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Research status and prospect of spacecraft solar array charge-discharge effect and electrostatic discharge induced protection design

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Abstract

For a long time, the spacecraft solar tianchi array system USES 28V main voltage, with the continuous improvement of the requirements for energy system, the future spacecraft solar array power system will develop towards the trend of high power, high voltage.However, the significant increase of working voltage increases the coupling effect between solar array and space charged environment, and the permanent failure of solar array due to space electrostatic discharge (SESD) occurs.It is found that high voltage (HV) components are the main fault source of battery array failure.Therefore, in this paper, through summarizing the space solar cell array in a discharge and the mechanism of secondary discharge and domestic related research institute work, further induces cell array produced during orbiting inducing factors and the main protection methods of electrostatic discharge, put forward to strengthen the solar cell array under the influence of electromagnetic field outside the discharge mode and law of exploration prospects, on how to carry out field induced protection has carried on the preliminary analysis, this paper introduces the principle and structure, plasma environment simulation equipment test method, to study to strengthen the influence law of electromagnetic fields on the sun tianchi array electrostatic discharge laid a foundation.

Keywords

Solar array;Electrostatic discharge;Predisposing factor;Protection method;Discharge patterns.

1. Introduction

With the continuous development of China's space technology, the new technology of satellite development puts forward higher requirements for the development of satellite energy system, and the satellite solar array power system will develop towards the trend of high voltage and high power [1].The capacity of solar cells to provide power has increased from a few hundred watts or kilowatts to dozens or even hundreds of kilowatts [2].However, with the increase of working voltage, a new solar array failure mode caused by space electrostatic discharge (SESD) appears in solar array [3], which seriously threatens the on-orbit operation safety of spacecraft.In 1997, four communications satellites of Laura space systems were arc discharged due to electrostatic discharge, resulting in a decrease of more than 20% of the output power of solar array, resulting in a substantial reduction of the power margin of the satellite [4].In 2007, NASA conducted fault statistics and found that the charge-discharge effect accounted for 54.2% of the 326 satellite faults caused by space environment [5].

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Due to the relatively complex structure of space solar array, its surface consists of different materials, such as glass cover plate, solar cell, interconnecting plate, bus bar, substrate structure (aluminum honeycomb) and so on.Whether in low earth orbit (LEO) or geostationary orbit (GEO), spacecraft are surrounded by plasma of varying densities during their operation.Different charging processes will occur between different materials and components of solar array, generating ESD events.Related personages, such as lanzhou institute of space technology physics, China academy of space technology, China national institute of electronic science and technology, have conducted preliminary researches on the charging-discharge effect and obtained some important results.Studies show that the spatial electrostatic discharge of solar array is mainly primary discharge (trigger discharge) and secondary discharge [6].One of the discharges does not have much impact on the spacecraft operation, but the long-term occurrence of spacecraft components will cause functional decline.Secondary discharge is an important factor affecting the safety of spacecraft operation, which can lead to thermal dissolution of battery array materials and long-term failure of battery array power supply system.

In this paper, based on the above research results, according to different environmental characteristics and the working conditions of the solar cell array, the analysis summarizes the solar cell array of ESD events induced factor and the basic mechanism of electrostatic discharge, further expand the existing test methods and test results, put forward in the outside strong electromagnetic field under the action of the solar cell array of electrostatic discharge test model, and the solar cell array for the future development direction was preliminary outlook, research on the solar cell array orbiting safe protection is of great significance.The introduction of the article should be straight to the point, concise and comprehensive, should not be the same as the abstract, should not be the notes of the abstract, avoid formula derivation, method introduction.

2. Mechanism of electrostatic discharge in solar array

2.1 The space environment.

According to current satellite data, the interaction between the solar wind and the earth's magnetic field distorts the earth's magnetic field and its captured band of charged ions.There is plasma distribution around space vehicles orbiting the earth. Due to the action of solar wind, the plasma concentration increases significantly in the shadow of geostationary orbit [7].In low earth orbit, space plasma is ionospheric plasma, which is characterized by high density and low energy and becomes cold dense plasma.Under the action of dense plasma, the space laboratory with high working voltage will generate complex charging and discharging processes such as the increase of collecting current, structural potential drift and electrostatic discharge, which will seriously affect the work of the spacecraft and induce the secondary discharge of solar array, causing its battery to burn down and the system to fail [8].

A plasma is a fully ionized or partially ionized gas that contains exactly the same number of positive and negative charges.This height area is mainly ionospheric plasma, which is a low-energy quasi-neutral plasma area composed of its own electrons, ions and neutral particles that are ionized by solar light energy electromagnetic radiation, cosmic rays and fallout particles acting on the upper atmosphere.The plasma density in this region is four to six orders of magnitude higher than in geosynchronous orbits.Plasma in geosynchronous orbits consists mainly of protons and electrons [9-11].

