Design and Implementation of Power Supply and Distribution System for Mars Landing Mission

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Abstract. Combined with the characteristics of Mars exploration mission, the functions, main indicators and system schemes of the power supply and distribution subsystem of China's first Mars landing and rover mission are briefly introduced, and the design of high-specific energy lithium fluorocarbon batteries, the design of Mars solar spectrum-matched solar cells, the design of dust-proof coating, the design of MPPT, the estimation and management of on-orbit capacity, etc. are briefly introduced, and the design problems of power supply and distribution systems in the extreme environment of Mars landing and rover mission are proposed. The results of the on-orbit flight test show that the power supply and distribution system has normal function, reliable work and excellent performance, and the design scheme of the power supply and distribution system proposed for the landing and rover mission has successfully supported China's first interplanetary exploration mission. Through the design and implementation of this project, a large amount of valuable experience and data have been accumulated, which provides a high scientific and engineering reference value for the design and verification of power supply and distribution systems for subsequent Mars sampling and return missions.

Keywords: Mars · landing and rover · power supply and distribution system · lithium fluorocarbon battery · spectral matching solar cell · dust-proof coating

1 Introduction

"Tianwen-1" is China's first probe to implement an extraterrestrial planet exploration mission, and to achieve the "orbit, landing and rover" mission of Mars through a single launch. Tianwen-1 was launched from the "Long March 5" Yaosi carrier rocket at Wenchang Cosmodrome on July 23, 2020, and the landing rover successfully landed on the Utopian Plain of Mars on May 15, 2021, and successfully completed the 90-day regional rover and exploration mission of the fire surface on August 30, 2021. The rover successfully entered a dormant state after successfully completing the expansion mission for another 9 months. The power supply and distribution subsystem effectively ensures the safe power supply of the system throughout the mission period, and is a key subsystem that restricts the on-orbit work project and life of the rover.

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The Mars rover has a long flight time, many key and unique links, faces many extreme environments and uncertainties, and has high requirements for multi-mission coupling design [1]. The landing and rover power supply and distribution system is responsible for the power supply, regulation and transmission of the full-cycle landing rover, and is a key subsystem of the Mars rover, which is crucial to the successful completion of the Mars exploration mission [2].

From the pre-launch to the end of the mission, the probe is divided into six mission stages: active section, ground fire transfer section, Mars capture section, Mars mooring section, de-orbit landing section and scientific exploration section, and the power supply and distribution subsystem has the following characteristics and design difficulties in the whole mission cycle.

2 Power Supply and Distribution System Design

2.1 System Functions

The functions of the power supply and distribution system are: the function of charging the lithium-ion battery of the landing rover by the orbiter in the state of the detector assembly, and the function of independently supplying power to the landing rover when the power of the orbiter is tight; After separating from the orbiter, the power supply of the landing rover is guaranteed by the battery pack of the landing rover, of which the battery pack of the entry module is the main part and the battery pack of the Mars rover is used as the backup; After the entry module and the rover are separated, the two vehicles independently supply power, and the rover forms an independent solar cell array-battery pack joint power supply system to provide electrical energy for the rover.

2.2 System Design

The landing rover power supply and distribution system is designed for dual-cabin combined power supply and adopts an unregulated busbar. The entry module is equipped with a short-term power supply and is equipped with a set of 120Ah lithium fluorocarbon batteries, which is mainly responsible for completing the power supply task of the Mars EDL (entry, descent and landing) section; The rover is equipped with a set of Mars spectral matching solar arrays with dust-proof coatings, a set of 80Ah lithium-ion battery packs, and a power controller using MPPT power conditioning technology, which is mainly responsible for the power supply task of fire and rover detection (Fig. 1).

