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CPV solar cell modeling and metallization optimization

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ABSTRACT

Concentrated photovoltaics (CPV) has recently gained popularity due to its ability to deliver significantly more power at relatively lower absorber material costs. In CPVs, lenses and mirrors are used to concentrate illumination over a small solar cell, thereby increasing the incident light by several folds. This leads to non-uniform illumination and temperature distribution on the front side of the cell, which reduces performance. A way to limit this reduction is to optimize the metallization design of the solar cell for certain non-uniform illumination and temperature profiles. Most of the existing metallization optimization methods are restricted to the conventional H-pattern, which limits the achievable improvements. Topology optimization alleviates such restrictions and is capable of generating complex metallization patterns, which cannot be captured by the traditional optimization methods. In this paper, the application of topology optimization is explored for concentrated illumination conditions. A finite element model that includes all relevant resistances combined with topology optimization method is presented and the applicability is demonstrated on non-uniform illumination and temperature profiles. The finite element model allows accurate modeling of the current density and voltage distributions. Metallization designs obtained by topology optimization significantly improve the power output of concentrating solar cells.

1. Introduction

Concentrated photovoltaic (CPV) systems allow a large amount of solar power generation at a relatively lower cost, since the required solar cell material is reduced (Mellor et al., 2009). In CPV systems, lenses and curved mirrors are used to concentrate sunlight on small, but highly efficient solar cells (Baig et al., 2012). For further improvement in performance, additional elements such as sun trackers and cooling systems are also used. The use of lenses and mirrors modifies the incident radiation on the solar cells, amplifying it several folds in some parts of the cell (Baig et al., 2012). Thus, a concentrated, non-uniform illumination profile and a non-uniform temperature distribution are created on the front side of the cell. Due to illumination being higher in some parts of the cell, the photoillumination current density as well as temperature increase locally, leading to a higher voltage drop and increased ohmic losses. Mitchell (1977) showed that under non-uniform illumination, series resistance can lead to significant reductions in power output.

For a CPV system to be efficient, it is important that each of its elements performs well individually as well as collectively. One of the ways to improve the efficiency of CPVs is to improve the design of the metallization patterns of the solar cells. Optimization of metallization has been rigorously studied in the past in the context of uniform illumination and one sun intensity (Beckman, 1967; Flat and Milnes, 1979; Conti, 1981; Burgers, 1999; Gupta et al., 2014). In addition, there exist works on designing efficient metallization patterns for certain solar cell geometries under higher sun concentrations with uniform illumination (Moore, 1979; Algora and Díaz, 2000; Bissels et al., 2011). However, optimizing the metal grids under non-uniform sun intensity has received relatively little attention. Mellor et al. (2009) optimized a conventional H-pattern metallization for a Gaussian illumination profile and constant temperature, and showed that the solar cell with such metallizations could perform better under non-uniform illumination conditions. Domenech-Garret (2011) studied the effect of several illumination and temperature profiles on the performance of solar cells. In these studies, linear concentrators were considered and non-uniformity was only assumed along the finger direction (Mellor et al., 2009; Domenech-Garret, 2011). Shifts in the illumination profile due to tracking misalignment and the non-uniformity in the busbar direction were not considered. Both studies restricted themselves to H-patterns and spacing between the metal finger lines was optimized.

The H-pattern is known to be a very efficient metallization geometry for uniformly illuminated, constant temperature cells. However, for CPV, it is likely that other patterns are superior given the non-uniform

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illumination and temperature conditions. While simplifying the optimization, geometrical restrictions (*e.g.* assumption of straight metal fingers oriented parallel to each other, as in H-pattern) reduce the flexibility of the optimization process and only limited improvements in performance can be expected. More general metallization geometries have been explored for solar cells under uniform illumination as well. Burgers (1999) presented a two-step approach to optimize solar cell front metallizations without any pre-assumptions of topology. In the first step, a smeared version of electrode material distribution is optimized in the whole domain. The second step involves a heuristic procedure to translate the optimized material distribution into a line pattern. During the translation step, some prior information is needed from the side of the designer (Burgers, 2005). The applicability of this approach for non-uniform illumination was briefly discussed.

In an earlier study concerned with uniform illumination and one sun intensity (Gupta et al., 2014), we have presented a topology optimization (TO) formulation that can optimize the metallization patterns without any interference from the side of the user. TO does not impose any restriction on the design of the metal grids and is capable of generating metallization patterns that cannot be obtained with any of the previously existing methods (Gupta et al., 2015). An application where the advantage of TO has been particularly clear is the design of metallization patterns for freeform solar cells, where the traditional patterns are not suited and intuition based designs are far from optimal (Gupta et al., 2016, 2017). Under higher illumination intensity (more than one sun), the photoillumination current density is increased, which in turn leads to a larger voltage drop on the front side of the cell. Due to increased non-uniformity of the voltage profile, relatively larger power losses occur and the solar cell efficiency is reduced. This effect is more prominent under nonuniform illumination, where it is seen that the efficiency of the solar cells drops dramatically (Johnston, 1998; Luque et al., 1998; Mellor et al., 2009). Thus, it is of interest to optimize the metal grids with minimal restrictions on the design and tailor them for certain illumination and temperature profiles. With TO, it is not required to restrict the non-uniformity only in x-direction. In this study, we optimize the metallization designs for more general illumination and temperature profiles, with non-uniformity in two dimensions, using topology optimization.

