# A COMPARATIVE ANALYSIS BETWEEN RECTANGULAR AND CIRCULAR STRUCTURES USING VARIOUS NUMBER OF RESONATOR COIL SYSTEM FOR WIRELESS POWER TRANSFER

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# A COMPARATIVE ANALYSIS BETWEEN RECTANGULAR AND CIRCULAR STRUCTURES USING VARIOUS NUMBER OF RESONATOR COIL SYSTEM FOR WIRELESS POWER TRANSFER

by

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## LIST OF SYMBOLS

| | |
|---|---|
| k | Coupling Coefficient |
| Q | Quality Factor |
| $M_{ij}$ | Mutual Inductance b/w $i^{th}$ and $j^{th}$ Coil |
| $L_i$ | Self-Inductance of $i^{th}$ Coil |
| R | AC Resistance of Coil's Windings |
| C | Capacitance |
| η | Efficiency |
| $\omega$ | Resonance Frequency |
| Qi | A Wireless Charging Standard |
| d | The gap between Transmitter and Receiver Coil |
| H | Height of the Rectangular Coil |
| W | Width of the Rectangular Coil |
| N | Number of turns of Coil |
| $\mu_o$ | Permeability of Free Space |

# LIST OF ABBREVIATIONS

| | |
|---|---|
| ADS | Advanced Design System |
| CMT | Coupled Mode Theory |
| EV | Electric Vehicle |
| EM | Electromagnetic |
| HF | High Frequency |
| IPT | Inductive Power Transfer |
| IEEE | Institute of Electrical and Electronics Engineers |
| KVL | Kirchoff’s Voltage Law |
| LRV | Light Rail Vehicle |
| MRC | Magnetic Resonance Coupling |
| OLEV | Online Electric Vehicle |
| PTE | Power Transfer Efficiency |
| PMPT | Permanent Magnet Power Transfer |
| PSC | Printed Spiral Coil |
| PCB | Printed Circuit Board |
| SPM | Synchronous Permanent Magnet |
| SOC | System On Chip |
| WPC | Wireless Power Consortium |

**ANALISIS PERBANDINGAN ANTARA STRUKTUR SEGI EMPAT TEPAT DAN BULATAN MENGGUNAKAN KEPELBAGAIAN BILANGAN SISTEM GEGELUNG PENYALUN UNTUK PEMINDAHAN KUASA TANPA WAYAR**

## ABSTRAK

Sistem Pindahan Kuasa Tanpa Wayar (WPT) merupakan alternatif dan calon yang berpotensi untuk memenuhi keperluan mengecas pelbagai peralatan elektrik dan peranti seperti kenderaan elektrik, implan bioperubatan, alat mudah alih, telefon pintar dan penderia rangkaian. Teknik WPT yang paling banyak digunakan adalah gandingan induktif dan gandingan salunan magnet (MRC). Dalam tesis ini, pemodelan dan analisis sistem gegelung empat penyalun jarak pertengahan dan kuasa pertengahan untuk WPT dibentangkan. Dalam sistem yang dicadangkan ini, analisis perbandingan bagi kecekapan dan pindahan kuasa untuk struktur gegelung yang berbeza iaitu segi empat tepat dan bulatan menggunakan topologi gegelung yang berbeza seperti dua-gegelung, tiga-gegelung dan empat-gegelung penyalun telah dijalankan. Simulasi bagi sistem yang dicadangkan telah dilaksanakan menggunakan alatan Keysight ADS dan seterusnya disahkan melalui binaan prototaip. Berdasarkan keputusan, kecekapan pindahan kuasa (PTE) dan kuasa yang berjaya dipindahkan menggunakan sistem gegelung empat penyalun yang dicadangkan adalah 74.670% dan 3.8 W bagi struktur gegelung bulat, dan 81.487% dan 4.7 W bagi struktur gegelung segi empat tepat pada jarak penghantaran antara gegelung sejauh 13 cm. Oleh itu, dari pengukuran PTE dan Pindahan Kuasa di atas, jelaslah bahawa dari segi struktur gegelung, struktur segi empat tepat mempunyai prestasi yang lebih baik berbanding struktur bulatan. Sementara binaan sistem penyalun WPT empat gegelung memberikan kecekapan dan pindahan kuasa yang paling tinggi pada frekuensi resonans 120 kHz. Keputusan yang diperoleh adalah amat setara dengan keputusan simulasi dengan hanya sedikit perbezaan. Penemuan kajian ini menunjukkan bahawa sistem gegelung empat-resonator dengan struktur segi empat tepat adalah pilihan yang paling wajar untuk keperluan kecekapan melebihi 70%.

