Solar Energy Materials & Solar Cells 134 (2015) 236–243

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Simplified technique for calculating mismatch loss in mass production

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ARTICLE INFO

Article history:
Received 15 October 2014
Accepted 17 November 2014
Available online 19 December 2014

Keywords:
Photovoltaics
Solar cells
Solar modules
Mismatch
Manufacturing
Cell-to-module

ABSTRACT

This paper describes a generalised approach to estimating mismatch loss for series connected cells, utilising the result that the deviation from maximum power as a function of deviation from maximum power–point–current is a relatively stable relationship for a wide range of cell performances. This Power–Current relationship can be used to verify the strong link between mismatch loss and the variance in the maximum power–point–current values for the cells being mixed together. The mismatch loss in a modern photovoltaic module is low – below 0.1% even when there is no cell sorting whatsoever. Cell-to-module variance effects need to be understood and controlled to ensure mismatch loss remains low in a finished module. Without the constraints of mismatch loss in module design, other motivations for cell sorting should be considered, such as for optimising the manufacturing system or meeting particular product requirements.

1. Introduction

As manufactured, all individual solar cells exhibit some slight differences in their performance. When these cells are series connected in a module and that module is operating at maximum power, the individual cells will typically output some power slightly below their maximum. The difference between the maximum power of a module and the sum of the maximum powers of the individual cells is known as mismatch loss. It is important to understand mismatch loss when optimising module manufacturing strategies.

Mismatch loss is a well known effect and calculations of the mismatch loss resultant from the mixing of groups of cells has been a subject of study for over 30 years. The original work in this field by Bucciarelli [1] remains one of the most well cited, thorough and generalizable and it is further discussed throughout this work. Many of the papers [2–7] examine the mismatch loss resulting from different ways to bin and interconnect cells of different properties. The main limitations of these works are that it is difficult to generalise the results and there is no direction for dealing with encapsulation effects. Some of the works phrase the mismatch loss issue in the larger context of manufacturing yield and total Watts produced [8,9]. Total mismatch loss is also dependent on solar insolation level [3] and so the issue has also been explored in terms of its influence on energy yield [10,11]. Many works investigate mismatch loss in the context of stressed or non-standard operating conditions such as partial cell shading ([6,12] to name a few) and many more studies ([13–15] to name a few) deal with the additional subject of mismatch loss at an array level. Both of these topics are important issues to which the results here are applicable, but neither is the immediate focus of this work.

Mismatch loss is itself one component of a broader group of changes typically referred to as Cell to Module (CTM) effects. Usually expressed as a loss [16] or a conversion ratio [17], CTM calculations account for all the changes in average performance when cells are encapsulated into modules. For the purpose of this study, the term encapsulation refers to the group of processes by which cells are made into modules, including tabbing, stringing and lamination. Three studies make attempts to quantify mismatch loss at a final module level, rather than just as a consequence of cell mixing [18–20]. One [18] is particularly notable as the only study that attempts to measure mismatch loss at the final module level through direct experimentation. Unfortunately, the resolution of the technique described is insufficient to calculate loss for cells sorted in ways typical of modern manufacturing, and the technique is not directly generalisable to all module making strategies. This is not a weakness in the approach: rather it serves

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http://dx.doi.org/10.1016/j.solmat.2014.11.036
0927-0248/

to highlight the important fact that mismatch loss is very low for a modern photovoltaic module, a fact that can also be verified by following the derivations of Bucciarelli from over 30 years ago. The second [19] builds a mathematical model for CTM effects that also includes mismatch, and the third [20] uses the expected difference between module *I*–*V* and SunsVoc curves to calculate mismatch loss. But the emphasis of both techniques is to deal with non-standard conditions such as partial cell shading and so neither apparently has sufficient accuracy to detect the relatively small mismatch effect in standard modules. In this study, the new concept of CTM variance (CTMV) is also introduced and changes in variance associated with cell encapsulated are examined. This will highlight a new set of issues that need to be considered to keep mismatch loss to the low levels expected from modern production.