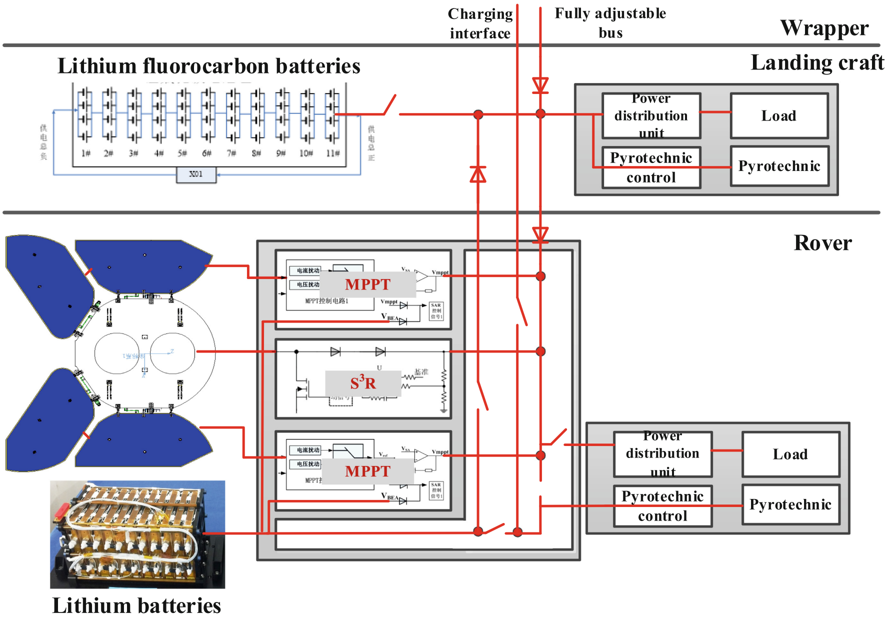


Fig. 1. Topology of the power supply and distribution system of the Mars landing and rover mission

3 Key Technologies of Power Supply and Distribution Systems

3.1 Mars Spectral Modification Technology for Solar Cells

The surface of Mars is affected by the atmosphere and shows a spectral "redshift", and the proportion of long-wave bands is high. The performance of the three-junction gallium arsenide solar cell developed for AM0 spectrum will change abnormally under the light conditions of Mars ground, and the originally matched interjunction current will mismatch, affecting the power output of the solar cell, and the current mismatch under the Mars 30° spectral condition will reach 9.3%, resulting in a decrease in the photoelectric conversion efficiency of the solar cell (Table 1).

Table 1. Current values of the battery under various spectral conditions

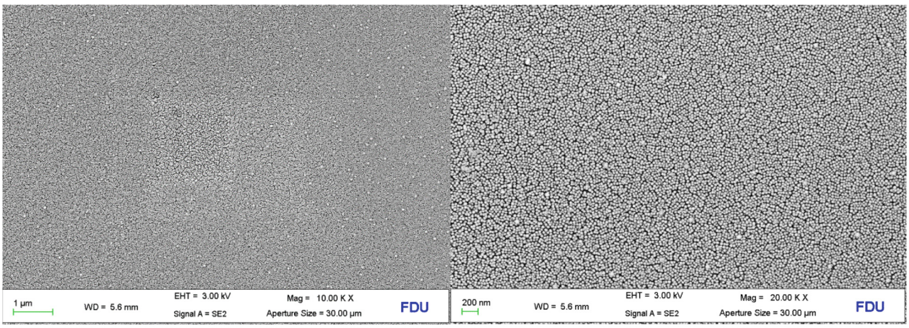
Spectral conditions	Top battery Jsc_top (mA/cm^2)	Medium battery Jsc_mid (mA/cm^2)	Bottom battery Jsc_bot (mA/cm^2)	Top middle battery current mismatch (%)
Earth AM0	16.989	17.265	27.703	1.62
Mars 30 degrees	5.476	5.994	9.439	9.46
Mars 60 degrees	2.747	3.133	4.844	14.05

In view of the above problems, the rover adopts the Mars spectral matching three-junction gallium arsenide solar cell technology, adjusts the top-cell and medium-cell structure of the three-junction gallium arsenide solar cell during the design of the solar cell, so that the top cell and the medium cell current match, thereby improving the conversion efficiency of the three-junction gallium arsenide solar cell in the Mars spectrum, so that the solar cell output is reduced by more than 9% to about 2% in the Martian 30° latitude spectral environment, and the photoelectric conversion efficiency is increased from 29% to 31.7%. Enables solar cells to achieve the best performance and power output under special lighting conditions on the surface of Mars.

