**International Journal of Electrical and Computer Engineering (IJECE)**
Vol. 13, No. 2, April 2023, pp. 1314~1319
ISSN: 2088-8708, DOI: 10.11591/ijece.v13i2.pp1314-1319


# Experimental review of an improving system on wireless power transfer via auto tuning of frequency

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**Article Info**

***Article history:***

Received Mar 30, 2022
Revised Oct 10, 2022
Accepted Oct 30, 2022

***Keywords:***

Adjustment of frequency
Axial displacement
Mutual inductance
Power electronics
Wireless power transfer

**ABSTRACT**

Wireless power transfer for electric vehicles is focused because these vehicles cannot run long distance without frequently charging. If these vehicles are charged from outside wirelessly, for example an alternating current (AC) power supply is embed under road, the problem is going to be solved. However, efficiency of wireless power transfer depends on various factors, therefore many contrivances should be considered to realize optimal transfer. In this paper, we focused on frequency of inverter, and created auto tuning system of it in response to the distance of inductors. On this system, frequency was modified automatically by a microcontroller and sensor at the same time position of a load changed. Finally, we confirmed that voltage of light emitting diode (LED) was improved by utilizing our system compared with non-tuning frequency.



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## 1. INTRODUCTION

Since early times, many vehicles depend on fossil fuel because efficiency of charging these is greatly high. In fact, a lot of $CO_2$ is egested by consuming fossil fuel, and it contributes global warming in the long run [1], [2]. Moreover, fossil fuel is limited material, therefore people cannot utilize it permanently. On the other hand, in the industry of vehicles, electric vehicles are focused instead of gasoline powered vehicles and expected to reduce $CO_2$, contribute energy security, and resolve environmental concerns [3]–[6]. However, electric vehicles have a problem that these cannot run long distance without frequently energy supply [7]. Accordingly, wireless power transfer (WPT) from a road or roadside is examined for these to resolve the problem [8]–[10].

WPT bases on electromagnetic induction which is established by Michael Faraday and Joseph Henry in the 19$^{th}$ century. In 20$^{th}$ century, 200 mW power could be gained on distance of 1.5 m by using a vacuum tube as rectifier [11]. In these days, 60 W power could be gained on 2 m, and an electric light bulb flashed via strongly coupled magnetic resonance in 2007 [12]. These reports moreover caused great development of next-generation method to send information while electric power is transferred wirelessly [13], [14]. Not only in an industry field, but WPT is expanded to a medical field; for example, a micro implant device in human body can be charged from outside [15]–[18].

In conventional WPT which is based on magnetically coupled resonance, frequency of an alternating current (AC) power supply is significant factor, and it is determined by distance of inductors [19]. Therefore, when WPT for electric vehicles is treated, we must notice that the optimal frequency which gives high power transmission shifts constantly. In addition to this, calculation of mutual inductance depends on a position of inductors, therefore axial displacement of these must be examined for flexible WPT [20].

In this study, we create the frequency auto tuning system which realizes efficient WPT, and demonstrate WPT based on circuit simulation to drive light emitting diode (LED), as a load. Voltage of LED are measured on 2 situations, tuned frequency and non–tuned frequency to verify the availability of frequency tuning. Finally, this study indicates a method to contribute various electric vehicles so that these can run on long distance without frequent wired charging.

## 2. THE OPTIMAL FREQUENCY TO KEEP HIGH EFFICIENCY

### 2.1. Experimental circuit and the values of elements

To realize efficient transportation of electric power, frequency of sending circuit must be adjusted, and it is determined by various elements [21], [22]. Especially in this study, the distance between sending inductor and receiving inductor is deeply considered because it changes frequently in contrast with other elements. Hence, the relational expression from distance to frequency is required with various elements on an experimental circuit Figure 1.

