The Author and publisher of this book have used their best effort in preparing this book. These efforts include the development research and testing of the theories and programs to determine their effectiveness. The Author makes no warranty of any kind, expressed or implied, with regard to this program or the documentation contained in this book. The Author shall not be liable in any event for incidental or consequential damage in connection with, or arising out of the furnishing, performance, or use of these programs.

PSpice is a registered trademark of Cadence Design Systems
Preface
The first edition of *Wireless Charging* is carefully planned description of the Capstone Design Project held by undergraduate students at Rutgers University. The goals are:

- To build and understanding of concepts and ideas in terms of learning
- To emphasize the relationship between conceptual understanding and real world applications of the theory
- To provide engineers strong foundation for developing the project.

**Fundamental Equations and Concepts**

Throughout the text, you will see fundamental equations and concepts set apart from main text. This is done to help you focus on some of the key principles in design of the product and to help you navigate through the important topics.

**Integration of Computer tools**

Computer tools assisted students in learning process by providing visual representation of design’s behavior, validating a calculated solution, reducing the computational burden of more complex circuits, and iterating toward a desired solution using parameter variation. This support is mostly taken in design process. Tool that we used include pspice, AutoCAD and Microsoft Office.

**Design Emphasis**

This book supports the emphasis on the design aspect of the product including electrical circuit and physical product. Design oriented material has been labeled appropriately.

**Accuracy**

All material presented in this book has been doubled checked before presenting to ensure the most error-free book possible.

**Resources for Students and Instructors:**

Website address
Prerequisites

In writing this book, we have assumed that the reader has taken major undergraduate courses in electrical engineering. Courses include Principles of Electrical Engineering, Electronic Devices, Digital Electronics, Analog Electronics, and Power Electronics. Reader must be familiar with basic electrical concepts and components such as energy power, electric charge, voltage, current, power and phase/frequency of AC power supplies. In understanding first two chapters, reader does not have to be in the profession of electrical engineering but expected to know current technologies in electronic market.

Acknowledgements

We express our appreciation for the contributions of Ivan Seskar and Narayan Mandayam of WINLAB, Rutgers University for sharing his knowledge and experience in electrical engineering with us. His contributions to the practical perspectives greatly enhanced this book. Also, Special thanks to following people:
Part 1: Theory

Chapter 1  : Motivation
1.1: Electrical Engineering

Electrical Engineering is a very broad field in recent infrastructure of the world due to increasing demand of electronic devices which reduced human efforts by factor of tens. One of the largest and hottest streams of this sea is Wireless Electronics Systems. Electrical Engineering is slightly saturating in some of the streams such as pure digital electronics. This lead us put the effort into Wireless Electronics.

1.2: Market in Electronic Systems

In this fast growing electronics world, number of electronics devices have increased dramatically over the years. There are few tradeoffs in the field of electronics, such as, efficiency, convenience and cost issues. Efficiency issue includes losses due to heating of the devices and other losses in the transmission and transfers of energy. Also, some of the electronics devices are not available commercially because the efficiency problem is solved with higher cost and high-tech logic circuits and their user interface comes with lots of human efforts. One of the biggest issues encountered is the convenience issue for the portable devices such as; carrying the charging cords and adapters everywhere you go. Many people have more than one portable device now a days and each comes with its own power charger. Wireless world lacks the successful use of Wireless Power Transfer.
1.3: Wireless World and Wireless Charging

We have come a long way in development of very high tech mobile devices. Cables and cords have almost been eliminated from our day to day lives, but at the end of the day these devices need to be charged and that is when the cables come in. In the case of portable devices, we need cords to charge the devices; such as, cell phone charger, laptop charger etc. Power is required for every electronic device and without power all the high tech gadgets are useless. Wireless Power Transfer (WPT) with spatial freedom has caught researchers’ attention since 2007 when students at MIT came up with the WPT technology taking advantage of magnetic resonance. This had caught attention of many researchers and technology giants from all around the world. Of Course, it will be a breakthrough technology when it becomes more popular and widely used. Unfortunately, that day is yet to come.

1.4: Motivation

This increasing demand for the WPT technology needed more focus so our team has decided to research in this area and try to contribute to the community in order to make this technology available to people at lower cost and higher efficiency. As senior electrical engineering students at Rutgers University, we took this project as an opportunity to research and address issues with wireless charging systems available in the market. This research is dedicated to make a functional WTP system based on market survey for wireless charging devices available in the world. The rest of this paper will describe our bird’s eye market survey and issues with available technologies as well as solutions to some of the pre-existing devices. However, our basic and the very first task will be to make a working wireless charger from bottom up using fundamental electrical engineering concepts.
Chapter 2 : Survey and Selection
2.1: Different products in the Market of 2013

There is various kind of wireless charger available to charge various electrical devices and cars. Various available wireless products are discussed below.