3.2 Dustproof Coating Technology on the Surface of Solar Cells

There is a large amount of dust in the atmosphere on the surface of Mars, and there will also be violent dust storms, which will make the surface of the solar cell receive a large amount of sunlight due to dust deposition, which will eventually lead to a decrease in the output power of the solar cell, which will seriously affect the safety of the probe's power supply. The power of the Courageous solar cell array is approximately linearly linearly decayed, with a decline of about 9% per month. The accumulation of dust on Mars and the dust storm effect accelerate the decay of solar cell output power.

The rover adopts dust-proof coating technology on the surface of solar cells based on micro-nano structure. The technology has short, medium and long full band high transmittance, high surface hardness, temperature shock resistance, UV/charged particle radiation resistance, low vacuum volatility and many other advantages, in terms of composition, mainly by introducing hydrophobic silicon methyl groups to reduce the force between inorganic dust and coating; In terms of structure, the bionic micro-nano structure design similar to the lotus leaf was carried out to reduce the contact area between the dust and the glass cover and thus reduce the force; The new space dust removal technology based on the new coating has made a useful attempt to develop the dust removal technology on the surface of Mars under the premise of ensuring the safe and reliable power supply of the probe.



(a) Magnification 10000x, ruler 1mμ (b) The magnification is 20,000x, the ruler 200nm

Fig. 2. SEM (scanning electron microscope) photo of the dustproof coating

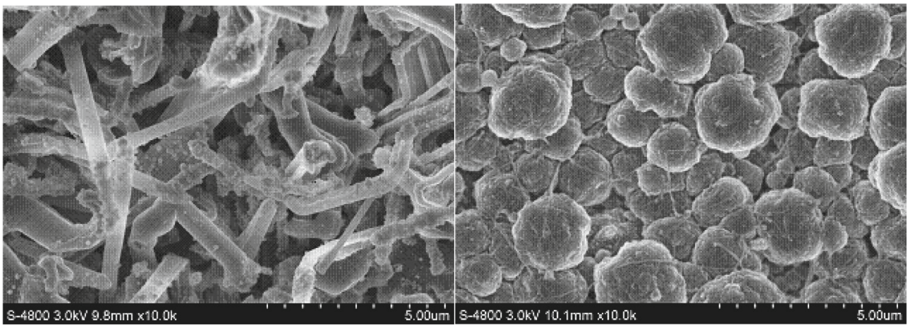
3.3 Design and Management Technology of Wide Temperature and High Specific Energy Battery

(1) Enter the cabin lithium fluorocarbon battery.

Lithium fluorocarbon battery has the advantages of high specific energy, long storage life and good safety, adapting to the long-term storage needs of Benhuo, because it saves the on-orbit charging link, it is more conducive to on-orbit maintenance, so that the weight of the entry cabin system is reduced by more than 5kg. However, there are also limitations in its use, which is suitable for discharge rates below 0.1C, and high discharge rates under the original design will lead to heat accumulation, increased temperature rise, and affect battery safety. The lithium fluorinated carbon battery is selected as the main energy source of the EDL segment, which will face the high rate discharge demand of 0.5C long-term discharge and ultra-1.1C pulse discharge, so the lithium fluorocarbon battery needs to be adaptively improved.

In the Mars mission, a high-specific energy lithium fluorocarbon battery based on a new cathode material was adopted to effectively improve the conductivity of the cathode material, improve the discharge rate of the battery while ensuring the high specific energy of the battery, effectively suppress the heat generation under the high rate of discharge, improve the working safety of the EDL section of the battery, and realize that the specific energy of the battery 0.2C discharge is better than 500Wh/Kg, and the self-discharge rate of 10 months in orbit is 1 5% high specific energy design.

Due to its excellent performance, since Tianwen-1, lithium fluorocarbon batteries have appeared on the historical stage as the main energy source of spacecraft, and have become the first choice for primary batteries for China's spacecraft follow-up missions (Fig. 3).



(a) Conductive grid (b) Graphite fluoride of a new cathode material

Fig. 3. Conductive grid of lithium fluorocarbon battery and SEM photo of cathode material

(2) Mars rover lithium-ion battery.

The rover landed near 30° north latitude of the fire surface, and the lithium-ion battery pack faced a wide temperature environment of −30 °C ~ 55 °C per day, and the rover had no nuclear source support to design the battery pack Challenges. The following figure shows the charge and discharge curve of the lithium-ion battery unit of the rover at −20 °C, and it can be seen that the discharge capacity of the lithium-ion battery pack at a low temperature of −20 °C is less than 80% of the normal temperature capacity, and less than 50% of the −30 °C.

