John Macharia

Wireless Inductive Charging for Low Power Devices

Helsinki Metropolia University of Applied Sciences

Bacherol of Engineering

Electronics

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Currently wireless charging for most consumer electronics is still evolving in the mainstream market. This technology has taken a slow adoption. I n a world faced with variety of handheld devices demand for a shorter charging time is constantly being explored. Wireless charging has its challenges and successes

The goal of this project was to design a prototype through research and design that would critically address and analyze the major design challenges that bring about longer charging periods of the new inductive wireless charging compared to the old fashioned, wired charging method and provide probable solutions.

All the sections of the prototype namely transmitter, receiver and coil arrangement were designed and tested. The entire circuit was finally simulated and later fabricated on a PCB to come up with a prototype. Results were compared. This study showed that proper choice of coils must be made during design in order to minimize power losses and therefore increase efficiency.

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1 Introduction

Around 1891 Nikola Tesla conducted the first experiments in wireless power transfer and investigated wireless transmission of electrical energy using radio frequency resonant transformer called the Tesla coil, which produced high voltage, high frequency alternating currents. Since then this technology has evolved and with the advent of cordless appliances, inductive charging stands were developed for appliances used in wet environments like, electric toothbrushes and electric razors to reduce the hazard of electric shock.

In the recent years portable wireless communication devices such as mobile phones, tablets, and laptops are currently driving the development of wireless powering and charging technology to another level. Wireless energy harvesting is a useful method of powering electrical devices in cases where interconnecting wires are inconvenient, hazardous, or not possible.

The goal of this project is to design a prototype wireless energy charger for low power devices with specific emphasis on mobile phones. Through research and design, this prototype will critically address and analyze the major design challenges that bring about longer charging periods of the new inductive wireless charging compared to the old fashioned, wired charging method, and provide probable solutions.

1.1   A Brief History

The wireless power transfer has along history. The timeline below shows the development of the wireless power transfer from the beginning.

1826 –1830
Andre-Marie Ampere discovered Ampere circuital law .This law illustrates how electric current produces a magnetic field. Michael Faraday developed Faraday law of induction which explains how a changing electromagnetic force is able to be induced in a wire using a changing magnetic flux. [1,136.]

1889 –1895

Nikola Tesla used a high-tension induction coil to show the first wireless power transfer by means of electrostatic induction. [1,140.]

1894–1900

Tesla lighted incandescent lamps wirelessly by resonant inductive coupling. Jagdish Chandra Bose was able to ring a bell at a distance using electromagnetic waves. Marconi demonstrated radio transmission over a distance of around two kilometers. [1,138.]

1905–1918

Tesla Tower was built around 1902 for commercial and scientific demonstration of wireless power transmission, telephony and broadcasting. [1,138.]

1927–1969

William Brown put forward a proposal to transmit solar energy using wireless means in space for use to power a satellite [1,145].

1974–1999

RFID first passive system was discovered. Goldstone Deep Space Communications experimented how RFID tags can be powered by electro-dynamic induction over a distance of few meters [2].

2008–2013

WiTricity research from MIT wirelessly powered 60 watts bulb using magnetic resonance with forty percent power efficiency at a distance of 200 cm. Sony demonstrated powering wirelessly sixty volts to an electro-dynamic-induction TV set, over a distance of half a meter. [2].

1.2   Current Wireless Power Technologies

A variety of wireless power technologies have been explored recently over different power levels as shown in figure 1 below
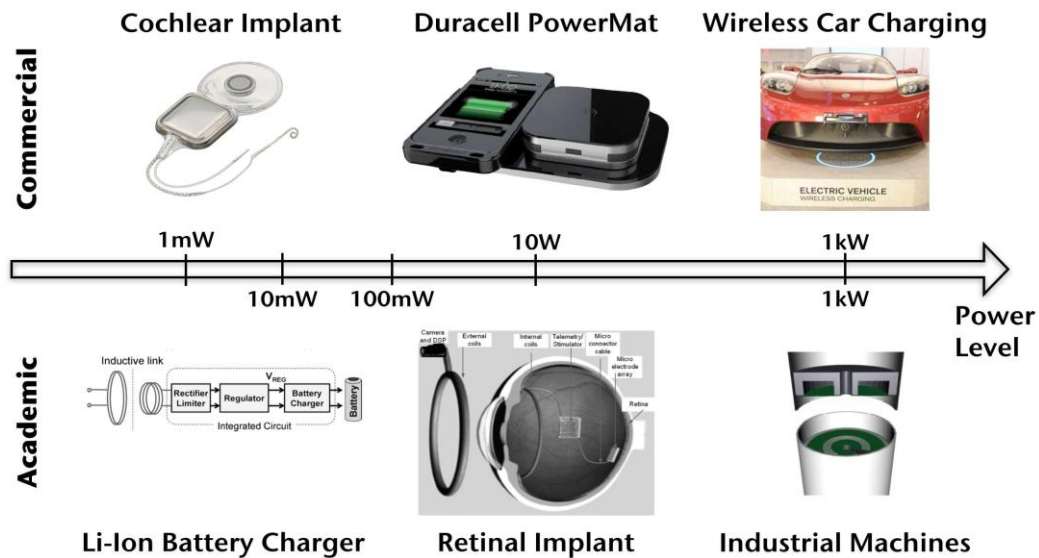

Figure 1 Overview of current wireless power technologies (Reprinted from Tianjia Sun (2013) [5]

A lot of medical implants rely on wireless power to function. Cochlear ear implant is a good example of such a device. It has implanted electrodes which stimulate auditory nerves to aid people with hearing problems. Work on retinal implants that stimulate electrodes in the eye to promote sight is been explored too. Midway along the spectrum a lot of consumer electronics are in the market today they include cell phones and tablets.

Leading phone giant and tablet manufacturers like Nokia Samsung and Sony are also fighting for a share in the market with their product already in the market. Current cell phones may be outfitted with a special case to support wireless recharging. Research work is also been conducted on how to wirelessly charge lithium ion batteries at low energy rates. Many leading car manufactures have also embraced the wireless charging methods in the newly introduced electric cars.

[3,100; 4, 33]

1.3   Wireless charging standards

Currently mobile device manufacturers are working with two major standards namely Alliance for Wireless Power and Wireless Power Consortium.

Alliance for Wireless Power standard describes analogue power transfer for both inductive and resonant, digital transceiver communication and uses a transfer technology using magnetic resonance. It consists of the following

1. A power transmitter unit that can use more than one power receiver units.
2. Supports power transfer of up to fifty watts, at distances up to 50mm
3. Frequency of operation is around 6.77 MHz
4. Powers up to eight devices from a single power station depending on transmitter and receiver orientation and power demands.
5. Uses Bluetooth to control and indentify loads and reject any non compliant device.

Qi standard was developed by the Wireless Power Consortium for inductive electrical power transfer over distances of up to 40mm.Qi systems comprises the following

1. A power transmission pad which charges the receiver using resonant inductive coupling.
2. Delivers power for devices below five watts.
3. The distance between the two coils should be between 5 to 40 mm.
4. A digital control loop regulates the output power through transmitter-receiver radio frequency communication.
5. Backscatter communication is used between transmitter and receiver

Qi is the most popular currently and is adopted by most companies and end users due to its user-friendly infrastructure initiatives. [5,130-140]

2 Theoretical Background of a Wireless Power System

2.1 Fundamental Working Principles

Before designing this prototype, fundamental working principles of the wireless power transfer are introduced. The various types of the wireless power transfers are also discussed. These fundamentals mainly include the basic concepts of the time-varying Electromagnetic field, like the Ampere's circuital law, the Biot-Savart law, and the Faraday's law of induction. Understanding these fundamental working principles is important for further discussion later.