**A COMPARATIVE ANALYSIS BETWEEN RECTANGULAR AND CIRCULAR STRUCTURES USING VARIOUS NUMBER OF RESONATOR COIL SYSTEM FOR WIRELESS POWER TRANSFER**

## ABSTRACT

WPT system is an alternative and promising candidate for the charging need of many electrical devices and equipment such as electric vehicles, biomedical implants, portable tools, smartphones and network sensors. The most widely used WPT techniques are inductive coupling and MRC (MRC). In this thesis, modeling and analysis of mid-range and mid-power four-resonator coil system for WPT is presented. In the proposed system, comparative analysis of efficiency and transferred power for different coil structures i.e. rectangular and circular using different coil topologies such as two-coil, three-coil and four-resonator coil have been carried out. The proposed system is simulated using the Keysight ADS tool and later verified by fabricating a prototype. From the results, the power transmission efficiency (PTE) and the transferred power in the proposed four-resonator coil system are 74.670% and 3.8 W for circular coil structure, and 81.487% and 4.7 W for rectangular coil structure at 13-cm transmission distance between the coils respectively. Therefore, from the above measurements of PTE and Transferred Power, it is evident that in terms of coil structure, the rectangular structure has better performance than the circular one. While four-coil WPT system architecture gives the highest efficiency and transferred power at 120 kHz resonance frequency. The measured results are well agreed with simulation results with a little deviation.

The findings of this research show that the four-resonator coil system with a rectangular structure is the most desirable option for efficiency requirements above 70%.

# CHAPTER 1

# INTRODUCTION

## 1.1 Overview

Wireless power transfer (WPT) system is an alternative and promising candidate for the charging issue of many daily life applications e.g. electric vehicles, biomedical implants, portable devices and sensor networks. Extensive research is being carried out in WPT for various power levels using various WPT techniques, as shown in Table 1.1. The most widely used techniques are Inductive Power Transfer (IPT) and Magnetic Resonance Coupling (MRC).

Wireless power transfer can be categorized into two categories, namely, far-field wireless power transfer system and near-field wireless power transfer system. The far-field region of the Electromagnetic (EM) waves is beyond one wavelength of the antenna. In this region, electric and magnetic fields travel perpendicular to each other and propagate in the space. In the far-field wireless power transfer system, the EM waves are used to transfer power from the source to load at a distance of several hundred meters. The power transfer level is very low may be less than 1 Watt.

The techniques used in the far-field wireless power transfer system are

- Microwaves
- Lasers

The near-field region of the EM waves is the area within the one wavelength of the antenna. One wavelength is the distance in which the electric and magnetic fields are separated and power from source can be transferred to the load via electric field or magnetic field. This power is transferred through the electric field in the capacitive coupling and magnetic field in IPT and MRC respectively. The transmission distance is very small as compared to the far-field may range from few mms to 200 or 300 mms. The power transfer level ranges from a few mWs to kWs.

There are many applications of the WPT system such as biomedical implants, electric vehicles, portable devices and sensor networks. Table 1.1 lists different WPT techniques and their characteristics and applications.

Table 1.1 Different wireless power transfer techniques and their specifications

| Technology | Range | Directivity | Freq. | Tx & Rx | Applications |
|---|---|---|---|---|---|
| IPT | Short | Low | Hz-MHz | Wire Coils | Electric Vehicles, Electric toothbrush and razor battery charging |
| MRC | Mid | Low | KHz-GHz | Tuned coils or lumped resonator coils | Portable devices charging (Qi), Biomedical Implants, RFID, Sensor networks and smartcards |
| Capacitive Coupling | Short | Low | kHz-MHz | Metal Plates | Power routing in large-scale Integrated Circuits and Portable devices |
| Magneto-dynamic Coupling | Short | Low | Hz | Rotating Magnet | Charging electric vehicles, buses and implants |
| Microwaves | Long | High | GHz | Antenna, Parabolic dishes, Phase arrays | Solar Satellites, drone aircraft charging and wireless devices charging |
| Optical Waves | Long | High | THz | Lasers and Photocells | Drone aircraft powering |

### 1.2 Wireless Power Transfer Technology

The wireless power transfer is a trending topic in current research and development (R&D) organizations and universities. Today, there is extensive research being carried out in this field. Recent trends towards the electrification of vehicles are due to the high oil prices and global warming tends the researchers to investigate the technologies for the charging of electric vehicles (EVs). Because the size of a battery and charging of EVs are a bottleneck for the commercialization of EVs in the consumer market, so research is being carried out for the alternative options of EVs charging. The conventional method of plug-in charging has many inherent issues and safety problems.