**PowerMat 3X**

PowerMat 3X is a sleek, slim three position wireless charging device. There is a magnetic attraction between every receiver and each access point on every mat assures that alignment is accurate and the most efficient charging occurs. Communication between the Mat and the Receiver allows the mat to deliver an exact amount of power for the proper length of time so that the transfer of power is safe and efficient and no energy is wasted. One big advantage of this device reaches full charge, power is shut off to that device, which avoids overcharging of the device’s battery as well as saves energy. The efficiency of this device is about 80 to 85% and it cost is approximately $100.

**Energizer Wireless Charger**

Energizer Inductive Charger is based on Qi Technology and aims to be the next-generation charging solution for many devices. The Energizer Inductive Charger conveniently charges up to three devices at a time. This energizer (“Qi(Chee)” inductive charger is Available for iPhone 3G, 3Gs, 4 and Blackberry Curve8900. Two inductive Qi charging zones are located on the top surface of the pad for simple, easy charging. For both Qi and non-Qi devices, the USB port on the back is ideal for charging additional phones, headsets, mp3 players, cameras, GPS devices, and any other device up to 5 watts. The efficiency of this device is about 80% to 90% and it cost is approximately $110 including sleeve for the device.

**Mobee Wireless Charger (Magic Charger for Apple devices)**

Mobee (Magic charger) is Inductive charger and it is specially made for Apple Devices. With the use of this product we will never have to replace the battery of our apple’s Wireless mouse, Keyboard and Track pad. Magic Bar is the world’s most eco-friendly, inductive charger for Apple’s Wireless Keyboard (2AA version) and Magic Track pad. It is also very friendly to use it, all you need to do is replace the battery with magic bar and magic bar will charge wirelessly. Efficiency of this device is about 40% and it cost range is from $40 to $150.
**Duracell mygrid**

The Duracell MyGrid Charging Pad is a flat square with a single raised edge. It consists primarily of 12 magnetic strips, which carry the actual charge to the devices. With a maximum power output of 15 VDC/1A, it's a very efficient device, charging all four gadgets in more or less the same amount of time as by using their bespoke power adapters, all the while saving around 15% on energy consumption.

**Wildcharge Pad**

Pure Energy Solution’s WildCharge Pad offers comparable features and output capabilities. The WildCharge Pad provides 15 watts of output power, enough to charge multiple devices simultaneously. It works through the traditional contact-point transference principle where two conductive materials transfer electricity to charge the battery. Its cost and efficiency is same as Duracell and Powermat chargers.

**Witricity Wireless charger**

The WiT-2000M solution enables developers of mobile devices to shorten the design cycle for integrating highly-resonant wireless power transfer into ultrathin smartphones, tablets, and comparable devices. The WiT-2000M is an optimized design covered by WiTricity's patented technology for highly resonant wireless power transfer. This technology transfers power over distance and through many materials in a manner that is safe, efficient and cost effective.
Wireless charging for Transportation:

Transportation sector is the largest consumer of fossil fuel worldwide and thus important factor in reducing fossil fuel demand. Pollutant emissions and oil consumption are caused by transportation sector. Currently the transformation in automobiles from internal combustion engines (ICE) vehicles to hybrid fuel cells vehicles (FCV). The limited availability of fossil fuel and to reduce the emissions in transportation sector, the development of electric vehicles worldwide over the past decade has been initiated. The price of EV is nearly twice than that of ICE vehicles which is largely due to the limitation of battery technology. The charging time of EV is very long when compared to ICE car. Currently, plugin connections are used in EVs for charging where the user inserts the plug into the receptacle of the car to charge the batteries. It has the following disadvantages. The major disadvantage of using cable and connector type is the risk of electrocution especially in wet and hostile environments since it delivers 2-3 times more power than standard plugs at home. Long wires also pose a tripping hazard and are also aesthetically poor. In harsh climate locations that have snow and ice, the plug-in charge point may become frozen onto the vehicle. Thus in order to eliminate the above disadvantages, the resonance wireless charging has been developed which can charge the batteries wirelessly.
As shown in figure we can charge our Vehicle battery Wirelessly through resonance. There are Wireless charging Vehicles by Evatran, Delphi and witricity. Delphi Corporation (Using Future technology by witricity) has designed power system that can charge your phone and EV car wireless. Also Evatran has its Plugless Power hands-free charging system for Nissan Leaf and for Chevrolet Volt. There are also public transportation bus that is also charged wirelessly. In south korea there are wireless charging bus with a 6.7-inch gap between the road and the bus, there’s 85 percent charging efficiency at 100 kW from the road to the bus. Wireless charging is already powering buses in Utah and in Germany. Buses in Torino, Italy have used induction since 2003, and routes in Utrecht, the Netherlands got induction back in 2010.

