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UNDERGRADUATE APPLICATION BASED RESEARCH: DESIGN AND TESTING OF WIRELESS PHONE CHARGER

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Abstract

Currently, there exists an abundance of handheld electronic devices, especially smart phones that require frequent charging. Traditionally, these devices were charged by using wired power adapters (chargers). However, the use of wires poses limits in terms of user convenience and distance from electrical outlets. While wireless chargers exist, commercial widespread use of the technology for consumer electronics is relatively recent. Also, the application of the underlying science and engineering principles of power transfer wirelessly are not commonly explored in Electrical Engineering Technology (EET) programs. In this paper, the authors report their findings and present the results of application-based research on the prototyping and testing of a wireless charger. This research was conducted as an independent study course by one student, who was supervised by an Electrical Engineering Technology professor. The design procedure is explained, tests results are presented, lessons learned are discussed, and ways in which the project could be incorporated into the lab component of an Electrical Engineering Technology course are suggested. Lastly, the authors suggest ways in which their design and approach could be improved.

Introduction

Ever since Tesla demonstrated lighting phosphorescent lamps wirelessly in 1893, the scientific community has been aware of the principles of power transfer through magnetic induction [1]. However, in the past, the inherent inefficiency of this method and the typical amount of power required for operation of electrical devices inhibited the proliferation of wireless adapters. Nowadays, the advancements in integrated circuit (IC), communication, computing, and battery technologies have led to much smaller and more powerful communication and computing devices with highly efficient batteries. These devices consume much less power than comparable devices years ago. A Blackberry smart-phone only needs electric current on the order of milli-Amperes (mA) to operate properly. Thus, if it is possible to transfer a small amount of power wirelessly, even considering significant power loss, it would be sufficient to charge a Blackberry, iPhone, or a similar smart phone. Due to the quantity of power required by these contemporary devices, the tradeoff of inefficiency in the transfer of power can be reasonably sacrificed for the convenience of charging wirelessly. However, the underlying science ultimately limits the amount of power that is transferred over varying distances.

Wireless electricity is an emerging technology and, thus, there exists much room for innovation. There are several consumer electronic devices that can be charged without using an electrical wire. Wireless power adapters are now commercially available for smart phones, iPods, and other similar low-powered devices. The underlying engineering concept for the wireless power adapter is similar to electric toothbrush chargers, in that they use the principle of magnetic induction to transfer power from the base to the brush handle (functioning device) [2]. However, the latest wireless chargers are more sophisticated and more powerful through the utilization of magnetic resonance that enhances power transmission speed and efficiency.

There are two fundamental types of wireless electricity transmissions. The first method uses magnetic induction technology and requires some kind of charging pad on which to place devices. These pads facilitate the charging of multiple devices such as smart phones, cameras, and iPods, simultaneously. The second method uses wireless antennae to transmit power through the air, requiring no charging pads. This method is quite promising but is not without its drawbacks; some researchers are concerned about the potential health hazard this poses through prolonged exposure to emitted electromagnetic waves. This current research project focused on the former method that utilizes a charging pad.

The objectives of this application-based research project were: (i) design and build a prototype of a wireless power adapter for smart phones, (ii) demonstrate its operation, and (iii) measure the amount of power transferred with varying distance of air or through a nonmetallic surface. The motivation for this project was the need to develop an avenue for application-based research in a crowded EET curriculum. The thrust of this project was to conduct an empirical investigation. Software simulation, while utilized in the design phase, was not a main driver in the overall design. It was hoped that the successful completion of this project would allow both researcher (student) and research supervisor (professor) to gain valuable insights into the usefulness and role of application-based research in the EET program through the shared experiences.

Theory of Induction

Induction can be defined as the production of an electric current through a conductor placed in a varying magnetic field. Ampere's law states that "the magnetic field in a space around an electric current is proportional to the electric current which serves as a source" [3]. This basically means that when a current is moving through a conductor, a magnetic field proportional to the current is produced around the conductor. From this law of physics, it was derived that the amount of current that flows through a wire/ inductor coil would have an effect on the distance that power could be transferred between two conductors separated by air. In addition, Faraday's law of induction states that "the magnitude of the electromotive force (emf), or voltage, induced in a circuit is proportional to the rate of change of the magnetic flux that cuts across the circuit"[4]. In other words, when a conductor is placed in an alternating magnetic field, a voltage is induced across that conductor.

