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Investigation of energy harvesting for magnetic sensor arrays on Mars by wireless power transmission

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This paper proposes the energy harvesting for magnetic sensor arrays on Mars, which can receive the power from Mars Rover by wireless power transmission (WPT). The schematic idea is presented with the energy receiver as the magnetic sensor and the energy transmitter as the transducer on Mars Rover. The key is to adopt the resonant inductive power transmission (IPT) topology between the magnetic sensor and Mars Rover. The basic topology and its operating principle are discussed. By using the magnetic frequency analysis with the finite element method, the output power and efficiency of the WPT system are calculated. The results show that Mars Rover could flexibly transmit its power to different types of small-size magnetic sensors based on their energy on demand using different resonant frequencies and distances. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4854995]

In recent years, exploring Mars attracts more and more attention with NASA Spirit Rover, Opportunity Rover, and Curiosity Rover running on Mars. The Spirit Rover worked on Mars over 64 months. Meanwhile, the Opportunity Rover is still working on Mars since January 25, 2004. These two rovers work much longer than their design period of 3 months. Thus, it indicates that electromagnetic devices are capable of adapting to the Mars environment. However, only with several rovers and their limited equipped sensors, it is not enough to investigate the Mars.

Wireless power transmission (WPT) technologies become more and more attractive in recent years from industry to academia.[1,2] These technologies for near-field energy transmission generally divide into inductive and capacitive coupling types.[3] Concerning the efficiency and near-field distance, the inductive power transmission (IPT) is highly promoted with resonant frequency control.[4,5]

This paper aims to propose and investigate the energy harvesting for magnetic sensor arrays on Mars, which can receive the power from Mars Rover by midrange near-field WPT. The key is to adopt the resonant IPT topology between the magnetic sensor and Mars Rover. Thus, tens of or even hundreds of magnetic sensors can distribute over Mars surface for different purposes. In this way, Mars Rover can stop around the sensors for charging based on their energy on demand (EOD) using different resonant frequencies.

As shown in Fig. 1, magnetic sensors are distributed over Mars surface with the array pattern. These sensors operate with different purposes for Mars exploration and they have to be charged within a certain period. The proposed charging strategy for these sensors obeys the following rules: (1) Different types of sensors may possess different charging power and frequency, but their power level and frequency should be at the ranges of dozen of Watts and Mega Hz, respectively. (2) The Mars Rover is able to collect the solar power on Mars and individually charge the magnetic sensor with tunable charging based on power and frequency. (3) Based on EOD sent from the magnetic sensors, the Mars Rover will make a decision to run in the area of magnetic sensor arrays for energy transmission. (4) Considering the number of sensors, each magnetic sensor should be around 100 mm in each dimension and its charging distance should be 500 mm to 1000 mm from the Mars Rover.

Fig. 2 shows the basic circuit topology for WPT on Mars, which consists of two parts. The transmitting part and the receiving part consist of energy source of I_S, load of R_L, two resistors of R_1 and R_2, capacitor of C_2, adjustable capacitor C_1 as well as inductors of L_1 and L_2. Based on the

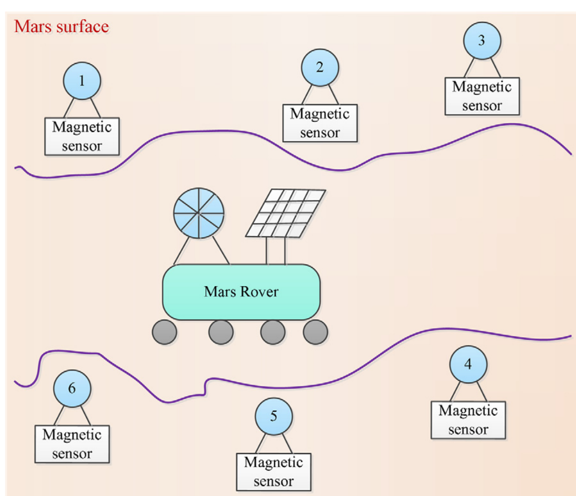

FIG. 1. Magnetic sensor arrays on Mars by WPT for energy harvesting.

