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Wireless Power Transfer to Charge Mobile Devices in Automobile Vehicles by using Solar Energy

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ABSTRACT

We discuss the low cost, yet effective solution to create power fidelity inside the automobile vehicle to power-up the mobile devices. The proposed system consists of off-the-shelf electronics components such as high frequency generators; power MOSFETs for high frequency power amplification; copper coils for generating magnetic field; etc. The detailed guidelines for the components selection and thereby design of complete system forms the main theme of this paper. The experimental prototype of the system substantiates the practical applicability of the proposed system for efficient transfer of solar power making mobile devices truly portable.

Keywords**—** Wireless power transfer, Strongly coupled magnetic field, Solar power, Magnetic Resonance, Mobile charger

I. INTRODUCTION

We live in the era where mobile devices like cell phones, tablets, PDA, laptops etc became the fourth basic need of humanity after food, shelter, and clothing. These devices have made our life more comfortable, efficient and portable. However, unlike three basic needs, the fourth need is a power hungry. They need to be charged on regular basis. During this period, the meaning of portability is lost completely since it has to be connected to the wall outlet. Moreover, when we are traveling in a vehicle, suppose a car, we need to generate the electricity for charging mobile devices using the alternator connected to the axle of that vehicle. If the power is generated using photo-voltaic (PV) cells on the rooftop and transferred without wires to the devices, it will keep electrical system independent of the other systems of the vehicle. Moreover we can connect the mobile devices to power source just like connecting them to Wi-Fi hotspot, creating the network of power fidelity.

Advancement in Photo-voltaic cells technology enables low-cost and efficient solar panels that can be mounted on the rooftop of houses or vehicles. On the other hand, recent activity of wireless power transfer (WPT) using strongly coupled magnetic field gives efficient mid-range wireless transfer of electrical power up to 2 to 10 meters [1].

The WPT systems typically fall into one of two categories; short range (near- field) and long range (far-field) designs. Modern literature on wireless power transmission falls into one of the following three categories, namely, inductive coupling, electromagnetic radiation (EMR), and strong coupling of magnetic field at resonance.

A transformer is an example of an inductive coupling. When an AC source is connected to a primary coil, the generated magnetic field induces a voltage across the terminals of the secondary coil of the receiver. This technique, having high power transfer efficiency for the short range, is simple, safe and convenient. This enables us utility of this technique for the applications like electric toothbrush; charging pads [2] for cell phones, laptops; and medical implants [3]; etc. This technique works better if the nodes are close to each other, especially less than a coil diameter and having a perfect alignment for charging direction, however its efficiency drops significantly as we increase a distance even by a small amount. This keeps the limitation on the application of this technique for our proposed system.

Another technique for WPT is to development of microwave power transmission [4]. Transmitting antenna transmits the electromagnetic radiations to receiving antenna in the form of electromagnetic waves. They are classified into two types as per the energy-emitting direction such as Omni-directional and unidirectional. The Omni-directional transmitter emits electromagnetic waves in ISM band (e.g., 850 – 950 MHz [5] or 902 – 928 MHz [6]. Receiver (E.g., RFID tags) harvests the radio power by tuning it to the same frequency band. But, the electromagnetic waves decay quickly over distance [1]. The Omni-directional radiation is appropriate for ultra low-power sensor nodes (e.g., up to 10 mW [4, 5]) with very low sensing activities (e.g., temperature, moisture, and light) to prevent potential health hazards. The unidirectional transmitter needs Line of sight path and it can achieve high power transmission over kilometer range by using laser or microwave. It works on ISM band (2.45 or 5.8 GHz). However, because of LOS requirements, complicated tracking mechanisms, and inherently large scale of devices, it is not suitable for transfer of power inside complicated environment such as automobile vehicle.

Kurs et al. [1] have developed a strongly coupled magnetic resonance based technique for WPT. In this technique, when two magnetic resonant coils operate at the same frequency (desirably high frequency up to 10 MHz), they become strongly coupled by non-radiative magnetic resonant induction. This enables the efficient transfer of energy from a source coil to a receiver coil with negligible loss of energy. Magnetic resonant coupling has the higher power transfer efficiency even under Omni-direction, and does not require line of sight constraint. The application, this technology is used to charge multiple devices, mutual coupling among various receiving coils and other objects may cause interference, and therefore careful tuning is necessary. It is also used for charging electric vehicles, implantable devices and the wireless sensor networks.

