A Frequency-Tracking Algorithm for Inductively Coupled Wireless Power Transfer Systems

Cenk Özdemir and A. Naci Mete

Mersin University, Department of Electrical and Electronics Engineering, Mersin, Turkey
cenkozdemir@mersin.edu.tr, mete@mersin.edu.tr

Abstract

Transmitting power through an air gap without any cable called as Wireless Power Transfer (WPT). Inductive Coupling is one of most preferred method for WPT. In this method, selection of the WPT circuit parameters is done according to the distance between coils. Therefore, changes in distance or medium has great effect on power transfer. In this paper an adaptive frequency tracking method is proposed to reduce the effect of distance or medium changes during recharging period. Proposed algorithm can track the maximum power transfer point with respect to coupling variations. Advantages of the proposed algorithm has been verified by the simulation results.

1. Introduction

The concept of transferring power without wires has been developed at the late 1890s [1]. This concept makes it possible to transfer power through an air gap without any cables. The technological development in the field of Wireless Power Transfer (WPT) has been drawing attention. With the recent applications, more power can be transferred from higher distances with more efficiency in comparing to previous technologies [2]. Thus electronic devices, e.g., mobile phones, laptops, electrical vehicles, can be recharged by using WPT [3].

The WPT system includes two coils, namely a transmitter and a receiver coil. The transmitter coil is energized from a supply and creates a magnetic field. By the force of this magnetic field, induced current is generated in the receiver coil. Selected method for WPT system has remarkable effect on transferred power and efficiency. The common methods for WPT are Inductive Power Transfer (IPT), Microwave Power Transfer (MPT), and Inductive Coupled Power Transfer (ICPT). ICPT and IPT methods are the prevailing methods for the current applications of WPT [4]. In these methods, circuit components have to be selected very carefully in order to work at the resonant frequency.

To keep the transferred power and transfer efficiency at ideal levels, two main types of control methods are used [5-6]. Primary-side control is the first method, which controls the system with the information gathered from the transmitter side of the circuit. This method is suitable for applications requiring avoidance of added complexity necessary for control circuits at the receiver side. Biomedical implants are examples of such applications [7, 8]. Primary-side power flow control [9], and primary-side variable capacitor control [10] are some examples of these methods. The second method directly interfere the secondary side of the circuit and it is called secondary-side control. Secondary-side power control and efficiency maximization [11], secondary-side control using dc-dc converter [12] are examples of this method.

Also, there are some frequency control methods to achieve maximum power transfer and its efficiency. These methods either set a minimum level for efficiency or maximum current level for power transfer. In other words, these methods use pre-set aims to achieve their goal. Another drawback of these methods is discontinuity of charging. In these methods, system searches the ideal frequency for charging. When the search is over, source frequency is set and the charging period starts. In [13], an automatic frequency tuning system tracking the maximum power point with pre-set maximum power information is proposed. However, when the recharging period begins, the tracking system stops. Hence the tracking system proposed cannot detect the changes in recharging period. In [14], the tracking system has a minimum efficiency condition set as 0.7. If the efficiency is high enough, the system will not check the magnitude of power.

In this paper, an adaptive frequency tracking method which can continuously track the ideal frequency at which the maximum power is transferred to the load is proposed. Proposed method aims stable power transfer over varying coupling conditions. Therefore, efficiency of the power transfer is not a primary objective. Any changes during the recharging period can be detected and the operating frequency is adjusted accordingly to achieve maximum power transmission. Frequency splitting phenomenon of overcoupled WPT systems is also considered in the frequency searching algorithm. This method is classified under primary side control techniques since it gathers information from the source and sets the source frequency.

2. Wireless Power Transfer System

Wireless Power Transfer is a method that transmits the power through an air gap with different technologies such as laser, photoelectric, radio waves, microwaves, inductive coupling and magnetic coupling. These technologies are categorized according to transmission range and power rating. Inductive coupling systems are used in short / mid-range applications [15].