The power supply and distribution system adopts a wide temperature range high specific energy lithium-ion battery, through the positive and negative plate parameters, electrolyte formula, etc. to optimize the adjustment, so that the specific energy of the lithium-ion battery for Mars reaches 193Wh/kg, the −20 °C low-temperature charge-discharge capacity retention rate is better than 90% (compared to normal temperature, the same below), -30 °C low-temperature charge-discharge capacity retention rate is greater than 73%, 10% higher than the conventional long-life lithium cobalt oxide battery, and the normal operating temperature range of the battery is extended from 0 °C ~ 50 °C to -30 °C ~ + 55 °C, on the basis of maintaining high specific energy, improves the wide temperature adaptability of lithium-ion batteries, and improves the robustness of Mars rover to cope with various complex working conditions on the Martian surface;
(3) Lithium-ion battery pack capacity assessment and management.

Based on the calculation of the residual charge of the lithium battery pack based on the fusion estimation of the charge state and calibration method, the results of the fuel gauge and the lookup table method are combined, and the fuel gauge integral data is usually used, and in specific cases, the battery capacity of the battery pack is calibrated by the meter power, so as to ensure that the battery capacity is always known in the case of complex working conditions and reawakening after long-term sleep It provides favorable support for the realization of spacecraft autonomous management under unmanned intervention.

3.4 Hardware-Based Solar Array Maximum Power Point Tracking (MPPT) Technology

According to the overall input, the daytime temperature range of the rover on the surface of Mars is −65 °C ~ + 40 °C, the impact factor of ambient temperature on the output voltage of solar cells is −6.8mV/°C, and the effect factor on the output current is 0.011 mA/^{cm2}· °C。 Since the temperature change has a great impact on the output voltage of the solar cell, in order to make full use of the output power of the solar array, the power supply and distribution system adopts the maximum power point tracking (MPPT) technology of the solar cell array based on hardware circuits for the Martian environment. It solves the problem of efficient utilization of solar cell array power under the complex light and wide temperature conditions of Mars, and the comprehensive utilization efficiency of solar cell array reaches 91%, which effectively reduces the area and weight of the solar cell array and improves the specific energy of the power supply system.

The MPPT main power topology circuit adopts a super-buck circuit with continuous input and output currents, which is tracked by the interleaved perturbation method.

The circuit control mode includes two modes: MPPT ring and constant voltage ring. At heavy loads, the full capacity output of the solar array is required to operate in the MPPT ring. At light loads, not all solar array power is required and works in a constant voltage ring. In order to realize the step-by-step access and exit function of the opposing array power, a three-way solar cell array is designed, the solar array 3 constant voltage point is 29.1V, and the solar array 1 constant voltage point is 29.0V, solar array 2 constant voltage point is 28.9V, so in the process of gradually increasing bus voltage, the three-way solar cell array will exit the MPPT control mode in the order of solar array 2 → solar array 1 → solar array 3.

3.5 Rover Sleep Wake-Up Technology

According to the data, the temperature change range of the Martian surface is −103 °C ~ + 27 °C. During the night of fire, because the solar cell cannot produce electrical energy and the surface temperature is low, the heater must provide a thermal control environment for the basic survival of the rover. The rover's normal operating mode takes into account the power consumption requirements of maintaining a minimum power mode at night; Considering that under the worst conditions of a strong dust storm, the output power of the solar array during the fire day is seriously reduced, and in order to avoid excessive discharge of the battery, the rover will enter sleep mode.

In view of the long-term survival problem of the fire surface caused by bad weather such as random sand and dust that is difficult to predict the time and duration, a fully autonomous wake-up circuit based on dual enabling of light and temperature is designed to ensure safe and reliable wake-up when the battery temperature and solar cell output power meet the standard, which is the first application in the world (foreign nuclear sources, regardless of temperature problems). Compared with the sleep wake-up circuit of the rover, the rover sleep wake-up technology has the following two main improvements:

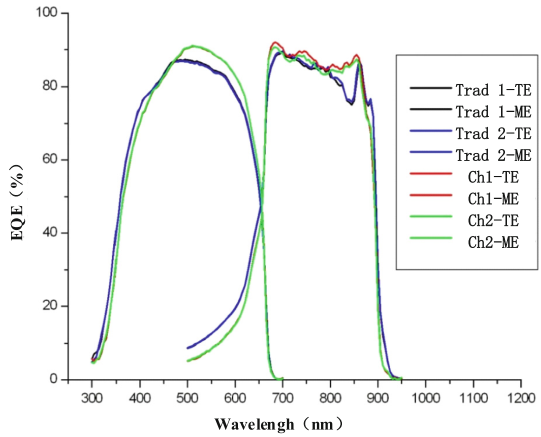
Circuit Design: Since the rover adopts MPPT technology, in order to achieve bus cut, a secondary power supply and corresponding switches are added.

Sleep Wake-Up Strategy: Add parameter items such as battery discharge depth and Mars time to the sleep condition; The wake-up load voltage threshold in the wake-up condition is designed to correlate with the battery pack temperature.

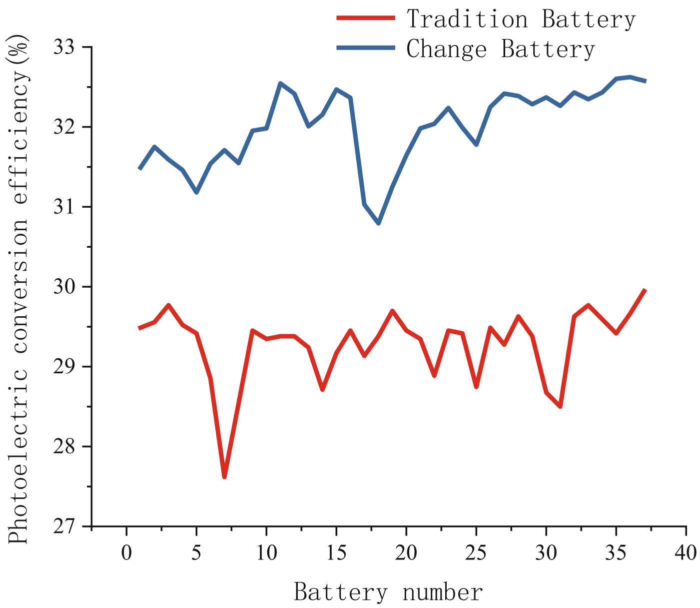
4 Test Verification

4.1 Solar Cell Mars Spectral Matching Modification Technology Verification

High-efficiency gallium arsenide solar cells for conventional space have a photoelectric conversion efficiency of about 29% in the Martian spectrum. The photoelectric conversion efficiency of high-efficiency gallium arsenide solar cells developed for the Martian spectrum is about 32%. The following figure shows the ground test data (TE: top battery; ME: Medium battery) (Fig. 4).



(a) Comparison of quantum efficiency test results before and after improvement



(b) Improve the surface measured photoelectric conversion efficiency curve before and after

Fig. 4. Spectral matching solar cell ground validation data

The rover carried four calibration batteries in orbit, namely the improved front single battery, the improved rear top battery, the improved medium battery and the improved single battery, and the on-orbit output current of the four calibration batteries also intuitively showed the output effect before and after the improvement. Evaluating the power generation capacity of the vehicle, the solar wing power generation capacity is 2900Wh/day, the load power consumption is about 1000Wh per day, and about 1750Wh of energy can support additional tasks, and it can be seen that the Mars rover has sufficient energy in the early stage of the fire (Fig. 5).

