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

Kazuya Yamaguchi, Ryusei Okamura, Haruto Terada, Kenichi Iida
Department of Control Engineering, National Institute of Technology, Nara College, Nara, Japan

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.

Corresponding Author:

Kazuya Yamaguchi
Department of Control Engineering, National Institute of Technology, Nara College
22 Yata-cho, Yamatokoriyama, Nara, Japan
Email: k-yamaguchi@ctrl.nara-k.ac.jp

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 19th century. In 20th 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].

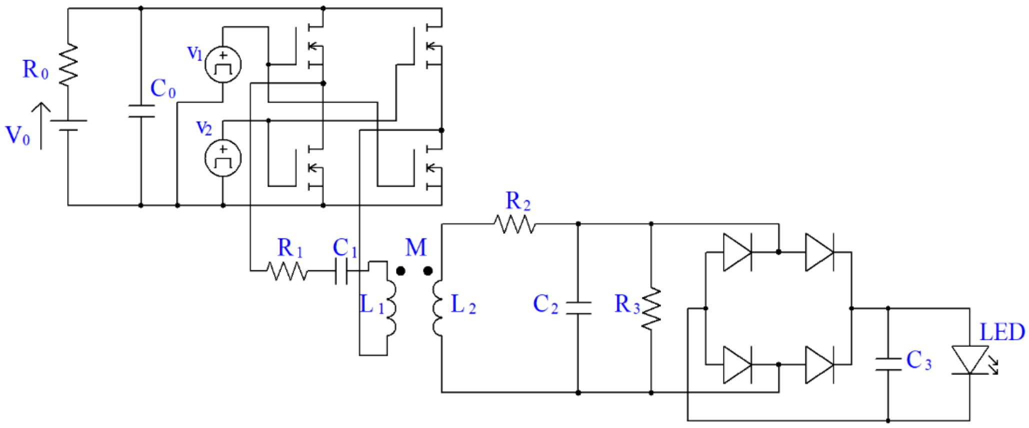

Figure 1. Experimental circuit of WPT to transport energy to LED

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_{opt} is calculated by circuit elements as (1) [24], [25].

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

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].

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

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 7.97×10^{-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.