Wireless Charging inside Vehicles:
Chrysler adds built-in wireless charging option to 2013 Dodge Dart. It will about $199.99 plus installation (case included). It will be launched in the second quarter of this year. It is capable of charging Apple, Android, and BlackBerry devices. The technology is called Qi (pronounced "chee"), and it will be available on the 2014 Jeep Cherokee and also in Toyota Avalon due this fall. Chevrolet announced a similar product was in development for the Volt. Also, GM car will have this future in their 2014 products. A group of electronics companies and suppliers who hope to see Qi become an international wireless charging standard, the group says to expect Qi in more new models soon.

2.2: Safety Standards of Wireless Energy Transfer

2.3: Issues with Current Wireless Charging Products

There have been many issues with wireless charger. First of all, Most of the wireless chargers on the market today have a limited range of few inches so It just can't be charged if it's not on the charger. Secondly, It is impossible to use your device or talk while device is being charged. Third, as device is being charged wirelessly it takes little longer to charge then charging with cables.

2.4: Challenges that Researchers May Have Found
2.5: Defining Ultimate product

Our goal is to charge device wirelessly with possible maximum distance and so we should be able to use the device while it’s charging.

Chapter 3 : Product Design

Components:

3.1: Resonators: Transmitter & Receiver

As mentioned in earlier chapters, the whole idea behind this technology is to use the phenomenon of resonance in order to achieve most efficient power transfer at certain distance, over the air[1]. If the transmitter and receiver are inductively coupled, the distance between them is minimal and efficiency suffers substantially as the distance is increased.
3.1.1 : Resonance

Scientific definition of resonance is *tendency of a device to oscillate at higher amplitude at certain frequency*. The resonance frequency the system is at its peak and in our application, maximum output power can be achieved when source and device are coupled at resonant frequency. In other words, most energy is transferred between two objects if they are in the state of same frequency. Glass breaking at certain high pitch sound is a very good illustration of this concept of physics.

3.1.2 : Resonator

A resonator is any system that is operating at its natural frequency (i.e. resonant frequency). In our example of glass breaking at sound, high pitch sound generator is resonator which resonates at certain frequency. In electrical circuit design, a simplest resonator could be a tank circuit tuned to oscillate at resonant frequency, which is nothing but a pair of an inductor and a capacitor tuned at certain frequency. There are many other ways to make a resonator circuit using operational amplifiers, transistors crystal oscillator, etc. For our purpose the tank circuit can work perfectly. The inductor of the RLC tank can work as an coil (antenna) to radiate a magnetic field which then resonates the other coil in the range, inducing current in the other coil henceforth successfully transmitting power over some distance.

\[ \omega = \frac{1}{\sqrt{LC}} \]
3.1.3 : Optimum frequency selection

This is one of the most difficult questions that we asked to ourselves. We all know by now that in order to transfer the most energy we need both the receiver and the transmitter coil to run at same frequency. In other words, impedance of both receiver and transmitter should be matched in order to transfer maximum possible energy.

\[ \omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \]
The question is, what could that frequency, $\omega_0$, be? Resonating frequency is expressed in terms of Capacitance and Inductance. We can have many choices for this elements resulting in many frequencies. What is the frequency at which we can get the most efficiency out of the system?

This question led us to research deep in to the radio and communication theories. Even though radio theories do not apply explicitly here, there is a good amount of information adapted from those. As we discussed previously, resonating frequency depends on both the inductor and the capacitor. Inductor is most likely not of our choice, since our coil is our inductor; and the coil size will be decided by the size of the mobile phone that we choose.

Radio communication is a huge field of study and it was not feasible for us to study the entire theory. There are many books written in that topic but it becomes a whole different research on its own. We had to reduce the amount of information that we should read. To narrow down our research, we approached following questionnaire.