A changing magnetic field can be achieved by reversing the polarity or direction the current flows through the conductor. This can be easily done by connecting the wire/ conductor to an alternating current source such as a 120V AC power outlet. Therefore, theoretically, utilizing a direct current (dc) source would not result in any transference of power.

Design

The purpose of this application-based research project was to design, build, and test a circuit that could charge the battery of a smart-phone wirelessly. The wireless transfer of power is possible by using two inductively coupled coils that transfer power via the magnetic field of the coils, in accordance with the scientific principle of magnetic induction [5]. In this design, two separate circuits were utilized, one attached to the primary coil and the other connected to the secondary coil. The primary coil was connected to the driver circuitry, which was sourced by the power supply. The secondary coil received power from the primary coil's magnetic field and its circuitry transformed the signal into an appropriate form so that it could be used to charge the smart-phone device. In order to successfully transfer power through the air using magnetic induction, a certain signal needs to be applied to the primary coil. According to the definition of induction, an AC signal needs to be applied to the primary coil and received by the secondary coil.

The base/pad of the device was plugged into the wall. However, the voltage of 120V RMS and a frequency of 60 Hz from the wall outlet were unsuitable for transferring the power required for our design. Thus, it was necessary to increase the frequency, which made it much more efficient in transferring power via magnetic induction. However, since smart phones operate at much less than 120V, it was also necessary to reduce the voltage. This was achieved by placing a transformer-based power supply between the AC outlet and the primary coil (see Figure 1).

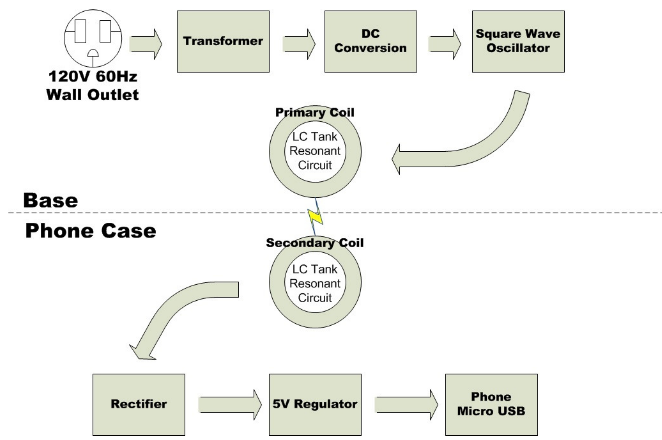

Figure 1. Block Diagram of a Wireless Power Adapter

Transformer and Power Supply

The operational amplifier, or op amp, is powered by a DC voltage source. Since the op amp had to be powered by a DC voltage source, the researchers decided to build a DC power supply that was able to plug into the AC wall outlet. A +15 to -15V split power supply that delivered a 30V peak -to-peak square wave signal at the output was designed and constructed. The 30V peak-to-peak signal was selected as a design specification because that voltage level was sufficient for this application. Also, this voltage level was not too high so as to interfere with the limits of the electronic devices that were being utilized [6].

The operation of the transformer was also based on the principle of magnetic inductance. It consists of a primary and secondary coil, which are wrapped around two sides of a square ferrite magnetic core. The voltage on the primary side creates a flux in the magnetic core and, thus, transfers electrical power to the secondary side. The voltage on the secondary side was determined by the ratio of the primary and secondary windings. This relationship is defined by Equation (1). A step-down transformer was used for this project in order to convert the 120V RMS voltage and transform it to 36V RMS on the secondary side [7].

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \qquad (1)$$

where,
Vs and Vp represent the voltage across the secondary and primary coils, respectively. Ns and Np represent the number of turns on the secondary and primary coils, respectively.

