

Study on Surface Charging Effect and Electric Field Distribution of Spacecraft Solar Cells in Low Earth Orbit

Dejie Wei¹, Jianwen Wu¹, *Senior Member, IEEE* and Liying Zhu²

¹School of Automation Science and Electrical Engineering, Beihang University, Beijing, 100191 China

²Institute of Spacecraft System Engineering CAST, Beijing, 100094 China

The surface charging effect causes an inverted potential gradient at the triple junction of solar cells, which may easily trigger the primary discharge and threaten the safe operation of the spacecraft. In this study, based on the current balance equation, the PIC (Particle-In-Cell) method is used to simulate the surface charging effect of LEO (Low Earth Orbit) spacecraft solar cells under three operating conditions: shadow, illumination, and polar, and the surface potential distribution under different operating voltages is obtained. The electric field distortion distribution at the triple junction is also obtained by the finite element method. This study can provide important theoretical guidance and technical support for evaluating the primary discharge risk of spacecraft solar cells.

Index Terms— electric potential, electric field, plasma, solar cells

I. INTRODUCTION

AS THE main power supply source of the spacecraft, solar cells play a vital role in the safe and reliable operation of the entire spacecraft. When the solar cells are in the plasma environment, the surface charging effect occurs, and an inverted potential gradient (IPG) is formed among the coverglass, the metal interconnects, and the substrate (also called “triple junction”) [1]. Due to the irregular geometry such as micro tips, the electric field distribution is distorted. Under the combined action of surface field effect emission, secondary electron emission, and collision ionization, the primary discharge is caused, which affects the power transmission of the solar cells and causes signal interference [2].

NASA developed the NASCAP-LEO surface charging module [3]. The finite element method was used to simulate the plasma interaction and LEO characteristics of high density and short Debye radius. ESA has developed the Spacecraft Plasma Interaction System (SPIS) [4], which can model and analyze the interaction of spacecraft in different plasma environments by using the finite element method, PIC method, and particle tracking method. Quan et al. proposed an inversion model based on back propagation neural network, which can quickly derive the surface charging potential of the non-detection area through the detector potential in the same charging environment [5].

II. SURFACE CHARGING EFFECT

A. The surface charging model

The interaction between solar cells and space plasma is shown in Fig. 1.

When the dynamic equilibrium is reached, the surface electrostatic current is 0, and the current balance equation can be expressed as:

$$I_e(\phi) - [I_i(\phi) + I_{ph}(\phi) + I_{sec}(\phi) + I_{bs}(\phi)] = 0 \quad (1)$$

where, I_e is the incident electron current, I_i is the incident ion current, I_{sec} is the secondary electron current, I_{bs} is the backscattered electron current, I_{ph} is the photoelectron current, and ϕ is the surface potential.

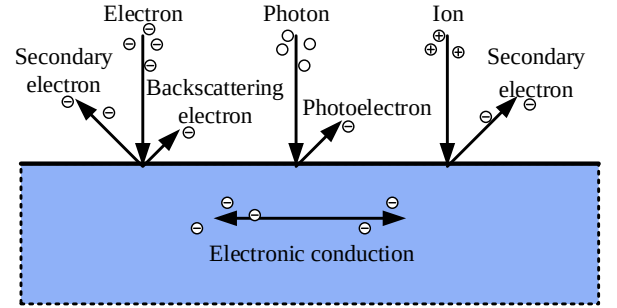


Fig. 1. The interaction between solar cells and space plasma.