2.1. Equivalent Model

Equivalent model of WPT system consist of two circuits, transmitter circuit and receiver circuit. Compensation capacitor of circuits can either be parallel or series to the coil. This choice of capacitor replacement changes the characteristic of WPT system. If the capacitor is parallel to the coil, WPT system will work as a current source and otherwise it behaves like a voltage source [9]. WPT via magnetic resonance coupling with Series-Series topology is examined in this work. Equivalent circuit diagram of this topology is given in Fig. 1. Fig. 2 shows the T-type equivalent circuit diagram of the same system.

We assume that both values of circuit components are equal and the system is fully resonant. Then angular frequency of the transmitter and the receiver are obtained as follows:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \,. \quad \textbf{(1)}$$

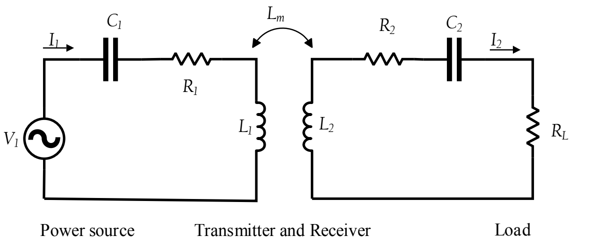

Fig. 1. Equivalent circuit of WPT system

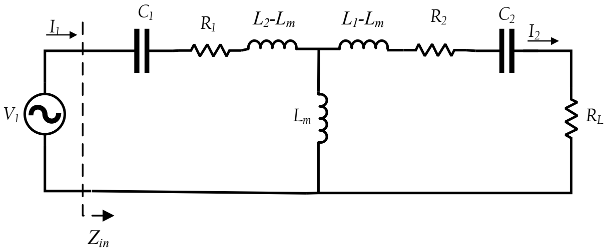

Fig. 2. T–type equivalent of WPT system

The input impedance of this circuit is expressed as:

$$Z_{in} = \frac{V_1}{I_1}(\cos\phi + j\sin\phi). \quad \textbf{(2)}$$

Real and imaginary parts of Z_{in} can be expressed by using circuit parameters as:

$$Re\{Z_{in}\} = R_1 + \frac{(\omega L_m)^2 (Z_L + R_2)}{(Z_L + R_2)^2 + (Z_{A2})^2}, \quad \textbf{(3)}$$

$$Im\{Z_{in}\} = Z_{A1} + \frac{(\omega L_m)^2 (Z_{A2})}{(Z_L + R_2)^2 + (Z_{A2})^2}, \quad \textbf{(4)}$$

$$Z_{A1} = \omega L_1 - \left(\frac{1}{\omega C_1}\right), \quad \textbf{(5)}$$

$$Z_{A2} = \omega L_2 - \left(\frac{1}{\omega C_2}\right), \quad \textbf{(6)}$$

where,

Z_{in}	Input Impedance
$Re\{Z_{in}\}$	Real part of Z_{in}
$Im\{Z_{in}\}$	Imaginary part of Z_{in}
P_{source}	Active power generated by source
V_{source}	Voltage of Source
I_{source}	Current of Source
k	Coupling Coefficient
L_1	Inductance of primary-side coil
L_2	Inductance of secondary-side coil
C_1	Capacitance of primary-side capacitor
C_2	Capacitance of secondary-side capacitor
R_1	Resistance of primary-side coil
R_2	Resistance of secondary-side coil
R_L	Load resistance

By using (3) the charging power P, is found as follows:

$$P = \frac{(\omega_0 L_m)^2 R_L}{(R_2 + R_L)\{R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2\}^2} V_1^2. \quad \textbf{(7)}$$

The transmitting efficiency of this WPT system varies with the change of mutual inductance. However, any change in k, which directly affects the mutual inductance, does not sweep the frequency at where system has maximum efficiency. The maximum efficiency is always obtained at the natural frequency. This is illustrated for two different coupling coefficients in Fig. 3.