So, the motivation for getting rid of these concerns took researchers to investigate alternative EV charging technologies. The most promising candidate for this comes out to be WPT technology. In WPT, power is transmitted wirelessly by various methods, which will be explained in detail later.

Similarly, the dependence on portable devices such as laptops and mobile phones is increasing day by day and their batteries need charging from time to time. It is hectic to plug-in the device and charge it again and again. So, there is a need for wire-free charging so that the user can easily use the device while charging. Nowadays, a lot of inductive and magnetic resonance-based chargers are in the market, for example, the wireless charger for Nokia Lumia 92. A new platform has been formed for WPT called Wireless Power Consortium (WPC). Moreover, WPC has also endorsed as the first international standard of wireless power transfer known as 'Qi' [3].

One of the essential challenging parts in the design of WPT is the wireless link and the efficiency of this part is crucial for the WPT system. There are many ways in which the efficiency of the wireless link can be maximized, and one of them is the load transformation method. In the load transformation method, the load resistance is transformed to its optimum value. There are four different load transformation methods which are DC-DC converters to alter the load impedance, passive circuits for impedance matching, variable frequency control and reconfigurable resonant circuits for impedance matching [4].

The coil optimization in the WPT system is an essential and crucial factor in enhancing the Power Transfer Efficiency (PTE) of the system. In coil optimization, the coil parameters such as inductance, capacitance and quality factor are optimized. Besides, the coupling parameters for the WPT system such as the coupling coefficient and mutual inductance also lies in this category. Similarly, many researchers worked on a multi-coil system. Categorically, there are three main general topologies in the WPT system with regard to the number of coils i.e. two-coil, three-coil and four-coil system.

In [5], the author used a circular four-coil system in which the first and the fourth are source and load transformation coils respectively. While in [6], the four-coil system is used with second and the third are Transmitting and Receiver boosters respectively. In another reference [7], work on the three-coil system is done using T-type impedance matching for biomedical implants.

### 1.3 Problem Statement

In the previous sections, different works on coil configuration and WPT system architectures have been discussed. With the increase in distance, the coupling coefficient is degraded and hence the efficiency. Efficiency is the main bottleneck for WPT, so we have to trade-off between efficiency and distance.

Most researchers used two-coil and four coil WPT systems using coupled-mode theory or circuit analysis theory. Work on coil's architecture (structure) is rarely reported in the current research and development (R&D) trend on the WPT system. However, in [8] the authors designed a rectangular and circular two-coil WPT system using a transformer model. The authors performed 3-D modeling of their two-coil WPT in Ansys Maxwell. In [5], the authors proposed a conventional four-coil WPT system using circuit analysis theory. Similarly, in [6], the author proposed a four-coil system with second and third coils acting as transmitter and receiver booster coils respectively.

In [9][5], the authors performed an analysis of the four-coil system. In this four-coil system, the first and fourth coils are just source and load transformation loops and not as transmission coils. By considering the work done by renowned researchers, it is necessary to examine and investigate the various number of resonator coils using rectangular and circular coil structures. The main focus of the research should be on four-resonator coil system. However, three-coil and two coil systems should be discussed for performance comparison. A mid-range and low power WPT system will be designed and invesgated for various number of resonator coils.

## 1.4 Research Objectives

The main focus of this research is to examine and investigate the relation between Power Efficiency vs Transmission Distance as well as the relation between Output Power vs Transmission Distance. This research on WPT will be carried-out at mid-range and low power WPT system using various number of resonator coils. The following objectives are being set in this research.

a) To study different WPT technologies and systems as well as their applications such as EVs, Portable Electronics and Biomedical Implants.

b) To analyze the power transfer efficiency and transferred the power of both circular coil and rectangular coil structures.

c) To evaluate the performance of the various number of resonator coils using both rectangular and circular coil structures.

## 1.5 Research Scope

In this research, a comparative analysis of two-coil, three-coil and four-coil wireless power transfer systems is done using different coil structures i.e. rectangular and circular. PTE is evaluated at a midrange e.g. 5-23 cm transmission distance between the coils and at a resonance frequency of 120 kHz.

This research involves the design and optimization of WPT coils based on circuit analysis. Both circuit analysis and coupled-mode theory (CMT) have the same efficiency analysis for WPT systems. For the sake of simplicity, the PTE and electrical, magnetic parameters for coils are calculated using circuit analysis theory.