Near Field and Far Field

There are two major categories for transferring energy wirelessly: Near field transmission and Far field transmission. Radio communication is the Far field transmission as it may sound obvious to some of us. To describe the difference between these two types, let us look at picture below.

![Near Field and Far Field Diagram](image)
Any energy transmission that takes place at distance larger than a wavelength of the signal, is considered transmission in Far field. Any transmission that takes place within a wavelength of the signal is considered near field transmission. Our goal is to transfer the energy at reasonable distance and not so far away, however, we want the most efficiency since we are transmitting power and not the massage. That means, we should transmit energy in the nearest part of the near field. Radio propagation theory does not apply in our case since it applies only for far field.

**Radiative and Non-Radiative (Reactive)**

Also, there are radiative and non-radiative ways of transmitting energy; radiative way is too lossy but can transfer the signal up to larger distances. Radio communication uses radiative type of energy transfer (which has both electrical and magnetic components separated by 90 degree in phase) since it goes further away in far field due to its decaying factor $1/r$. As shown in the figure, 0.159 of the wavelength is considered to be the nearest part of the near field in which there is least amount of radiation, if a high current coil is used as transmitter. In other words, within nearest part of the near field, energy is purely magnetic and not electromagnetic. Unlike electromagnetic radiation, magnetic resonance coupling has negligible amount of radiative losses. In near field, the loop emits most of its energy through magnetic field. Here, Resonant Evanescent Coupling is the most effective theory. Using this method, we can couple the transmitter and receiver so that no energy is lost in the air. Ideally, 100% energy is communicated. Another way to look at this is, as it is an *Air-core Transformer*. 
Hint: Very close to high current antenna, magnetic field dominates; and, very close to high voltage antenna electric field dominates.

**Resonance Coupling and Quality Factor**

In this section, we will talk how strongly the coils should be coupled in order to transfer the energy most efficiently. Coupling coefficient $k$ is the measure of coupling strength. In near field, reactive component (pure magnetic field) has higher intensity but it also decay’s quickly by factor if $1/r^2$ unless coupled.

$$K = \frac{2\sqrt{r \ast R}}{\sqrt{(R + r)^2 + h^2}}$$

From above formula, we can see that $k$ is inversely proportional to, $h$, distance between two coils. This distance decides wavelength with which we can stay within the nearest part of the near field to avoid radiative losses. This wavelength decides our optimum frequency ($f = c / \lambda$) as long as our proposed coil can transmit that frequency and is allowed in ISM band.

Quality factor of two coils and coupling coefficient $k$, combine, decides efficiency of the wireless power transfer with this

$$\eta_{max} = \frac{k^2Q_1Q_2}{(1 + \sqrt{1 + k^2Q_1Q_2})^2}.$$  

Where $Q_1$ and $Q_2$ are quality factors of transmitter and receiver coil respectively.
Where

\[ Q = \frac{1}{1/Q_L + 1/Q_C} \]

Where,

\[ Q_C = \frac{X_C}{R_C} = \frac{1}{\omega_0 C R_C} \quad , \quad Q_L = \frac{X_L}{R_L} = \frac{\omega_0 L}{R_L} \]

Quality factor and coupling coefficient are major factors contributing to efficiency. Where, \( Q_1 \) and \( Q_2 \) will be locked by coil limitations. There are different kinds of coils available for energy transmission.

Flat Spiral coil can give us the best \( Q \) for smallest size of coil because it provides higher inductance for given size of coil.

\[ L_s = \frac{a^2 N^2}{8a + 11c} \]
3.1.4: Final Resonator Design

Summarizing all previous discussion in this section, we concluded following theory:

1. We should transmit the energy at the state of resonance between transmitter and receiver coil, in order to build the most efficient WPT system.
2. It is not efficient to transmit the energy like radio communication(Far-field), rather, we should transmit the power in near field so that least radiation occur and we can couple pure magnetic field through resonance.(High current coil can generate good magnetic field coupling two coils) - How much current?
3. In addition, efficiency of the coil is directly determined from two measures:
   a. Coupling Coefficient
   b. Quality factor of coils

3.2: DC/RF Amplifier

3.3.1: Different Systems and Selection

As we know that in order to excite any coil, we need AC at certain frequency since coils do not generate magnetic field at DC. There are various techniques to convert DC in to AC. There are invertors, switching circuits, oscillators and many other types of DC-AC converters. Inverters are used in High Voltage power conversion at relatively low frequencies (few hundred Hz). Inverters are not capable of generating high frequency voltage (in few MHz) but they are capable of converting high power(up to few MWs). They are used to convert Dc-AC on utility plants such as solar power plant and other DC generator plants.