The output signal of the secondary coil was rectified by the configuration of diodes, filtered (smoothing) by the capacitors, and then regulated by the LM 7815 IC regulators, as shown in Figure 2. The resulting signal was a positive and negative split DC supply. A 36V CT Transformer [7] was selected because a regulated 15V was desired. The center tap enabled 18V to be on both the positive and negative rail, splitting the 36V. The voltage on the regulators was 18V and not 15V in order to compensate for the voltage drops across other passive components, thus keeping the regulators' input above 15V [7]. The spilt DC signal from the power supply was fed into the oscillator circuit. [7]

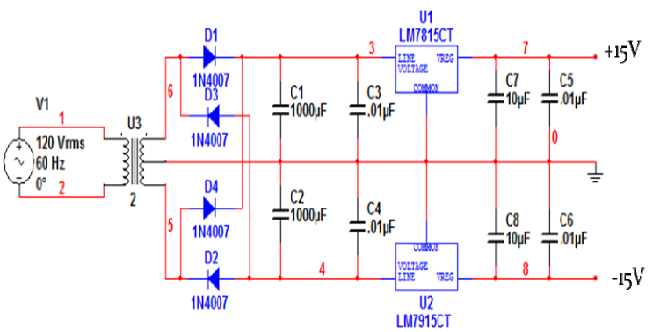

Figure 2. DC Power Supply

Oscillator

The output of the oscillator was an AC signal with a frequency much higher than 60Hz. The oscillator is the last stage that drives the primary coil, as shown in Figure 1. This AC signal in the primary coil produces an alternating magnetic field around it. Since the secondary coil lies in the magnetic field of the primary coil, a current is induced in the secondary coil. It was certain, based on the theory and laws of physics, that it had to be an AC signal, but it had to be determined whether this should be a square or a sine wave. To figure this out, the primary coil was connected to a function generator so that the emf induced on the secondary coil could be measured. By doing this, it was observed that the voltage induced on the secondary coil was consistently larger when a square wave was used in comparison to using a sine wave. From this empirical investigation, it was decided that it would be more appropriate for power transfer. The theoretical and or mathematical explanation as to why this occurred was beyond the scope of this project. [8]

To generate the square wave, it was necessary to transform the main voltage signal from a wall outlet to a square wave of the desired frequency and voltage. One might consider generating a square wave with a 555 timer integrated circuit (IC). However, this IC does not have a high enough output voltage and the output signal is a pulse and not an AC waveform, as was desired. The 555 timer chip specifications do not accept a negative supply voltage in order to output the necessary AC signal [9]. Based upon previous research, it was decided that an op-amp-based square-wave oscillator would be used. This oscillator circuit is shown in Figure 3 [8]. Equation (2) expresses the relationship between the frequency and the values of the passive components in the oscillator circuit used, where R_1, R_2, and R_3 are resistors and C_1 is the capacitance of the capacitor.

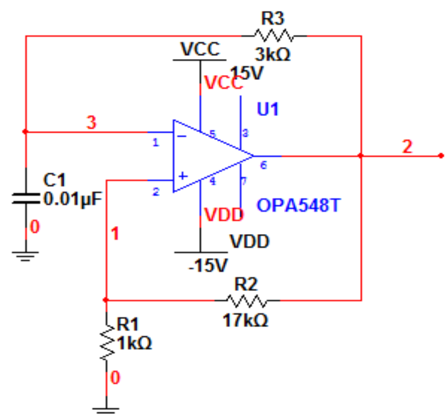

Figure 3. Square-Wave Oscillator

$$f = \frac{1}{2R_3C_1 \ln\left\{\dfrac{1+\left(\dfrac{R_1}{R_1+R_2}\right)}{1-\left(\dfrac{R_1}{R_1+R_2}\right)}\right\}} \qquad (2)$$

The square-wave oscillator outputs an AC waveform with a frequency of 150 kHz [10]. The combination of its feedback loops and timing capacitor causes the circuit to act like a comparator. This results in the oscillation of the output signal between +15V and -15 V. The frequency of 150 KHz was selected in order to match the self-resonant frequency of practical inductor coils [11]. If the frequency is too high or too low, skin effect and the inductor's size affect the inductor's ability to transfer power without significant power loss. A frequency of 150 kHz facilitated the creation of practical coil windings and the use of standard capacitor values in the construction of the resonant tank circuit, which is described later in this section.

Coils

The parallel tank circuit provided a high-impedance matching given that the load resistance of the inductor coils was very low. Since the desired design frequency was 150 kHz and a standard and reasonable capacitor value of 0.1 µF was selected, Equation 3 was used to calculate the required inductance of the coils [12].

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{3}$$

where,
f represents the operating frequency, *L* represents the inductance of the coils, and *C* represents the value of the capacitance of the capacitor in the tank circuit [5], [12]. Using this formula, a value of 11.2 µH for the inductance of the coils was computed [13].

In addition, the relationship between the inductance and the dimensions of the coils can be expressed as follows by Equation (4).

$$L = \frac{R^2 N^2}{9R + 10l} \tag{4}$$

where,
L represents the inductance of the coil, R represents the radius of the coil, N represents the number of turns of the coil, and *l* represents the length of the coil. Equation (4) was used as a design constraint for the phone-charger application. A coil with a diameter of 2 inches was able to fit on the back of a typical size smart phone. Using 12 turns made it so that the coil was not too thick to fit in a phone case. (Bearing in mind that 22 AWG wires were used to wind the coils) The wire was wrapped around a 2-inch-diameter bottle, and then fixed into that shape by electrical tape to form a coil, as pictured in Figure 4 [5], [9], [13].

Figure 5 shows the schematic for the tank circuit. The operation of this is explained in more detail later in this section. Because of the slew rate, the time delay between the input and output of the op amp, the square wave signal was distorted, especially when the circuit was loaded. Hence, a Schmitt trigger was used to clean up the square wave. The Schmitt trigger outputs a square wave at its positive peak or negative peak voltage, depending on the values and configuration of the external components of the op amp. A Schmitt trigger is shown in Figure 6. Since the op amp of the Schmitt trigger is the last stage before the coil, this op amp had to be a power op amp with high output current to drive the coil. For this project, the Texas Instruments' OPA548 op amp was selected [14], which accepts relatively higher voltage inputs and outputs, along with continuous 3A and 5A peak output currents. Although a smart phone only needs current on the order of mA to properly charge, the air losses of the induction coils need significantly more current to overcome the loss.

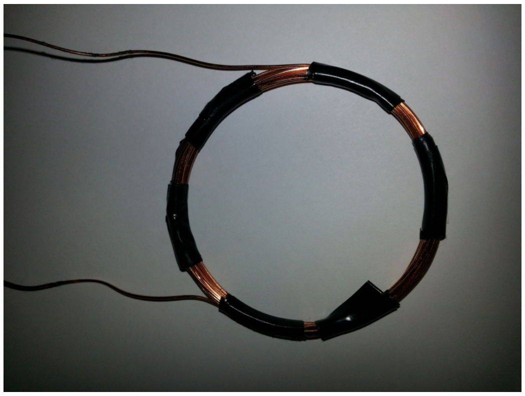

Figure 4. Taped Coil

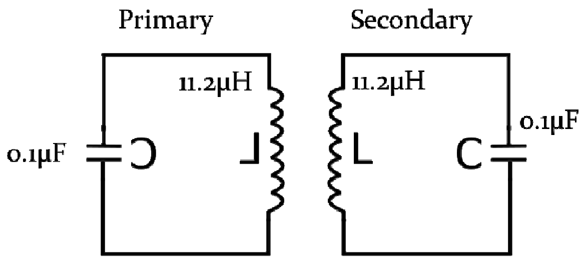

Figure 5. Parallel Resonant Coils

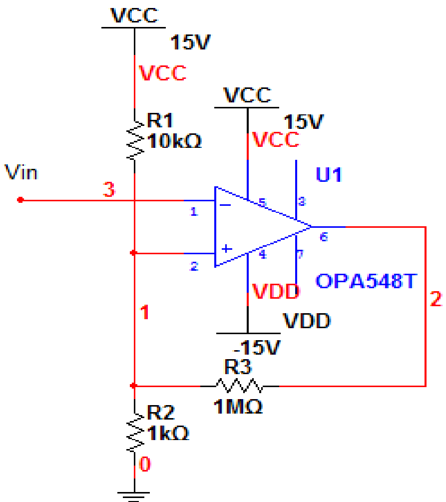

Figure 6. Schmitt Trigger

Also, in order to transfer power with minimal interference, a parallel resonant tank circuit, as shown in Figure 5, was used. This meant attaching capacitors in parallel with the primary and secondary coils separately. When a capacitor and an inductor are connected in parallel, they oscillate the signal between the two devices. The capacitor charges to capacity and then discharges into the inductor. The inductor generates a magnetic field that gradually increases in strength as the capacitor discharges into it. The magnetic field eventually collapses as the capacitor is discharged. After this, the capacitor starts charging again. The charging of the capacitor and the collapse of the magnetic field occurs repeatedly. This exchange causes the configuration of the two components, called a tank circuit, to produce an oscillating signal whose frequency is determined by the values of the components, and is expressed by Equation 3. If the primary and secondary coils have the same inductance and capacitor values, then they will both resonate at the same frequency [5]. Since they are interacting with each other by providing power to the second coil, the same resonant frequency of both tanks is used to block out unwanted interference and allow only the resonant frequency to be transferred. Figure 7 shows a schematic for the circuitry connected to the primary coil.

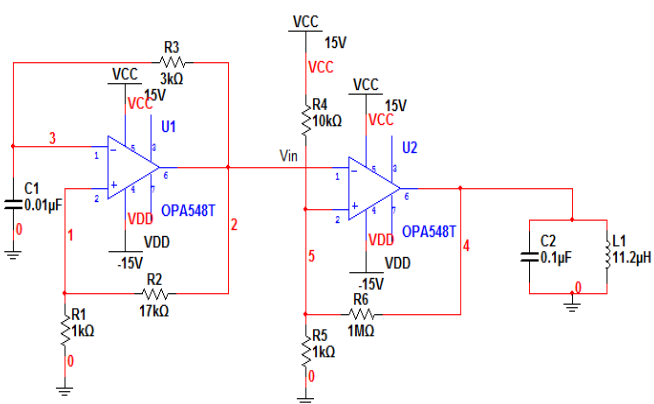

Figure 7. Primary Circuit Design

Receiving Circuit

The secondary side of the circuit was built into a phone case. Nowadays, a smart phone device uses a 5V USB plug to charge the battery. In order to achieve this voltage level, a bridge rectifier and a 5V regulator were used to convert the voltage signal in the secondary coil, which is AC, into a regulated 5V DC to power the phone. The receiving circuit takes the AC signal that was transferred into the secondary coil and converts it to a regulated DC using a bridge rectifier, capacitors, and regulator. In this research project the Blackberry Storm 9530 was used as the test tool that verified if the charging circuit was designed and constructed properly. The secondary side of the circuit was connected to this phone via its micro USB connector.

The bridge rectifier used four diodes to convert the AC waveform into a positive full "ripple" waveform. Filter capacitors were used in the same way as in the DC power supply described previously [2]. Also, for a more precise regulation, a 5V IC was utilized with its output connected to the micro USB male plug. The schematic diagram for this circuit is shown in Figure 8.

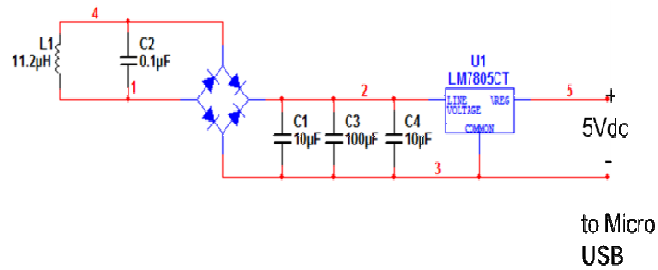

Figure 8. Secondary Circuit

Results and Discussion

Once the prototype was built, testing began in order to determine the charging capability of the wireless charger. It was quickly verified that there was current flowing in the micro USB and the phone began charging. The operational amplifiers and voltage regulators pulled about 500 mA, enough to heat the T0-220 transistor packages. Heat sinks were attached to the T0-220 packages to dissipate excess heat. From the testing, loading characteristics were noticed. Since the inductor was a wire wound in a coil shape, it had very low resistance. Due to the low resistance of the inductor, as the additional load was introduced in the primary circuit, a significant current flow was observed. The AC signal prevented the inductor from resulting in a short circuit. A large current through the inductor was necessary in order to generate a significant magnetic flux to transfer power.

Table 1 shows the amount of current flowing into the phone as the distance between the inductor coils was increased. This is consistent with initial expectations that power transfer diminishes as the distance between the inductor coils is increased. Typical wired micro USB phone chargers, on average, are rated at 500 mA output. A smart phone may draw more than 500 mA of current at times. The current output rating of the charger relates to the time in which the phone will charge. Since the circuit drew about 260 mA, as can be seen in Table 1, when the coils are closest together, the phone would charge at a slower rate compared with a typical commercially available wired charger [15].