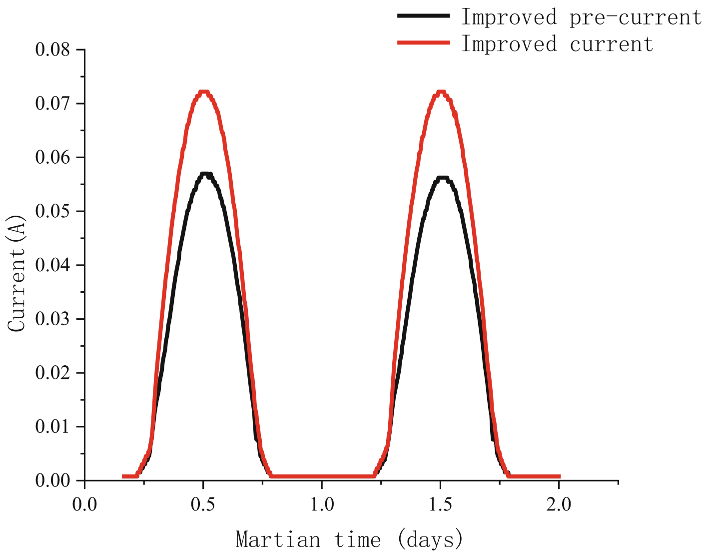


Fig. 5. Solar cell output current curve in orbit before and after improvement

4.2 Solar Cell Dust-Proof Coating Technology Verification

After the surface of the solar cell glass cover sheet adopts the dust-proof coating technology based on micro-nano structure, it has achieved a dust removal efficiency of more than 87% after being verified by ground tests. The following figure is a dust-proof coating and dust-free coating glass cover for dust removal test, after the sand dust has a coated cover sheet is not easy to adhere, after increasing the inclination, most of the dust on the surface of the dust-proof coating has slipped off, and the conventional cover surface There is also a lot of dust left (Fig. 6).

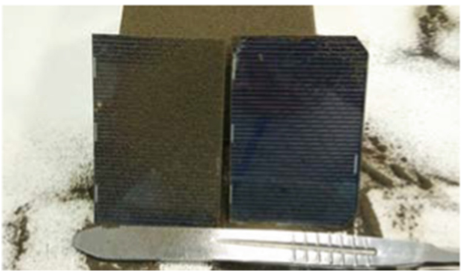


Fig. 6. Ground dust removal test

The solar cell has excellent results in orbit, because the top plate solar cell circuit is the priority output, and the on-orbit is the full power output state, and the decline trend of the output of the solar cell array can be judged by the change trend of the output current of the top plate. The output current range of the rover is 0 to 1.493A at sunset on May 16, and the output current range is 0 to 1 413A, from landing to mission end, power generation decays by about 2% / month. The output current curve of the top plate solar array 3 is shown in the figure below. It can be seen from the curve that the attenuation of solar cell output power is flat, and which is much less than the dust decay data of 9% / month abroad (Fig. 7).

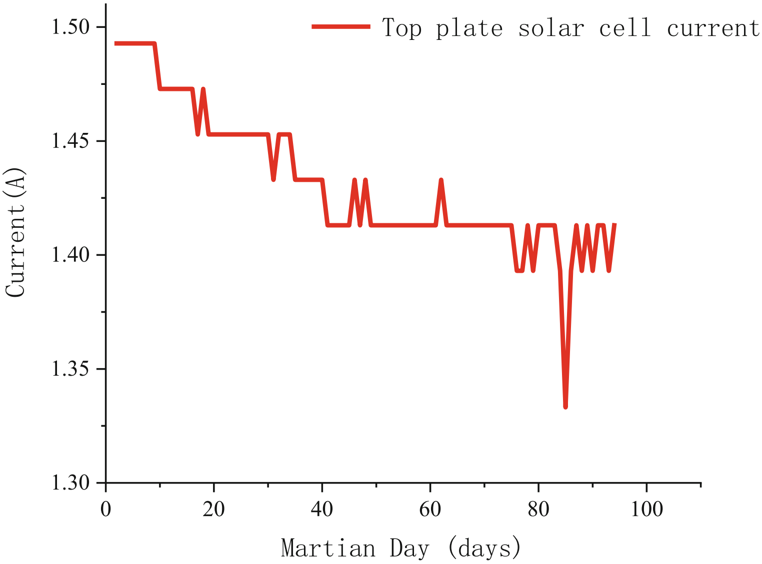


Fig. 7. Top plate solar cell output current

4.3 Wide Temperature and High Specific Energy Battery Design and Management Technology Verification

(1) Enter the cabin lithium fluorocarbon battery.

The heat generation of lithium fluorinated carbon batteries has been reduced by 76.3% after improvement. The landing rover successfully landed on Mars in the early morning of May 15, 2021, and was degraded by telemetry from the EDL segment to the fire on the day of landing, and the EDL process entered the cabin bus bar voltage from the post-fire stage to the post-fire stage, and the voltage was stable and satisfied 25V index requirements, discharge current stability without abnormal transition, the cumulative discharge of the battery is about 37.7Ah, the discharge depth of 30%, in line with the design expectations, successfully completed the landing task of the EDL section (Fig. 8).