During the optimization, it is important that at every iteration, the current and voltage distributions on the front side of the cell are modeled accurately. For this purpose, the finite element method (Zienkiewicz et al., 2005) is a very suited approach, and has been used in the past (Burgers, 1999, 2005; Mellor et al., 2009; Domenech-Garret, 2011; Wong et al., 2011). In Mellor et al. (2009) and Domenech-Garret (2011), COMSOL© models have been used for FEM based modeling, however, only limited mathematical details of the numerical model are discussed. A discussion of FEM based implementation is provided in Burgers (2005), where the numerical model is embedded into a two-step optimization scheme for metallization design. Further, the TO based approach presented by us in Gupta et al. (2014, 2015) uses a two-dimensional finite element scheme for modeling the local current densities and voltage distributions. However, this simplified model did not include the shunt resistance and resistance due to contact of the emitter with the metal electrode material, and is limited to uniform illumination and temperature conditions for a single sun intensity. Although the role of contact resistance can be neglected for good devices, this may not be true in general. More importantly, the allowable contact resistance is inversely proportional to the current density, due to which it becomes important for concentrated illumination conditions (Schroder and Meier, 1984).

To enable accurate modeling and optimization of concentrating solar cells, this paper presents an advanced two-dimensional finite element model and a topology optimization strategy. The numerical model can be used to accurately model the current density and voltage distributions on the front surface of the solar cell. Contact and shunt resistances are included in the model and the effect of contact resistance on the solar cell performance is studied. The numerical model is generalized for 1-diode and 2-diode models as well as other empirical I-V relations. Based on this numerical model, a topology optimization formulation and the associated adjoint sensitivity analysis are developed. The proposed topology optimization methodology can optimize the metallization patterns for solar cells under concentrating, non-uniform illumination and temperature conditions. While the focus of this paper is on CPV applications, the presented model as well as the optimization strategy are equally applicable for uniform illumination conditions. The numerical implementations are kept generic for follow up research and a MATLAB® implementation of the modeling and optimization procedure is provided.[1] Using the proposed method, metallization patterns are optimized for several cases, and relative performance improvements of up to 26% are observed.

The outline for the rest of the paper is as follows. Section 2 discusses the formulation of the two-layer finite element model. The results obtained from the numerical model for several tests are presented in Section 3. This includes numerical tests related to validation of the proposed numerical model against the results reported in Mellor et al. (2009) (Section 3.2), and study of the effect of contact resistance (Section 3.3). Section 4 presents the optimization strategy and the obtained results for various illumination and temperature profiles are presented in Section 5. Finally, the conclusions related to this work are stated in Section 6.

2. Modeling approach

In this section, a detailed numerical model is presented that can efficiently model the current flow and voltage distributions on the front surface of the solar cell. While the discussion is restricted to modeling only the front metallization pattern, the rear side can as well be modeled with slight modifications. To adapt the model for the rear side metallization design, see (Gupta et al., 2017).

2.1. Equivalent circuit

Fig. 1 shows a simple solar cell circuit diagram applicable to both the 1-diode (Shockley, 1950) as well the 2-diode model (Wolf and Rauschenbach, 1963). Based on this circuit diagram, the characteristic equation for the solar cell can then be stated as

$$I = I_L - I_{d1} - I_{d2} - I_{SH}, \tag{1}$$

where I,I_L,I_{d1},I_{d2} and I_{SH} denote the output current, photoillumination current, the reverse saturation diode currents across diodes 1 and 2 and the shunt current, respectively. Let V_j denote the junction potential, then Eq. (1) can be rewritten as

$$I = I_L - I_{01}\left(e^{\frac{\beta V_j}{n_1}} - 1\right) - I_{02}\left(e^{\frac{\beta V_j}{n_2}} - 1\right) - \frac{V_j}{R_{SH}}. \tag{2}$$

Here, n_1 and n_2 are the ideality factors for diode 1 and 2, respectively and $\beta = \frac{q}{k_B T}$, where q,k_B and T denote elementary charge, Boltzmann's constant and absolute temperature of the cell, respectively. For a 1-diode model, n_1 and n_2 can be set to 1 and ∞ respectively and for a 2-diode model to 1 and 2, respectively. The shunt resistance R_{SH} can occur due to defects in the active layer. Due to this, a certain part of the current, termed as shunt current I_{SH} can take an alternate path (Wolf and Rauschenbach, 1963). In case there are no defects in the circuit, R_{SH} can be set to ∞, and no shunt current is generated.

Next, the junction potential V_j is further expressed as

$$V_j = V + IR_s, \tag{3}$$

where V is the voltage across the circuit and R_s denotes the total series

[1] A MATLAB® implementation is available to download from the repository at https://github.com/dkgupta90/topsol.