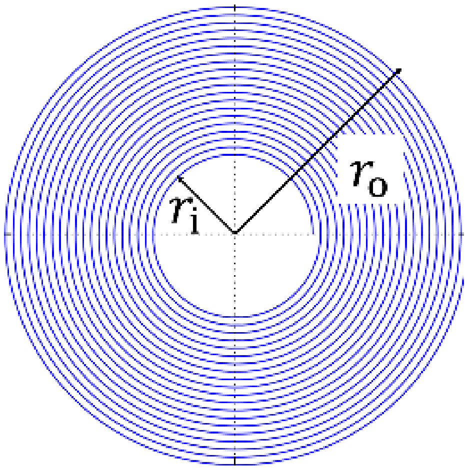

Figure 2. Spiral inductor L_1 and L_2

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

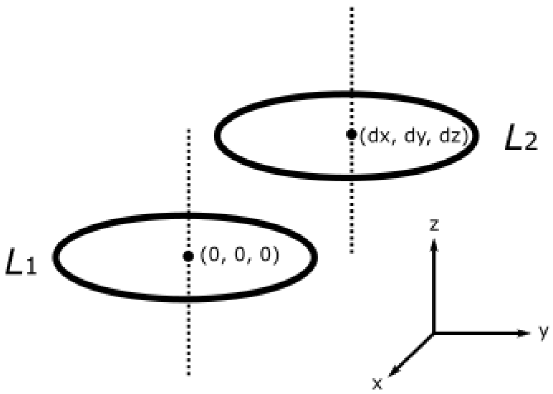

Figure 3. Coordinate setting to calculate mutual inductance M

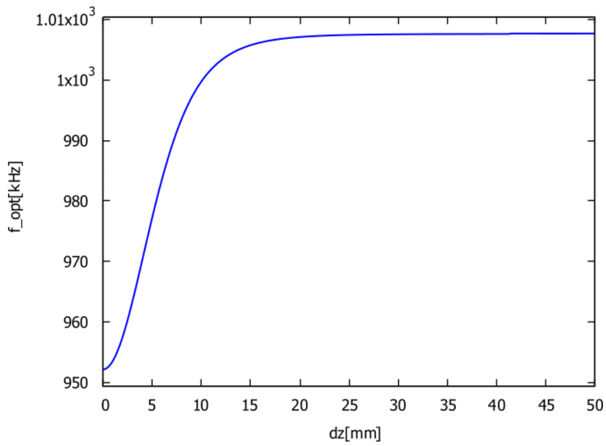

Figure 4. The variation of f_{opt} regarding d_z

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.

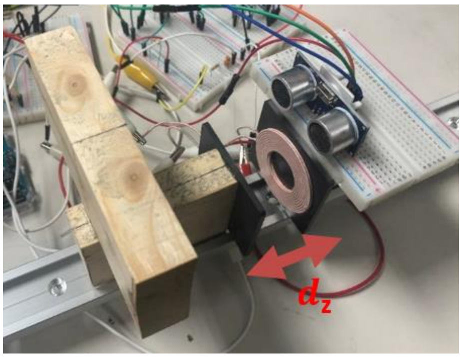

Figure 5. Frequency auto tuning system consisted of Arduino UNO and an ultrasound sensor

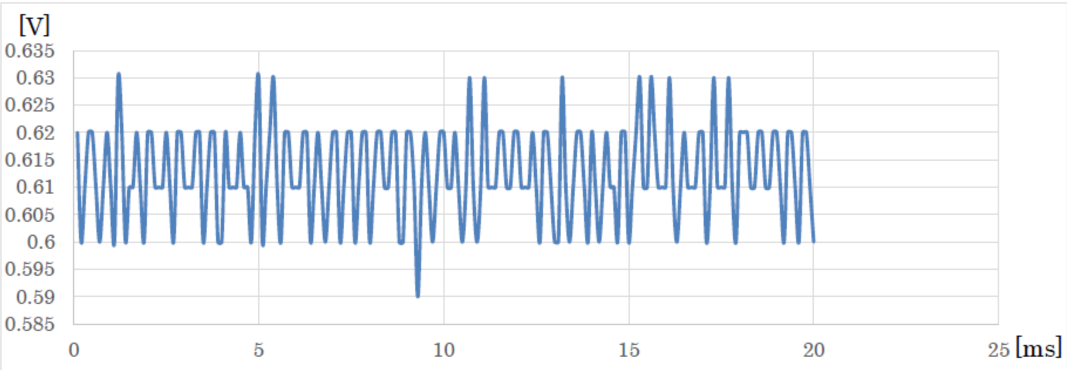

Figure 6. Instantaneous voltage of LED by driven 847 kHz

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.

REFERENCES

[1] K. R. Abbasi, M. Shahbaz, J. Zhang, M. Irfan, and R. Alvarado, "Analyze the environmental sustainability factors of China: The role of fossil fuel energy and renewable energy," *Renewable Energy*, vol. 187, pp. 390–402, Mar. 2022, doi: 10.1016/j.renene.2022.01.066.

[2] R. Sharma, R. K. Kunchala, S. Ojha, P. Kumar, S. Gargari, and S. Chopra, "Spatial distribution of fossil fuel derived CO_2 over India using radiocarbon measurements in crop plants," *Journal of Environmental Sciences*, vol. 124, pp. 19–30, Feb. 2022, doi: 10.1016/j.jes.2021.11.003.

[3] R. Komiyama and Y. Fujii, "Assessment of energy saving and CO_2 mitigation potential by electric vehicle and plug-in hybrid vehicle under Japan's power generation mix," *IEEJ Transactions on Power and Energy*, vol. 133, no. 1, pp. 10–18, 2013, doi: 10.1541/ieejpes.133.10.