The movement of particles in the plasma mainly comes from the influence of the internal electrostatic field, so it is necessary to solve the Poisson equation:

$$\begin{cases} M_a \frac{d\mathbf{v}_n}{dt} = Q_a (\mathbf{E} + \mathbf{v}_n \times \mathbf{B}) \\ \frac{d\mathbf{r}_n}{dt} = \mathbf{v}_n \\ \mathbf{E} = -\nabla\phi \\ \nabla^2\phi = -\frac{\rho}{\epsilon_0} \end{cases} \quad (2)$$

where, M_a and Q_a are the mass and charge of the particle cloud respectively, $\mathbf{r}_n$ and $\mathbf{v}_n$ are the position and velocity respectively, $\mathbf{E}$ and $\mathbf{B}$ are the electric field and magnetic field respectively, ρ is the space charge density, and ϵ_0 is the vacuum dielectric constant. In the simulation process, in order to simplify the calculation, Boltzmann approximation and PIC particle tracking are used for electrons and ions, respectively. The Neumann boundary condition is used for the outer boundary condition, and the Dirichlet boundary condition is used for the inner boundary condition.

To simplify the distribution of the field in the calculation space, it is assumed that the space environment has a static magnetic field, that is, the magnetic field is constant. The finite difference method is used to solve the field distribution in the Cartesian grid.

$$\frac{\phi^{i+1,j,k} - 2\phi^{i,j,k} + \phi^{i-1,j,k}}{(\Delta x)^2} + \frac{\phi^{i,j+1,k} - 2\phi^{i,j,k} + \phi^{i,j-1,k}}{(\Delta y)^2} + \frac{\phi^{i,j,k+1} - 2\phi^{i,j,k} + \phi^{i,j,k-1}}{(\Delta z)^2} = \frac{\rho^{i,j,k}}{\epsilon_0} \quad (3)$$

$$\begin{cases} E_x^i = \frac{\phi^{i+1,j,k} - \phi^{i-1,j,k}}{2\Delta x} \\ E_y^j = \frac{\phi^{i,j+1,k} - \phi^{i,j-1,k}}{2\Delta y} \\ E_z^k = \frac{\phi^{i,j,k+1} - \phi^{i,j,k-1}}{2\Delta z} \end{cases} \quad (4)$$

B. The equivalent circuit model

The equivalent circuit of the spacecraft is shown in Fig. 2. The corresponding electrical nodes are set on different parts of the spacecraft, and the material is equivalent to the parallel connection of capacitance and resistance. Under the action of low-energy electrons and ions, the current is emitted and absorbed into space until the dynamic balance is reached, and the surface electrostatic current is 0.

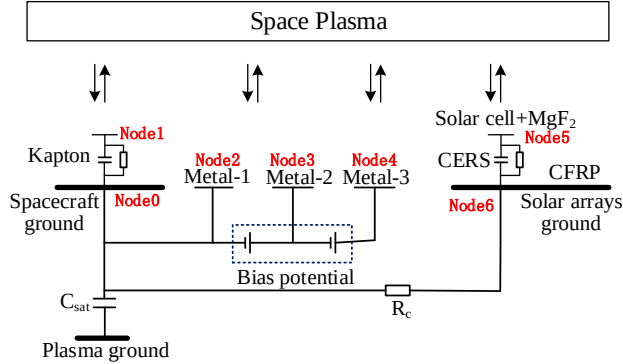


Fig. 2. The equivalent circuit of the spacecraft.

III. RESULTS AND DISCUSSIONS

At present, the operating voltage of spacecraft mainly includes 28V, 42V, and 100V. In the future, the voltage level of high-voltage solar cells may reach 400V. Therefore, the surface charging simulation of solar cells with 28V, 100V, 200V, and 400V voltage levels is carried out in this study. The simulation results of surface charging at 100V are shown in Figs. 3 and 4.

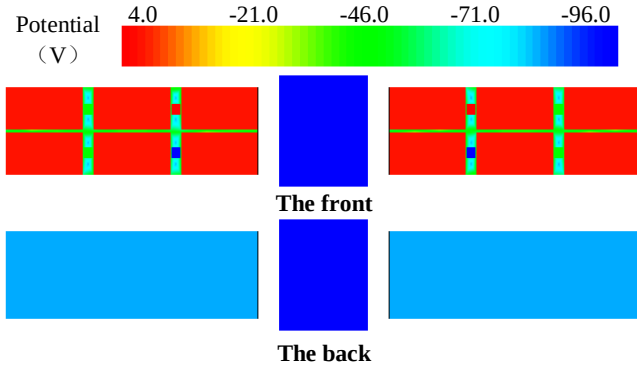


Fig. 3. Surface potential distribution of solar cells.