On the other hand, oscillators are used to generate very high frequency voltage from DC; In fact, they can generate up to many GHz. Oscillators are typically used in radio communication as they can generate very high frequency. Oscillators are not meant to generate high power since in radio communication signals are low power (typically mW) and radio signals are amplified at receiver end. However there are few types of design specific oscillators which provides both high frequency and close to sufficient power. In Wireless Power Transfer, efficiency is the major consideration and we cannot afford to amplify the voltage at receiver and due to size and cost constrain of receiving end.
Switching Circuits’ outputs are square waves which typically are used in digital electronics as timer/sampler. Square wave is harmonically rich and so it can interfere with many other signals and electronics.

The Best type of oscillator that we found is the colpitts Oscillator is one of the types of Oscillators and has different designs specific for different applications. i.e. A crystal Colpitts oscillator is very precise but does not output enough power for this application. Therefore the best choice would be a Colpitts Oscillator with Transistor as it has a high gain and good frequency response.

Picture of colpitts Oscillator

3.3.4: Final DC/RF block design

We need to transmit the power at selected frequency based on selection analysis conducted in 3.1.3. Colpitt’s oscillator is not producing enough current so we have to amplify the current at tuned frequency. So, our DC-RF Block will comprise of an oscillator and tuned oscillator. We will amplify the current so that it does not exceed coil’s maximum current rating. More current generated more inductance and so Quality factor improves.

How much power efficiency it has?

3.3: RF/DC Converter

3.3.1: What is RF/DC Block?
RF to DC is used to convert RF (AC) to DC by use of rectifiers and this process is known as rectification. As shown in above figure Rectifier is made using the diode because diode current flows only unidirectional and so using different configuration of diode we can get DC output. In rectification diodes are mostly used because diodes are inexpensive and readily available with low and high power capabilities. As this circuit allows power to flow only from source to load, they often termed unidirectional converters. When rectifiers are used solely, their outputs consist of DC along with high ripple ac components and so we have to add additional filtering circuit to reduce these ac ripples.

3.3.2: Why do we need RF/DC?

Looking at our block diagram we can see that our Load needs Pure DC voltage and current. When we transfer energy wirelessly through coils we get alternating voltage (AC) and so to get DC voltage we need to use rectifiers.

3.3.3: What are the possible ways, limitations?

There are many different ways to convert RF (AC) to DC. Such possible ways are following.

Single Phase and Three Phase Half Wave Rectifiers:

Half-wave rectifier with resistive load
Half-wave rectifier With Capacitive load
Half-wave rectifier With Inductive load

Single Phase and Three phase Full-Wave Rectifiers:

Full-wave rectifier with resistive load
Full wave rectifier With Capacitive load
Full-wave rectifier With Inductive load
Full-wave rectifier With Capacitive Inductive loads (LC Filter).

Block Diagram for Single Phase (a) and three phase rectification (b).
Half wave rectifier with resistive load:

Looking at above figure here when we apply positive voltage diode conduct and become short circuit and so current flow through source to load and we get output, but when we apply negative voltage diode becomes open circuit and so we don’t get output.

Half wave rectifier with Inductive load:

Adding Inductor with in series with load we can see that output voltage have no effect but because of inductor we still get output current even if input voltage goes to zero

Half Wave rectifier with capacitive load:

Here when add capacitor parallel with the load and when we apply positive voltage parallel load capacitor get charge and when input voltage goes below zero the diode stops conducting but charged

Full-wave rectifier with resistive load

Full-Wave rectifier with Inductive load

Full- wave rectifier with capacitive load

Full wave rectifier with Inductor
3.3.4: Final RF/DC block design

What Voltage, frequency is received?
What size would fit in our design?
How much power efficiency it has?

3.4: Source/Load

3.4.1: Source Capacities

3.4.2: Load Requirements

3.4.3: Overall Efficiency of the System

Operating Mode

3.5: System Design

3.6. Impedance Matching

Learning from the chapter

Chapter 4 : Improvement in Design

Part 2: Simulations
Chapter 5  : Simulations

Part 3: Experimental

Chapter 6  : Manufacturing

Chapter 7  : Product Cost

Part 4: Work Distribution
Chapter 8: Citations