2.1.1 Wireless Charging Technologies

Wireless power transfer is a collective term that refers to a number of different technologies for transmitting energy by means of electromagnetic fields. These technologies differ in the distance over which they can transfer power but all use time varying electric fields.
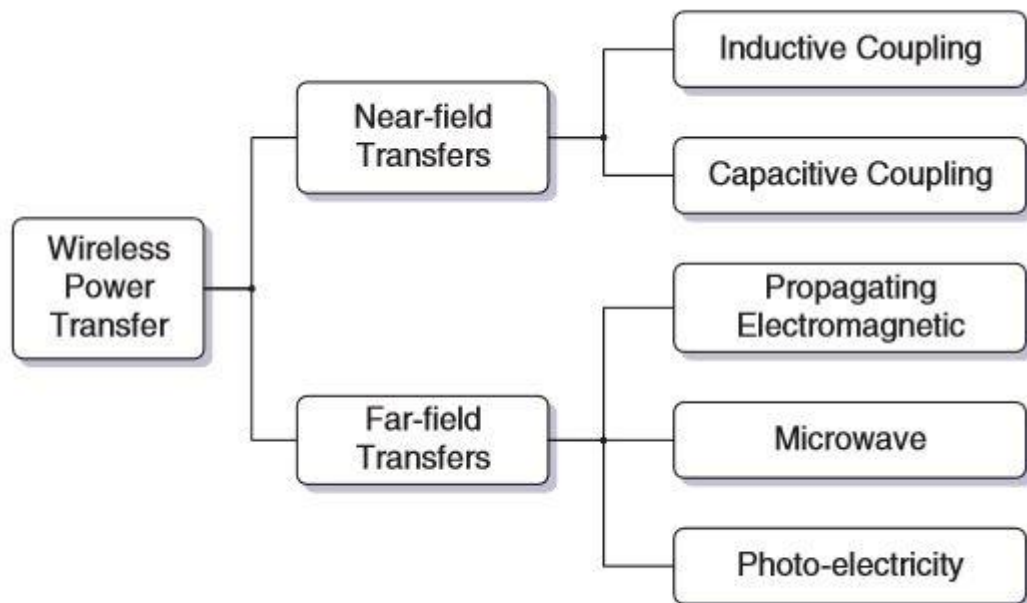

Figure 2 Classification of wireless charging technologies (Reprinted from Tianjia Sun (2013) [5])

The transmitter is usually connected to a source of power such as a mains power line. The transmitter changes this power to a time-varying electromagnetic field. The receiver converts intercepts the magnetic field and convert it back to the required output

ready for use by an electrical load. Depending on the working principle wireless charging can be categorised as shown in the figure 2 above, namely near-field transfers and the far-field transfers.

The main difference between the two is the frequency range and transfer distance. When the resonant frequency of the changing electromagnetic field is relatively low around one megahertz and the transfer distance is only few centimetres that belongs to the near-field power transfer. Higher frequencies in the range of gigahertz employ longer distances which fall in the Far field transfers. Due to the low charging efficiency and safety issues far field is not employed in low power portable devices.

Transmission using microwave works on far field at a greater distance. The far-field power decreases according to the square of the reciprocal of the charging distance. With the transmitting antenna and the receiving antenna not coupled for the far-field technique the absorption of radiation by the receiver does not affect the transmitter.

Mostly the near field transfer has higher power transfer efficiency over the far-field transfer. Capacitive coupling largely depends on the available area of the device. However, for a hand-held portable electronic device, it is hard to obtain enough power for charging, making the design a big challenge. [3, 23 – 26]

2.1.2 Inductive Charging

Inductive power transfer comprises a primary coil of an energy transmitter that generates a varying magnetic field across the secondary coil of the energy receiver within the field. The secondary coil should be tuned at the operating frequency to enhance charging efficiency. The quality factor is usually designed in small values usually below 10, because the transferred power attenuates quickly for larger quality factor values. Ease of implementation, convenient operation, high efficiency in close distance and ensured safety makes inductive charging most applicable and popular for portable low power devices, more emphasis is therefore paid to inductive resonant coupling in this project.

Advantages of inductive charging

Compared to traditional charging with cord, wireless charging introduces many benefits as follows.

1. The hassle of connecting cables is eliminated. Different models of devices can also use the same charger.
2. It makes the design and manufacture of much smaller devices without the attachment of batteries.
3. A waterproof and dustproof property gives these devices a longer lifespan.
4. The technology makes it easy to charge body implanted sensors.
5. Power can regulated and supplied only when on required. [4].

Disadvantages of inductive charging

1. Higher implementation cost since from the current situation receiver circuitry have to be introduced during the manufacture of mobile gargets
2. Produces more heat while charging
3. Slower and less efficient

Resonant inductive coupling is the near field wireless transmission of electrical energy between two coils coupled together by a magnetic field. Additionally the two must be tuned to resonate at the same frequency. Power is transferred by magnetic fields between two resonant tuned circuits, one in the transmitter and one in the receiver as shown in figure 3 below. Each resonant circuit consists of a coil connected to a capacitor. For increased coupling and maximum power transfer [1].

1. The two coils must be tuned at the same resonant frequency.
2. A high Q factor of the coils is used for a higher rate of energy exchange.
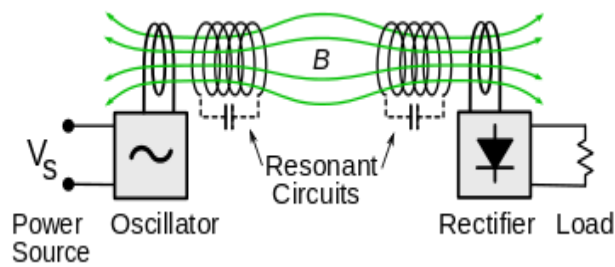3. Coupling factor should be high.

Figure 3 Resonant inductive wireless power system (Reprinted from Marin (2005) [2])

2.1.3 Resonance

Electrical resonance occurs in an electric circuit at a particular resonance frequency. At this frequency the imaginary parts of impedances or admittances of circuit elements are equal and therefore cancel each other. Resonance of a circuit involving capacitors and inductors occurs because the collapsing magnetic field of the inductor generates an electric current in its windings that charges the capacitor, and then the discharging capacitor provides an electric current that builds the magnetic field in the inductor. This process is repeated continually back and forth creating a resonant frequency.

For a series RLC circuit at resonant frequency,

1. Inductive reactance XL is equal to capacitive reactance XC.
2. Total impedance Z of circuit becomes minimum which is equal to R
3. Circuit current attains a maximum value while impedance reduces.
4. Inductor and capacitor voltages cancel each other, so voltage across resistor equals supply voltage.
5. Since the resultant reactance is zero, entire circuit is purely resistive circuit and therefore the voltage and the current are in phase making the phase angle between them to be zero.
6. Power factor is unity.

Frequency at which resonance in series RLC circuit occurs is given by

$$\frac{1}{2\pi\sqrt{LC}} = f_r \; H_Z$$

(1)

2.1.4 Quality Factor, Q

The Q-factor of a coil, is a measure of the capability of the inductor to save energy, it is an important parameter. Every coil possesses a small resistance in addition to its inductance. The lower the value of this resistance R, the better the quality or the Q factor of the coil. This is mainly due to the fact that a small resistance takes less power and draws a very little line current. The quality factor of a coil at the operating frequency ω is defined using a ratio. This is the ratio of reactance of the coil to its resistance. Thus, at resonant frequency, quality factor is defined as

$$Q = \frac{X_L}{R} = \frac{2\pi f_r L}{R}$$

(2)

The quality factor Q may have a value between zero and infinity, expected values are mostly around between 10 and 100. A quality factor that is below ten is of no use. Quality factor Q is mainly dependent on the shape and size of the coil as well as the materials used. [3, 13-20.]

2.1.5 Coupling Factor, K

The coupling factor is a dimensionless value that defines interaction between the primary and secondary coils of any wireless power transfer system. A higher coupling factor means a more efficient power transfer through reduced magnetic flux loss and less heating. A system could either be tightly or loosely coupled as shown in figure 4.

In tightly coupled systems, the transmitter and receiver coils align themselves such that they have the same diameter size and have a minimal distance in-between them. This setup ensures most of the magnetic flux is captured by the receiver coil to be able to be converted into an electrical current.