Table 1. Measured Average Current Draw

Coil Distance (cm)	Phone Current Draw (mA)
0	260
0.5	150
1	100
1.5	50
2	10

After the square wave oscillator (OPA 551 op amp) received its DC supply, it outputted an AC square wave at a frequency based on its external capacitor-resistor values and configuration. The output waveform, as displayed on an oscilloscope, is shown in Figure 9. The waveform is oscillating at a frequency of 150 kHz [7] with a peak-to-peak voltage of about 30V. The waveform has more of a trapezoid shape than a square shape of the traditional square wave, due to the slew rate of the op amp. This is a practical characteristic of the op amp because of its inability to output the signal without a slight delay. However, no noticeable effect on the performance of the circuit that could be attributed to the slew rate of the op amp utilized was observed.

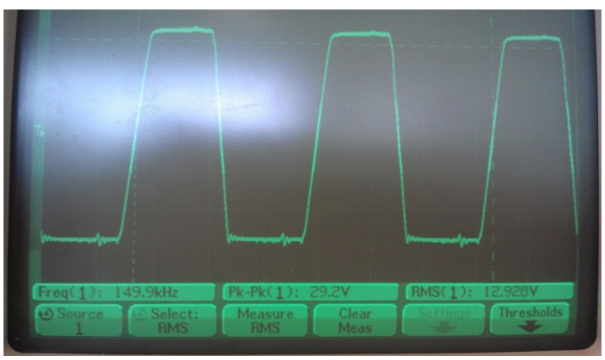

Figure 9. Square-Wave Generator Output

The output of the square wave generator was connected to the input of the Schmitt trigger. This, as can be seen in Figure 10, cleaned up the signal by reducing the small oscillations (ringing effect) on the peaks of the signal, while maintaining the same frequency and voltage.

After the transfer of power between the coils, the secondary coil was measured under load, as seen in Figure 11. The square-wave signal input had an effect on the output waveform of the received coil. The wave looks more like a sine wave because of the inductor's characteristic to resist the change in current, while building and collapsing the magnetic field. It resists by producing a back emf. The distorted sine wave was the result of this property. The frequency was relatively the same and the air gap losses were evident because a 16.4V peak-to-peak signal was received from the 30V supplied by the primary coil circuitry.

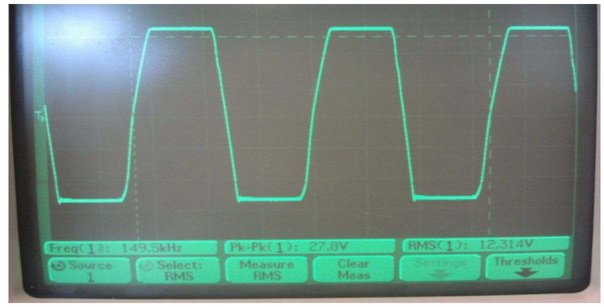

Figure 10. Schmitt Trigger Output

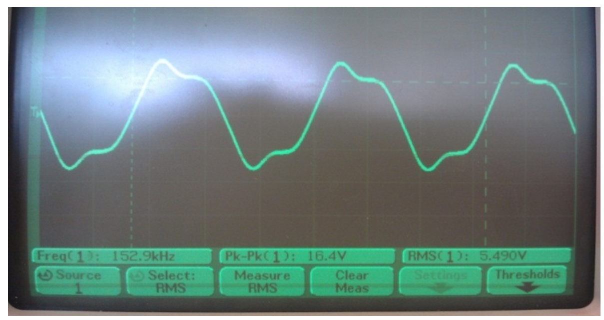

Figure 11. Signal at Secondary Coil

The received waveform was then rectified and regulated by the secondary coil circuitry. Figure 12 shows the output of the 5V regulator that was connected to the Blackberry phone. The oscilloscope shows no frequency and measures a peak-to-peak voltage of 160 mV. These measurements show that a low ripple "clean" DC signal was being outputted at 5V.