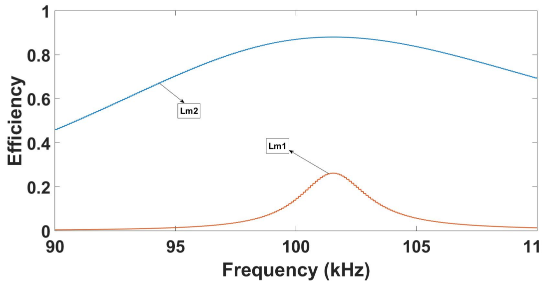

Fig. 3. Efficiency vs. frequency graph for L_{m1}=3.78µH and L_{m2}=57.8 µH

In Fig. 4, the charging power vs. frequency graph is given for two different mutual inductances. As it is seen from the Fig. 4 that the maximum charging frequency sweeps with the change of the mutual inductance value. When the mutual inductance value becomes greater than a critical value, the frequency splitting phenomenon is observed. Two different peak frequencies around the natural frequency arise. It is showed that the smaller frequency has slightly greater efficiency [14].

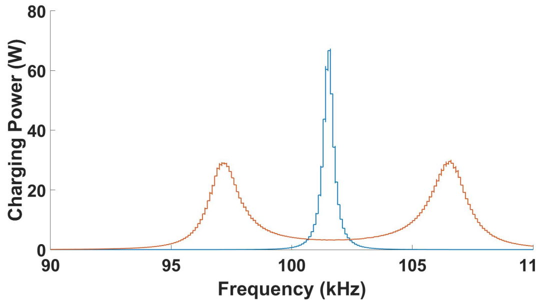

Fig. 4. Power vs. frequency graph for L_{m1}=3.78µH and L_{m2}=57.8 µH

2.2. Proposed Adaptive Frequency Control Method

We propose a method that aims tracking of the maximum power transfer point continuously. By using the information of source voltage and current values, proposed system checks for any change at transmitting power. Then source frequency is adjusted to achieve maximum power transfer accordingly.

In order to understand the algorithm, one should aware of the major problems with frequency tracking. First of all, the algorithm is required to find the peak value of the maximum power without any information about load resistance, distance between coils and medium specifications. If WPT system has only one peak, then the algorithm will increase the frequency to track the maximum power till find the peak. Since the system delivers AC power, the algorithm calculates the average power and tracks it. If the frequency is over increased, the power starts to decrease, and the algorithm returns few steps back to search that frequency interval more detailed. However, the WPT system have two peaks when coils are overcoupled. In this situation, these two peaks are located around the natural frequency (f_r). The algorithm is designed to reach the peak at which power transfer is more efficient. That peak has smaller frequency than f_r [14]. For this reason, the algorithm has a maximum frequency limit as f_r.

Secondly, the algorithm should react the distance or medium changes which directly affect mutual inductance (L_m). In this case not only the maximum power frequency sweeps but also the maximum power level changes. Therefore, the algorithm clears the previous data related with previous L_m and start the frequency tracking over again. To detect any changes, the algorithm checks ΔP periodically. For a desired precision, ΔP can be set preliminarily. When a change exceeding ΔP occurs, the algorithm returns the set stage and clear all power and frequency data. Fig 4. shows the flowchart of the proposed frequency tracking algorithm.

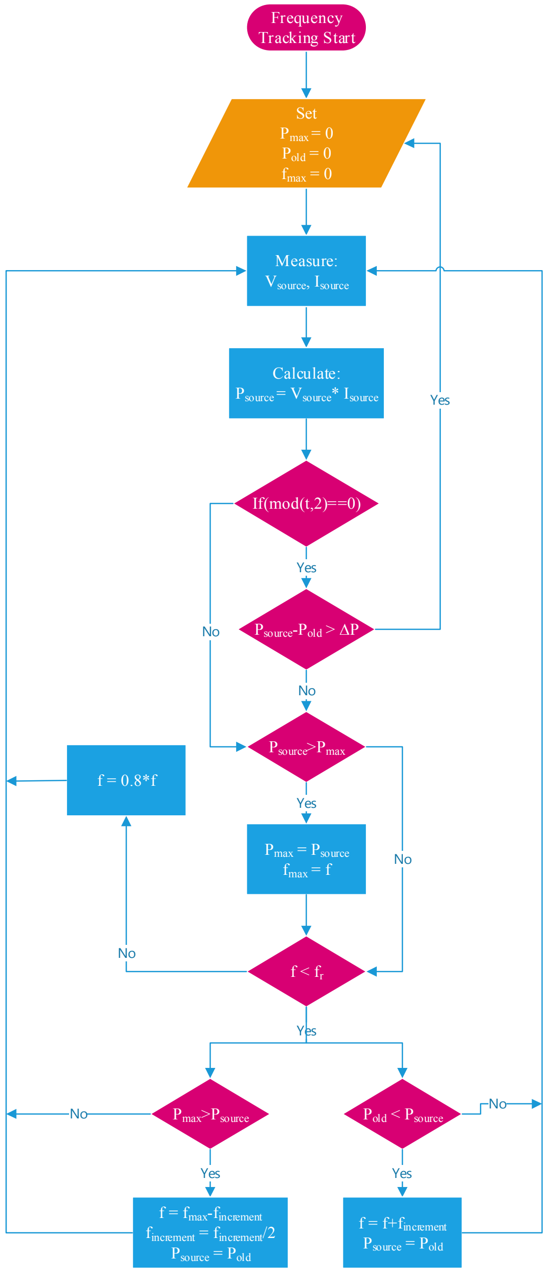

Fig.4 Flowchart of adaptive frequency control method

Where,

P_{source}	Active power generated by source
P_{old}	Previous data of P_{source}
ΔP	Allowed maximum change in supply power
P_{max}	Recorded maximum power
f_{max}	Frequency of P_{max}
f	Frequency of source
$f_{increment}$	Increment step of frequency

In order to implement this algorithm, a voltage source with controllable frequency is needed. Electric network can be used as a source by changing its frequency with high frequency inverter. Also with switching IGBTs, a dc source can be used to get square wave with controllable frequency.

3. Simulation and Results

Simulation of the proposed system was performed on Matlab. In order to get reasonable results, real parameters used. The circuit parameters are taken from [11]. Parameters of the WPT system are given in Table 1.

Table 1. WPT System Parameters

Parameter	Primary-Side	Secondary-Side
Resistance R_1, R_2	1.24 Ω	1.23 Ω
Inductance L_1, L_2	615 µH	615 µH
Capacitance C_1, C_2	4000 pF	4000 pF
R_L		10 Ω
L_{ms1}	37.8 µH	
L_{ms2}	39.8 µH	
L_{ms3}	61.5 µH	

Proposed algorithm was tested with different mutual inductance levels to prove its effectiveness. A case with 3 different mutual inductances is created to represent a slight and a sharp change for recharging conditions. For the first interval which is from t=0 s to t=18 s, L_{ms1} is set to 37.8 µH. For the second interval from t=18 s to t=38 s, mutual inductance is set to L_{ms2} =39.8 µH with a slight increase. In the third interval which is starting after t=38 s, mutual inductance value jumps to L_{ms3}= 61.5 µH.

Fig. 5 shows the frequency tracking response of the WPT system with the proposed tracking algorithm. At t=0 s, the mutual inductance of the system is 37.8 µH. The algorithm finds the frequency at which system transmits maximum power as 98.74 kHz in two seconds. From t=2 s to t=18 s the source works at this frequency. Then at t=18 s, mutual inductance is slightly changed and the new settled frequency is obtained as 98.50 kHz. At t=38 s, there is a sharp change of mutual inductance from 39.8 µH to 61.5 µH. The system starts tracking again and the frequency is tuned as 96.63 kHz.

Fig. 6 shows the amount of transferred power during recharging period for the WPT system with the proposed frequency tracking algorithm. For the first interval, system transmits 30.33 W which is maximum available power at 98.74

kHz. When the mutual inductance was increased slightly from 37.8 µH to 39.8 µH, transmitted power remained almost unchanged and became 30.06 W. After the sharp increase of mutual inductance value to 61.5 µH, transmitted power showed a slight decrease to 27.13 W. Fig. 7 shows the transmitted power amount against the time for the same WPT system without frequency tracking. There is a significant power drop from 28.02 W to 6.03 W at the third interval where a sharp increment of mutual inductance value occurred. The advantage of frequency tracking system is obvious against constant frequency system. Simulation results are also summarized in Table 2.

