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A mathematical model for cell-to-module conversion considering mismatching solar cells and the resistance of the interconnection ribbon

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Abstract

The electrical cell-to-module (CTM) loss for a photovoltaic (PV) module excluding the optical loss is analyzed and a mathematical model is proposed to predict the output of the module due to CTM loss. The model is obtained based on the equation that was released to the output characteristics of a partially shaded module. The electrical CTM loss is predominantly affected by two key factors, the resistance of the soldered interconnection ribbon and mismatching solar cells. We suppose that all carriers of a solar cell exposed to light are generated at half the length of the soldered interconnection ribbon and pass through the interconnection ribbon, which is in contact with both surfaces of the solar cell. The mathematical model for the electrical output of the solar cells soldered with the interconnection ribbon is completed under these assumptions. The reasons for the mismatching loss of the solar cells in the module are the photocurrent, the series resistance and the shunt resistance, which are applied to the proposed equation. The mathematical model is validated by comparing the calculated results from the newly proposed equation with the measured data of the manufactured module. The absolute error of maximum power between these results is less than 2.45%.

Keywords: PV module; CTM (cell to module) conversion loss; Mismatching; Interconnection ribbon

1. Introduction

The total output power of the completed module is mostly less than the sum power of all the connected solar cells, defined as cell to module (CTM) conversion efficiency. CTM conversion loss is inevitable in the module fabrication and results from optical factors such as glass, encapsulation materials, the back sheet as well as electrical reasons caused by the different performance of each solar cell and the additional resistance of the electrode, such as the interconnection ribbon and external connectors.

To reduce the optical CTM loss, the inter space between solar cells or strings was controlled to maximize light reflected in the back sheet (Su et al., 2011; Grunow and Krauter, 2006). The literature reported how a white EVA sheet was applied to the back side of solar cells to increase the photocurrent of the module due to the diffused reflection on the EVA/back sheet (Chung et al., 2012). The increase in power output of modules fabricated with anti-reflection coated (ARC) glass was attributed to the effect

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of more absorption and less reflectance of incident light (Wohlgemuth et al., 2005; Bunea et al., 2010).

In the soldering process between the solar cell and the interconnection ribbon, the electrical power loss of the solar cells results from the resistance of the interconnection ribbon and the contact resistance between the ribbon and the solar cells. The contact condition of the interconnection ribbon affects CTM loss as well as the long term durability of the PV module. Recent studies introduced a new soldering technology, conductive adhesive (CA), which attaches the interconnection ribbon to solar cells at low temperature, to improve the CTM loss and the reliability of the module (Hsieh et al., 2010; Zemen et al., 2013). To simulate the output power of the module made of interconnection ribbon-soldered solar cells, others developed a mathematical model that took into account the resistances generated in the soldering process (Caballero et al., 2006). However, it is difficult for the model to be used to calculate the output of a solar cell connected to the interconnection ribbon because this model requires the resistances of all the compositions of the solar cell and the ribbon. For this reason, a more simplified model that predicts the variations of the solar cell output according to the soldered interconnection ribbon needs to be developed.

The electrical mismatching loss is generally derived from the differences in the photocurrent, the series resistance and the shunt resistance in individual solar cells. The non-uniform photocurrent of solar cells leads to serious electrical CTM loss when all the solar cells in the PV module or array are connected in series (Louis and Bucciarelli, 1979; Kaushika and Rai, 2007). The relations between mismatching loss and the output characteristics of the individual solar cells in a module were analyzed by statistical methods based on Monte Carlo (MC) simulation techniques (Iannone et al., 1998; Webber and Riley, 2013). An equation for the output of a module or array was proposed to predict mismatching loss according to the various solar cell configurations in an array (Gautam and Kaushika, 2001). Some studies proposed mathematical models that exactly consider the reverse characteristics of solar cells in a module to simulate the I–V curves of the module with mismatching solar cells under partial shadow conditions (Silvestre and Chouder, 2008; Henze et al., 2009; Jung et al., 2013). However, it has been difficult for the previous models to exactly calculate the output variation of the entire module by mismatching performance among solar cells because the models could not simultaneously consider all the module conditions, such as the reverse characteristics of the solar cells, the performance of individual solar cells and the number of connected solar cells.

In this study, we analyze the electrical CTM loss excluding the optical loss. The mathematical model for the output of the PV module based on Jung's model is proposed to predict the electrical CTM loss in PV module production. Jung's equation was generally utilized to estimate the output change of the partially shaded PV module. Our investigations have focused on two process steps in the module fabrication as the main reasons for CTM loss: the electrical loss generated from the soldering procedure of the interconnection ribbon and the electrical mismatching loss by the difference in performance among all the solar cells. To validate the model, the results calculated by the proposed model were compared with the measured CTM conversion data of the manufactured module.

2. Mathematical model

2.1. The CTM loss in the process of the soldered interconnection ribbon

CTM loss generated in the soldered interconnection ribbon process is attributed to the series resistances of the interconnection ribbon and the contact resistance between the solder alloys of the interconnection ribbon and the electrode formed by the silver paste of the solar cell. It is known that the contact resistance is primarily influenced by the number of soldered spots (Caballero et al., 2006; Heimann et al., 2012). However, it was reported that the contact resistance between the solar cell and the ribbon could be constant and negligible if there were a sufficient number of solder spots (Zemen et al., 2013). Therefore, CTM loss by the contact resistance of the solar cell linked to the interconnection ribbon is ignored in this paper.

CTM loss by the series resistance of the interconnection ribbon is taken into account. The main factors that affect the series resistance of the interconnection ribbon can be considered as the specific resistance of the interconnection ribbon and the measurement method. Particularly, the movement direction of carriers on the surface of the solar cell is different according to the measurement method for the output power of solar cells with or without an interconnection ribbon, as shown in Fig. 1. The carriers generated in the solar cell without an interconnection ribbon move vertically on the surface of solar cell through the measurement probes in the performance tester. On the other hand, the carriers in the solar cell assembled with an interconnection ribbon horizontally flow through the interconnection ribbon. These carrier movements affect the electrical CTM loss differently.

We assumed that interconnection ribbons were soldered on the entire bus bar of the solar cell to confirm CTM loss derived from only the soldered interconnection ribbon. Even though the carriers are uniformly generated in a solar cell exposed to light, we supposed that all carriers at the half-way point of the soldered interconnection ribbon are produced and move along the interconnection ribbon to express the mathematical model for an average loss for all carriers due to the series resistance of the soldered interconnection ribbon on the solar cell. Also, Eq. (1) especially reflects the proportional reduction of total resistance of the soldered interconnection ribbon according to the increase of the number of bus bar on solar cell. The additional series resistance (R_a) that results in CTM loss in the interconnection ribbon soldering process is proposed as follows: