www.ijemr.net ISSN (ONLINE): 2250-0758, ISSN (PRINT): 2394-6962

Vandana Publications
IJEMR

Volume-7, Issue-3, May-June 2017
International Journal of Engineering and Management Research
Page Number: 778-782

Adaptive Control of the Receiver by Resonant Frequency Estimation in Strongly Coupled Magnetic Resonance based Wireless Power Transfer

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ABSTRACT

This article proposes a novel method for controlling the resonance frequency of the receiver coil in magnetically coupled resonance-based wireless power transmission. We utilize the output voltage levels at the receiving coil corresponding to different operating frequencies by adjusting the tuning capacitor. The acquired data points were then parameterized using Gaussian model, whose mean is used to indicate the location of resonance frequency. This procedure is iterated to fine tune the resonant frequency of the receiver circuit to that of the transmitter circuit thereby improving the overall efficiency of the wireless power transfer system. Proposed method is validated with theoretical formulation and experimental prototype of the wireless power transfer system.

Keywords-- Wireless Power Transmission; Strongly Coupled Magnetic Resonance; Frequency Adaptation

I. INTRODUCTION

Experimental demonstration with the theoretical formulation of strongly coupled magnetic resonance-based wireless power transfer by Kurs et al. [1] intensified the research activity in the area of wireless power transfer. Many researchers have contributed to this area by proposing various insights and modifications to the model proposed by Kurs et al. The performance of the wireless power transmission technique is influenced by factors such as operating frequency, the distance between transmitter and receiver, load at the receiving end, material of the coils, matching of the resonant frequency of both the coils and many others. These factors have been the subject of various research articles such as parameter optimization [2–4], range adaptation [5], efficiency improvement [6], operating frequency tracking [7, 8], energy efficiency optimization [9], and others [10–12]. Since the power transfer is carried out according to the concept of strongly coupled magnetic resonance, frequency tuning between transmitting and receiving coils plays a crucial role for the efficiency and the range of the power transfer. It is possible to make both resonant circuits (transmitting and receiving) to operate at same frequency theoretically; but since it involves design and construction of an inductor coil, the experimental values deviate from those that are calculated carefully from theoretical equations. Thus, fine tuning of the resonant frequency between transmitting and receiving coils becomes a necessity but at the same time tedious and time-consuming.

We propose a novel technique to fine tune the resonant frequency by adjusting the tuning capacitor of receiving coil and controlling it using inexpensive hardware such as Arduino. Tuning of the capacitor can be achieved by mechanical or electronic manipulations. We change the value of the variable capacitor of receiving coil from minimum to maximum in coarse scale and record the corresponding output voltage. The recorded data is then modeled using the Gaussian curve and its mean provides rough estimates for resonant frequency. These estimates are then further fine tuned by changing the value around mean with finer scales. When the receiving coil is in resonance with transmitting coil, it improves efficiency and range of the overall power transmission. Finally, this method is validated via experimental prototype designed in our laboratory.

Section 2 describes the process and methodology of the proposed approach. Section 3 gives complete details about experimental setup and discusses the experimental results. Finally, we conclude our paper in Section4.

II. METHODOLOGY

2.1 System Construction:

Oersted’s experiment demonstrates that when the current flows through the conductor, the magnetic field of proportional magnitude will be generated around the conductor. The range of the magnetic field (in terms of distance from the coil) depends up on many factors like amount of current passing through the coil, the frequency of the alternating current, etc. On contrary, Faraday's experiment demonstrates that when the conductor coil comes under the influence of varying the magnetic field, the emf will be induced in the coil. Modern wireless power transmission technique combined these two experiments to transfer power from one coil to another that are kept at a distance from each other. The maximum power efficiency is confirmed when two coils resonate at the same frequency. In this research work, we built a strongly coupled magnetic resonance-based wireless power transfer system for investigation of proposed methodology and demonstrate the need for automatic tuning of receiver resonance.

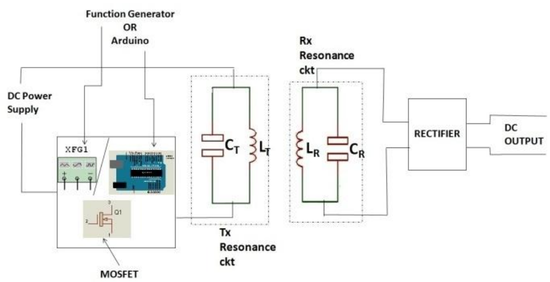

Figure 1: Structure of strongly coupled magnetic resonance wireless transfer

A generic structure of the strongly coupled magnetic resonance-based wireless power transfer system is outlined in figure1. The transmitting resonance circuit is formed by parallel connection of copper coil LT and capacitor CT that generate the non-radiative magnetic field around the copper coil. This coil is energized by providing power from the DC source, preferably solar panel. This DC power is controlled by power MOSFET to create a high frequency signal by providing the gate of power MOSFET with a low power high frequency function generator. It can also be controlled by inexpensive high frequency generators such as micro-controller board, astable multivibrator etc. The receiving circuit is formed by the identical copper coil as that of the transmitter circuit .A parallel connection of copper coil LR with tuning capacitor CR forms the resonant circuit that resonates at the resonance frequency of the transmitter. The receiver circuit can be tuned to transmitter resonance by adjusting the tuning capacitor.

We use function generator (Scientech4061) as a high frequency source which is directly connected to the parallel L-C circuit consisting of transmitting copper coil (see table 1 for specifications) and a tuning capacitor. An identical copper coil, which is kept at a distance of 30 cm from and in perfect alignment with the transmitting coil, is used as a receiving coil. This coil is connected in parallel with a variable air gang capacitor which can be adjusted either mechanically or electronically. This forms a parallel L-C resonant circuit at the receiving end whose resonance frequency is given by the equation:

$$f_o = \frac{1}{2\pi\sqrt{LC}} \quad \text{--(1)}$$

When the receiver circuit with same resonance frequency is kept near the transmitter, the voltage with same frequency is generated in the receiving coil, which is visualized using an oscilloscope. Complete setup of the wireless power transfer system is depicted in figure 2.

TABLE I
COIL SPECIFICATIONS

	Tx Coil	Rx Coil
Diameter of the wire (w)	3.21 mm	3.21 mm
Spacing between the coils (p)	10 mm	10 mm
Number of Turns (N)	15	15
Outer Diameter (Do)	350 mm	350 mm
Inductance (L)	40 µH	36.5 µH

Figure 2: Complete experimental setup for tuning of receiving coil in strongly coupled magnetic resonance based wireless power transfer system.

Spiral copper coil was designed according to the wheeler's formula for a single-layered helical coil [13],

$$L(H) = \frac{N^2(D_O - N(w+p))^2}{16D + 28N(w+p)} \times 39.37 \times 10^6 \quad \text{--(2)}$$

Power loss in a spiral coil consists of radiation and conduction losses. Typically WPT coils are relatively small compared to operating wavelength. Thus the conduction loss is the dominating loss mechanism, while radiation loss is typically negligible. Conduction loss depends up on the skin effect and proximity effect. Both effects confine the current flow to smaller cross-sectional areas through the conductor; which increases the effective resistance of the conductor [13].

2.2 Flowchart

Flowchart of the proposed methodology is given in figure 3. The main idea of the proposed approach lies in the fact that the resonant frequency can be achieved without explicitly measuring the operating frequency of the transmitter. Change in the tuning capacitor value changes the resonant frequency of the receiving circuit. When this resonant frequency matches with the transmitting circuit, power transfer will be maximum and hence the efficiency will be maximum. This efficiency decreases suddenly as we try to change the frequency of receiver away from the resonant frequency. This behavior of the reduction in power transfer can be modeled using the normal distribution.

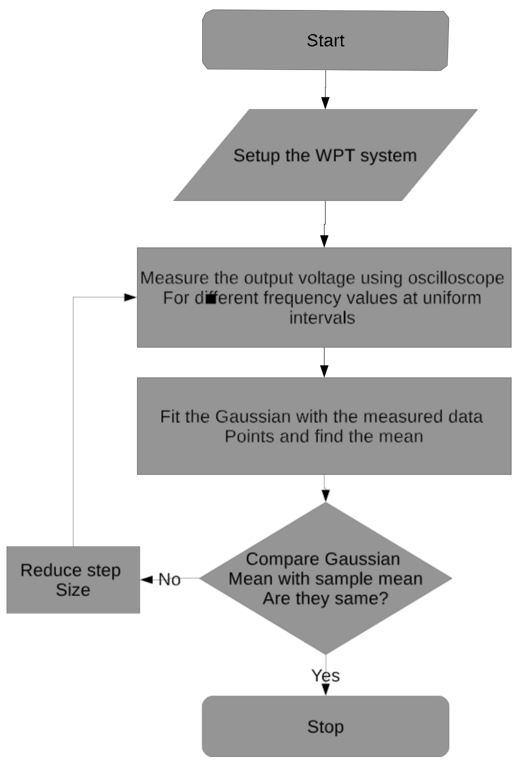

Figure 3: Flowchart of the proposed system

In proposed approach, we change the value of tuning capacitor from minimum value to the maximum value in coarse steps. This will give us an idea about the probable location of resonant frequency with respect to tuning capacitor's position. We further fine tune the position by changing the value of capacitor along this position with finer steps. This procedure further reiterated by reducing the size of scale in which we change the capacitance value of the tuning capacitor. We terminate the tuning process when there is no much of improvement even after fine tuning.

III. EXPERIMENTAL RESULTS

The complete wireless power transfer system was constructed according to the parameters discussed in the previous section. The complete setup is shown in figure 3. The capacitor (0.01µF) was then connected across the receiving coil that forms the resonant circuit. The inductance value of the receiving coil was measured using LCR meter and found to be 40µH. Therefore, the theoretical value of the resonance frequency, calculated using equation (1) becomes 251.65 kHz. We then supply high frequency power directly from function generator by controlling the frequency in the steps of 2 kHz starting from 246 kHz up to 270 kHz. This high frequency current generates the magnetic field around the transmitting coil, thus inducing the voltage of same frequency into the receiving coil. This voltage is visualized using an oscilloscope for qualitative analysis and measurement. The same procedure was repeated by changing the value of the capacitor in the receiving circuit to 0.022 µF. The resonant frequency of this circuit becomes 169.65 kHz. We then tabulate those values as shown in table 2.

TABLE II
RECORDED OUTPUT VOLTAGE AGAINST OPERATING FREQUENCY

Capacitor value 0.01μF		Capacitor value 0.022μF	
Frequency (kHz)	Output voltage (V)	Frequency (kHz)	Output voltage (V)
246	7	160	5.5
248	9	162	7
250	11	164	10
252	14	166	17
254	20	168	23.5
256	34	170	14
258	40	172	10
260	23	174	7
262	16	176	5
264	12		
266	9		
268	8		
270	6		

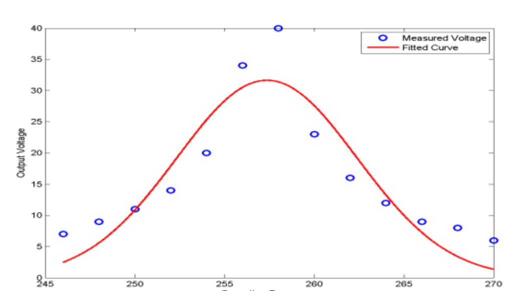

Figure 4: Recorded data points and its Gaussian function fitting for *0.01 pF*

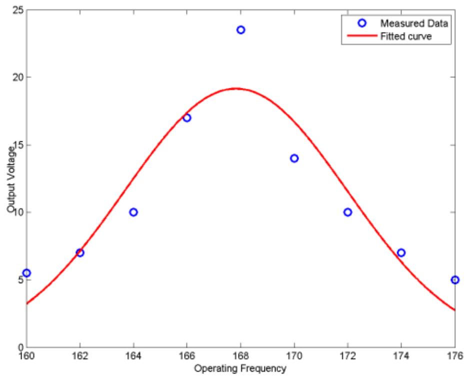

Figure 5: Recorded data points and its Gaussian function fitting for ***0.022 pF***

We then fit the acquired data in the Gaussian function using MATLAB's fit function. Graph of output voltage against operating frequency is shown in figure 4 and 5. The mean value of this Gaussian function gives us the resonant frequency under working condition. By this method, the resonant frequency calculated was 257.4 kHz for capacitor value 0.01 µF and 167.8 kHz for capacitor value 0.022 µF. The system may be fine-tuned further by reducing the step size and selecting frequencies around this estimated frequency.

In real-time applications, this process may be automated by replacing the capacitor of receiving coil by the variable capacitor and changing its value by mechanical or electronic manipulations. First, by changing the capacitance at the coarse level and recording the data points, fitting them on to Gaussian function and finding the resonant frequency in terms of capacitor position. Iterating this procedure further by making fine adjustment to the capacitor, receiving coil may be tuned to the exact resonant frequency of the transmitting coil, thereby achieving the maximum efficiency of the wireless power transmission system.

In order to validate this concept, we connected a variable capacitor (10–300pF) across receiving coil making it a resonant circuit, whose resonant frequency been controlled by tuning the value of the capacitor. The tuning capacitor was then adjusted using stepper motor controlled by Arduino UNO. The output voltage values were then recorded using same Arduino board. These recorded values were modeled using the Gaussian function inside Arduino using a small C program. Then the capacitor value is adjusted according to the resonant frequency obtained from the Gaussian function.

It was observed that the resonant frequency tuning performed using Arduino provides better efficiency as compared to the manual tuning. Moreover, in manual tuning instruments like oscilloscope, multimeters are required. Connecting them to the real-time system affects the overall efficiency of the system, which is effectively avoided by proposed automatic tuning method.

IV. CONCLUSION

We proposed a novel method for improving an efficiency of the wireless power transmission system by adjusting and tuning the resonant frequency of the transmitting and receiving circuits. It was observed that the range of the tuned circuits is extended up to 300 mm at very low power levels with much better efficiency. One may further investigate the possibility of making complete system automatic, and without human intervention in the tuning process. The complete system proposed in this article may be used for charging of electric vehicles such as bicycles by keeping receiving coils on the front wheel of the cycle which will automatically tune to the resonant frequency of transmitter thereby warranting the efficient transfer of electric power for charging the battery of the bicycle.

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