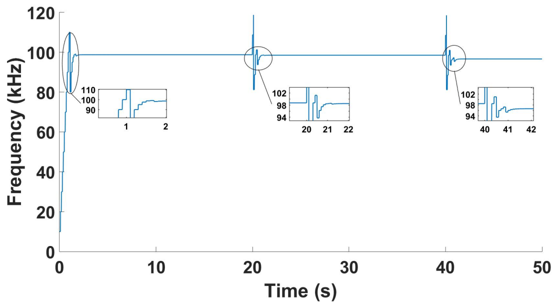

Fig. 5. Frequency vs. time graph of WPT system with frequency tracking algorithm

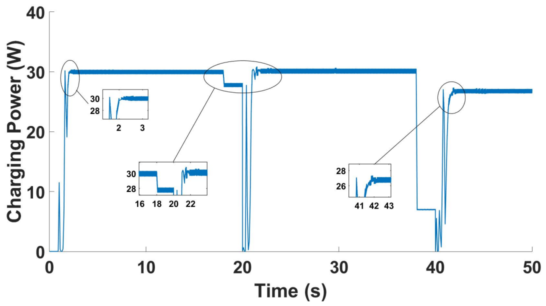

Fig. 6. Charging Power vs. time graph of WPT system with frequency tracking algorithm

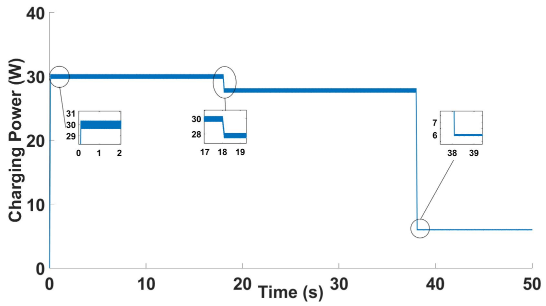

Fig. 7. Charging Power vs. Time graph of WPT system at constant frequency, f=98.74 kHz

Table 2. Simulation Parameters and Results

Parameter	t < 18 s	18 s < t < 38 s	t > 38 s
L_{ms1}- L_{ms2}- L_{ms3}	37.8 µH	39.8 µH	61.5 µH
P with tracking	30.33 W	30.06 W	27.13 W
f_{Pmax}	98.74 kHz	98.50 kHz	96.63 kHz
P without tracking	30.33 W	28.02 W	6.03 W
Constant f	98.74 kHz	98.74 kHz	98.74 kHz

When the algorithm tracks the maximum power transfer point, it also keeps the efficiency of transmitting power at an acceptable level. Fig. 8 shows that the efficiency is around 80% at transmission period for the WPT system considered.

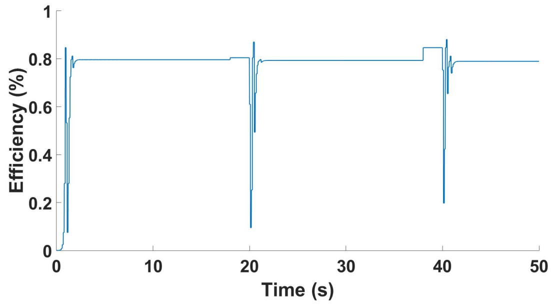

Fig. 8. Efficiency vs. time graph of WPT system with frequency tracking algorithm

4. Conclusions

In this paper, a new adaptive frequency tracking algorithm is proposed and simulated. Simulation of the proposed system performed on Matlab. The proposed algorithm can track the frequency to obtain maximum power transfer. The influences of medium and distance on power transfer are minimized. Also the proposed algorithm can select the best efficiency in frequency splitting situations.

Structure of WPT system should be designed according to estimated distance between transmitting and receiving coils. The change in distance dramatically affect transmitted power without frequency control. Simulation results prove that, WPT systems with the proposed algorithm can continuously transmit maximum available power even if the coupling coefficient varies.

