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Layout optimization of spacecraft-based solar array under partially shaded conditions

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ABSTRACT

The solar arrays of space stations, communication satellites and lunar/Mars rovers, are occasionally partially shaded by the vehicles themselves. The shading can cause the output power of the solar array to significantly decrease even when the shaded area is quite small. This effect is stronger in direct energy transfer power systems, which are widely used in space applications because of their simplicity and reliability. In this study, we develop a model of solar arrays to evaluate their power performance under partially shaded conditions. Our analysis considers the various impacts of irradiation, partial shading, and layout of the solar array. Two objective functions that can be used to assess the overall power performance of solar arrays under various conditions are proposed. A multi-objective genetic algorithm with a small population is also proposed to optimize the layout of the solar array. The experimental results on a scaled-down equivalent model verify the effectiveness of the proposed method, and demonstrate that the magnitude of the power reduction and variation under partially shaded conditions decreases without increasing the system complexity.

1. Introduction

The most common energy source used in spacecraft is solar. However, the solar arrays of orbiting spacecraft, such as those in space stations and communication satellites, and those on ground-based vehicles, such as lunar/Mars rovers, include relatively large components outside the cabin that are at times partially shaded by the vehicle. This shading is irregular and fast-changing, and can cause the output power of the solar array to significantly decrease even when the shaded area is quite small, thereby affecting the energy balance and the power quality of the spacecraft. The impact of partial shading on the International Space Station (ISS) was analyzed by Fincannon (1995, 2002).

The solar cells in a solar array are connected in series because the voltage of a single cell is not sufficiently high to warrant power processing. The shaded cells limit the current in the series circuit and causes the power output of the solar array to decrease. In previous space applications, additional solar cells were connected in series to minimize the power reduction caused by shading, but this increased the cost and the weight, which were both undesirable. Researchers identified several ways to address this problem, including power processing methods or connecting panels in a special configuration. However, these methods are accompanied by several shortcomings.

Power processing methods were developed to balance the power mismatch between shaded and unshaded cells by adding extra capacitors, inductors, and switching devices to store and transfer the mismatched power (Stauth et al., 2013; Villa et al., 2013, 2014). To avoid the need for additional capacitors, Chang et al. (2015) utilized the intrinsic diffusion capacitance of solar cells to store the mismatched power. However, the switching frequency must be increased under these circumstances because the diffusion capacitance is considerably smaller than the capacitance of a discrete capacitor. In another study, converters with distributed maximum power point tracking (DMPPT) were used to separately process the power of the photovoltaic (PV) panels (Solórzano and Egido, 2014; Carbone, 2015), allowing each panel to operate at its own maximum power point (MPP), thereby eliminating the power mismatch between the panels. Other researchers proposed the dynamic reconfiguration of the connections between PV panels to organize the panels with similar irradiance in the same string. However, this approach required the addition of many switching devices and complex control algorithms (Velasco-Quesada et al., 2009; EL-Dein et al., 2013a; Storey et al., 2014; Sanseverino et al., 2015). These power processing approaches are generally not ideal because they require additional electronic components and complex control strategies.

More power can be produced under partially shaded conditions by optimizing the interconnections between PV panels, such as in a total-

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cross-tied (TCT) configuration (Villa et al., 2012; Belhachat and Larbes, 2015). The output power can further be increased by repositioning the PV panels, which balances the current reduction in each row of the TCT array (El-Dein et al., 2012, 2013b; Rani et al., 2013; Rao et al., 2014; Deshkar et al., 2015). However, the interconnections of a repositioned TCT configuration are extremely complicated and, thus, are only practical at the panel level. Moreover, this configuration was developed for arbitrary occurrences of partial shading, and specific environments were not considered.

Most published studies pertain to terrestrial PV systems. Space applications are highly sensitive to weight, and anti-radiation space microcontrollers are rare and expensive. Therefore, additional components or complex control strategies should be avoided for as long as possible. Furthermore, as terrestrial PV can be shaded by unpredictable clouds and birds, the associated optimization strategies must account for these types of arbitrary partial shading scenarios.

Even though evaluating and optimizing solar arrays for use on spacecraft are important, to the best of our knowledge, no studies have yet been published regarding the optimization of the layout of spacecraft solar arrays at the solar cell level to minimize the impact of partial shading. With the support of the lunar exploration project of China, we researched on the application of genetic algorithms to this optimization. Genetic algorithms are used to optimize space systems based on multi-objective approaches (Terrile et al., 2005, 2006, 2007). We employed genetic algorithms herein to optimize the layout of the series–parallel spacecraft solar array with the purpose of minimizing the output power reduction and variation under partially shaded conditions. We considered the specific form factors of the spacecraft, and followed a roadmap that consisted of three steps: (1) optimizing the solar array layouts using a numerical simulation; (2) verifying the optimization by conducting experiments on a scaled-down equivalent model; and (3) constructing a space solar array using the optimized layout and launching the array into space. Even though launching an array into space is the long-term objective of our research, it is outside the scope of this paper. In the current research, we validated our optimization method using a scaled-down physical model of a rover in a terrestrial testing environment.