At the typical altitude of a spacecraft, 300km in orbit, the atmosphere is about 10 orders of magnitude less dense than at sea level.In such an environment, neutral particles can not only through the impact of the kinetic energy of the spacecraft to produce mechanical effects, but also through its own reaction characteristics and produce chemical interactions, so that the spacecraft surface charge the formation of high voltage, electrostatic discharge.

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2.2 Solar array surface charge and discharge.

With the increasing demand for power supply capacity of solar battery array, the power supply capacity of solar battery array has been greatly improved. Currently, the working voltage of solar battery array is above 100V.Due to the large increase of power supply voltage, the charge-discharge effect has become an increasingly important factor affecting the work of spacecraft, whether in LEO solar array or in GEO solar array.

This charge and discharge happens all the time.For solar array (as shown in figure 1), the charge and discharge phenomenon mainly occurs between solar array glass cover sheet, interconnecting sheet and polyimide film [12].

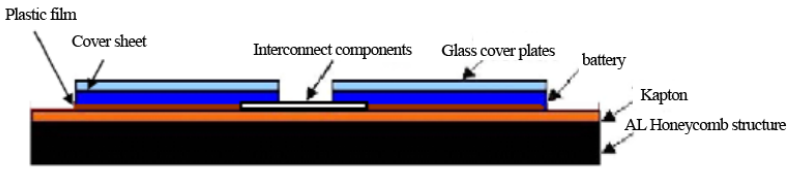

Fig. 1 Structural diagram of solar array

(1) Charging mechanism

According to previous research results, due to different dielectric constants and secondary electron emission coefficients of solar array materials and their special structural characteristics, these cells will charge at different rates in the space plasma environment, thus generating unequal charge accumulation and leading to electrostatic discharge.In addition, due to the lighting to make light surface potential near space plasma potential, and the shadow area medium surface has charge to high negative potential, so the surface of the solar cell array relative to the base plate material formed a big reversal potential gradient, namely the sun battery array glass cover potential is greater than the surface of substrate material and the metal bus-bar potential formation of the electrical potential difference induced by space electrostatic discharge in the solar cell array surface.The main charging process is shown in figure 1.

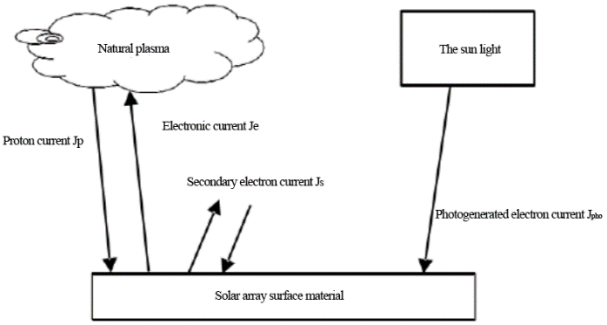

Fig. 2 Charging process of different ions on the surface of solar array

(2) Discharge mechanism

Discharge is divided into first discharge (trigger discharge) and second discharge.The results show that the first discharge usually occurs in the three bonding areas of the battery array (that is, the area where the plasma, the glass cover and the interconnecting plates contact) and the edge area.The primary discharge will cause the interference of the electronic system, but will not cause systematic damage, but it is the main inducing factor of the secondary discharge.Secondary discharge usually occurs between adjacent battery strings, and its energy is large, which can cause pyrolysis and melting of materials and cause permanent damage to the hardware system, which is the key to affect the normal work of solar array.

A discharge is a general discharge phenomenon, in the spacecraft solar array surface, the phenomenon has been occurring.It is found that the surface charge of glass cover of solar array mainly comes from three aspects: environmental ion, ion-induced secondary electron and field-induced enhanced

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electron emission (EFEE).When an arc occurs, ambient ions will charge the glass cover, and the electric field at the junction will increase. When the electric field on the conductor surface is large enough, EFEE will happen.A short discharge time, generally maintain microsecond level.

The energy of the second discharge is much larger than that of the first discharge, and the main conditions of its occurrence are related to voltage and power, which can generally maintain the time of milliseconds.It is found that if the potential difference between the solar array strings is higher than a certain threshold voltage, the current between the high potential and the low potential of the solar cell circuit flows through the path of the high concentration of plasma, and the secondary discharge can be generated.The discharge mechanism of solar array can be summarized as the following four steps:

1) due to the secondary electron emission generated by electron bombardment and light, the surface of the glass cover plate emits electrons. After a long period of accumulation, the glass cover plate loses a large number of electrons and becomes positively charged.At this time, the negative potential of the substrate material increases gradually because it has few electron emission and is in the plasma environment for a long time.When the potential difference between the glass cover and the substrate material increases to a certain threshold, ESD events occur at the interface of vacuum, medium and metal.

