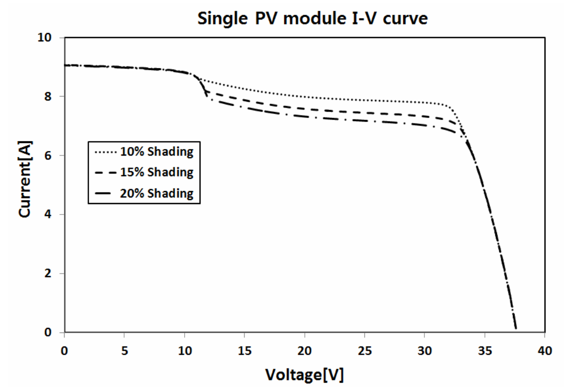


(a) Bypass diode operation of single c-Si PV module by 0–10% shading ratio

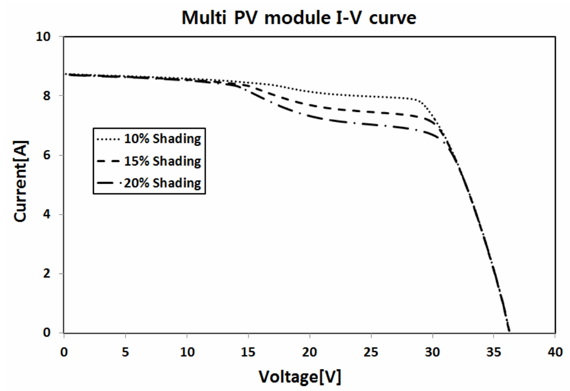


(b) Bypass diode operation of multi c-Si PV module by 0–10% shading ratio

Fig. 8. Bypass diode operation of c-Si PV module by 0–10% shading ratio



(a) Bypass diode operation of single c-Si PV module by 10–20% shading ratio



(b) Bypass diode operation of multi c-Si PV module by 10–20% shading ratio

Fig. 9. Bypass diode operation of c-Si PV module by 10–20% shading ratio

because there was no reverse voltage on the bypass diode. This occurred because the value of the forward bias is larger than the value of the reverse voltage as the forward voltage increases with the number of strings.

From the results, the bypass diode operates in the case of a single c-Si solar cell even with small shading, as shown in Figs. 8 and 9. However, the bypass diode with multi c-Si solar cell operates when the shading ratio is larger than that of the single c-Si solar cell, even though we have the same number of strings.

The graphs in Figs. 10 and 11 show the turn-on point of the bypass diode as the shading ratio increases with the number of strings. The voltage of Figs. 10 and 11 is – Bypass diode is operating when the sum of the value of the reverse voltage and forward bias is -0.6 [V] – the total value of string except the reverse voltage when bypass diode is operating.

A single c-Si PV module operates in 10% shading with a forward bias below 22 V, and a multi c-Si PV module

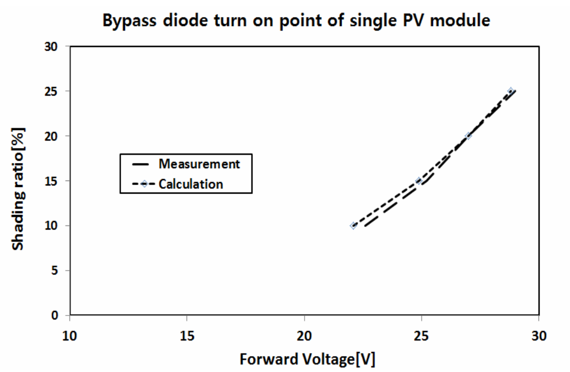


Fig. 10. Bypass diode turn-on point of single PV string

operates at around 11 V. This means that the bypass diode of single c-Si PV module operates sensitively.

Figs. 10 and 11 show the turn-on point of the bypass diode using Eq. (6) and the experimental results. Eq. (6) also models the characteristics of reverse voltage in two parts depending on the shading ratio as explained before.

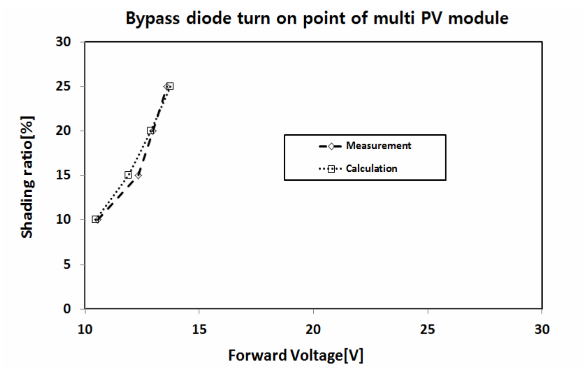


Fig. 11. Bypass diode turn-on point of multi PV string

In addition, the modification factors α, β consider reverse voltage characteristics for different materials such as single or multi c-Si. The factor γ is calculated considering the leakage current and depends on the shading ratio. The shading ratio could interpret in short circuit current for solar cell sorting.

It could be confirmed in Figs. 10 and 11 that the bypass diode of the single c-Si solar cell could operate, but that of the multi c-Si solar cell would not, under the same shading ratio because reverse voltage in shaded single c-Si solar cell is high.

V. CONCLUSION

This paper reviews the turn-on points of bypass diodes in solar cells that have different I-V characteristics. The bypass diode of a PV module connects with the string - which is in series – in parallel. Theoretically, when the sum of the voltage value of the string (consisting of the solar cell with reverse voltage that degrades the output and keeps the solar cell from generating current normally) has an operating voltage of -0.6 [V].

In fact, with the same shading ratio and the same number of strings, the turn-on point of the bypass diode is different, as shown in Figs. 8 and 9. This means that, in the case of a single c-Si solar cell, the bypass diode could operate in a small shading compared with the multi c-Si solar cell.

The characteristic curve of reverse voltage in this experiment is suggested by modeling with new equations that consider leakage current and breakdown voltage. This shows that the turn-on point of the bypass diode of a single c-Si solar cell and a multi c-Si solar cell are different depending on the forward bias voltage and the shading ratio.

Most existing research approached the bypass operation depending on shading, and the I–V characteristic curve. However, in this paper, this research confirmed that reverse-voltage characteristics were different for each type of solar cell, and we suggested that the operation of the bypass diode should consider the reverse voltage characteristics.

Finally it is, therefore, very important to have different sorting standards for single and multi c-Si solar cells in manufacturing PV module.

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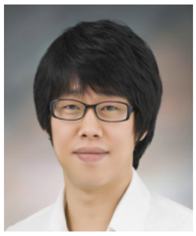

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