

Multi-Objective Optimization of Coil Parameters and Operation Frequency for Lunar Rover Wireless Power Transfer System

一月面探査機ワイヤレス給電システムにおけるコイルパラメータと動作周波数の多目的最適化に関する研究一

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1. Introduction

1-1. Lunar Rover Wireless Power Transfer System

Since ancient times, exploring the moon has been one of the common goals of mankind. With scientific and mineralogical objectives, several lunar rovers have been landed on the lunar surface.

Conventional Lunar rover is powered by photovoltaic cells by wire connection, which leads heat leakage through the wire at lunar night.

Novel structure has been proposed recently [1], applying wireless power transfer to replace the wire connection. In this scheme, the rover side is able to be wrapped by a specialized thermal isolation material, namely Magnetic Trans-missive Multi-Layer Insulation (MT-MLI) [2], eliminating the heat leakage.

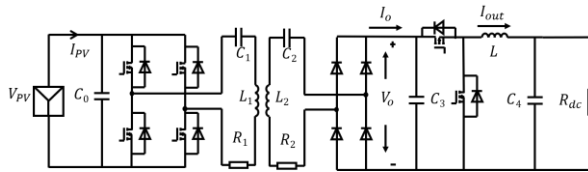


Fig. 1 Prototype Topology

1-2. Frequency and Coil Optimization Background

Previous lunar rover WPT system uses 85kHz frequency and unoptimized coil, the PV-load efficiency of the previous prototype [1] is only 75% at about 50-watt operation power. These facts show necessity for optimization.

Previous systematic multi-objective optimization for WPT [3] suffers from large amount of calculation and ignorance of frequency splitting, and discussion for PV-WPT system is still in absence.

In order to improve the performance of Lunar Rover WPT system, in this research, optimization with systematic consideration of MPPT and WPT properties, as well as computation cost reduction by metaheuristic algorithm is proposed. (Chapter 1)

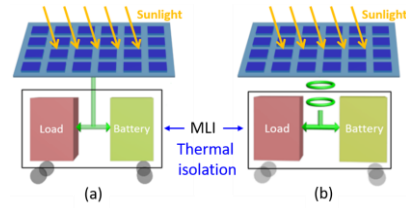


Fig. 2 (a) Lunar Rover (b) Lunar Rover WPT

2. Modeling of Lunar Rover WPT

In order to optimize operation frequency and coil, we modeled Lunar Rover WPT system losses through half-Numerical half Finite Element approach. In order to include frequency-splitting phenomenon, the WPT circuit is modeled by admittance in s-domain. Coil parameters are obtained by magnetic field calculated by FEMM software and numerical model of AC resistance. Other parts of the system are estimated by numerical calculation. Modeling has been verified by experiment and measurements. (Chapter 2)

3. Proposed MPPT with Frequency Adjustment

Frequency splitting, caused by the variation of the reflected impedance of 2nd side towards the 1st side in WPT circuit, is dependent on load, frequency and mutual inductance. In WPT circuit it leads to multiple peaks in efficiency and power transfer capacity at different operation frequency. General practice is to operate the WPT system at upper resonant peak during splitting in order to eliminate higher current harmonics and avoid inverter lagging voltage operation, but the consideration of splitting in PV-WPT system as Lunar rover WPT is in absence.

In this research, MPPT algorithm with frequency adjustment is proposed, to track the upper split frequency. The operation strategies have been verified by experiments on manufactured experiment platform and implied in the operation status determination for latter optimization. (Chapter 3)

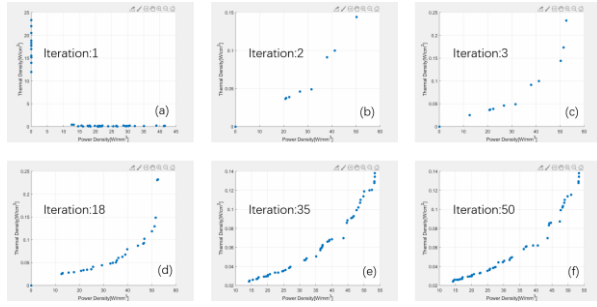


Fig.3 Pareto Front Convergence of thermal-power density optimization

4. A Multi-Objective Optimization Example

4-1. Proposed Logistic PSO

In this research, algorithms such as GA, PSO, MOEA/D, MOPSO has been implemented in various of optimizations. Through discussion of algorithms, we proposed a modified PSO algorithm namely LPSO and its multi-objective version LMOPSO, and implemented it in our optimization process.

The principle of modification is to apply logistic distribution in the learning coefficients in velocity update of PSO, as well as a random velocity to improve the exploration capability. (Section 4.3)

4-2. Thermal-density & Power-density Optimization

Based on the above loss estimation and operation status, we conducted optimization for WPT thermal density and power density for Lunar Rover WPT.

We obtained the Pareto Front (optimum solution set) and concluded design intuitions. (section 5.4)

For WPT system with the same switching device, lower frequency together with zero pitch, high number of turns large coil is benefit for thermal design. Higher frequency together with large pitch, low number of turns small coil can achieve higher power density, with acceptable thermal density.

We selected one example on the Pareto Front and conducted MPPT experiment using PV simulator and manufactured Lunar rover prototype, and obtained 99.52% MPPT efficiency as well as 90.09% PV-Load efficiency, including secondary MPPT converter.

5. Evaluation of JAXA's Coil Design

JAXA has designed coils for Lunar Rover WPT.

Based on our proposed Pareto-optimization, we are able to visualize the designs space as well as the performance space for the design.

As another application example of the proposed optimization, we briefly reproduced JAXA's design experiment by half-FE half-numerical approach and LMOPSO. (Chapter 6)

The results show JAXA's design is on the Pareto

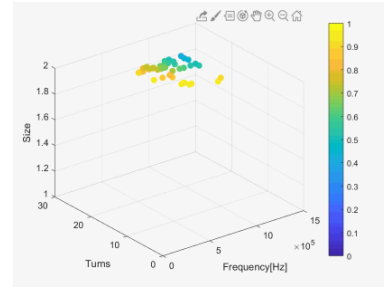


Fig.4 Visualization S₂₁ on the S₂₁ and KQ Pareto Front in JAXA's design space

Front of KQ product-S₂₁ optimization, and design intuitions for JAXA's coil is concluded.

5-1. Design Intuitions for JAXA's Coil

From Pareto Front, we can conclude that JAXA's coil design is pareto-optimal, and we can adjust it considering design tradeoffs. Reducing the number of turns and increasing the frequency simultaneously can further increase the power transfer capacity, but at the cost of reduced efficiency.

On the contrary, directly increasing the frequency without change of turns can increase efficiency, but will lose transmission capacity.

6. Conclusion

In this research, half-numerical half-FE loss estimation model for Lunar Rover WPT is established, MPPT with frequency adjustment considering frequency splitting for PV-WPT system is proposed. Single and multi-objective optimization for operation frequency and coil parameters is carried out based on proposed loss estimation and operation strategies, through metaheuristic algorithms. Evaluation for JAXA's coil design is conducted based on the proposed method, result shows the consistency of JAXA's experiments and the optimization in this research.

7. Reference

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