Loosely coupled systems are characterised by setups which do not capture all of the transmitter's magnetic flux, mainly because the receiver coil distance is too big or because the coil diameters do not match. This can also occur if the receiver coil is smaller than the transmitter coil [4].
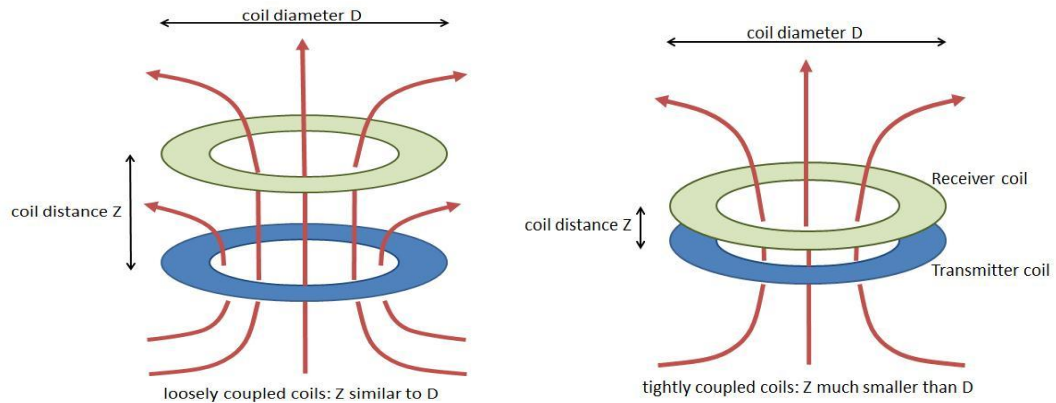
Figure 4 Effect of coil distance and diameter on coupling factor (Reprinted from consortium (2017) [6])

Depending on the distance between transmitter and receiver coils, not all of the magnetic flux generated by the transmitter coil reaches the receiver coil to contribute for the power transmission. The more the flux reaches the receiver, the better the coupling. The grade of coupling is expressed by the coupling factor k.

The coupling factor should be a value between zero and one. A value of one indentifies a perfect coupling, i.e. all flux generated penetrates the receiver coil. 0 means that with such a system the transmitter and receiver coils are totally independent of each other. The coupling factor is determined by the distance between the inductors and their relative size. This is further dependent upon the shape of the coils and the angle between them. Axial misalignment is the worst. Figure 5 shows this effect for an ideal planar coils arrangement both having a diameter of 30 mm .The graph show the effect of both horizontal and vertical misalignment to the coupling factor. Coupling factors in the range of 0.32 to 0.65 are very common. A negative coupling factor signifies the capture of magnetic flux from behind. The definition of the coupling factor is given by:

$$k = \frac{L_{12}}{\sqrt{L_{11} \cdot L_{22}}}$$

(3)

This is from the general equation of a system having coupled inductors:

$$\frac{U_2}{j \cdot \omega} = L_{12} \cdot I_1 + L_{22} \cdot I_2 \qquad \frac{U_1}{j \cdot \omega} = L_{11} \cdot I_1 + L_{12} \cdot I_2$$

(4)

where U1 and U2 are the voltages applied to the respective coils, I1 and I2 are the currents in the coils, L11 and L22 are the self inductances, L12 is the coupling inductance and ω = 2πf is the angular frequency. Using equation 3 above the voltage of the system can be measured as relative open loop voltage u as shown in equation below (4).

$$u = \frac{U_2}{U_1} = k.\sqrt{\frac{L_2}{L_1}}$$

(5)

It therefore follows that if the two coils have the same inductance value, the measured open loop voltage u automatically equals k. Figure 5 below is a graphical representation of how coil alignment affects coupling factor from extreme lateral and axial misalignment to closely coupled pair of coils [4].
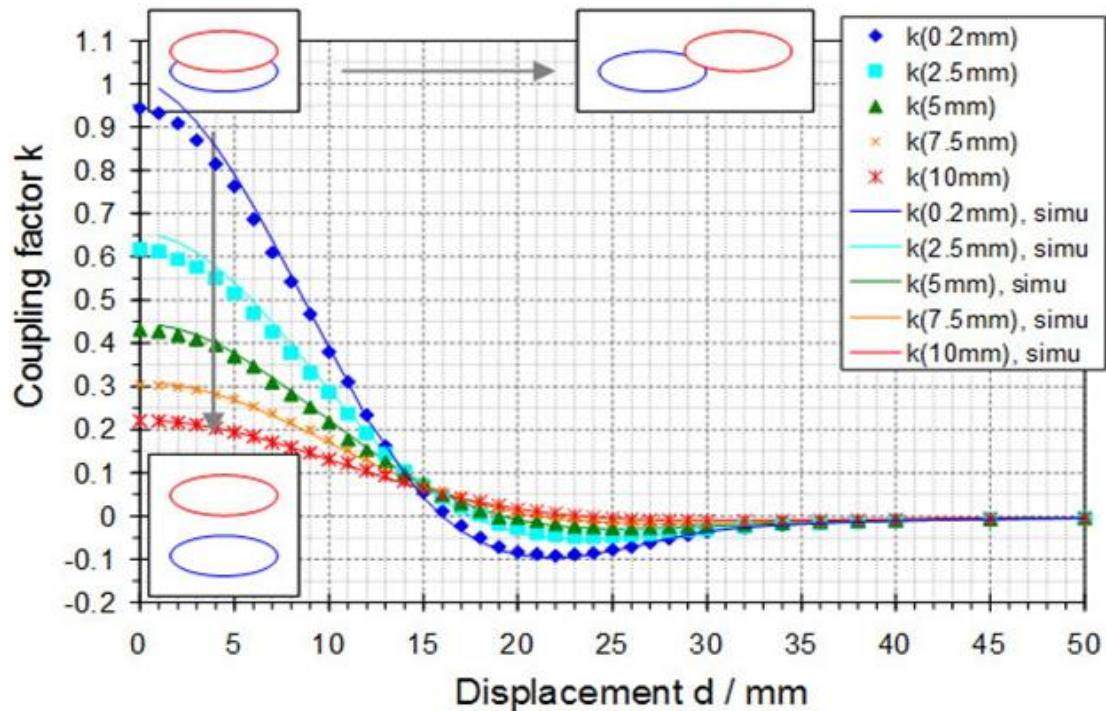

Figure 5 Coil displacement verses coupling factor (Reprinted from consortium (2017) [6])

2.1.6 Magnetic Flux Density Generated by the Primary Coil

Electromagnetic force is made up of electric and magnetic fields. Stagnant current pro-
duce electric fields, but when current flows through a wire, it creates magnetic fields.
The Biot-Savart Law is an equation that describes the magnetic field created by a cur-
rent-carrying wire, and allows you to calculate its strength at various points

$$B = -\frac{\mu_0}{4\pi} \oint_l \frac{Idl \times e_r}{r^2}$$

(6)

Here r is the full displacement vector from the wire element to the point, at which the
field is being computed, er is the unit vector of r. ldl is linear-current-element in the
wire, and μ_0 is the permeability.

In most hand-held wireless power transfer systems, the transmitting coil is usually a
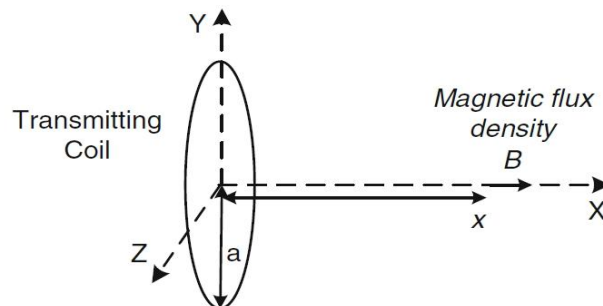circular coil as illustrated in Fig. 6 below

Figure 6 Magnetic field generated by a circular coil (Reprinted Frederic (2009) [8])

For a circular coil, the generated magnetic flux density B at the point x in Fig. 6 can be
expressed by:

$$B_x = \frac{\mu_0 N I a^2}{2(a^2 + x^2)^{3/2}} e_x$$

(7)

Here N is the number of turns, I is the current in each of the individual turn, a is the
radius of the circular coil, x is the distance from the center of the coil to the point x, and

ex is the unit vector of distant between point a and x. With a varying transmitter current I, the generated magnetic flux density Bx would also change over time. [6

