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An optimized metal grid design to improve the solar cell performance under solar concentration using multiobjective computation

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ABSTRACT

In this paper, a new multiobjective genetic algorithm (MOGA)-based approach is proposed to optimize the metal grid design in order to improve the electrical performance and the conversion efficiency behavior of the solar cells under high intensities of illumination. The proposed approach is applied to investigate the effect of two different metal grid patterns (one with 2 busbars outside the active area (linear grid) and another one with a circular busbar surrounding the active area (circular grid)) on the electrical performance of high efficiency c-Si solar cells under concentrated light (up to 150 suns). The dimensional and electrical parameters of the solar cell have been ascertained, and analytical expressions of the power losses and conversion efficiency, including high illumination effects, have been presented. The presented analytical models are used to formulate different objective functions, which are the prerequisite of the multiobjective optimization. The optimized design can also be incorporated into photovoltaic circuit simulator to study the impact of our approach on the photovoltaic circuit design.

1. Introduction

The strong demand for alternatives to fossil fuel based energy sources and growing environmental concerns have increased interest in solar cells as a long-term, exhaustless, environmental friendly and reliable energy technology [1–4]. Continuous efforts to develop new materials and modeling techniques for solar cells are being made in order to produce new photovoltaic devices with improved electrical performance. In addition to the new semi conducting materials, solar cells consist of a top metallic grid or other electrical contact to collect electrons from the semiconductor and transfer them to the external load. In a solar cell operating under the normal conditions, even a small deviation from the optimum power condition can cause a loss of conversion efficiency [1]. Moreover, the enhancement of a solar cell's conversion efficiency does not only depend on materials and device structure; but it is also very important to optimize the front metal grid design [1]. Several authors have studied the impact of the metal grid design on the conversion efficiency and the loss mechanism, using different metal grid configurations (circular, linear, square, etc.) [1,5–7]. It has been found, in these studies, that the front metal grid design has a great impact on the solar cell electrical performance. The losses associated with the grid influence directly the conversion efficiency of solar cells [1,5–7]. This effect is even more pronounced at high intensities of illumination [1,5–7]. Maximum power can be extracted from a solar cell only when it is operating with optimum design parameters. In order to minimize the solar cell power losses and maximize the conversion efficiency, new design approaches are required to enhance the reliability and the electrical performance of the solar cell for photovoltaic applications. Numerous authors have modeled and studied the impact of power loss effect on the solar cell electrical behavior, where analytical and empirical methods have been used to minimize the loss effect. In these techniques, the global optimization of the power loss effect cannot be achieved [1,5–8]. In addition, until now, there are no studies to investigate the global electrical performance optimization of the metal grid design by using a global evolutionary-based optimization technique. One preferable approach is the multiobjective-based optimization, which could provide practical solutions for the photovoltaic circuit design. The first step of our approach consists of an accurate analytical presentation of different loss mechanisms including solar illumination effect. The different analytical models will be used in our study as objective functions.

In this paper, we present the applicability of the multiobjective genetic algorithm (MOGA) computation approach to optimize the front metal grid design for photovoltaic applications. The key idea of this approach is to find out the best dimensions and electrical parameters of the metal grid to facilitate and improve the device design strategy. The MOGA-based approach, adopted in this work, is the process of finding the minimum/maximum of the power losses and conversion efficiency. These latter called the objective

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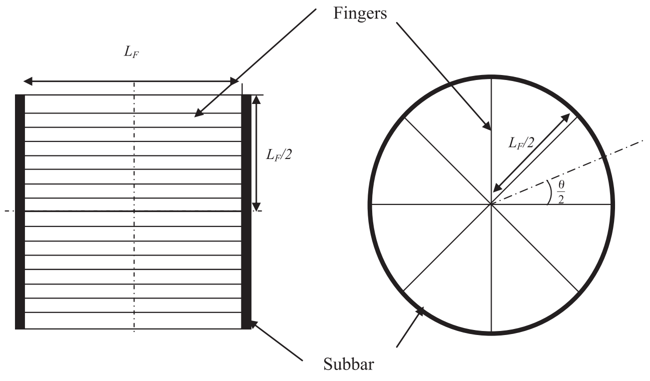

Fig. 1. Investigated front metal grid designs: (a) linear grid and (b) circular grid pattern.

functions, which must satisfy a certain set of specified requirements within constraints [9,10]. In this paper, we present an alternative approach based on MOGAs, where the designer can specify several objective functions simultaneously. The main advantages of this approach are its simplicity of implementation and provision of several possible solutions to the designer to choose the best device front metal grid design.

2. MOGA-based computation

We have investigated two different top contact grid structures: the first one with two busbars outside the active area of the device (linear grid, Fig. 1a), and the second one with four busbars surrounding the active area (circular grid pattern, Fig. 1b). For both geometries, the fingers are considered uniform and equally spaced.