A powerful radio frequency (RF) design tool, Keysight ADS is used for the simulation purpose. Prototypes for both rectangular and circular structures are built and set-up for testing and measurements.

## 1.6 Thesis Outline

This thesis on WPT includes five chapters. Chapter two gives an overview of the literature on the WPT system, with the discussion on historical background and the contributions of the renowned researchers in WPT. Moreover, different WPT techniques and applications are thoroughly presented.

Chapter three outlines the methods for carrying out research using analytical modeling. Modeling of the four–coil system using software such as ADS is discussed in this section. Finally, the hardware prototype designed for experiments is discussed.

Chapter four discusses both simulated and measured results. The results are presented in the form of graphs, tables, and Figures. Moreover, PTE and output power for both rectangular and circular structures are compared and then analyzed.

Chapter five presents the conclusion of the research work done and recommendations for future research in MRC-WPT.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

The history of WPT dates back to the 19$^{th}$-century era when Nikola Tesla performed wireless transmission of energy to light up a fluorescent bulb. He also proposed and experimented wireless transmission of AC electricity. After Nikola Tesla, this field was neglected and ignored until the Massachusetts Institute of Technology (MIT) brought a breakthrough in the field of WPT. The experiment was performed at MIT by transmitting 60 W of power at a distance of 2 to 3-meter using a self-resonant two-coil system. The transmission distance was 8 times the coil's radius with 40 % efficiency.

Following the breakthrough by MIT, many recent research works and active program by Maxwell and Panasonic, government organizations and R&D centers such as Phillips Research Europe, ORNL (Oak Ridge National Lab), ANL (Argonne National Laboratory) and EDL (Energy Dynamics Laboratory); universities such as University of British Columbia, Korea Advanced Institute of Science And Technology (KAIST), Utah State University; as well as automobiles such as Nissan, Audi, Chrysler, Ford, Mitsubishi and Toyota on WPT system are genuinely showing the significance of WPT in applications such as portable devices and electric vehicles. Present day-active WPT suppliers include Witricity, Evatran, cConductix-Wampfler, LG, HaloIPT (Qualcomm) and Momentum Dynamics. In total, there is a wide array of research activities on various WPT concepts. Figure 2.1 shows the flow chart for wireless power transfer and its techniques and categories. These WPT categories and techniques are explained in the next sections.