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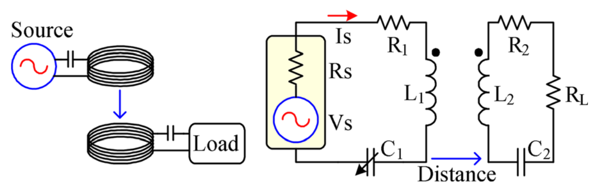

FIG. 2. Basic circuit topology for WPT on Mars.

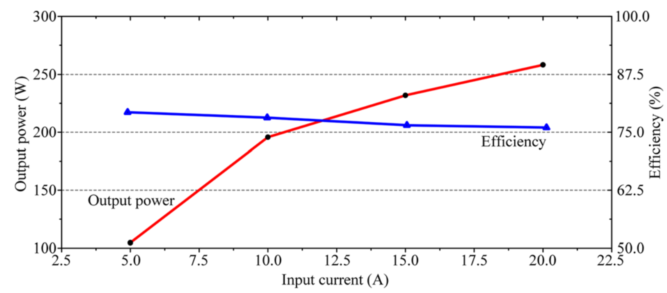

FIG. 4. Output power and efficiency at 5 MHz and in 500 mm under different input currents.

previous research,[1,3] the transmitting power and efficiency are significantly sensitive to the power level and switching frequency of source, the tunable capacitor, and the transmission distance. The corresponding operation principle can be illustrated by the following equations:[2]

$$\begin{bmatrix} V_S \\ V_L \end{bmatrix} = \begin{bmatrix} R_1 + j\omega L_1 + 1/j\omega C_1 & j\omega M \\ j\omega M & R_2 + j\omega L_2 + 1/j\omega C_2 \end{bmatrix} \cdot \begin{bmatrix} I_S \\ I_L \end{bmatrix}, \tag{1}$$

where V_S denotes the source voltage, V_L denotes the load voltage, I_L denotes the load current, M denotes the mutual inductance, and ω denotes the switching frequency.

At resonance, it yields $j\omega L_x + 1/j\omega C_x = 0$. So, Eq. (1) can be simplified as

$$\begin{bmatrix} V_S \\ V_L \end{bmatrix} = \begin{bmatrix} R_1 & j\omega M \\ j\omega M & R_2 \end{bmatrix} \cdot \begin{bmatrix} I_S \\ I_L \end{bmatrix}. \tag{2}$$

Thus, the corresponding output power and efficiency can be obtained as

$$P_L = \frac{V_S^2 \omega^2 M^2 R_L}{\left(R_1(R_2 + R_L) + \omega^2 M^2\right)^2}, \tag{3}$$

$$\eta = \frac{\omega^2 M^2 R_L}{R_1 (R_2 + R_L)^2 + \omega^2 M^2 (R_2 + R_L)}. \tag{4}$$

Therefore, for the proposed system on Mars, the Mars Rover stops around the corresponding sensor array and then tunes its frequency at resonance to charge the one who is requesting by EOD. It should be noted that the load R_L could be the battery of magnetic sensor during charging.

Fig. 3 shows the testing system, in which the left power pad represents the transmitting transducer on the Mars Rover and the right power pad represents the receiver on the magnetic sensor. The basic parameters of the power pad are summarized as follow: pad radius of 120 mm, ferrite spoke inside and outside radii of 20 mm and 100 mm, copper coil inside and outside radii of 40 mm and 80 mm. By using magnetic frequency analysis of the finite element method with the J-Mag Tool, the corresponding pad power can be calculated and obtained. It should be noted that all the power transmission results are based on the resonant frequency.