2.1.7 Induced Voltage in the Secondary Coil

Introducing a receiver coil as shown in figure 7 below a fraction of the transmitted magnetic flux is captured by the secondary coil.
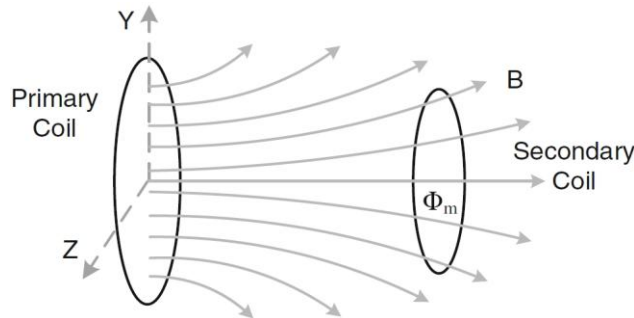

Figure 7 Magnetic field received by the secondary coil (Reprinted from Frederic (2009) [8])

The total magnetic flux captured by the secondary coil can be expressed by equation:

$$\Phi_{\mathrm{m}} = \int_S B \cdot dS$$

(8)

Here B is taken as the magnetic flux density generated by the primary coil and S is the surface area of the secondary coil. According to the Faraday's law of induction the induced voltage in the secondary coil is given by the equation:

$$V(t) = -\frac{d\Phi_m(t)}{dt}$$

(9)

Here $\Phi_{\mathrm{m}}(t)$ is the total time-varying magnetic flux crossing the second coil, this voltage causes an induced current in the secondary coil. An induced magnetic field is also generated. According to the Faraday's law, the polarity of the induced magnetic field is such that it produces a magnetic field that opposes the change which produces it. Because the induced voltage and the current are produced at the secondary side, power

is successfully transferred to the secondary side. This is the basic working principle of the wireless power transfer or the inductive coupling. [5, 18-22.]

2.1.8 Power Losses

Losses experienced during power transfer lead to wasted energy which generates heat. Reducing these losses goes a long way in increasing the overall efficiency of the system. These losses at the minimum level can be expressed using the equation below.

$$\lambda_{min} = \frac{2}{(kQ)^2}\left(1 + \sqrt{1 + (kQ)^2}\right)$$

(10)

From this equation it is clear that power losses predominantly depend on two basic parameters of the wireless power system

1. The coupling factor k, between the receiver and transmitter coil.
2. The system quality factor Q. The system quality factor is the geometrical average of the transmitter's and receiver's coil quality factors. [6]

This means, that the system quality factor and the coupling factor determine the performance of an inductive wireless power transfer system. Poor coupling can be linearly compensated by a better quality factor and vice versa.

Other important design parameters which should be put into consideration are resonance and frequency. All these factors had been introduced earlier in the previous chapter; now we shall see how they can be optimized in design to minimize power transfer losses.

3   Design of the Prototype

As mentioned earlier the primary objective is to address and analyze the major design challenges that bring about longer charging periods of the new inductive wireless charging compared to the old fashioned. These factors surround coil design particularly quality and coupling factor. Therefore more emphasis is hereby channeled toward coil design

3.1   Target of the Design

Transmitter circuit is expected to have a 15 - 25 Vdc input and convert it to a high frequency signal using an oscillator that will be able to drive the transmitter coil.
Receiver circuit takes up the high frequency signal and converts the power to a steady 5 Vdc to charge the battery. Figure 8 below illustrates the key sections of the design layout.
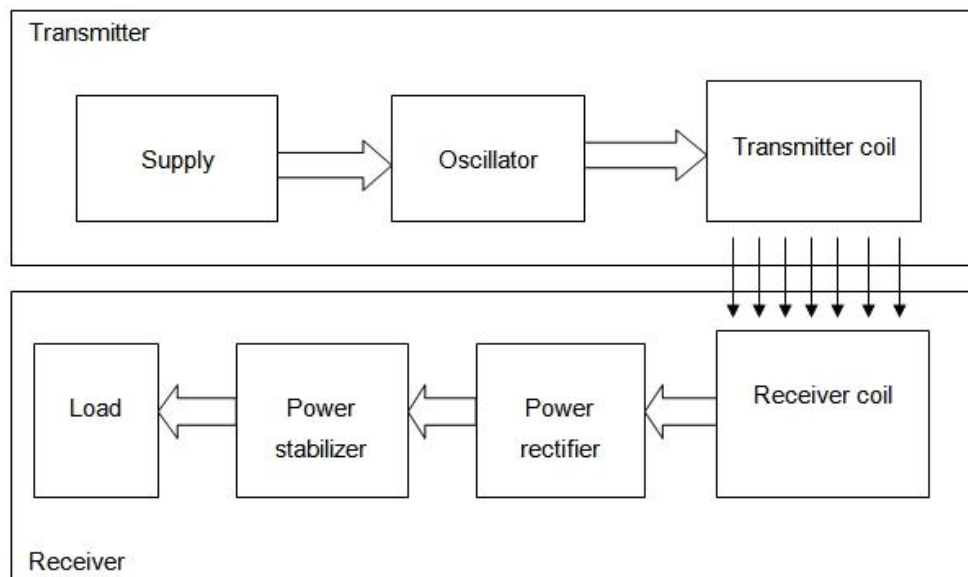

Figure 8 Sections of an inductive coupled wireless power transfer system

3.2   Oscillator design

The main aim of the oscillator circuit is to generate a sine wave having a very high os-
cillating current. This is necessary in order to come up with a strong magnetic field.
Therefore a sinusoidal oscillator is required having a regenerative (positive) feedback
The other major requirements are a tuned LC tank network in order to selectively
choose our working frequency and a higher amplification value to drive the transmitter
coil and create a strong magnetic field.

3.2.1   Frequency Consideration

While taking safety guidelines for public exposure into account, and maximum power
transfer, we can obtain a suitable frequency for the circuit within the range given on the
chart figure 9 below. This is a standard chart from International Commission on Non-
Ionizing Radiation Protection (ICNIRP) an international commission specialized in non-
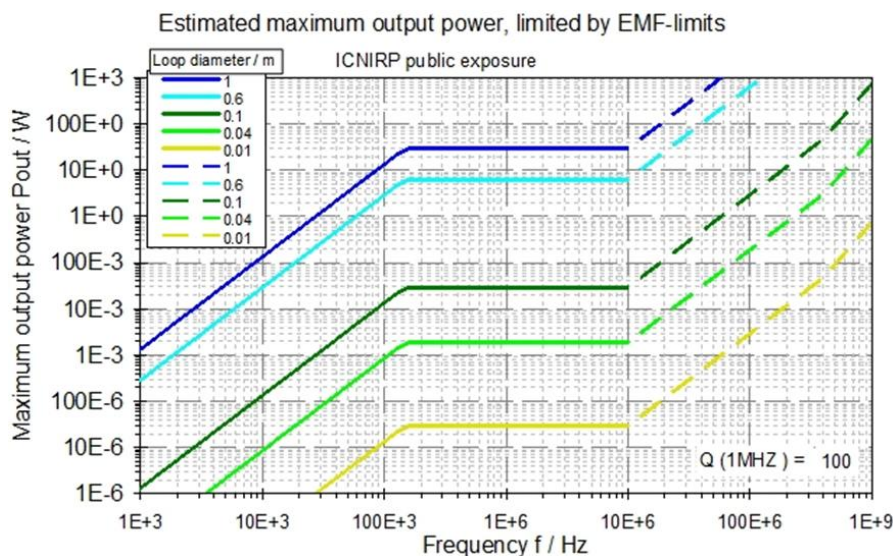ionizing protection [5].

Figure 9 Maximum power output at various frequencies. (Reprinted from icnirp (2017)
[7])

From the chart its clear for frequency range between 150 kHz and 10 MHz the maxi-
mum power is independent of the operating frequency. For frequencies lower than 150
kHz, the maximum power reduces with reducing frequency. Considering interference,

charging distance, transmission efficiency, thermal properties lower frequencies are more preferred than higher frequencies [7].