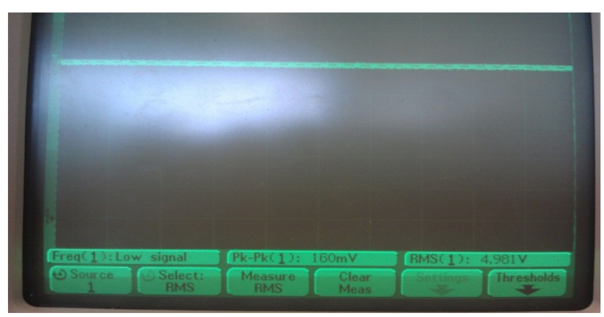

Figure 12. Secondary Circuit Regulated Output

Curriculum Integration

This project was completed in the students' final semester in Electrical Engineering Technology. The researchers believe, however, depending upon the sequence of electronics courses that it could have been completed in the junior year or the first semester of the senior year. It is recommended that this project be introduced as a series of mini-projects and be completed during regular lab times. Most EET introductory courses in electronics introduce students to the following devices and concepts: op amps, semi-conductor devices such as diodes and transistors, rectification, voltage regulators, power supplies, and pulse-generating circuits. In addition, the transformer and the principles of magnetic induction are usually introduced to students in introductory circuit courses and or physics, prior to doing electronics.

The laboratory work, depending on institution and instructor, will vary in approach. Some are very proscriptive and detailed and require the students to follow procedures in a mechanistic manner, while some simply give design specifications and allow the students a lot of flexibility in the design. Each approach has its advantages and weaknesses. The former tend to reinforce the theoretical concepts introduced in lectures and require comparatively less time. However, the student is not encouraged to be creative and these labs sometimes come across as being very boring. The latter allows students to be creative with predetermined design parameters. However, students lacking initiative may find these a bit too challenging. Also, more lab time has to be set aside for students. At SIUC, a combination of both approaches can be found in the junior and senior labs. Usually, the students begin their lab experience with very proscriptive and detailed labs and, as they acquire the requisite skills and knowledge, design labs are introduced with increasing complexity as the semester progresses. A similar approach is recommended in introducing this application-based research into the regular curriculum.

Conclusion

Today's engineers are always trying to improve technology in order to enhance the quality of life. The technology and theoretical foundations of power transfer through magnetic induction have been in existence for a long time. However, this method was not practical for most practical applications due to the inefficiency, power loss, and amount of power that would be required to operate electronic devices. Nowadays, with the advent of low-powered devices such as smart phones and tablet PCs, the application of magnetic induction has become much more practical. This technology allows consumers the flexibility and convenience of wirelessly charging their phones and other computing devices. This application-based research project included the research, design, construction, and testing of a wireless smart phone charger. The results of the tests demonstrated that the prototype performed well up to 260 mA at 5VDC. These values are comparable to commercial wired charges (power adapters) and satisfied the operating requirements of the smart phone.

Future Work

As with most electronic designs, there are different ways to achieve the same results and even improve on the original design. The design choices for this project were motivated by three factors: energy efficiency, physical dimension of coils, and cost. However, several improvements could be made as the design choices and constraints are modified. For this project, a sine wave signal instead of a square wave signal could be used to drive the coil. The sine wave will still transfer power as long as the waveform is AC. In order to drive the coil with a sine wave, the square-wave generator and the Schmitt trigger should be replaced by a sine wave oscillator [16]. Also, instead of using op amps to drive the coil, Bipolar Junction Transistors (BJTs) or Field Effect Transistors (FETs) can be used for better power handling capabilities. [17]

Push-pull transistor designs can create a very efficient sine wave oscillator that is able to produce high currents with less heat generation. MOSFET transistors are also good choices for the push-pull design. During the post analysis of the project, it was determined that the ZVS (zero-voltage switching) driver circuit may have been an appropriate improvement of the design. This circuit is a MOSFET oscillator that is able to oscillate a large amount of power with little loss. In the ZVS circuit, the MOSFETs switch when there is a potential difference of 0V across them. Since they switch at 0V, the power loss due to switching is very small, resulting in the production of very little heat by the MOSFETs [18].

In the near future, the researchers envision the development of furniture that has the power transfer via magnetic induction capability built-in. For example, a desk can have this device built-in and could power/charge a compatible cell phone or laptop just by setting it on the surface of the desk. This is the beginning of this kind of technology; the ultimate goal would be to have your device charge by just walking into a room. Your cell phone would charge in your pocket and your laptop would charge at any location in that room.

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Biographies

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