2) frequent ESD events occur between the glass cover sheet and the solar array interconnect sheet or between the glass cover sheet and the substrate material, resulting in increasing plasma concentration at the discharge site.

3) when the potential difference between solar array strings is higher than the threshold voltage, the current flow between high potential and low potential of the battery array circuit passes through the high-concentration plasma path.

4) because the pathways to produce enough energy between solar cell or solar battery and battery array substrate material between pyrolysis, pyrolysis carbonization polyimide film with a low resistance path, solar battery string of electric current through the low resistance path, form a closed loop circuit, lead to the solar array permanent short circuit, the power supply system to provide power for the spacecraft.

3. Existing charge-discharge performance simulation test methods and expansion

3.1 Current research and test devices.

Domestic related personnel have carried out a lot of ground simulation research on the charge and discharge effect of solar array and obtained a lot of experimental results for reference.The experiment started from the simulation of the primary electrostatic discharge of the high-voltage solar array, and eventually caused the secondary discharge of the solar array in the working state. All the experimental devices used in the research institutes were similar, and the single-energy electron gun was used to generate the electron beam to simulate the solar irradiation in space.The electron beam irradiates the surface of the solar array material, generating an unequal amount of surface charge to trigger a discharge, which in turn causes a second discharge.Three - junction gallium arsenide solar cells were used.The test device is shown in Fig. 3.

According to the previous research, the design of the test device is made according to the design specification of solar array.Considering that the purpose of the test is to obtain the damage degree of the battery array circuit caused by the primary discharge at the edge of the battery and the secondary discharge between the strings in the plasma environment, the sample selection of the test device should cover all the boundary relations and the distance between the strings that can be encountered in the design of the solar cell.At the same time, considering many factors such as test scale, cost, vacuum tank size and sample representativeness, a series of 5 pieces and 3 series and parallel connections is selected, as shown in figure 3.As can be seen from the figure, this scheme covers three

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situations where the two sides, three sides and four sides of the cell are adjacent to other cells, and also covers different distance relations between the strings. These situations are sufficient to characterize the position relations between the cells and the strings on all substrates, and can meet all the requirements for verification of test data.

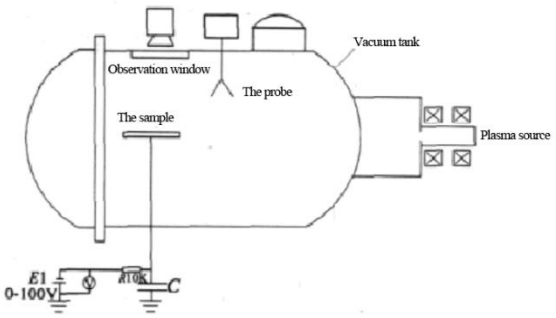

Fig. 3 Schematic diagram of test device

3.2 Experimental method research

The purpose of the solar array charge and discharge effect simulation test is to reproduce the on-orbit charge and discharge phenomenon and to simulate the charge in vacuum environment by using the ground test conditions.

As we all know, the scale and area of ESD simulation are related to energy, charge and current.In the experiment, compared with space vehicles with large solar panels, the samples have lower capacitance to the ground, so they have lower storage charge and energy capacity.Since the plasma concentration generated by ESD is proportional to the charge released, the plasma generated by the sample cannot be compared with the real solar array concentration. In order to compensate the plasma environment and make it reach the same concentration, the method of injecting plasma into the vacuum environment by the plasma source is adopted to make it reach the test conditions.Meanwhile, the ground capacitance is increased to simulate the real ground capacitance environment.

In the experiment, the electron beam energy can be selected by using the electron gun to irradiate the battery array surface to simulate the real solar radiation environment.The vacuum degree of the vacuum environment can also be adjusted, the temperature range can be adjusted, and the bias voltage between the battery series can be adjusted.

In the test, as the electron gun continues to irradiate the surface of solar array, electric potential difference between solar array structures appears. When the battery difference is greater than a certain threshold, discharge begins to occur.In a discharge event, the energy in the capacitor is released completely.The bias voltage is applied between the batteries, and the current is measured between the batteries.

3.3 Test method expansion

The on-orbit operating environment of spacecraft has not only been affected by the space environment, with the continuous development of human space resources, the development and use of all kinds of electromagnetic weapons, spacecraft are facing interference from all kinds of artificial electromagnetic signals.For spacecraft can normal operation in the complex electromagnetic environment, to strengthen the effect of aircraft power supply system anti-jamming in complex electromagnetic environment of the depth of the research, on the basis of previous research, increasing the strengthen the interference of electromagnetic field, explore the spacecraft solar cell array in cosmic rays and strong external field, the solar wind, magnetic substorms comprehensive factors under the influence of electrostatic discharge effect, especially the external electric field on the electrostatic discharge induced effect of the solar cell array, is the focus of the current research topic.To this end, we explore the experimental simulation system of electrostatic discharge induced

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by external intensification field in solar cell array (the applied electric field is added on the basis of figure 3, mainly using electromagnetic pulse radiation field).The system can be used in real space electromagnetic environment, and can be used to enhance the induced effect of external field, so it is of great significance to research the electromagnetic protection of battery array.