3.2.2 Implementation: Royer Oscillator

Comparing with other types of oscillators Royer oscillator was most preferred because of its simplicity, low component count, rectangle waveforms which can be turned into sine waves easily. Figure 10 below shows a modified Royer oscillator utilizing N-channel MOSFET chosen for its fast switching speed and high gain.
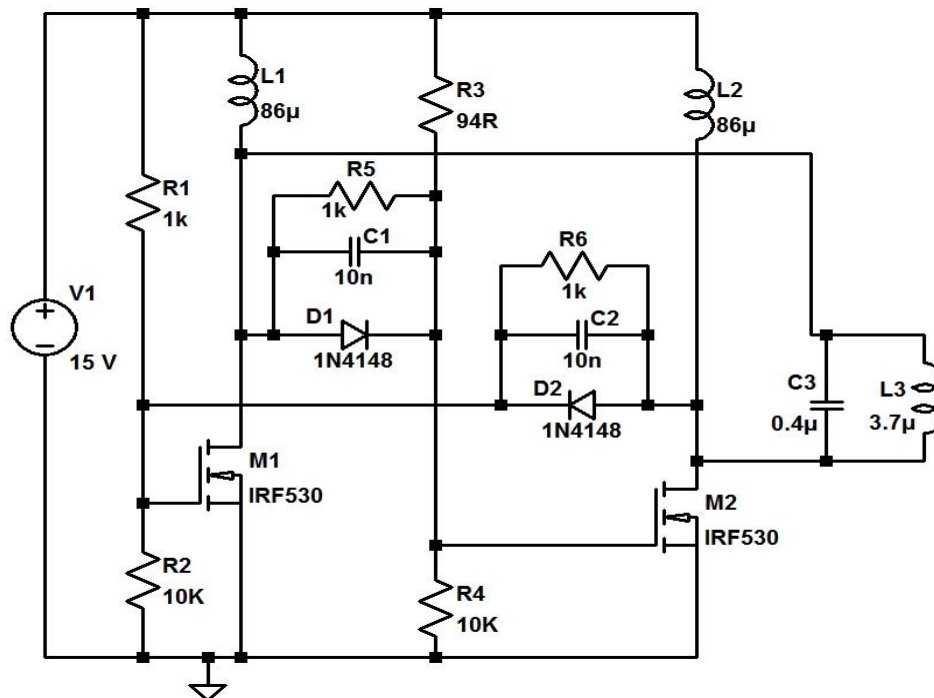

Figure 10 Modified Royer oscillator circuit.

The coil arrangement replaces the transformer, while a capacitor is introduced across to obtain proper tuning for resonance. The transmitter coil is driven by two power MOSFETs in a push-pull configuration. The resonating capacitor C3 causes the voltage across the coil to first rise and then fall in a standard sine wave pattern. The diodes provide positive feedback thus generating oscillation. A RC snubber circuit is employed in parallel to the diode to enhance the performance of the switching MOS-FET and to suppress voltage spikes and damp the ringing caused by circuit inductance

when the MOSFET opens. The oscillator runs at the frequency determined by the inductance of the transmitter coil L3, the capacitor C3 value. This is calculated using the resonant frequency equation earlier mention in equation (1). [7, 25-30.]

3.3   Coil Design

Referring to equation for minimum losses, coil design is very important since it determines both the coefficient k and Q-factors therefore proper coil design will directly enhance efficiency. The overall coil performance depends on the following geometrical characteristics:

1. The number of turns
2. Method of winding the coil.
3. length of the coil
4. Coil diameter

3.3.1   Coil Modelling using ANSY Maxwell software

In order to come up with precise coils having the required optimum working properties ANSYS Maxwell software is used as shown in figure 11 below. Simulation using various combinations of coil geometry and orientation in order to determine inductance for the optimum coupling factor follows after modeling. Considering low power devices a coil diameter of between 30-35 mm is most suitable. Therefore modeling using a 30 mm diameter coil the final design parameters were

N = 16, Internal diameter = 5 mm, Inductance L= 3.7 µH for the transmitter coil

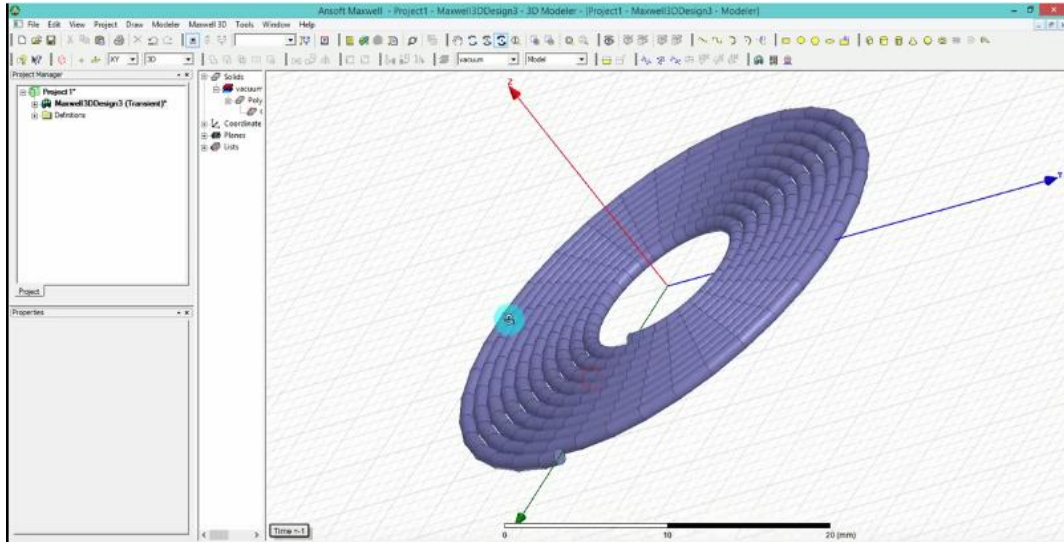N = 17, Internal diameter = 5 mm, Inductance L= 4 µH for the receiver coil

Figure 11 Coil parameters modeling using ANSYS Maxwell

Flat spiral coils were used since they have a higher efficiency with longer distance of transmission compared to other designs plus better axial planar orientation for use in low power devices [8, 33].

3.3.2   LTspice Simulation

Further simulations of the two coils were conducted using LTspice simulation to compare the voltage induced in the receiver coil with different coupling coefficient at 130 kHz resonant frequency. Effect of turns ratio (inductance) and coupling coefficient on received voltage were conducted in order to obtain optimum efficiency. Figure 12 shows the circuit set-up for this simulation.
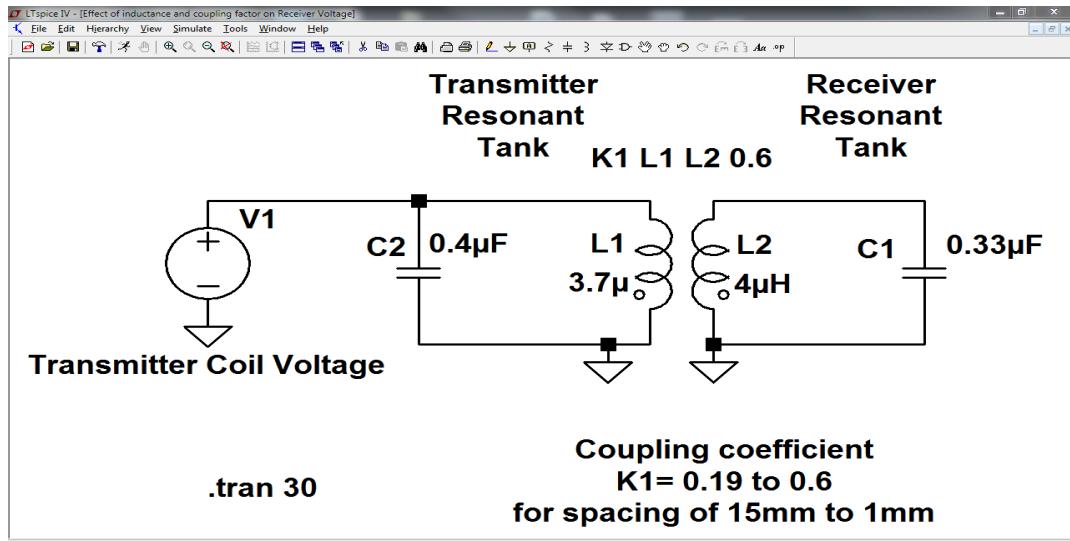
Figure 12 Inductance and coupling coefficient effect on the output voltage.

