論 文 の 内 容 の 要 旨

論文題目　　Research on Wireless Power Transfer System for PV Powered Lunar Rover with Maximum Power Point Tracking Control
（太陽電池給電月面ローバーのための無線電力伝送システムと最大電力追従制御に関する研究）

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With the rapid developments of economy and technology in the past decades, the Moon exploration activities are focused all over the world. As one of the most convenient instruments for lunar investigations, the lunar rover has achieved great developments in various areas, such as the lunar magnetic field distribution, water existence and Moon origin as well as evolution. So far, almost all of the launched lunar rovers are powered by the PV panel, and the solar irradiance at lunar day can be utilized to generate electricity to be stored to provide energy to the lunar rover at lunar night. However, in the conventional lunar rover structure, the PV panel is connected to the rover instruments via a wire connection through the multilayer insulation (MLI) materials which is employed to block the heat exchange between the rover inside instruments and outside circumstances. Because the wire connection brings about a slit on the MLI materials, there will be a heat leakage from the internal instruments to the outside at lunar night. Because the rover internal temperature is kept by the thermal management system which is powered by battery, the heat leakage will need extra battery volume to cover the thermal dissipation. Therefore, the extra battery volume will cause excess burden to the lunar rover launch mission.

In this paper, a wireless power transfer (WPT) system is proposed for lunar rover to replace the conventional wire connection in order to avoid the heat leakage at lunar night. The main content can be summarized into three parts: a novel lunar rover WPT system is proposed; a simulated annealing (SA) method to track the maximum DC-to-DC efficiency of the WPT system with parameter variations is proposed; two PV maximum power point tracking (MPPT) methods under partial shading conditions are proposed. The paper is organized as follows.

Chapter 1 introduces the recent lunar rover developments and analyzes the corresponding unsolved problems. In recent years, various lunar rovers have been launched to the Moon surface to conduct the lunar investigations, and currently, there are more lunar rover projects planned for the future. However, there are two issues which still need to be paid attention to, namely the heat leakage and PV MPPT under partial shading conditions. With the theory and simulation analysis, it can be concluded that for the lunar rover 1 W heat leakage power should be covered by approximately 2 kg lithium battery. Based on the designed lunar rover parameters, the expected heat leakage will be approximately 20 W, indicating there should be at least 40 kg lithium battery required to balance the thermal dissipation and generation. Furthermore, when the lunar rover moves on the Moon surface, the PV panel is highly probable to be partially shaded. In this case, in order to make the most of solar energy, the PV global MPPT control should be conducted.

Chapter 2 presents the proposed lunar rover WPT system structure and the PV output property with different solar irradiance cases. In the proposed lunar rover structure, the conventional wire connection is replaced with a WPT system, and in this way, there is no slit on the MLI materials, indicating the heat leakage is completely avoided at lunar night. Furthermore, the PV output property is analyzed based on the 1-diode and 2-diode PV cell models, and it is concluded that when the solar irradiance on the PV panel is not uniform, namely the PV panel works under the partial shading conditions, the global MPPT control should be conducted to make the full utilization of solar energy.

Chapter 3 presents the proposed lunar rover WPT systems. Based on the position of the converter used to conduct the PV MPPT control, the proposed WPT systems can be divided into the transmitter side converter (TC) WPT system and receiver side converter (RC) WPT system, respectively. The feasibility of the TC and RC topologies in the PV MPPT control aspect is analyzed respectively, and both of them can meet the MPPT tracking accuracy and time requirements. Furthermore, considering the Moon surface circumstances and the lunar rover structure, the TC and RC topology WPT system feasibility for the lunar rover application is analyzed. Mainly based on the circuit device limitations, the RC topology is more applicable for the current lunar rover designs.

Chapter 4 presents the power management strategy for the TC and RC topology lunar rover WPT systems. The WPT system is composed of 3 parts which are related to the energy supply/requirement, and they are the PV, battery and load. The PV and load are the power supply and request respectively, and the battery is employed to achieve the system power balance. Considering the Moon surface solar irradiance distribution and lunar rover mission design, 6 working modes are designed for the lunar rover. Furthermore, based on the different topologies of TC and RC WPT systems, different system control methods are employed. The proposed power management strategy and control methods are verified by experiments.

Chapter 5 presents the maximum DC-to-DC efficiency tracking method of WPT system with parameter variations. Due to the extreme temperature conditions of the Moon surface, the WPT system transmitter side which is exposed to the lunar circumstances will encounter the circuit device parameter variations. With the parameter variations, the DC-to-DC efficiency of the whole WPT system will be sharply reduced with the preset nominal system parameters. Considering this issue, in this paper, a SA method is proposed to track the maximum value of the WPT system DC-to-DC efficiency. The proposed SA method is verified with simulations.

Chapter 6 presents the proposed PV MPPT algorithms under working conditions. In order to make the most of solar energy on the Moon surface, the PV MPPT control should be conducted. Based on the solar irradiance uniformity, the algorithm can be divided into the local and global MPPT algorithms. When the solar irradiance is uniform, the PV only possesses one peak at the power-voltage (P-V) curve, and local MPPT algorithm can track the power peak. In this paper, the variant step incremental conductance (InCon) method is proposed. In the proposed method, the power peak height is employed to tune the variant step to improve the tracking time sensitivity and accuracy. When the solar irradiance is not uniform, namely the PV works in the partial shading conditions, the PV outputs multiple peaks with respect to voltage. Therefore, the global MPPT method should be employed to track the power maximum. In this paper, two global MPPT algorithms are proposed, namely the simulated annealing assisted particle replaced Gaussian particle swarm optimization (SA-PR-GPSO) method and the simulated annealing assisted particle jump particle swarm optimization (SA-PJ-PSO) method. In the SA-PR-GPSO algorithm, the tracking process is divided into two stages. In this first stage, the particles at each iteration are replaced with Gaussian distribution to achieve the fast convergence, and in the second stage, the accurate optimal position tracking is conduced with GPSO method. Based on the two-stage algorithm structure, the tracking time will be reduced while the tracking accuracy will be increased. On the other hand, in the proposed SA-PJ-PSO algorithms, the two-stage algorithm structure is also employed, while in the first stage the fast particle convergence is achieved with particle jump and in the second stage, the accurate particle positioning is conducted with PSO algorithm. All of the 3 proposed algorithms are verified with experiments.

Chapter 7 summarizes the main research contents and also analyzes the future research prospects of the proposed combined method of PV and WPT system.

In this paper, a novel lunar rover WPT system is proposed to replace the wire connection in the conventional structure. The PV power can be transferred via magnetic coupling in the WPT system, and then the heat leakage at lunar night can be avoided. The PV MPPT control is achieved with a receiver side converter and in this way the transmitter side facility can be effectively reduced. Furthermore, considering the potential parameter variations caused by harsh Lunar circumstances, a SA method is proposed to track the maximum system DC-to-DC efficiency when the parameter variations happen. Finally, in order to conduct the global MPPT control when the lunar rover PV works under partial shading conditions, a SA-PR-GPSO and SA-PJ-PSO methods are proposed to accelerate the tracking process with fast particle position convergence.