[4] S. Wang, P. Yu, D. Shi, C. Yu, and C. Yin, "Research on eco-driving optimization of hybrid electric vehicle queue considering the driving style," *Journal of Cleaner Production*, vol. 343, Apr. 2022, doi: 10.1016/j.jclepro.2022.130985.

[5] P. Lazzeroni, V. Cirimele, and A. Canova, "Economic and environmental sustainability of dynamic wireless power transfer for electric vehicles supporting reduction of local air pollutant emissions," *Renewable and Sustainable Energy Reviews*, vol. 138, Mar. 2021, doi: 10.1016/j.rser.2020.110537.

[6] G. Zhao and J. Baker, "Effects on environmental impacts of introducing electric vehicle batteries as storage - a case study of the United Kingdom," *Energy Strategy Reviews*, vol. 40, Mar. 2022, doi: 10.1016/j.esr.2022.100819.

[7] B.-M. Nguyen, M. Kawanishi, D. Hasegawa, K. Ohara, and T. Narikiyo, "Range extension control of a three-wheel electric vehicle prototype based on aggregation and distribution," *IEEJ Journal of Industry Applications*, vol. 10, no. 5, Art. no. 21000320, Sep. 2021, doi: 10.1541/ieejjia.21000320.

[8] V. Kandasamy, K. Keerthika, and M. Mathankumar, "Solar based wireless on road charging station for electric vehicles," *Materials Today: Proceedings*, vol. 45, pp. 8059–8063, 2021, doi: 10.1016/j.matpr.2021.01.102.

[9] L. Soares and H. Wang, "A study on renewed perspectives of electrified road for wireless power transfer of electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 158, Apr. 2022, doi: 10.1016/j.rser.2022.112110.

[10] X. Wei *et al.*, "A novel dual-load wireless power transfer system applied to electric vehicles and its characteristics analysis," *Energy Reports*, vol. 8, pp. 863–871, Jul. 2022, doi: 10.1016/j.egyr.2022.02.030.

[11] H. Yagi and S. Uda, "On the feasibility of power transmission by electric waves," in *Proceedings of 3rd Pan-Pacific Science Congress Vol. 2*, 1926, pp. 1307–1313.

[12] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, no. 5834, pp. 83–86, Jul. 2007, doi: 10.1126/science.1143254.

[13] C. M. Huang *et al.*, "Implementation of a fiber-based resonant beam system for multiuser optical wireless information and power transfer," *Optics Communications*, vol. 486, May 2021, doi: 10.1016/j.optcom.2021.126778.

[14] Z. Na *et al.*, "Subcarrier allocation based information and power transfer algorithm in 5G cooperative OFDM communication systems," *Physical Communication*, vol. 29, pp. 164–170, Aug. 2018, doi: 10.1016/j.phycom.2018.05.008.

[15] D. B. Ahire, V. J. Gond, and J. J. Chopade, "Coil material and magnetic shielding methods for efficient wireless power transfer system for biomedical implant application," *Biosensors and Bioelectronics: X*, vol. 10, May 2022, doi: 10.1016/j.biosx.2022.100123.

[16] S. Jena, P. K. Sahu, and S. K. Mohapatra, "Efficient wireless power transfer system for biomedical applications," in *Electronic Devices, Circuits, and Systems for Biomedical Applications*, Elsevier, 2021, pp. 405–422.

[17] A. N. Khan, Y.-O. Cha, H. Giddens, and Y. Hao, "Recent advances in organ specific wireless bioelectronic devices: perspective on biotelemetry and power transfer using antenna systems," *Engineering*, vol. 11, pp. 27–41, Apr. 2022, doi: 10.1016/j.eng.2021.10.019.

[18] B. D. Truong, E. Andersen, C. Casados, and S. Roundy, "Magnetoelectric wireless power transfer for biomedical implants: effects of non-uniform magnetic field, alignment and orientation," *Sensors and Actuators A: Physical*, vol. 316, Dec. 2020, doi: 10.1016/j.sna.2020.112269.