The results of the above simulation were tabulated as show in the table in table 1 below. The results confirm that indeed both the coupling factor and quality factor play a significant role in coil design

Table 1 Simulation results

Coupling coefficient	Received Voltage (Vrms)
0.1	323.43 mV
0.3	5.88 V
0.5	7.46 V
0.7	7.49 V
1.0	7.56 V
Turns Ratio	Efficiency
1:3	73.9%
1:1.4	58%
1:4	71%

3.3.3   Summary of Coil Modelling

To combat the current density caused by the skin and proximity effects found in single strand and achieve a high Q factor for wireless coils Litz copper wire should be used. These are thin wire strands, individually insulated and twisted together. This way each strand shields against each other and the entire cable unit together. Litz wire gives coils excellent performance and efficiency.

The ideal coupling factor K is 1, but that isn't very achievable. Typical values range from 0.2 to 0.6

Considering Lateral, angular, and vertical orientations angular is the worst at 40-degree angular misalignment reduce the coupling factor from 0.9 to 0.4 bringing a drop in efficiency of over 5

A higher coil turns ratio directly affects inductance meaning Q factor is drastically reduced. 1:1 ratio is common but other options should be explored depending on the power requirements of each system. [9,119; 10, 19]

3.4   Receiver

This section is designed to have a tuned receiver coil, rectifier and a fixed voltage regulator. Expected output voltage is 5 Vdc with a current rating of 0.5-1 ampere. Figure 13 below illustrates a stabilized receiver circuit.
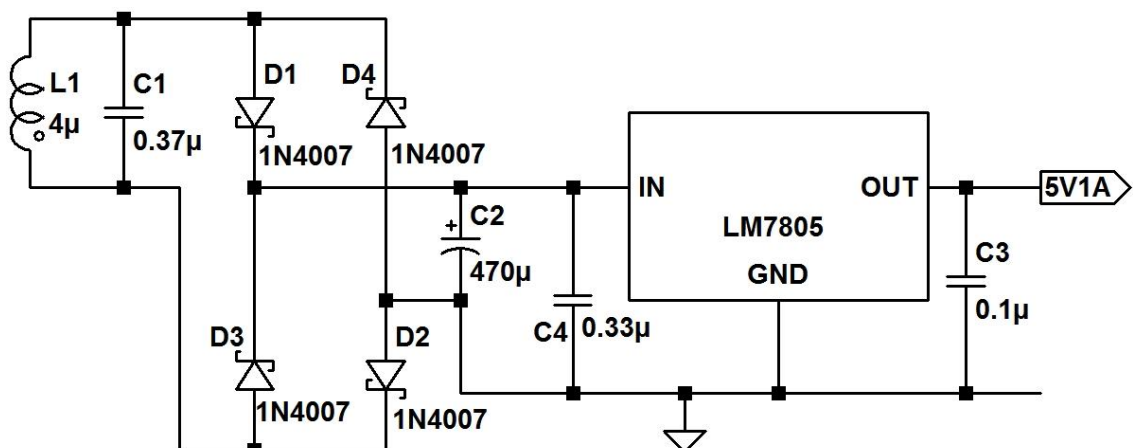

Figure 13 Receiver circuit design

A full wave bridge rectifier is used to rectify the high frequency voltage into a pulsating dc signal.The electrolytic capacitor C2 is used as a filter to smooth out the ripple dc voltage from the output of the bridge rectifier. This capacitor will reduce the ripple based on the discharge time constant of its capacitance. Voltage regulator 7805 is used to keep voltage at a stable level so that circuits can supply a constant charging voltage and current to the low power device.

The capacitors C3 and C4 are decoupling capacitors. They are more effective in filtering out high frequency noise that may still be present at the output stage. A constant voltage is supplied to the battery for charging purpose at the output. [11, 33]

3.5 Circuit Simulation

Before assembly the whole circuit is simulated using LTspice software. Various waveforms were obtained at four different test points marked 1, 2, 3 and 4 as illustrated in figure 14 below
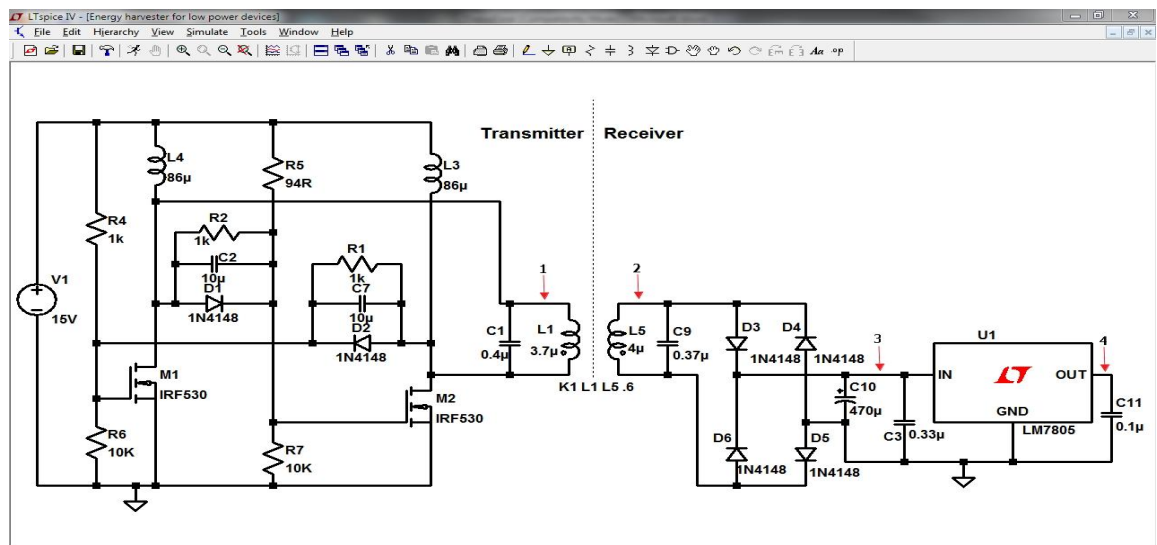

Figure 14 Circuit simulation

Since the circuit is tuned to the resonant frequency of around 130 kHz it was expected that maximum power will be delivered to the load at that resonant. Using the inbuilt oscilloscope ac analysis waveforms at those test points were generated as shown in figure 15.
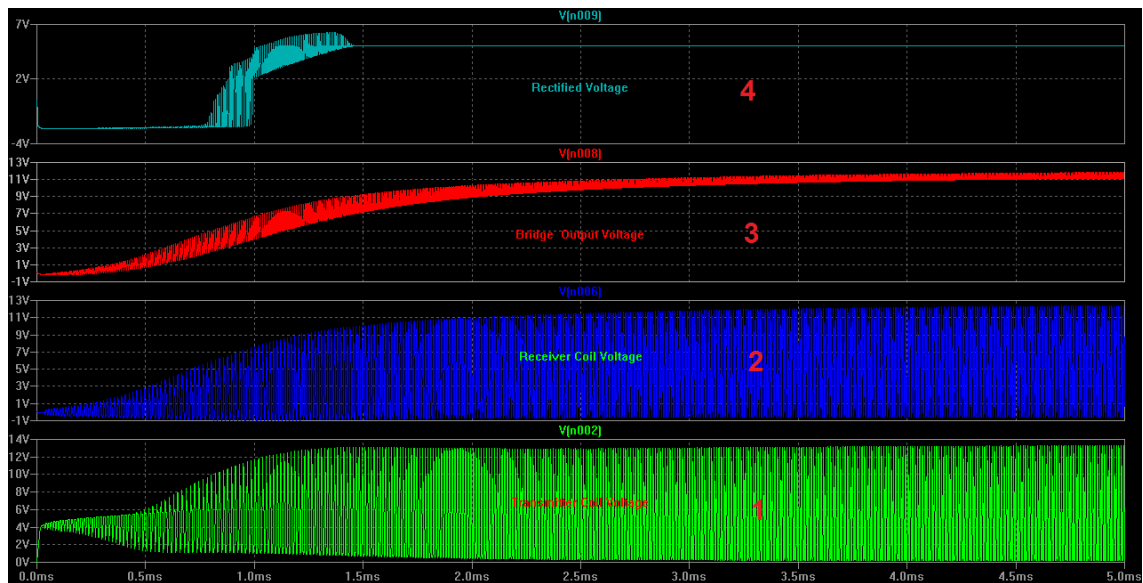
Figure 15 AC analysis waveforms of the circuit