The experimental method is the same as previous studies.Taking low orbit satellite (LEO) as an example, in order to create a more real space plasma environment, the induction experiment was carried out in a vacuum tank. The test device is shown in FIG. 3.The solar array sample (hereinafter referred to as the sample) is placed in the vacuum tank through the insulation layer. The vacuum tank has a plasma emission source and can inject plasma of different concentrations into the vacuum tank. Meanwhile, a plasma probe is placed near the sample to detect the plasma concentration in the vacuum tank at any time.In the experiment, the plasma concentration was determined by referring to the international standard.In order to ensure high reliability and rigor of the test, the humidity and temperature of the test environment are strictly controlled by the dehumidifier and air conditioner before the test, so as to make it as close as possible to the reference value of the international standard on space environment.Meanwhile, the vacuum degree should be better than Pa, and the degasing time of vacuum tank should be more than 12 hours. The maintenance time of each voltage in the test should be no less than 1 hour, so as to ensure the reliability of the experiment.

In the experiment, the influence effect of electromagnetic field is added on the basis of previous experiments.In order to study the induced discharge law of the typical strong electromagnetic field on solar array, the electrostatic electromagnetic radiation field is taken as the basic external radiation field.The electromagnetic radiation field has the characteristics of strong instantaneous field, steep pulse rising edge, narrow pulse width and so on.During the test, the test sample was designed to connect the circuit according to the above circuit, and the test sample was placed in a vacuum device. The plasma environment, temperature, humidity and other test conditions were set according to the above requirements, and the field intensity test probe was added to keep track of the outside field intensity at any time.After the test reaches the basic conditions, the bias voltage is set to be adjusted continuously from low to high, and the bias voltage value should be maintained for 1 hour for each adjustment. After no discharge occurs, the external field is applied to the device to observe the discharge situation.When no power generation occurs, increase the applied electromagnetic field until a discharge occurs, record the bias voltage and the applied field intensity, and record the threshold of a discharge at this time.Repeat the above method to record the primary discharge and secondary discharge thresholds.

The test results are summarized according to the next discharge threshold and the second discharge threshold test under different external field conditions.The effects of primary discharge and secondary discharge on the test samples were evaluated according to the properties of the samples.At the same time, the changes of the primary and secondary discharge thresholds of solar array under the action of external field in a specific environment are summarized, so as to compare the results with those without the action of external field and find out the influence rules of external field, which lays an experimental foundation for the protection research of solar array.

4. Research on solar array charge and discharge effects of spacecraft is facing challenges

It has been proved that solar arrays have bright prospects in both ground and space applications.Solar cells will continue to provide the most economical and safe source of power for unmanned and manned space vehicles at a time when other sources of energy are increasingly scarce and nuclear power is not yet widely available.Is becoming more and more obvious in the three-dimensional human activity today, satellites to provide a lot of convenience to our life, the development of space to a large extent is closely related to our life, so as to direct the energy of the solar cell array spacecraft development is extremely important, especially the development of the high pressure solar cell array has reached a critical stage.

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Meanwhile, the development of solar array also faces many challenges.With the continuous requirement of high power, high voltage and low quality of solar cell array, more breakthroughs and innovations are needed in main materials, manufacturing process and structure.As the space environment becomes more and more complex and the human high-power electromagnetic weapons continue to deepen, the operating environment of spacecraft appears unprecedented numerous threats and challenges.As one of the biggest threat sources of spacecraft solar array, electrostatic discharge effect has been paid more and more attention by various countries. How to protect strong electromagnetic field and minimize the harm of electrostatic discharge to solar array has become the most urgent research topic at present.

5. Conclusion

The development of solar array of spacecraft also witnessed the development of space industry.The research on the solar array charge-discharge effect of spacecraft has also witnessed the development of solving problems in space industry.It also represents the development and expansion of the space industry in the past half century.According to the working conditions of the spacecraft, the solar array need to inject different design theory in order to satisfy different working conditions, more and more widely applied in today, in the space environment is more and more complex today, in today's problem continuously emerging, how to innovation and breakthrough in the further thinking of researchers and effort is needed.Practice has proved that it is an effective way to enrich and innovate the design and manufacture of solar array and circuit protection by referring to relevant theories and technical achievements.

In the future, solar array will develop towards the direction of high power and low quality. How to make it more suitable for living in the complex space environment in the future and maintain good working stability will also be the main direction of research.If new theories and research results can be introduced, the development and application of solar array will be greatly promoted, and space exploration will make greater progress.

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