Efficient wireless power transfer for a moving electric vehicle by digital control of frequency

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Article Info

ABSTRACT

Recently, demand for electric vehicles has been increasing as a countermeasure against global warming, but they currently face many problems compared to gasoline-powered vehicles. For example, charging takes time, and there are few places where electric vehicles can be charged. If AC power supplies that can transfer energy to electric vehicles wirelessly exist under the lanes where electric vehicles drive, the cruising range will be increased. In this study, assuming wireless power transfer to a moving electric vehicle, an experiment was conducted to light up a light-emitting diode (LED) on a moving electric model car. To improve the efficiency of transfer, the optimal frequency for the position of the electric model car was calculated, and the value was fed back to the power supply to adjust the frequency in real time.

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1. INTRODUCTION

Recently, countermeasures against global warming have been discussed from various perspectives. Global warming causes various weather disasters, many human damages [1], and also have a significant negative effect on crops [2]. For those reasons, it is clear that further global warming must be prevented. One of the major causes of global warming is gas emissions from gasoline-powered vehicles, and in order to reduce these emissions as much as possible, electric vehicles (EVs) have been developed in many countries [3]. Success of efficient EVs operations would help combat global warming, however at present, problems such as short driving range and long charging times are cited [4], [5]. External power supply systems using wireless power transfer (WPT) have been designed and developed to solve those problems [6], [7].

WPT researches have been conducted for a variety of applications and environments [8]. There have also been many studies on WPT to EVs which is the focus of our study and solar cars [9], [10]. WPT is utilized not only on the ground, but also to transfer power to unmanned underwater vehicles (UUVs) underwater [11], [12], and to unmanned aerial vehicles (UAVs) in the air [13], [14]. Furthermore, WPT has been considered as a method of transmitting power to the ground in space, where stable solar power can be generated regardless of weather conditions .

As above, the use of WPT is environmentally friendly and can be expected to be applied to a variety of applications. On the other hand, it is also fact that there are many problems on WPT to EVs in terms of power transport efficiency. Since EVs are mobile, it may be necessary to assume that the targets which should be charged are always moving [15]. In the situation, a major barrier is the constantly changing positional relationship between the power supply and the inductors on an EV for the power transmission. In

addition, because EVs consist of a wide variety of structures and shapes [16], [17], it is necessary to transfer power appropriately to each of them. For example, in the case of two EVs with very different vehicle heights, there will be a large discrepancy between them in the value of the optimum frequency for WPT from the ground. In this study, WPT from down the lane is attempted to an electric model car that is always moving at a constant speed. Also the relationship between the positional relationship and the power supply frequency is clarified, and a system that can always measure the optimum frequency and perform highly efficient WPT is studied even if this position changes. This study clarifies fast switching for mobile devices and the ideal method of driving inverters with a switching regulator.

2. WPT FOR A RUNNING EV
2.1. Circuit design
A WPT circuit for a running EV is designed as Figure 1, and parameters are shown as Table 1. This cirtuit is composed of invertor, mutual induction, and rectify part. On invertor part, a relay switches power supply ON or OFF depending on whether the car is on the road or not. Also the frequency of power supply is decided on resonant frequency of circuit [18].
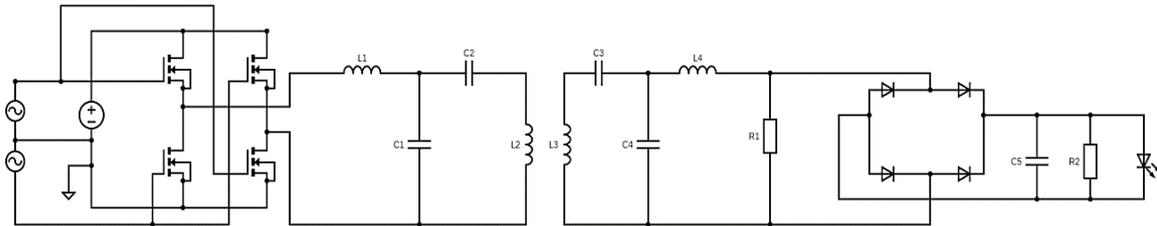

Figure 1. A circuit of WPT for runing Evs

Table 1. Parameters of circuit elements

Parameters	Values	Parameters	Values
VG1	0 or 5 V	C1	100 nF
VG2	0 or 5 V	C2	50 nF
V1	5 V	C3	50 nF
L1	6.66 μH	C4	100 nF
L2	20 μH	C5	100 nF
L3	20 μH	R1	100 Ω
L4	6.66 μH	R2	100 Ω