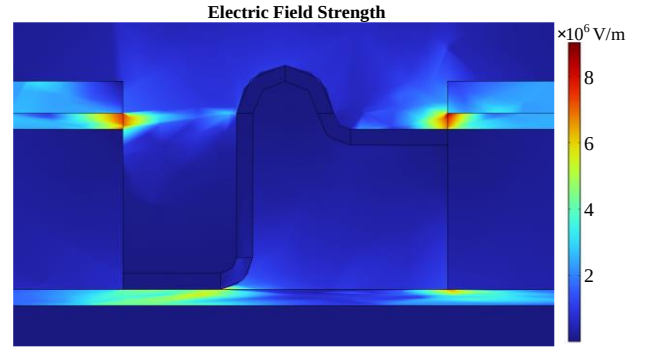


Fig. 4. Electric field strength at the triple junction of solar cells.

As shown in Figs. 3 and 4, the highest charging potential of the solar cell coverglass is -0.46V, the lowest charging potential of the substrate is -80.7V, and the maximum potential difference at the triple junction reaches about 81V. The electric field distortion is formed among the side of the coverglass, the metal interconnects, and the substrate, and the maximum electric field intensity reaches 1.05×10^7 V/m. The surface charging results in the illumination region are shown in Table 1.

TABLE I
SURFACE CHARGING RESULTS IN THE ILLUMINATION REGION

Operating voltage (V)	Charging balance time (ms)	$E_{\max}$ (V/m)
28	0.55	2.36×10^6
100	1.30	1.05×10^7
200	1.55	2.30×10^7
400	3.28	4.36×10^7

From Table 1, it can be seen that with the increase of the operating voltage, the surface charging potential of solar cells is more negative, and the charging balance time is longer. The main reason is that as the operating voltage increases, the stronger the ability to attract electrons, the greater the electron incident current. Although the ion incident current and the secondary electron emission also increase at the same time, the net absorption electron current of the spacecraft is still increasing. Therefore, more electrons are attached to the surface, that is, the surface potential is more negative, so that the maximum potential difference at the three junctions is larger, resulting in a gradual increase in the maximum electric field intensity.

REFERENCES

- [1] A. R. Khan, N. D. Minh, K. Toyoda, and M. Cho, "Electrostatic Discharge Threshold on Coverglass Used to Protect Solar Cells in the Low Earth Orbit," *IEEE Trans. Plasma Sci.*, vol. 47, no. 2, pp. 1445-1452, Feb. 2019.
- [2] T. Okumura, M. Imaizumi, K. Nitta, M. Takahashi, T. Suzuki, and K. Toyoda, "Flashover Discharge on Solar Arrays: Analysis of Discharge Current and Image," *J. Spacecr. Rockets*, vol. 48, no. 2, pp. 326-335, Apr. 2011.
- [3] I. Katz, M. J. Mandell, G. W. Schnuelle, D. E. Parks, and P. G. Steen, "Plasma Collection by High-Voltage Spacecraft at Low Earth Orbit," *J. Spacecr. Rockets*, vol. 18, no. 1, pp. 79-82, Feb. 1981.
- [4] J. F. Roussel, F. Rogier, G. Dufour, J. C. Mateo-Velez, J. Forest, A. Hilgers, D. Rodgers, L. Girard, and D. Payan, "SPIS Open-Source Code: Methods, Capabilities, Achievements, and Prospects," *IEEE Trans. Plasma Sci.*, vol. 36, no. 5, pp. 2360-2368, Oct. 2008.
- [5] R. Quan, C. Zhang, H. Zhang, "An Inversion Model to Obtain Spacecraft Surface Potential Based on Neural Network," *IEEE Trans. Plasma Sci.*, vol. 51, no. 4, pp. 1181-1187, Apr. 2023.