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Performance variation of dark current density-voltage characteristics for PID-affected monocrystalline silicon solar modules from the field

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ABSTRACT

Potential-induced degradation (PID) has caught considerable attention in recent years because of its detrimental influence on output power of solar module and energy yield of photovoltaic power plant. In this paper, performance variation of dark current density-voltage (dark J-V) characteristics for PID-affected monocrystalline silicon solar modules dismounted from photovoltaic power plant was investigated. By measuring dark J-V characteristics of the PID-affected modules, the deterioration trend of dark J-V characteristics for PID-affected modules was found for the first time. Based on diffusion theory of metal ions, a new field-assisted diffusion model of metal ions was built, and the deterioration of open-circuit voltage and increase of recombination current density were explained for solar modules affected by PID. The thermal characteristics of solar modules with different level of PID were revealed under forward and reverse bias. There is an obvious temperature difference between the substrings neighboring the frame and the middle substring within the PID-affected modules. The results obtained in this paper give out the reasonable explanation about mechanism of PID and the deterioration trend of dark J-V for PID-affected modules.

1. Introduction

Potential-induced degradation (PID) has attracted considerable attention in recent years because of its detrimental influence on output power of solar module and the energy yield of photovoltaic power plant [1–4]. Many investigators devoted themselves to this problem, but there have been some debates on mechanism of PID [5]. Some authors thought that PID of n-type crystalline silicon solar modules is caused by the surface polarization effect [6–9], but other authors thought that PID of p-type crystalline silicon solar modules is attributed to Na-decorated stacking fault [10–14]. Up to now, the true reason and mechanism of PID have not been revealed thoroughly because of complexity of PID phenomena. Searching the deterioration trend of PID, particularly from the field, is a key for solving problem of PID and verifying some authors' viewpoints.

The J-V characteristics measured under dark and light conditions are performed to provide an essential tool to assess the performance of solar cells [15–16]. Both light J-V and dark J-V measurements have been commonly used to determine the electrical parameters of solar cells [17]. The dark J-V measurement procedure is not affected by the light intensity, but is more susceptible than light J-V in determining some parameters including ideality factor, parallel resistance, and dark saturation current [18].

In most studies about PID, almost all of works focus on PID-affected solar modules reproduced in the laboratory [19–21], few have reported on the dark J-V characteristic of solar modules degraded by PID from the field. In this paper, by measuring dark J-V characteristics of the PID-affected modules, the deterioration trend of dark J-V for PID-affected modules was found for the first time. And a significant difference between the dark J-V characteristics for three substrings of PID-affected modules in the field is revealed, showing that two substrings close to the frame within a PID-affected module degrade more severely than the substring located in the middle. Based on diffusion theory of metal ions, a new field-assisted diffusion model of metal ions was built, which explains the deterioration of open-circuit voltage and increase of recombination current density for p-type single crystalline silicon solar modules affected by PID. The thermal characteristics of solar modules that have suffered different levels of PID were revealed under forward bias and reverse bias. There is an obvious temperature difference among the substrings neighboring the frame and the middle substring within the PID-affected modules. The results obtained in this paper give out the reasonable explanation about mechanism of PID and the

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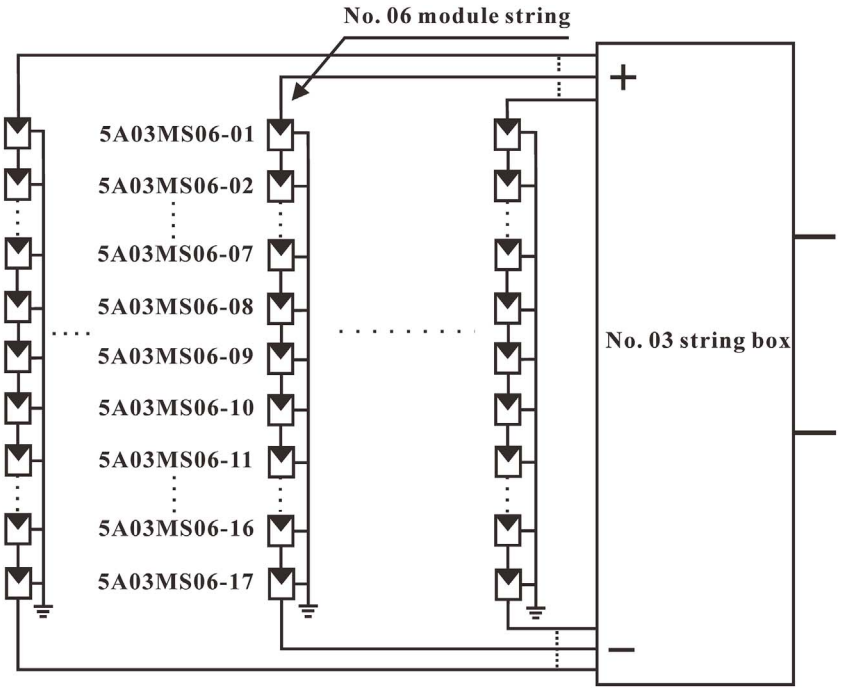

Fig. 1. The circuit diagram of module strings with 17 solar modules in series.