The remainder of this paper is organized as follows: first, we briefly describe the characteristics of direct energy transfer (DET) power systems in Section 2. A model for evaluating the power performance of solar arrays under partially shaded conditions is developed and two objective functions are proposed in Section 3. Section 4 presents a genetic algorithm for optimizing the layout of a spacecraft solar array. Section 5 discusses the simulation and experimental results, which illustrate the effectiveness of the optimization method. Finally, Section 6 provides the conclusions.

2. DET power systems for space applications

Reliability is vitally important in space applications, and DET power systems (e.g., sequential switching shunt regulator (S3R) (Zhu and Zhang, 2014; Goryashin et al., 2014) and sequential switching shunt series regulator (S4R) (Capel and Perol, 2001)), are widely used in space because their simple topologies and control strategies provide high reliability (Farahani and Taherbaneh, 2011). However, the effect of partial shading is more significant in DET power systems because they do not track the MPP.

As shown in Fig. 1, a solar array is electrically separated into several sections. Each section is paralleled with a shunt regulator. For the bus voltage regulation, both S3R and S4R control the power transferred to the bus by shunting current from the solar array. When the bus voltage is higher than the threshold, the power controller sequentially connects the shunt regulators while the current in those sections is drained to the array cathode. Consequently, both the power transferred to the bus and the bus voltage itself decrease. In contrast, the power controller sequentially disconnects the shunt regulators to increase the bus voltage when the it is lower than the threshold.

Compared with MPP tracking (MPPT) power systems, DET power systems are simple and have lower power losses. However, the solar arrays in DET power systems are operated on a fixed voltage (i.e., nominal bus voltage denoted as V_{bus}). V_{bus} is typically set close to the MPP voltage (V_{MPP}) of the array to maximize the power generated by the solar array. The V_{MPPT} value changes, and the ratio of the shaded output power versus the unshaded output power can be several times the ratio of the shaded to unshaded areas when the solar array is partially shaded. Fig. 2 shows a 12 × 22 series–parallel solar array. When one of the 12 cells in each string is completely shaded, V_{MPP} drops to a value lower than V_{bus}, and the solar array output power significantly decreases (Fig. 3). The output power reduction ratio in this case is four times the shaded area ratio.

3. Mathematical model for evaluating the power performance of solar arrays

3.1. Shaded condition calculation

In spacecraft applications, the transient reductions in the output power of a solar array because of shading are primarily caused by the body of the spacecraft. A previous work proposed a method to calculate the shadow on the solar array caused by the spacecraft itself (Li et al., 2013). In this method, the spacecraft body was modeled in 3-D using triangles, and a bounding box based on the solar array was used to divide the triangles of the model. The triangles inside the box were then projected onto the solar array. These projected triangles were filled, and the shadow graph was calculated.

3.2. Solar array output power calculation

3.2.1. Solar cell model

Fig. 4 shows the single-diode model of a solar cell, in which the current source is the photogenerated current. The diode represents the intrinsic characteristics of the p-n junction, and the shunt and series resistors represent the Ohmic characteristics of the cell. The characteristics of the solar cell can be expressed as follows:

$$I_{cell} = I_{ph} - I_0\left[\exp\left(\frac{q(V_{cell}+R_sI_{cell})}{\alpha kT}\right)-1\right] - \frac{V_{cell}+R_sI_{cell}}{R_{sh}}, \tag{1}$$

where I_{ph} is the photogenerated current, which is proportional to the intensity of illumination; I_0 is the reverse saturation current of the diode; q is the elementary charge; α is the diode ideality factor; k is Boltzmann's constant; and T is the absolute temperature of the cell. The second component in the equation is the diode characteristic. The third component is the Ohmic characteristic of the cell.

A partially shaded solar cell can be divided into illuminated and shaded parts that are connected in parallel (Quaschning and Hanitsch, 1996). The shaded area is represented herein by A_s while the illuminated area is represented by A_i.

The characteristics of the illuminated part can be calculated as follows:

$$I_{celli} = K_iI_{ph}\cos\theta - K_iI_0\left[\exp\left(\frac{q(V_{cell}+K_iR_sI_{celli})}{\alpha kT}\right)-1\right] - \frac{V_{cell}+K_iR_sI_{celli}}{R_{sh}/K_i} \tag{2}$$

where $K_i = A_i/(A_s + A_i)$ is the ratio between the illuminated and total areas, and θ is the incidence angle of the sunlight.

Similarly, the characteristics of the shaded part can be calculated as follows:

$$I_{cells} = -K_sI_0\left[\exp\left(\frac{q(V_{cell}+K_sR_sI_{cells})}{\alpha kT}\right)-1\right] - \frac{V_{cell}+K_sR_sI_{cells}}{R_{sh}/K_s} \tag{3}$$

where $K_s = A_s/(A_s + A_i)$ is the ratio between the shaded and total