An evolutionary-based optimization technique has been defined as finding a vector of decision variables satisfying constraints to give acceptable values to all objective functions [9,10]. The MOGAs differ from most of all optimization techniques because of their global searching carried out by one population of solutions rather than from one single solution. Due to the simple mechanism and high performance provided by MOGAs for multiobjective global optimization, MOGAs can be applied to study and improve the solar cell design strategy. Fig. 2 shows the proposed MOGA-based approach block diagram.

An optimum grid metal design minimizes the combined effect of the four loss mechanisms directly associated with the front metal grid design: (1) shadowing loss due to grid reflection; (2) grid-metal resistance; (3) contact resistance between the metal and the semiconductor; (4) emitting layer resistance. Other loss mechanisms in the solar cell typically have little or no dependence on the pattern selected for the metal grid, and therefore, are not included into the analysis [6,7].

In the front metal grid, the power losses caused by each mechanism for both investigated structures, including the illumination levels, the series resistance (Eqs. (1a) and (2a)), contact resistance (Eqs. (1b) and (2b)), metal resistance (Eqs. (1c) and (2c)) and by the shadowing (Eqs. (1d) and (2d)) can be calculated using the following analytical expressions [1,6,7,11,12] for both designs as

For linear grid pattern:

$$P_1 = \frac{\rho_s J_{mp}(C)}{12 V_{mp}(C)} S^2 \qquad (1a)$$

$$P_2 = \frac{\rho_m {L_F}^2 J_{mp}(C) S}{48 V_{mp}(C) W_F t} \qquad (1b)$$

$$P_3 = \frac{\rho_c J_{mp}(C) S}{V_{mp}(C) W_F} \qquad (1c)$$

$$P_4 = \frac{W_F}{S} \qquad (1d)$$

For circular grid pattern:

$$P_1 = \frac{\rho_s J_{mp}(C) L_F^2 \theta^2}{6 V_{mp}(C)} \qquad (2a)$$

$$P_2 = \frac{\rho_m L_F^3 J_{mp}(C) \theta}{5 V_{mp}(C) W_F t} \qquad (2b)$$

$$P_3 = \frac{\rho_c J_{mp}(C) \theta L_F}{V_{mp}(C) W_F} \qquad (2c)$$

$$P_4 = \frac{W_F L_F}{W_F L_F + L_F^2 \theta} \qquad (2d)$$

The global loss for both designs is given by:

$$GL = \sum_{1}^{4} P_i \qquad (3)$$

where P_1 represents the loss due to the lateral current flow in the top diffused layer, P_2 is the loss due to the series resistance of the metal lines, P_3 is the loss due to the contact resistance between these lines and the semiconductor, P_4 is the loss due to the grid shadowing. GL represents the global loss caused by four mechanisms simultaneously, W_F is the finger width, t represents the finger thickness, S is the distance between two fingers, ρ_m represents the metal resistivity, ρ_s is the sheet resistance of emitter layer, L_F represents the finger length, θ is half-angle formed between two consecutive fingers. $J_{mp}(C)$ and $V_{mp}(C)$ represent the optimum current density and voltage under solar illumination, respectively, given by: $J_{mp}(C) = CJ_{mp}(1)$ and $V_{mp}(C) = V_{mp}(1) + V_t \ln(C)$, with $J_{mp}(1)$ and $V_{mp}(1)$ are the optimum current density and voltage at 1 sun, respectively, C is the concentrator factor, V_t represents the thermal voltage [6,7,12,13]. It is to note that the fitting parameters (12, 48, 6 and 5) given in Eqs. (1a), (1b), (2a) and (2b), respectively, are dimension numbers with cm^{-1} unit for all equations.

The grid pattern is described by: W_F, t, S, ρ_m, ρ_s, L_F, θ and n. This latter can be calculated from: $n = L_F/s$. The quantities which depend on the illumination profile are: $J_{mp}(C)$ and $V_{mp}(C)$. Our study is focused on optimizing the metal grid design for both structures (linear and circular grid pattern).

For the purpose of MOGA-based optimization of the electrical performance of the solar cells, routines and programs for MOGAs computation were developed using MATLAB 7.2, and all simulations are carried out on a Pentium IV 3-GHz 1-GB-RAM computer. For the implementation of the MOGAs, tournament selection, which selects each parent by choosing individuals at random, is employed and then choosing the best individual out of that set to be a parent. Scattered crossover creates a random binary vector. An optimization process was performed for a population size of 100 for both structures and a maximum number of generations equals to 1000 for the linear grid and 1000 for circular grid design, for which the stabilization of the fitness function was obtained for both structures. Four objective functions are considered in this study (power losses). Thus, the obtained design can provide the best electrical performance by satisfying the following objective functions:

Minimization of global loss function GL as,

$$Min\ GL = Min\left(\sum_{i=1}^{4} w_i P_i\right) \qquad (4)$$

where w_i and P_i represent the weight function and the power loss associated with each mechanism, respectively.

The input normalized electrical and dimensional variable vector, which will be optimized using our approach, is given as $X = (W_F, t, L_F, \rho_m, \rho_s, S, \theta, n)$, where n represents the number of fingers.