Figure 1 is an experimental WPT circuit to drive a LED, and it is composed by 3 parts. First, an inverter part which is driven by the optimal frequency is needed because WPT utilizes an alternative current at inductor part. The part is composed by 4 transistors, and these are controlled by a micro controller which outputs square waves. Second, 2 inductors are set between a sending circuit and a receiving circuit for energy transfer wirelessly. These inductors generate mutual inductance whose value is determined by elements on circuit, configurations of inductor, and distance of inductors. Finally, rectifier which is configured by 4 diodes must be adopted for giving DC power to a load. If sufficient power is obtained towards LED, it generates red light. The values of elements on circuit are set as Table 1. Moreover, the configurations of $L_1$ and $L_2$ are shown in Figure 2 and Table 2 [23].

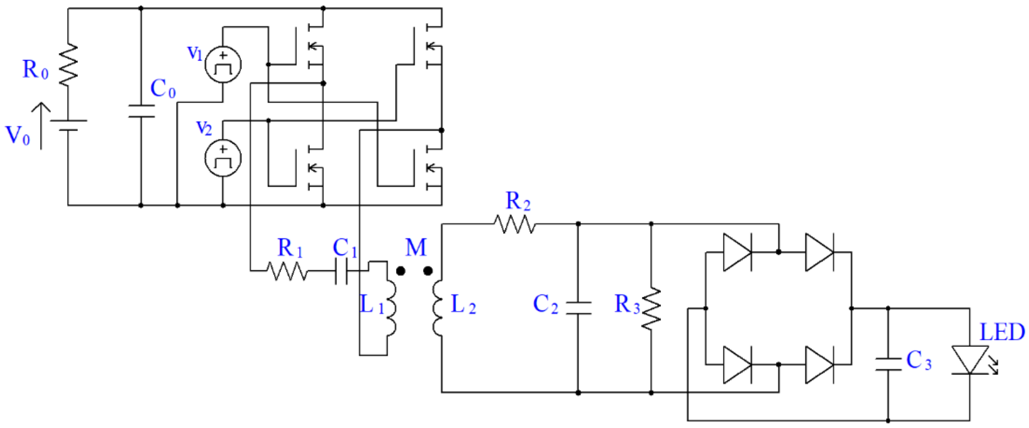


Figure 1. Experimental circuit of WPT to transport energy to LED

Table 1. The values of elements on circuit

| Variables | Values | Variables | Values |
|---|---|---|---|
| $V_0$ | 5 V | $C_0$ | 1 nF |
| $v_1$ | 5 or 0 V | $C_1$ | 1 nF |
| $v_2$ | 0 or 5 V | $C_2$ | 1 nF |
| $R_0$ | 0.1 Ω | $C_3$ | 100 nF |
| $R_1$ | 1 Ω | $L_1$ | 25.1 µH |
| $R_2$ | 1 Ω | $L_2$ | 25.2 µH |
| $R_3$ | 100 Ω | | |

$v_1$ *and* $v_2$ are square waves, and these are antiphase mutually

### 2.2. The optimal frequency with regards to distance of inductors for realizing high power transmission

The optimal frequency $f_{\rm opt}$ is calculated by circuit elements as (1) [24], [25].

$$f_{\rm opt} = \frac{1}{2\pi}\sqrt{\frac{R_2+R_3}{R_3C_2}}\left(\frac{R_1}{R_1L_2^2+R_2M^2}\right)^{\frac{1}{4}} \tag{1}$$

In (1), $M$ is mutual inductance which is made based on electromagnetic induction, and it is recalculate by the changing of disposition of $L_1$ and $L_2$ as shown in Figure 3. $M$ is obtained by Biot–Savart law as (2) [26], [27].

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

where μ is permeability, $S_1$ and $S_2$ are cross-sectional area of $L_1$ and $L_2$ respectively, and $d_x, d_y$, and $d_z$ are the distance between $L_1$ and $L_2$ towards axes. Therefore, the relational equation of $f_{opt}$ which is expressed by $d_x, d_y, d_z$ is found from (1) and (2). In this study, $S_1$ and $S_2$ are calculated as $7.97 \times 10^{-3}$ m$^2$, $d_x$ and $d_y$ are treated as 0, and $d_z$ changes from 0 to 30 mm. On these conditions, $f_{opt}$ changes regarding $d_z$ as Figure 4.