To future work, proposed algorithm will be implemented experimentally and simulation results will be verified. Also half active rectifier will be implemented to the seconder circuit of WPT system in order to get DC output voltage.

5. Acknowledgement

This work was supported by the Mersin University Research Foundation under project number 2017-1-TP2-2269.

6. References

[1] N. Tesla, “Apparatus for transmitting electrical energy,” U.S. Patent 1 119 732, Dec. 1, 1914.

[2] K. Wu, D. Choudhury, and H. Matsumoto, “Wireless power transmission, technology, and applications,” Proc. IEEE, vol. 101, no. 6, pp. 1271–1275, Jun. 2013.

[3] J. Kim, D. H. Kim, J. Choi, K. H. Kim, and Y. J. Park, “Free-positioning wireless charging system for small electronic devices using a bowlshaped transmitting coil,” IEEE Trans. Microw. Theory Techn., vol. 63, no. 3, pp. 791–800, Mar. 2015.

[4] J. Dai and D. C. Ludois, “A survey of wireless power transfer and a critical comparison of inductive and capacitive coupling for small gap applications,” IEEE Trans. Power Electron., vol. 30, no. 11, pp. 6017–6029, Nov 2015.

[5] H.L. Li, A.P. Hu, G.A. Covic, T. Chunsen, “A new primary power regulation method for contactless power transfer”, IEEE International Conference on Industrial Technology (ICIT), pp. 1-5, 2009.

[6] W. Chwei-Sen, O.H. Stielau, G.A. Covic, "Design considerations for a contactless electric vehicle battery charger", IEEE Transactions on Industrial Electronics, vol. 52, pp. 1308-1314, 2005.
[7] Y. Luo, Y. Yang, S. Chen, and X. Wen, "A Frequency-Tracking and Impedance-Matching Combined System for Robust Wireless Power Transfer," International Journal of Antennas and Propagation, vol. 2017, pp. 1-13, 2017.
[8] A. P. Sample, D. A. Meyer, and J. R. Smith, "Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," IEEE Trans. Industrial Electronics, vol. 58 (2), pp. 544-554, 2011.
[9] J. Miller, O. Onar, and M. Chinthavali, "Primary-side power flow control of wireless power transfer for electric vehicle charging," IEEE J. Emerg. Sel. Topics Power Electron., vol. 3, no. 1, pp. 147–162, Mar. 2015.
[10] J. Tian and A. P. Hu, "A DC-voltage-controlled variable capacitor for stabilizing the ZVS frequency of a resonant converter for wireless power transfer," IEEE Trans. Power Electron., vol. 32, no. 3, pp. 2312–2318, 2017.
[11] K. Hata, T. Imura and Y. Hori, "Dynamic wireless power transfer system for electric vehicles to simplify ground facilities - power control and efficiency maximization on the secondary side," Proc. of IEEE Applied Power Electronics Conference and Exposition (APEC), 2016, pp. 1-6.
[12] M. Kato, T. Imura, and Y. Hori, "Study on maximize efficiency by secondary side control using dc-dc converter in wireless power transfer via magnetic resonant coupling," in Proc. World Electr. Veh. Symp. Exhib., Nov. 2013, pp. 1–5.
[13] D. Kar, P. Nayak, S. Bhuyan, and S. Panda, "Automatic frequency tuning wireless charging system for enhancement of efficiency," Electronics Letters, vol. 50, pp. 1868-1870, 2014.
[14] K. Nam Yoon, K. Ki Young, R. Young-Ho, C. Jinsung, K. Dong-Zo, Y. Changwook, et al., "Automated adaptive frequency tracking system for efficient mid-range wireless power transfer via magnetic resonanc coupling," in Microwave Conference (EuMC), 2012 42nd European, 2012, pp. 221-224.
[15] F. Lu, H. Zhang, H. Hofmann, and C. C. Mi, "An Inductive and Capacitive Combined Wireless Power Transfer System With LCCompensated Topology," IEEE Transactions on Power Electronics, vol. 31, pp. 8471-8482, 2016