As seen above both the transmitter and receiver coil voltage waveforms represent a high frequency voltage sine wave with a none zero value since from our circuit in figure 14 the transmitter coil is center tapped to both power mosfets outputs

There is also a time delay response of the circuit when the signal is applied depending upon the reactive components present

4. Prototype Measurements and results

The prototype was further designed for PCB fabrication using PADS PCB design software milled and components assembled. Figure 16 below shows the complete prototype.
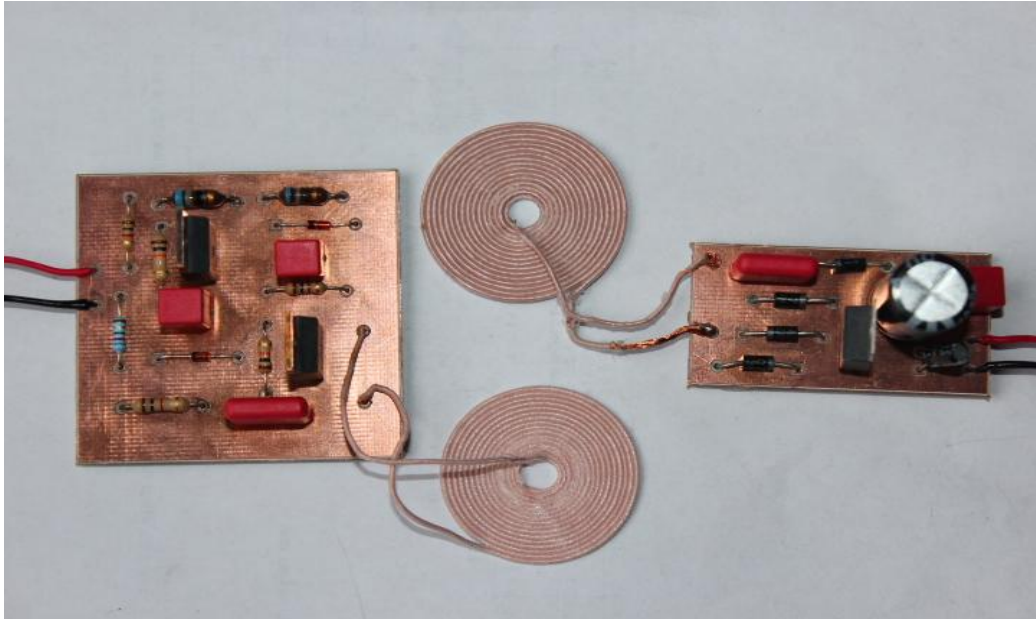
Figure16.Completed prototype

Measurements were conducted to compare the simulated and the actual readings. Tables 2, 3 and 4 below show all of the data collected during these experiments. Considering a maximum consumption of around 600mw of power in each case a different load in form of a resistor is used to determine the overall performance of the prototype.

Table 2 Prototype Test Results Using a 10 ohm Resistor as the Load

Distance	Output Voltage	Output Current
12 mm	2.78 V	90 m A
10 mm	4.02 V	127 m A
8 mm	4.13 V	154 m A
6 mm	4.42 V	210 m A
4 mm	4.24 V	323 m A

The results of table 2 clearly show that for the prototype the operating range is within 10mm.The current reduces more rapidly with distant than the voltage. Actually voltage

remains almost constant up to a distant of 10mm.Current reduction is directly proportional to the distance. Clearly there is a difference between these results and the simulated and calculated results

Table 3 Prototype Test Results Using a 20 ohm Resistor as the Load

Distance	Output Voltage	Output Current
12 mm	1.78 V	98 m A
10 mm	2.02 V	128 m A
8 mm	2.93 V	252 m A
6 mm	3.02 V	300 m A
4 mm	3.91 V	355 m A

Increasing the load seemed to affect both current and voltage values as shown in table 3 above. The current slightly increased to compensate for the voltage loss. Distance between the coils also played an important role too even with change in load. Demand for more power does not change the amount of magnetic flux received. From a broader perspective the prototype drew more current at the expense of voltage. This was a major drawback. Notably at this point the power mosfets started to overheat.

Table 4 Prototype Test Results Using a 40 ohm Resistor as the Load

Distance	Output Voltage	Output Current
12 mm	0.66 V	103 m A
10 mm	1.08 V	127 m A
8 mm	1.09V	254 m A
6 mm	2.62 V	300 m A
4 mm	3.01 V	360 m A

Clearly from table 3 above the circuit was not able to handle load fluctuations the main reason as load demands more power the receiver circuit was not able to obtain any additional flux and even with a stable voltage its value decreases significantly. This value was not enough to charge an ordinary phone. The receiver circuit needs additional circuit in order to completely regulate fluctuations in the load. This circuit should be able to communicate to the transmitter section in order to achieve a more regulated output voltage. Tolerance of the components, internal resistance and stray capacitances may also have contributed to these discrepancies. Figure 16 below shows the waveforms obtained using an oscilloscope showing a comparison between the transmitter and receiver coil.
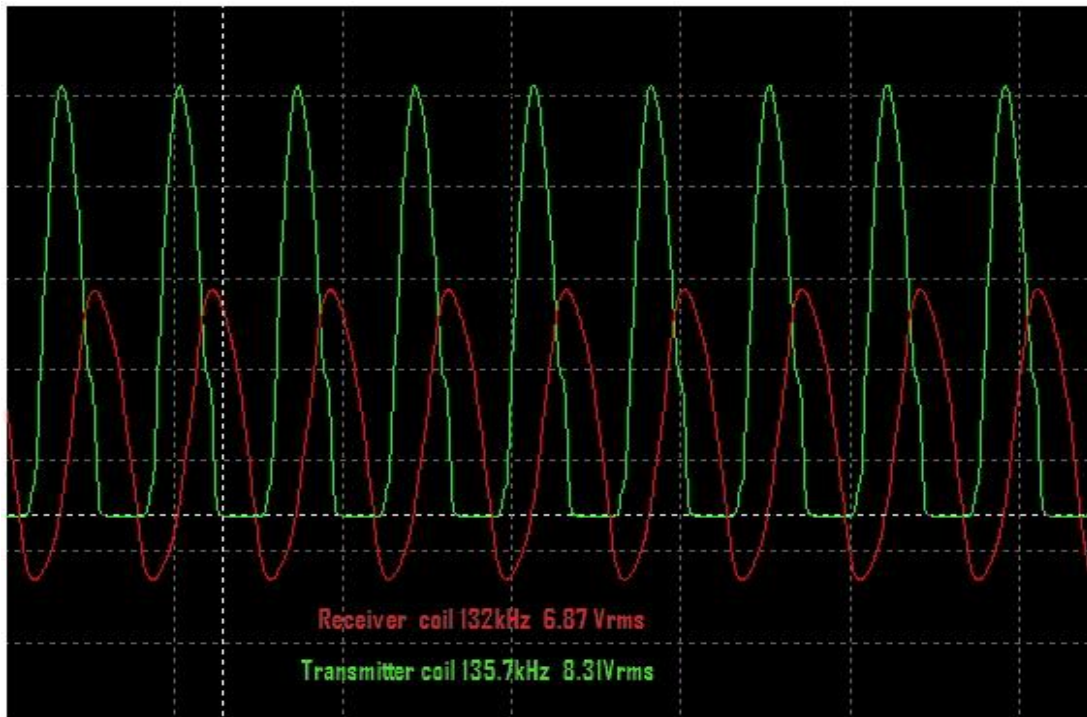