The main idea of this article is a system in which solar power is generated at the top of a vehicle and then it is transferred, using magnetically coupled resonance coils, to the mobile devices. The system can be a cost-effective way since we are using off-the-shelf and easily available electrical components. The theoretical foundation of the resonance circuit, calculations of the inductance, capacitance and Q-factor, and experimental design is discussed in section 2. While, complete details about experimental setup and discusses the experimental results is discussed in section 3. Finally, article is concluded in section 4.

II. THEORETICAL FOUNDATION

2.1 Resonance Circuit Theory

Oersted's experiment demonstrate 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 upon many factors like amount of current passing through the coil, the frequency of the alternating current, etc. On the contrary, Faraday's experiment demonstrates that when the conductor coil comes under the influence of varying magnetic field, the potential (e. m. f.) will be induced in the coil. Modern WPT technique combines these two experiments to transfer power from one coil to another that are kept at a mid range distance from each other. The maximum power efficiency is confirmed when two coils resonate at the same frequency.

In this research work, we are developing a wireless power transmission based system to transfer the solar power generated on the roof top of the vehicle to the mobile devices present inside the vehicle. The experimental block diagram of the proposed approach is given in figure 1.

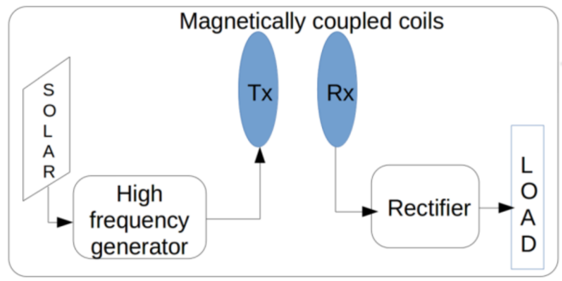


Figure 1: The experimental prototype for wireless transfer of solar power to a mobile charger

We feed the DC power generated by solar panel to the ultra-fast switching MOSFET, whose gate is controlled by high frequency at 71 KHz. This frequency is generated by simple 8 bit micro-controller using an Arduino-based platform. The generated high-frequency signal is then fed to the parallel L-C circuit, which resonated at the frequency given by the equation:

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

When the receiver circuit with same resonance frequency is kept near the transmitter, the potential (e. m. f.) of same high frequency is generated in the receiving coil, which is converted to DC via simple rectifier circuits, so that it can be used for charging the mobile devices. Subsequent sections provide guidelines for coil design and component selection.

2.2 Calculations of the Component Values

Basic requirement of magnetically coupled resonance system is the resonant coil that consists of parallel circuit of inductor and capacitors. Thus, design of transmitter and receiver resonant circuits, esp. inductor coils becomes crucial part of the complete system design. We choose a spiral planar coil using copper wire of proper gauge.

TABLE 1: NOMENCLATURE OF THE SYMBOLS

Symbol	Meaning
N	number of turns
Do	outermost diameter of coil
Di	inner diameter of coil

p	Spacing between adjacent turns
w	Width of the copper wire

Inductance

The self-inductance for the spiral coils L is derived from the wheeler's formula for a single-layered spiral coil [7],

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

Since inductor design is highly complex and sensitive to the choice of material and design structure, final value of the inductance deviates from the theoretical value. Proper frequency tuning is needed to achieve higher efficiency. Moreover, for efficient transmission of power it is always desired to have a higher quality factor (Q).

Capacitance

The tuning capacitor for resonance at about 71 KHz is one of the orders of a few microfarads and is small. The value of required tuning capacitor can be calculated using the inductance of copper coil, which we designed in last subsection and the given resonant frequency, f of the transmitter coil by the equation:

$$C(F) = \frac{1}{(2\pi f)^2 L} \quad (3)$$

Note that the parasitic self-capacitance is neglected for this simple expression.