First, based on the resonance frequency of 5 MHz, Figs. 4–6 show the output power and efficiency under different input currents with the distances of 500 mm, 750 mm, and 1000 mm, respectively. It can be found that for the distance of 500 mm, the efficiency is around 76% to 80%, and the power is 258 W with 20 A. Based on the criteria that the efficiency and output power are of equal weightings, the best operation should be at their crossover point. So, the corresponding best operation point is 77% and 210 W with 12.3 A. Furthermore, for the distance of 750 mm, the efficiency varies from 70% to 51%. The best operation point is 62% and 17 W with 11.0 A. In addition, for the distance of 1000 mm, the efficiency varies from 34% to 45%. And the best operation point is 42% and 7.4 W with 12.9 A. Therefore, it indicates that the transmitting power reduces greatly with increasing the distance. So, it is better for the Mars Rover to stop closer to the magnetic sensor. In addition, it confirms that even with the distance of 1000 mm, Mars Rover can still charge some types of sensors with the power level of several Watts.

Second, Figs. 7 and 8 show the output power and efficiency under different resonant frequencies with the distances of 500 mm and 750 mm, respectively. For the distance of 500 mm with the input current of 5 A, it can be observed that the magnetic sensor with 7.5 MHz can receive the power up to 278 W with the highest efficiency of 88.5%. For the distance of 750 mm with the input current of 10 A, it can also

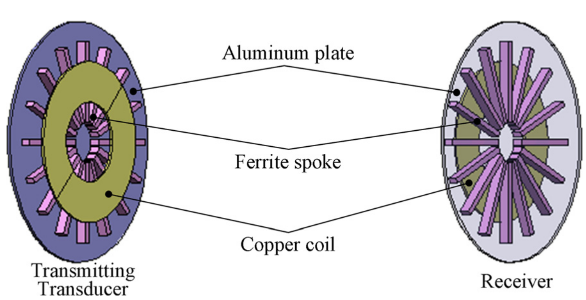

FIG. 3. Testing system.

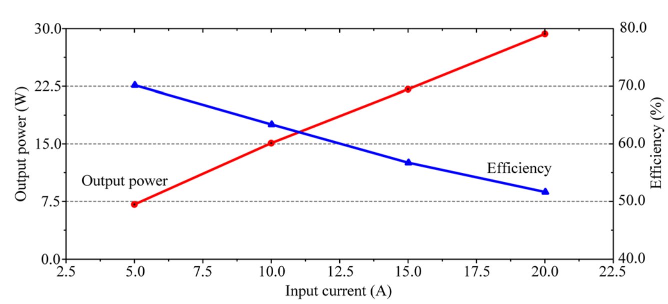

FIG. 5. Output power and efficiency at 5 MHz and in 750 mm under different input currents.

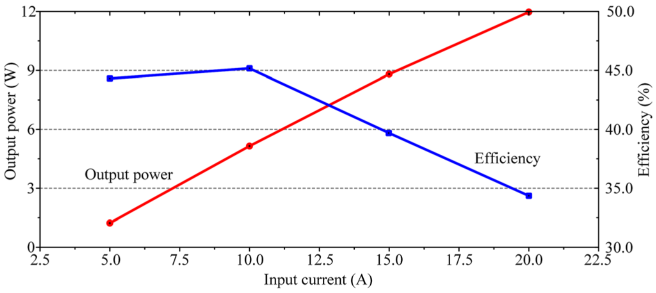

FIG. 6. Output power and efficiency at 5 MHz and in 1000 mm under different input currents.

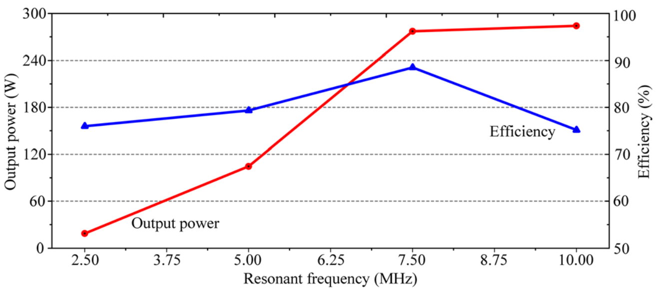

FIG. 7. Output power and efficiency with 5 A and in 500 mm under different resonant frequencies.