2.2. Experiment by using an electric model car instead of an EV
On this study, an electric model car runs on a lane filled with inductors instead of running an EV. The electric model car is equipped with light-emitting diode (LED), and it is charged wireless. The electric model car is shown as Figure 2, and the lane which is filled with inductors is shown as Figure 3.
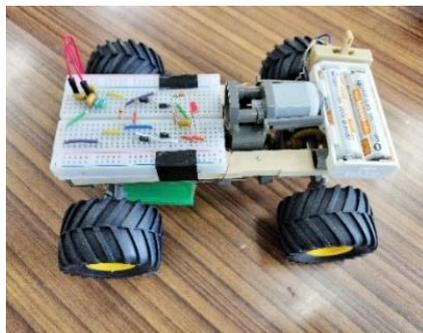

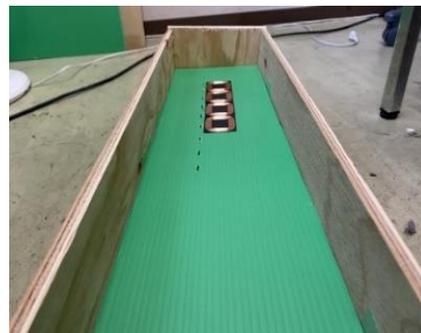Figure 2. An electric model car   Figure 3. A lane filled with inductors

The electric model car runs on the lane with 67.3 mm/sec, and dimensions of the inductor are 43.5 mm (length), 39.5 mm (width), and 0.6 mm (height) respectively. LED on the running electric model car is driven, and instantaneous voltage of it is measured continuously as Figure 4. From Figure 4, it is revealed that LED gets 1.5 ~ 2V when the electric model car is on inductors. Moreover, LED cannot get any voltage on 760, 1,370, and 1,950 ms because the electric model car passes between inductors on these time. Finaly, LED can get 24.5 mW averagely when the electric model car runs on the inductors.
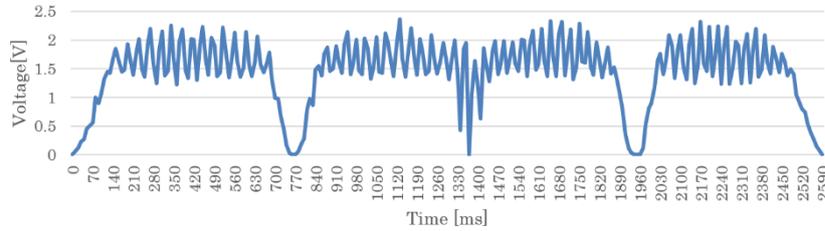

Figure 4. Instantaneous voltage of LED

3. DEGITAL CONTROL OF FREQUENCY

In above section, power of load to drive LED can be obtained wirelessly, and actually LED is drived while the electric model car runs right above inductors. On the other hand, LED is not drived between inductors, because optimal frequency for efficient WPT is frail to change of position of load. Therefore if a system which is resistant to change of positional relationship is developed, it is excepted that efficient WPT is kept regardless of distance between a power supply and an EV.

3.1. Circuit design for tracking optimal frequency

A circuit for tracking oputimal frequency versus position of a electric model car is designed on Figure 5, and its inductive part is categorized as S/P method [19]. In this experiment, effective values of voltage on resistance R_7 are indicated, and a rectifier is used to R_7 on real transmission. Further, a lithium-ion battery which is generally used for EVs is expressed by resistors and capacitors [20].
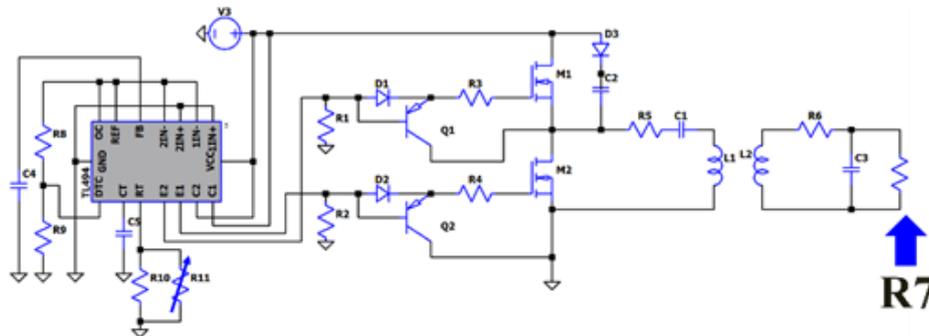

Figure 5. A circuit for tracking optimal frequency

Alternative current in inductors for induction generate an invertor and it is controlled by switching regulator TL 494. Moreover, it outputs a square wave and controls transistors. The frequency of output is determined by R_T and C_T terminals according to (1).

$$f = \frac{1}{2R_T C_T}$$

(1)