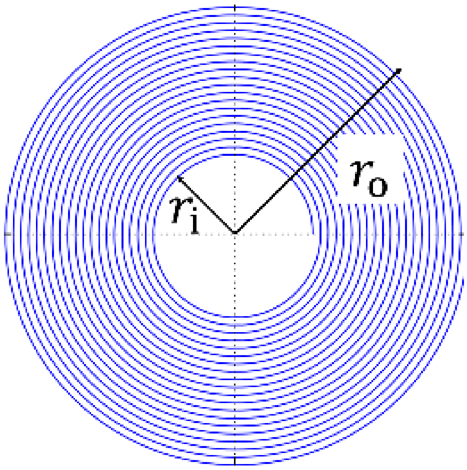


Figure 2. Spiral inductor $L_1$ and $L_2$

Table 2. Parameters of $L_1$ and $L_2$

| Elements | Values |
|---|---|
| radius $r_i$ | 10 mm |
| radius $r_0$ | 21 mm |
| winding number $n$ | 21 |
| wire radius $g$ | 0.5 mm |
| wire length $l$ | 2 m |

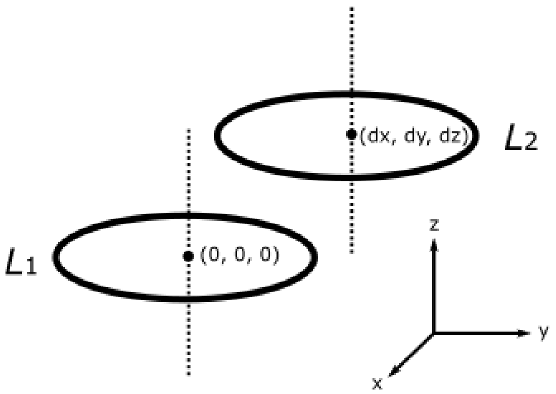


Figure 3. Coordinate setting to calculate mutual inductance $M$

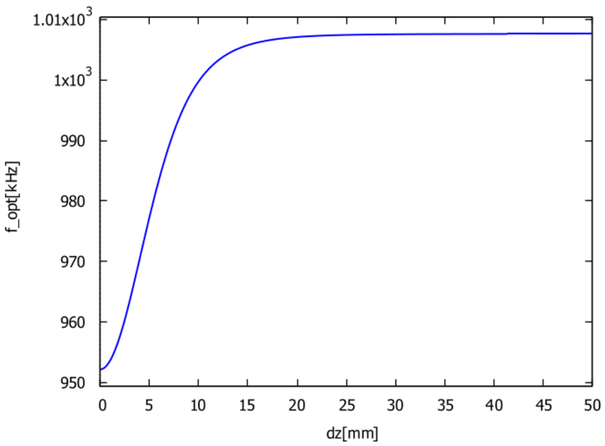


Figure 4. The variation of $f_{opt}$ regarding $d_z$

## 3. RESULTS AND DISCUSSION

### 3.1. Experiment of WPT by utilizing the system of auto tuning of frequency

In our experiment, Arduino UNO is adopted as a micro controller which reads the distance between inductors and outputs 2 square waves (antiphase mutually) [28]. For measuring the distance, an ultrasound sensor is attached over the inductors as Figure 5. In this apparatus, $d_z$ is the distance between coaxial 2 inductances $L_1$ and $L_2$.