(2) Mars rover lithium-ion battery capacity assessment and management.

Lithium-ion battery pack in orbit life (Sol90 within), the difference between the peak of the integral power and the meter of electricity are within 3Ah (temperature at 10 °C ~ 32 °C), during the extended mission period, as the rover enters the winter, the solar altitude angle gradually decreases, and the temperature of the rover gradually decreases. The temperature of the battery pack also gradually decreases, see Fig. 2 0, Sol328 began to calculate the daily calibration of the battery pack can not achieve the integral full charge, the difference between the integral charge and the meter power gradually increased, and the battery capacity error caused by the integral power error gradually appeared, see Fig. 2 for details 1。Since the temperature of the battery pack is stable above 10 °C during the life period, it is feasible for the rover to use the integral power as the default power, but entering the extended mission period, the rover faces a more stringent working environment, and the integral power is obviously unable to meet the mission requirements, so the strategy since sol331 has been self-calibrated for each Mars day (Fig. 9).

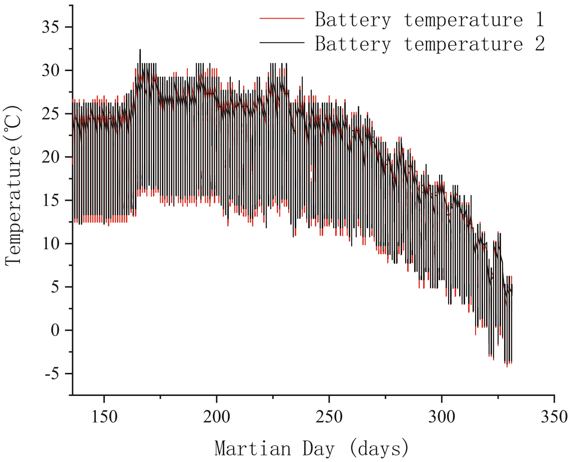


Fig. 8. Sol136 ~ Sol331 battery pack temperature curve

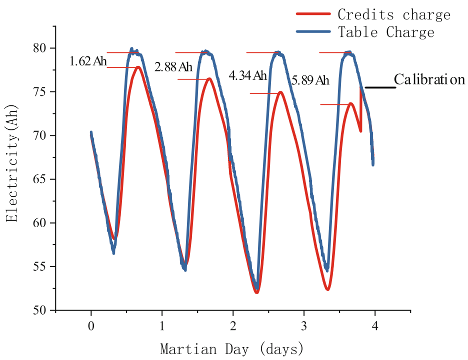


Fig. 9. Sol328 ~ Sol331 battery pack power curve

4.4 Hardware Circuit Based Solar Array Maximum Power Point Tracking (MPPT) Technology Verification

The MPPT circuit works normally in orbit, the solar cell power is fully output at the beginning of the fire day, and as the battery pack voltage gradually increases, the square array gradually exits, realizing the dynamic power regulation function. Figure 10 is the output current curve of the solar cell array on the second Martian day (Sol2), and it can be seen from the figure that when the battery pack is in a low state of charge, the solar array 1 and 2 are both operating MPPT mode, solar array 1 ~ 3 full output, the battery pack is in charge state. As the battery pack voltage gradually increases, solar array 2 begins to exit MPPT mode, solar array 1 still operates in MPPT mode, and solar array 3 still outputs full. Sun Array 2 operates in constant voltage ring mode, gradually moving from the maximum operating point to the open circuit point, and the current of Sun Array 2 is gradually reduced by the maximum power point current. If the battery pack voltage continues to rise, Solar Array 2 operates at the open circuit point and does not output. If the battery pack voltage continues to rise, Solar Array 1 begins to exit MPPT mode and Solar Array 3 is still fully output. Sun Array 1 operates in constant voltage ring mode, gradually moving from the maximum operating point to the open circuit point, and the current of solar array 1 is gradually reduced by the maximum power point current.