2. Overview of this study

The aim of this study is to develop a simple and generalisable method for the calculation of mismatch loss and the monitoring of CTMV in a manufacturing context, so it can be used as an input in the design of optimal photovoltaic products. As a first step, the *I*–*V* curves of groups of production cells are summed to form a hypothetical module *I*–*V* curve and the maximum power (P_{mp}) and maximum current (I_{mp}) calculated from this curve. The hypothetical curve includes no additional series resistance due to interconnection or changes in cell current due to encapsulation. Mismatch loss, *L*, is calculated from the difference between the sum of the maximum powers of the 72 component cells and the maximum power of the hypothetical module. This is the same technique as used in the Evergreen studies of more than 10 years ago [8,9]. A calculation of this form is referred to as Relative or Fractional Power Loss (RPL / FPL) in other studies [1,7,18]:

$$L = \frac{\sum_{i=1}^{72} p_i - P_{mp}}{\sum_{i=1}^{72} p_i} \quad (1)$$

where p_i is the maximum power of the *i*th cell and P_{mp} is the maximum power of the module as previously mentioned. Lower case variables are used here to describe cell properties, upper case variables being used for module properties. *L* is calculated for four different types of cell sorting arrangements as shown in Table 1. This curve summing exercise is intended to give the most direct estimate of mismatch loss to serve as a validation of the new techniques based on the Power–Current (*P*–*I*) relationship. The simplification of using the *P*–*I* relationship is only possible when the range of cells being mixed remains very small and when the cells are series connected, as is the case for the majority of modern production. Overall, as is verifiable from the derivations in other studies [1,6,18], the typical loss for even rudimentary sorting schemes is shown to be extremely low for the variance typical of modern manufacturing. In this situation of a small variance, many of the established notions of mismatch loss – such as the module being limited to the lowest performing cell [19,21], simply do not apply: rather the module maximum power current will tend to just be close to an average of the component cell currents. Another established notion that mismatch loss is simply reduced by classifying cells into even smaller ranges of performance also becomes less relevant – in the context of low overall variance, process variance associated with cell encapsulation and the limitations of measurement accuracy will also have an impact.

Table 1
The selection restriction for the four different cell grouping arrangements.

Group	Selection restriction
A	Random selection
B	Efficiency range < 0.2% abs.
C	i_{mp} range < 0.15 A
D	i_{mp} range < 0.05 A

2.1. Materials

For the simulations in this study, *I*–*V* curves were collected from 3000 cells from a production order in 2012 from a Suntech manufacturing facility in Jiangsu, Wuxi, China. The cells are standard multi-crystalline silicon (mc-Si) with acidic texturing, belt diffusion, SiN ARC, full rear aluminium BSF and front silver screen printed contacts. The cells were measured on an inline cell flash tester at two illumination levels. The *I*–*V* curves were assembled from temperature and illumination corrected measurements on 200 points in forward bias and to assist with summing these were recalculated to 400–450 point curves with a consistent set of current coordinates using polynomial interpolation. The histogram of the cell's normalised efficiency is shown in Fig. 1. All of the cell data is normalised to generalise the results and protect data sensitivity, without interfering with the interpretability of the outcomes. The variance is scaled to be a percentage of mean, and then the data is mean centred. The full range of cell efficiencies is a little over $\pm 3\%$ relative.

3. Results—calculation of losses from cell mixing

3.1. Loss calculated from summing I–V curves

A random number function was used to select groups of 72 cells from the group of 3000 according to the simple sorting restrictions outlined in Table 1, and without regard to the original time order sequence in which the cells were made. The hypothetical module *I*–*V* characteristics were calculated and *L* was determined for each arrangement, as shown in Fig. 2. This shows the loss to be extremely low. Fig. 3 shows *L* as a function of key summary parameters within the group of cells. Of all these simple statistics, the strongest relationship is with the standard deviation of cell i_{mp}. This is shown in detail in Fig. 4. This relationship has been shown in another theoretical study [1] but not directly by curve summing [8,9]. The strength of this relationship is affected by the precise technique used for the curve summing – less points on the original *I*–*V* curve and linear interpolation between the points can add significant levels of noise. Fig. 4 can be fit with a quadratic passing through, and with its minimum at the origin. The line of best fit has equation:

$$L = 9.23 \times \sigma_{iN}^2 \quad (2)$$

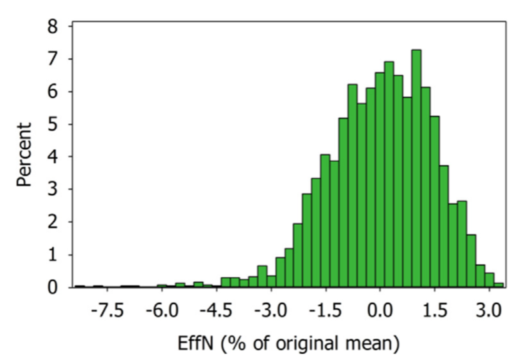

Fig. 1. Histogram of normalise cell efficiency for the 3000 cells used in this study.