Quality Factor

Using inductance of copper coil (L), tuning capacitor (C), and resistance of the resonant circuit (R); we can write the expression for quality factor (Q) as:

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \quad (4)$$

$$R = R_{dc}\frac{w}{4\delta} = \sqrt{\frac{f\pi\mu_o}{\sigma}}\frac{N(D_o - N(w+p))}{w} \quad (5)$$

$$R_{dc} = \frac{1}{\sigma\pi(w/2)^2}, \delta = \frac{1}{\sqrt{\pi f \sigma \mu_o}} \quad (6)$$

Here, R is Resistance of the spiral coil from very high-frequency model of AC resistance from Kaiser [8]. This expression can be used to optimize coil design for high Q and ensure resonance at the desired operating frequency.

Power loss in a spiral coil happens via two modes, namely, radiation and conduction. Since typically coils used for WPT are relatively small compared to operating wavelength (at 71 KHz), loss due to conduction dominates the loss due to radiation. In addition, WPT via strongly coupled magnetic field uses Evanescent wave coupling, which in non-radiative. This makes radiation losses in WPT negligible. Conduction loss depends upon the skin effect and proximity effect. Both effects confine the current flow to smaller cross-sectional areas through the conductor that increases the effective resistance of the conductor [7].

For the spiral coils, the parameter that contributes most to fluctuations in total resistance *R* is the pitch *p*. Because of the proximity effect, *R* is inversely proportional to *p*, and the effect is nonlinear. For tightly wound coils, accurate expressions for *R* that account for the proximity effect are complex and can be difficult to calculate [7]. For loosely coupled wound coils, the proximity effect can be negligible, so a similar *R* consists of the DC resistance R_{DC} and the skin depth delta, which can be approximated with expression is the shown in equation no 5 and 6. Where μ_o is the permittivity of the free space and the delta is the conductivity of the conductor δ = 59.6 x 106s/m for copper.

III. EXPERIMENTAL RESULTS

3.1 Experimental Design

In order to validate the performance of the proposed system, we constructed a prototype of the complete system. Figure 2 shows the block diagram of the experimental prototype. The solar panel is used as a power source. The Arduino Uno is used to generate and control the frequency via square wave generation. This square wave controls the gate of n-channel MOSFET (IRFP250N) for high speed switching. This high speed switching converts the DC power generated from solar panel into high frequency power which can directly fed into the transmitter resonant circuit.

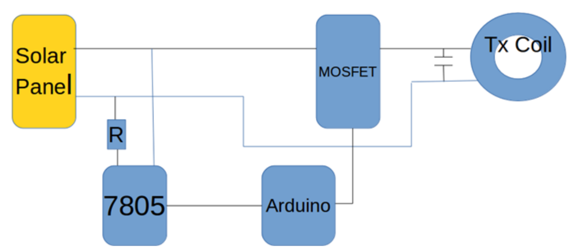


Figure 1: Experimental Setup

A small program was written in MATLAB to optimize the parameters and structure of the transmitter and receiver coils. We have calculated the values of the inductance for transmitter and receiver coils by defining the number of turns, pitch between them, wire gauge, etc. The transmitting and receiving coils were designed on the plain surface with the help of guideline maps generated using HFSS. The inductance of the coils was then verified using LCR meter. The inductances of Transmitter and receiver coils were measured to be 28.7 μH and 26.8 μH, respectively. These obtained values are found to deviate from the simulated and theoretical values. This is attributed to the fabrication error and can be reduced by careful selection of material and proper machining of the fabrication.

3.2 Coil Specifications

Table 2 below the values the parameters calculated to optimize. We have considered the frequency about 71 kHz for calculation of inductance. Capacitor used is of the value 0.022µF, which gave the value of inductance to be L = 22.743µH

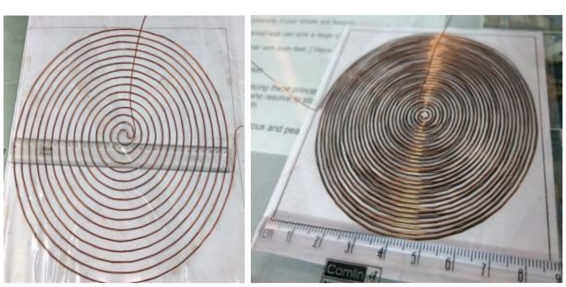
TABLE I
UNITS FOR MAGNETIC PROPERTIES

	Rx coil	Tx coil
Diameter of the wire (w)	0.315 mm	1.016 mm
Spacing between the coils (p)	1.1 mm	9.5 mm
Number of Turns (N)	29	15
Outer Diameter (Do)	82 mm	320 mm
Guage of the copper wire	32	19
Inductance (22.743 µH) (calculated by simulation software)	22.645 µH	24.455 µH
Inductance(measured on L-C-R meter)	26.8 µH	28.7 µH

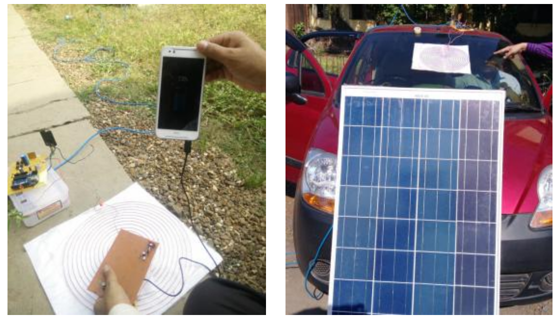
3.3 Results

For the prototype development, we first developed the primary and secondary coils as per the design specifications. The primary (Transmitter) coil is made up of 19 Gauge copper wire with 15 turns, 9.5 mm spacing [fig. 3(a)], whereas secondary (Receiver) coil is made from copper wire of 32 Gauge with 29 turns, 1.1 mm spacing [fig. 3(b)]. The inductance of the coil is about 25µH for both the primary and secondary calculated mathematically as well as measured on the L-C-R meter matches the inductance. Figure 3(c) shows the solar panel which will be mounted on the rooftop of the vehicle, and be used for generating DC power, which can be utilized as a source of electricity inside the vehicle such as charging mobile devices, powering miniaturized fan modules, playing car stereo, etc.

Initially, we conducted the experiment by controlling the primary coil using the pulse generator to study the effect of different waveforms on the efficiency of the system as a whole. It turns out that pure sinusoidal signal provides the best performance among all the waveforms which are supported by simple lab function generator. Since the generation of a pure sinusoidal signal at higher power rating is comparatively expensive, we opted for next candidate in-line: the square wave.



(a) Transmitter Coil **(b) Receiver Coil**



(c) Complete Setup **(d) Mobile charging setup**

Figure 3. Experimental Results

Generation of square wave using an 8-bit microcontroller is fairly cheap as computationally suitable for low-cost operations. The only issue with the square waves generated by microcontrollers is that their amplitude lies between 0 to 5 V, and their current capability is very low. To adapt these waveforms to a higher power we use the high-speed switching Power MOSFET. This MOSFET controls and converts the DC current generated by the solar panel to high-frequency alternative current. LEDs are used as the load to the secondary. We investigated the power transmission quality between primary and secondary coils at various frequencies. It was observed that the wireless power transmission supports the longest distance of 21 cm at about 70 KHz.

We then adopted this experiment for mobile charging. First, we have conducted the experiment at outdoor and then in the car [fig. 3(c and d)]. We have connected the output of the solar panel to the input of the MOSFET, which was triggered by the frequency generated using Arduino board. High frequency output of the MOSFET is used to excite the primary coil. Arduino is powered through tapping the solar panel output and regulating it using voltage regulator (LM7805). Then we have connected the secondary coil to the rectifier and the voltage regulator (LM7805), which shaped the output power suitable for mobile charging.

IV. CONCLUSIONS

We proposed a system for wireless power transfer to charge the mobile devices. The system consists of the solar panel to generate the DC power, Arduino based micro-controller board to generate high-frequency square wave signal, Power MOSFET to Convert DC power from the solar panel to high-frequency signal generated by Arduino and finally a transmitting coil of appropriate inductance. The power transmitted by the transmitter coil is coupled with the receiver coil. At receiving end, this high-frequency signal is converted back to DC signal using the rectifier, R-C filter, and voltage regulator. This regulated DC power is used to charge the various mobile devices.

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