At first, power transmission at $d_z$=0 mm is tried by a DC power supply $V_0$ and an invertor which is driven by $v_1$ and $v_2$ whose frequency are 847 kHz. On the situation, the instantaneous voltage of LED is shown in Figure 6. Figure 6 shows the average voltage of LED is approximately 610 mV. Further when frequency of the invertor is automatically tuning in response to the distance between $L_1$ and $L_2$, the average voltage of LED is measured each distance. The result of it is shown as Table 3, and it also shows non-tuned voltage.

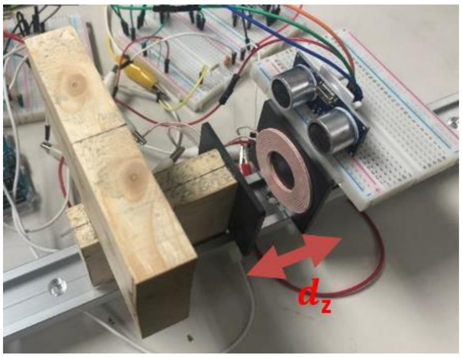


Figure 5. Frequency auto tuning system consisted of Arduino UNO and an ultrasound sensor

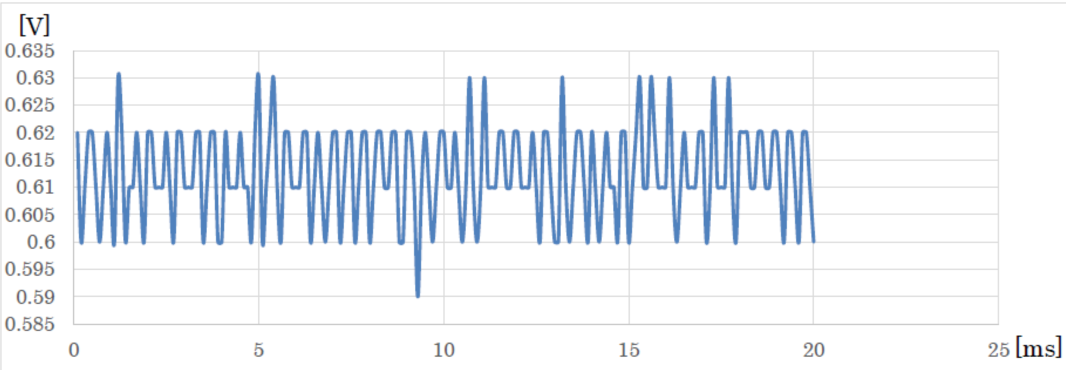


Figure 6. Instantaneous voltage of LED by driven 847 kHz

Table 3. Average voltage of LED by utilizing the frequency auto tuning system

| Distance between $L_1$ and $L_2$ | Optimal frequency of the invertor | Tuned voltage of LED | Non – tuned voltage of LED |
|---|---|---|---|
| 0 mm | 952 kHz | 1.56 V | 1.63 V |
| 15 mm | 1006 kHz | 1.53 V | 0.82 V |
| 30 mm | 1008 kHz | 0.60 V | 0.24 V |

### 3.2. Discussion

In this study, mutual inductance $M$ is in inverse proportion to $d_z$ cubed from (2). Hence, the optimal frequency converges on 1,008 kHz as $d_z$ increases as Figure 3. To keep high $M$, the configurations of inductors must be devised, for example a shape, wire, and iron core. In the experiment, tuned voltage indicates stable value to drive LED in the range from 0 to 15 mm. However, non–tuned voltage decreases on the same range. Therefore, the frequency auto tuning system can operate normally on a determinate range. On radiofrequency range, we must use high effectiveness microcontroller, and design fast response circuit.

## 4. CONCLUSION

This study tried to keep efficient WPT in spite of changing distance between a sending inductor and a receiving inductor. Based on a theoretical expression, the distance was measured, and the optimal frequency was calculated on real time. Through an experiment, we could verify that adjustment of frequency of an invertor contribute to high power transportation compared with non–tuned frequency. If this study is more expanded, efficient WPT for electric vehicles or solar cars can be accomplished on environmentally friendly world in the future.

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