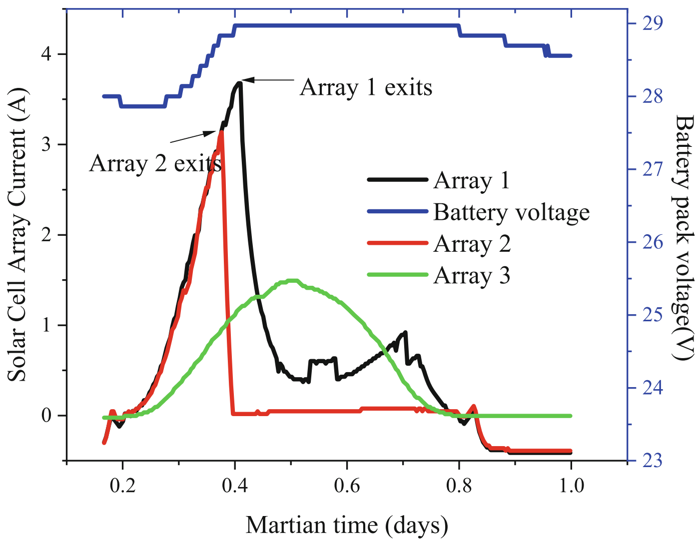


Fig. 10. Sol2 solar array output and battery pack voltage change curve

4.5 Rover Sleep Wake-Up Technology Verification

(1) Sleep process

Mars rover daily into the fire night to judge the battery pack capacity, when the fire during the solar array output power is insufficient, the battery capacity will decrease, when below the design threshold, the rover began to look for the appropriate terrain, set the body orientation, set the whole unit into the minimum working mode, when the battery pack continues to discharge to the discharge depth is greater than 50%, start the sleep setting, sleep setting through the number of tube program control to achieve.

(2) Wake-up process

When the solar wing output power gradually rises during the fire day, the wake-up load voltage also rises, and when the wake-up load voltage reaches about 27.4V, the power controller automatically wakes up the rover through the autonomous wake-up circuit.

5 Conclusions

The power supply and distribution system of the Mars mission proposed in this plan has broken through many key technologies with ultra-high specific energy and innovative design concepts, and successfully completed the Mars landing and rover mission at a very small cost. It provides important reference and reference for the design of power supply and distribution systems for future Mars rovers and other deep space probes.

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References

1. Sun, Z., et al. (eds.): Deep Space Exploration Technology. Beijing Institute of Technology Press, Beijing (2018)
2. Zhigang, L., Xiaodong, C., Qi, C., et al.: A review of power supply system of foreign deep space probes using MPPT technology. Spacecraft Eng. **20**(5), 105–110 (2011)
3. Guo, W., Liu, Z., Cai, X., Chen Qi, et al.: A review of power supply and distribution schemes for the "entry, descending, landing" process of mars rover. Spacecraft Eng. **23**(5), 111 (2014)
4. Liu, Z., Wang, F., Chen, Y., Huang, S., et al.: Analysis and countermeasures on the impact of mars surface environment on solar array design. Spacecraft Eng. **25**(2), 74–79 (2016). 1/6
5. Ye, P., Peng, J.: Deep space exploration and China's deep space exploration prospects. Chin. J. Eng. Sci. **8**(10), 13–18 (2006)
6. Ouyang, Z., Li, C., Zou, Y., et al.: Progress in deep space exploration and development strategy of deep space exploration in China. In: Proceedings of the 2002 International Symposium on Deep Space Exploration Technology and Application, pp. 237–244. Chinese Society of Astronautics, Beijing (2002)
7. Chu, Y., Li, X., Zhou, X.: Analysis of key technologies for Mars exploration. J. Test. Technol. **21**(6), 63–66 (2007)
8. Barlow, N.G.: Mars: an introduction to its interior, surface, and atmosphere. In: Wu, J., Zhao, H. (eds.) Translated by Beijing, pp. 17–20. Science Press (2010)
9. Shijun, M.A.: China Aerospace Press, Beijing, pp. 254–255 (2001)
10. Chen, Q., Liu, Z., Zhang, X., Fu, L., et al.: Spacecraft power technology. Beijing Institute of Technology Press, Beijing (2018) .3
11. Jensen, H., Laursen, J.: Power conditioning unit for Rosetta/Mars express. In: Proceedings of the 6th European Space Power Conference, pp. 249–257. ESA, Paris (2002)
12. Loche, D.: Mars express and venus express power subsystem in-flight behaviour. In: Proceedings of the 8th European Space Power Conference, pp. 1–7. ESA, Paris (2008)