Fig 16 Transmitter and Receiver Coil Waveforms

The frequency of operation was calculated to be 130 kHz although it was not realized since the exact values of the tuned circuits in both resonant LC circuit were not readily available. Approximate values were used instead. This made achieving maximum power at resonant rather difficult. As seen from the waveforms there was a big difference in their peak to peak voltage. The resultant rms voltages were as shown in the figure. A lot of power was lost to the surroundings.
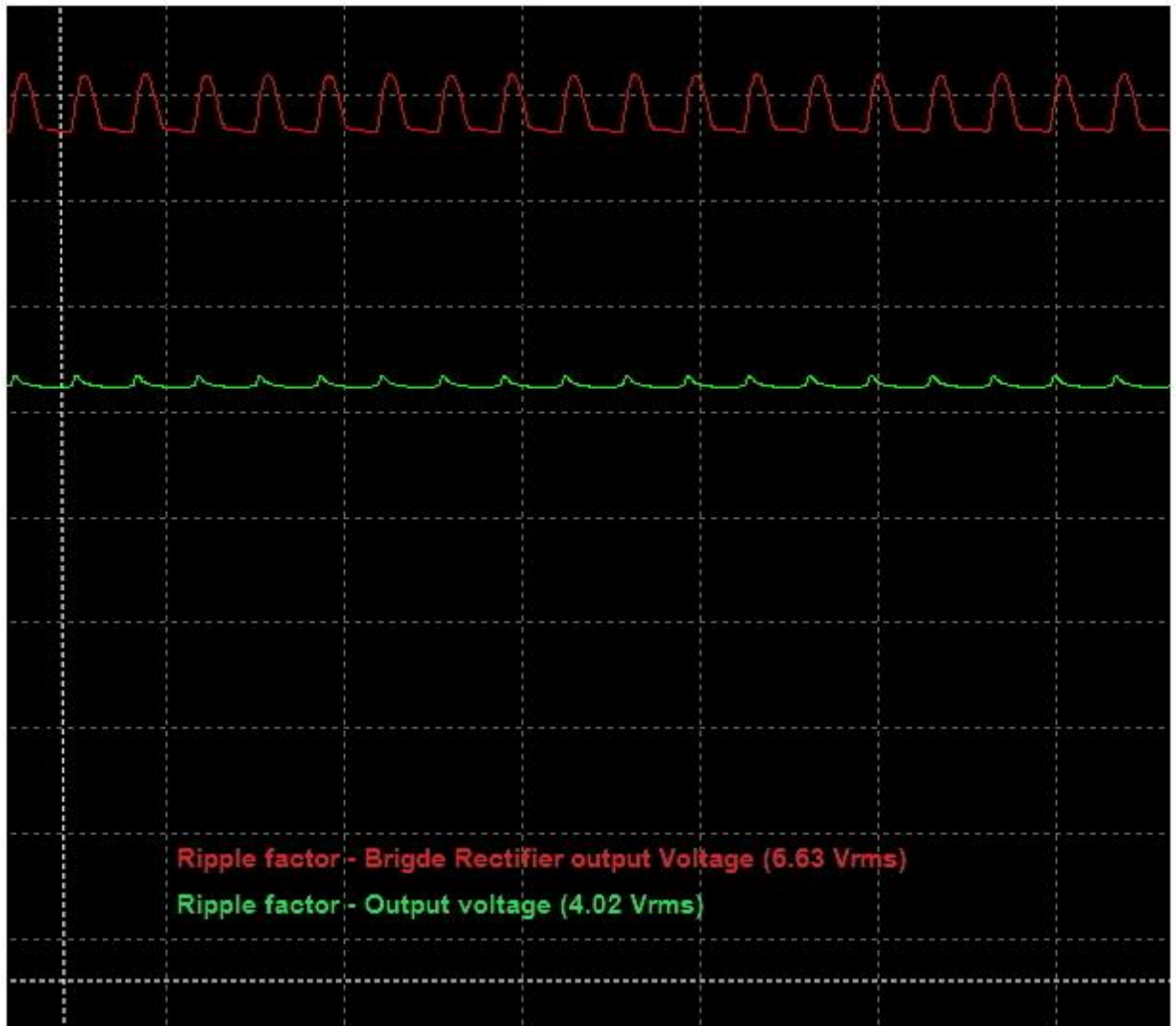
Figure 17 Ripple Factor Output Waveforms

Figure 17 above shows the results of filtering the receiver coil voltage. The bridge recti-
fier receives an alternating signal and gives out a pulsating dc signal as show in red
above. The voltage regulator is not able to give a completely smooth output voltage.
Changing the output decoupling capacitor did not have much effect on the ripple volt-
age and at certain higher values the output voltage was compromised.Further smooth-
ening of the output voltage can still be achieved.

5. Findings and Conclusion

The measured results did not closely match the calculated or the simulated values, however the main goal of this study was achieved since through the design considerations the main challenges of wireless inductive charging were thoroughly addressed.

5.1 Reviewing Main Goal

One of the main goals of this study was to research and analyze the major challenges that affect overall performance of the wireless charging system specifically addressing longer charging time as compared to the traditional methods. Secondly using the research and study attained in the first goal design a prototype keeping in mind the same challenges earlier surveyed.

The research confirmed that among other aspects slower charging time remain a big challenge as far as adopting the new technology in consumer hand – held electronics is concerned. Actually at the time of this study the technology was already in market but not well received by many users. From the study it is evident that slower charging duration in wireless chargers is mostly brought about by the energy losses experienced during power transfer.

Energy losses are brought about by stray magnetic flux produced by the transmitter section of the base charger never reaching the receiver section of the device been charged. These energy losses also account for heating of the base charger and most probably the device under charge. This was further studied and it was revealed that coil design and performance played a very important role in determining the strength and transfer of the magnetic field between the transmitter and the receiver.

To that end it was therefore noted necessary to address coils selection, manufacture and design at a more detailed level. Additionally depending on power demands different low power devices require different coil parameters.

5.2 Implementation: Problems Encountered and Solutions

Having studied and researched on the main goals a circuit design for the prototype followed. Through basic block section analysis and borrowing from some previous circuits it wasn't hard to come up with a complete circuit diagram. A number of changes were made since the target was low power devices. The initial circuit was a more recent but lacked a lot of information so it was dropped. This technology is new and getting even some ICs in the market was not easy.

The power mosfets were very challenging since without the snubber circuit a few blew while at the same time high spikes in the output waveform were encountered. Coil modeling took the centre stage and working backwards from the receiver section a coil pair was modeled that matched our design requirements. Further simulation of the coil and entire circuit achieved affirmed the design correct. Coils were readily available. From the datasheet provided low polypropylene capacitors were highly recommended for the royer oscillator circuit preferred performance. Exact figures were not available therefore approximate figures were used.

Lastly the whole circuit was powered but never oscillated. One of mosfets over heated and blew. It was later found out the snubber circuit was necessary.

5.3 Results

The results of the study showed that the most important aspect of wireless power transfer is the coupling between the transmitter and receiver coils. Their design should be very precise in order to minimize energy losses. The inductance and coupling coefficient of the coils should always match the working frequency and power transfer requirements.

Stranded copper wires give better efficiency compared to single copper wires for the coils design. Transmitter and receiver coil turns ratio must be taken into consideration since it determines the output power required. Electromagnetic shielded is important in order to comply with the EMI standards and reduce stray magnetic fields. Although this was not conducted its clear from the research that a ferrite sheet embedded onto the coils will help concentrate magnetic field thereby reduce losses, increase efficiency and shielding [6,200].Additionally a transmitter section with a multi-coil arrangement is used when free device-positioning is required.

5.4 Suggestions for Further Future Work

The prototype demonstrated the possibility of having a more efficient design to address the current low efficiency in wireless charging. The oscillator could be designed further to allow even a more stable and powerful frequency. Crystal oscillator can be incorporated.Further work and research should be conducted on ways aimed at concentrating the magnet field generated and making sure that it is all captured by the receiver coils.

Further effort on this study would be to explore the possibility of a transmitter that would allow close proximity between placement of the devices been charged. These would allow the capture of all the magnetic flux generated reaching any of the devices that are closely aligned next to each other. Such a system would not only reduce energy losses but greatly increase efficiency and performance of such a charging system.

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