To control R_T automatically, digital potentiometer AD8400 is adopted, and it is connected to Arduino UNO shown as Figure 6. The Arduino UNO directs AD8400 dependent on position of inductors, and an ultrasonic sensor measures the position shown as Figure 7. On this experience, inductors move on a rail only 1 axis.
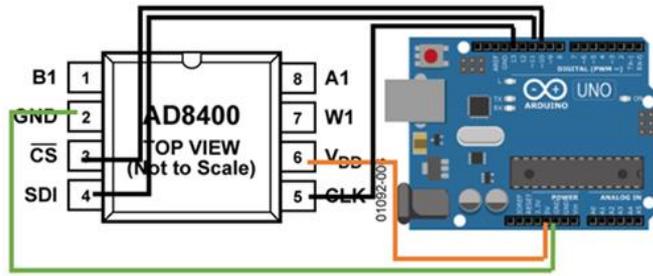
Figure 6. Connection of Arduino UNO
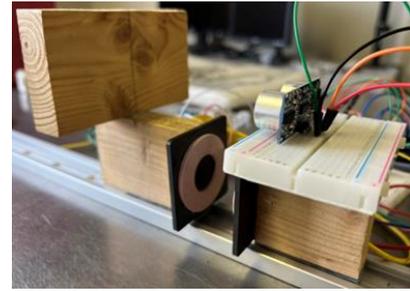to control AD8400

Figure 7. disposition of inductors and an
ultrasonic sensor

The optimal frequency f_{opt} is determined by (2). The derivation of (2) is based on theorm of modern control and a state equation [21], [22].

$$f_{\text{opt}} = \frac{1}{2\pi} \sqrt{\frac{R_6 + R_L}{R_L C_3} \left(\frac{R_5}{R_5 L_2^2 + R_6 M^2} \right)^{\frac{1}{4}}}$$ (2)

Equation (2) contains mutual inductance M, and it is calculated as in (3) [23], [24].

$$M = \frac{\mu S_1 S_2}{2\pi (r_1^2 + d_x^2 + d_y^2 + d_z^2)}$$ (3)

where μ is permeability, S_1 and S_2 are cross-sectional area of L_1 and L_2 respectively, r_1 is internal radius of inductors, and d_x, d_y, and d_z are the distance between L_1 and L_2 towards axes. In an experiment, voltage of load is measured constantly while an inductor moves on a rail.

4.   RESULTS AND DISCUSSION

On previous section, the WPT circuit which possesses frequency auto tuning system is prepared. Furthermore, the RMS values of a load are confirmed by simulation and an experiment on this section. The result of simulation is shown in Figure 8, and the experiment is shown in Figure 9. From these results, the errors are confirmed in terms of the peak voltage value and distance which provides maximum voltage. On the other hand, higher voltage can be obtained than an experiment which does not contain frequency auto tuning system on whole distance. Hence it is conclued that our frequency auto tuning system can contribute fine WPT for a moving thing.

As the cause of error, external factors are picked up, especially the existence of metals which affect magnetic flux [25], [26]. Hence when an experiment of WPT is done, the factors should be obstructed. Also, accuracy of an ultrasonic sensor may be not good on the distance area of the WPT observation. There are many sensors, and these have appropriate distance and frequency severally. Furthermore power must be considered not only voltage because even if high voltage is obtained, if current cannot be obtained enough, EVs cannot be drove.
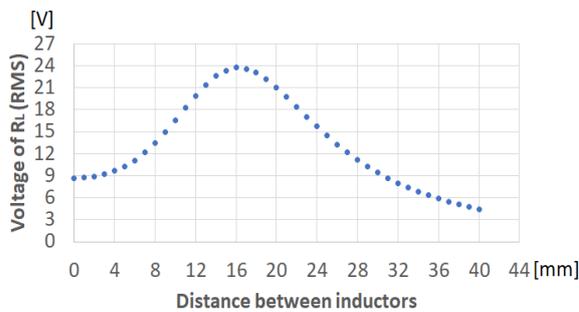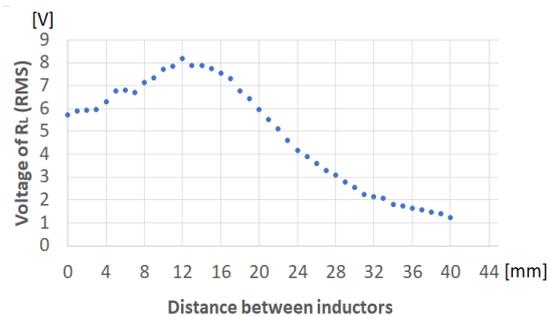

Figure 8. Voltage of the load on simulation

Figure 9. Voltage of the load on the experiment

5.   CONCLUSION

In this study, WPT for EVs is discussed in terms of in-running power feed and frequency. For WPT while driving, a rudder sensor was used to detect moving objects and to automatically switch the power transmission section. As a result, a LED on the moving EV was successfully turned on from the AC power supply under the lane. The frequency required for optimal WPT was calculated from theory, taking into account the vehicle height and stopping position of the EV. Furthermore, a circuit simulation and experiment confirmed that adjusting the frequency increases the transport voltage. Transmitting power to EVs moving at higher speeds and seeking improvements other than frequency are given as future issues.

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