Table 1
Relative change in the main electrical parameters (measured at STC) of module 1, module 2 and module 3 after grid-connected operation for 2 years. The V_{oc0}, I_{sc0}, V_{m0}, I_{m0}, FF_0 and P_{max0} were measured before shipments.

Module	Module 1	Module 2	Module 3
V_{oc0} (V)	44.52	44.56	44.50
ΔV_{oc} (%)	− 0.29	− 10.00	− 30.31
I_{sc0} (A)	5.72	5.73	5.72
ΔI_{sc} (%)	− 1.40	− 1.75	− 1.75
V_{m0} (V)	36.12	36.15	36.10
ΔV_m (%)	− 0.44	− 15.70	− 43.80
I_{m0} (A)	5.41	5.43	5.41
ΔI_m (%)	− 3.51	− 8.29	− 8.87
FF_0 (%)	76.73	76.89	76.70
ΔFF (%)	− 1.97	− 19.82	− 26.95
P_{max0} (W)	195.39	196.33	195.22
ΔP_{max} (%)	− 3.00	− 21.90	− 48.67

STC: 1 kW/m^2 irradiation, 25 °C module temperature and AM1.5 global spectrum.

deterioration trend of dark J-V for PID-affected modules.

2. Experimental details

After measuring a large number of modules dismounted from a solar power plant, three representative solar modules of No. 06 module string (5A03MS06-08, 16, 17) from No. 03 string box of No. 5 array were taken for the dark J-V measurements in the laboratory [12], as illustrated in Fig. 1. For convenience, the three solar modules were marked by module 1, 2 and 3 in sequence in the context. The solar modules consist of 72 pieces p-type monocrystalline silicon solar cells connected in series respectively. The cells feature an unpassivated full-area screen-printed aluminium rear side metallization aluminium back surface field with dimensions of 125 × 125 mm^2 and 70 nm SiNx:H antireflective coating. First, the performance of PID-affected solar modules dismounted from array was measured by solar simulator (PASAN Sunsim 3C) under standard test conditions (STC: 1 kW/m^2 irradiation, 25 °C module temperature and AM1.5 global spectrum). The procedure for dark J-V measurements on solar modules comprised covering the modules to eliminate light-generated current, removing the bypass diodes, using a variable power supply connected with the module from the positive electrode to the negative, and measuring current and voltage simultaneously recorded by two digital multimeters with the increase of the voltage from zero. In addition, both forward dark J-V characteristics and reverse dark J-V characteristics of three substrings of each module were also obtained.

During dark J-V characteristics measurement, it was found that thermal distribution arose in some cells of the modules under forward and reverse bias. For further research, backsheets of the PID-affected modules were divided into 72 regions based on the distribution of cells, and sequentially numbered. Then an external voltage was applied to three substrings of each module about 10 min, and the value of current was recorded until thermal region was no longer to heat up. And modules were investigated by electroluminescence (EL) measurement system (ITES Co., Ltd.) and an infrared camera with resolution of 320 × 240 pixels (FLIR systems). By these measurements, the distribution of thermal regions of PID-affected module was obtained.

3. Results and discussion

3.1. Forward and reverse dark J-V characteristics of PID-affected solar modules from the field

Table 1 shows the relative change of the electrical parameters of three PID-affected solar modules from the same module string in the field. These three solar modules are grid-connected for about two years. The values of the fundamental parameters V_{oc0}, I_{sc0}, V_{m0}, I_{m0}, FF_0 and P_{max0} were measured before shipments. Compared with the output power before grid-connected operation, the measurements under STC show that module 1 has a 3.00% power loss, and module 2 and module 3 have a 21.90% and 48.67% power loss, respectively. Fig. 2 shows the I-V curve of three solar modules measured under STC. Combining with the thermographic images decorated with special temperature pattern [2], it is detected that module 1 is a PID-free module, and module 2 and module 3 are affected by different levels of PID. In Fig. 3, the dark J-V curves obtained by using the identical measurement method are shown for three different modules. Fig. 3(a) illustrates that the forward current density of module 2 and module 3 with PID ascends faster than that of the module 1 as the growth of forward bias voltage. Furthermore, the forward current density of module 3 is larger than that of module 2. The