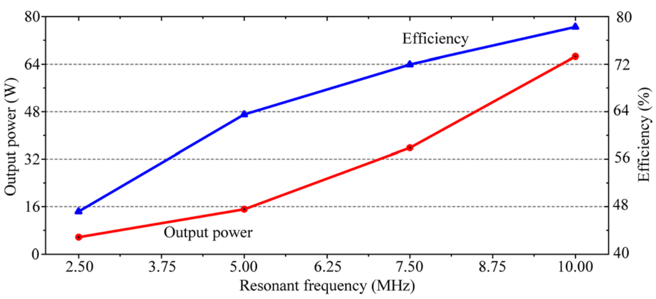

FIG. 8. Output power and efficiency with 10 A and in 750 mm under different resonant frequencies.

be found that the sensor with 10 MHz can receive the power up to 66.6 W with the highest efficiency of 78.2%. Thus, it illustrates that the Mars Rover can walk close to the magnetic sensor array and provides the hundred-Watt level of power for charging. Meanwhile, the Mars Rover can also charge those sensors with the ten-Watt level of power.

Finally, under different distances, Fig. 9 shows the output power and efficiency with the resonant frequency of 5 MHz under the fixed input current of 10 A. As expected, the charging power and efficiency drop quickly with increasing the distance. But the Mars Rover can still charge the magnetic sensors with the power level from several Watts to tens of Watts. Moreover, Fig. 10 shows the output power and efficiency under different distances with three optimal sets of input current and resonant frequency, namely (5 A, 7.5 MHz), (10 A, 10 MHz), and (15 A, 5 MHz). It can

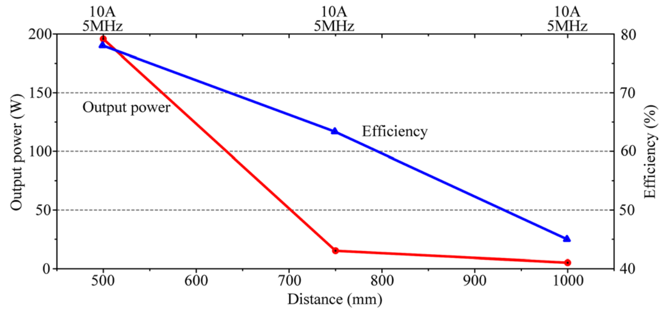

FIG. 9. Output power and efficiency with 10 A and at 5 MHz under different distances.

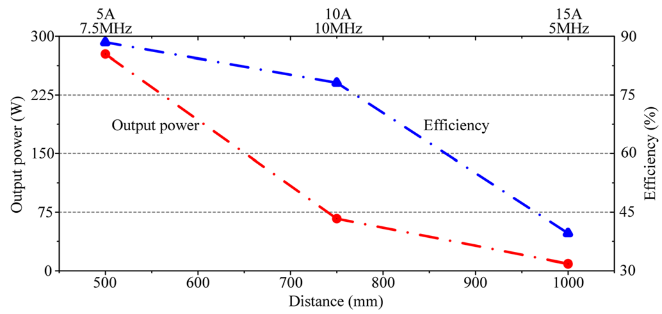

FIG. 10. Output power and efficiency in optimal cases under different distances.

be found that within the distance of 750 mm, the efficiency is over 78%. Also, their transmitting powers are impressive, which are up to 277 W within 500 mm and 66.6 W within 750 mm, respectively.

This paper proposes and investigates the magnetic sensor array on Mars by WPT for energy harvesting from the Mars Rover. The schematic idea is presented with the receiver of the magnetic sensor and the transmitting transducer of the Mars Rover. The basic topology and its operating principle are discussed. The results verify that even with the small size of the receiver, the magnetic sensor can effectively harness the energy from the Mars Rover. Also, the Mars Rover can flexibly transmit its power to different types of sensors based on their EOD with different resonant frequencies and distances.

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