[19] P. Dai, D. Zhou, S. Han, Y. Guo, C. Bai, and C. Cai, "Effective wireless power transfer at low-frequency enabled by high-temperature superconducting coils," *Physica C: Superconductivity and its Applications*, vol. 590, Nov. 2021, doi: 10.1016/j.physc.2021.1353952.

[20] J. Kim, H. C. Son, D. H. Kim, K. H. Kim, and Y. J. Park, "Efficiency of magnetic resonance WPT with two off-axis self-resonators," in *2011 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications, IMWS-IWPT 2011 - Proceedings*, May 2011, pp. 127–130, doi: 10.1109/IMWS.2011.5877106.

[21] T. Hosotani, "A novel direct-current-resonance ZVS wireless power transfer system with an electromagnetic resonance field and a 10 MHz-class experiment," *IEICE Technical Report*, vol. 113, 2013.

[22] D. P. Kar, S. S. Biswal, P. K. Sahoo, P. P. Nayak, and S. Bhuyan, "Selection of maximum power transfer region for resonant inductively coupled wireless charging system," *AEU - International Journal of Electronics and Communications*, vol. 84, pp. 84–92, Feb. 2018, doi: 10.1016/j.aeue.2017.11.023.

[23] R. Dengler, "Self inductance of a wire loop as a curve integral," *Advanced Electromagnetics*, vol. 5, no. 1, Jan. 2016, doi: 10.7716/aem.v5i1.331.

[24] K. Yamaguchi and K. Iida, "Auto tuning of frequency on wireless power transfer for an electric vehicle," *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 12, no. 2, pp. 1147–1152, Apr. 2022, doi: 10.11591/ijece.v12i2.pp1147-1152.

[25] L. Zhang, Z. Wang, X. Hu, F. Sun, and D. G. Dorrell, “A comparative study of equivalent circuit models of ultracapacitors for electric vehicles,” *Journal of Power Sources*, vol. 274, pp. 899–906, Jan. 2015, doi: 10.1016/j.jpowsour.2014.10.170.
[26] K. Onishi, K. Yamaguchi, and K. Iida, “Wireless power transfer using multiple-transmitters for high stability for position,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 10, no. 3, pp. 2245–2249, Jun. 2020, doi: 10.11591/ijece.v10i3.pp2245-2249.
[27] H. Tavakkoli, E. Abbaspour-Sani, A. Khalilzadegan, A.-M. Abazari, and G. Rezazadeh, “Mutual inductance calculation between two coaxial planar spiral coils with an arbitrary number of sides,” *Microelectronics Journal*, vol. 85, pp. 98–108, Mar. 2019, doi: 10.1016/j.mejo.2019.01.012.
[28] S. Ferdoush and X. Li, “Wireless sensor network system design using raspberry pi and Arduino for environmental monitoring applications,” *Procedia Computer Science*, vol. 34, pp. 103–110, 2014, doi: 10.1016/j.procs.2014.07.059.

BIOGRAPHIES OF AUTHORS

Kazuya Yamaguchi majored electrical and electronic engineering at Miyazaki University from 2007 to 2016. He established calculation of efficient frequency on wireless power transfer. After that, He transferred to National Institute of Technology, Nara college, and has continued his study. In there, he teaches electric circuit, electromagnetics, and some experiments about electrical and electronic engineering. He can be contacted at email: k-yamaguchi@ctrl.nara-k.ac.jp

Ryusei Okamura was graduated from National Institute of Technology, Nara college, and enrolled in advanced course on the college at 2022. He can be contacted at email: rokamura@nitnc.net.

Haruto Terada was graduated from National Institute of Technology, Nara college at 2022. He can be contacted at email: s10101@nara.kosen-ac.jp.

Kenichi Iida teaches control engineering, electromagnetics, and some experiments about electrical and electronic engineering at National Institute of Technology, Nara college. He can be contacted at email: iida@ctrl.nara-k.ac.jp.