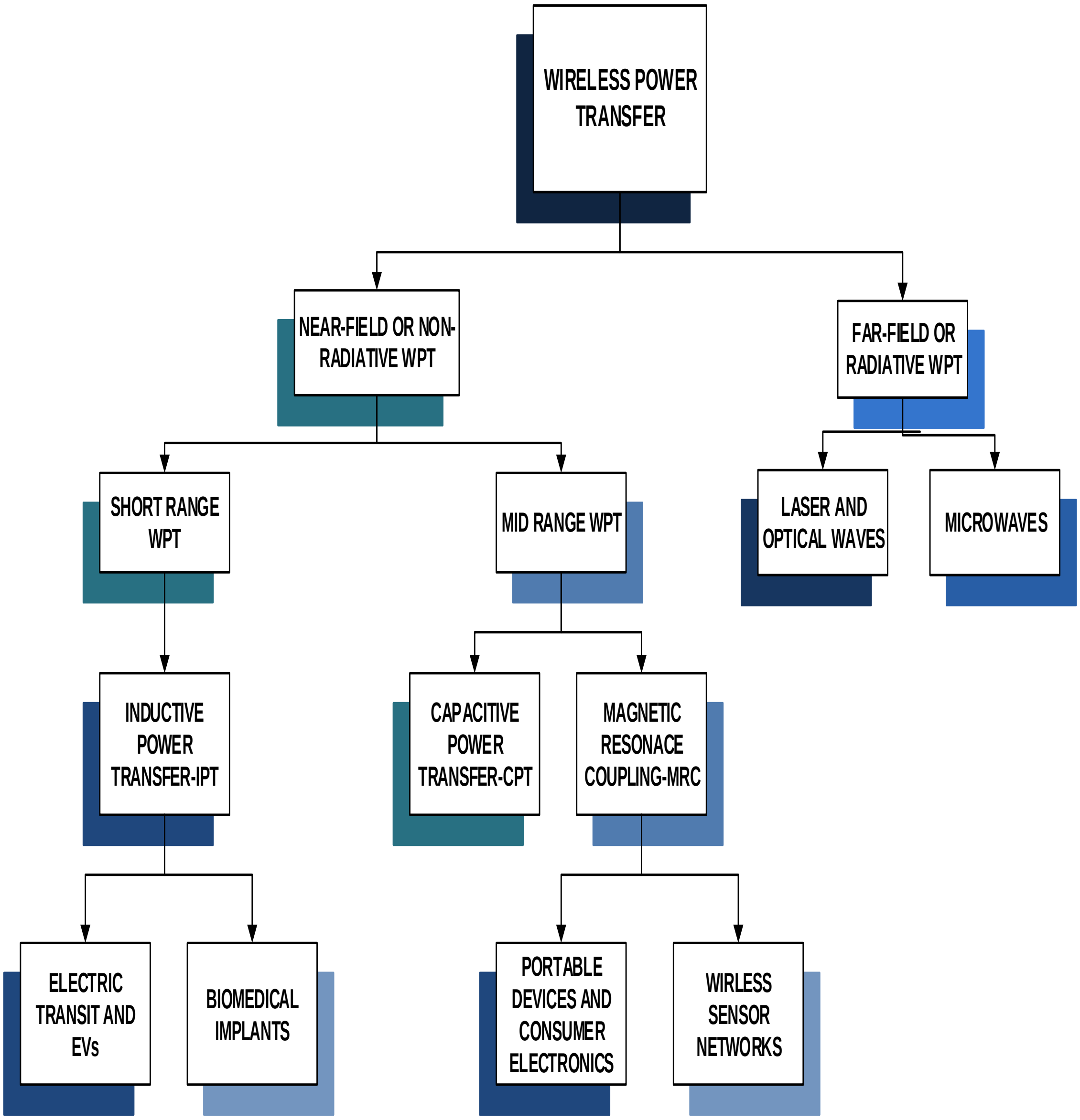


Figure 2.1 Categories of the wireless power transfer system

Generally, there are two main categories of WPT based on techniques that have already been discussed in chapter one. In this chapter, a more detailed discussion will be carried out on WPT techniques such as MRC, IPT, and CPT.

## 2.2 Inductive Power Transfer

IPT is mostly used in electric vehicles charging for both stationary and dynamic (On-Line Electric Vehicle) charging. IPT is based on Ampere's and Faraday's laws which apply a varying magnetic field to transfer power from the Primary side coil (Track coil in OLEV charging) to the secondary coil (Pick up Coil in OLEV charging). It is like a transformer with air-gap acting as a core of the transformer and the transmitter and receiver acting as a primary and secondary coil [10]. Below in figure 2.2 is the typical block diagram of IPT.

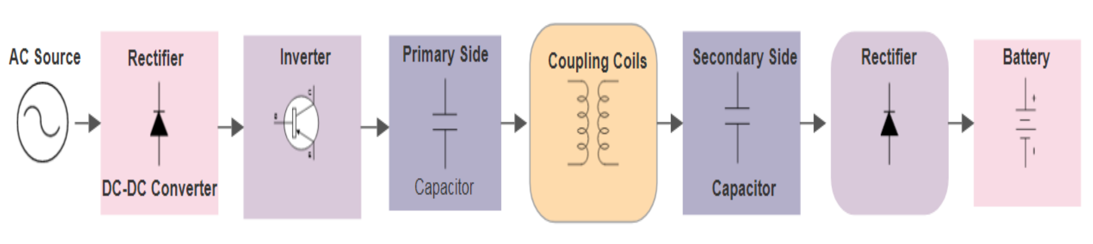


Figure 2.2 IPT system block diagram [10]

The basic principle of operation is that first at the primary side AC main source supply power which is rectified by the rectifier. Following the rectification, a high frequency (HF) inverter converts the DC voltage into HF-AC voltage. Next is the compensation network or resonant compensation network which comprises of resonant capacitors for producing resonating frequency. At the resonance frequency, maximum power efficiency can be achieved. When this HF AC will pass through the primary side coil, it will produce a changing magnetic field and this changing magnetic field will induce a voltage on the secondary side.

On the secondary side, there is also a resonant compensation network followed by a rectifier. The DC power from the rectifier will finally charge the battery.

## 2.3 Capacitive Power Transfer

Capacitive power transfer (CPT) technology has been proposed recently as an alternate contactless power transfer solution. In the CPT system, the electric field is used as a transmission medium [11] for WPT. The capacitor plates act as transmitters and receivers for energy transfer.

As the magnetic field does not scale down as desired with decreasing power, so at low power levels, the cost and size of the galvanic isolation components can be minimized with a capacitive interface. Therefore, the CPT is more appropriate at low power levels in terms of cost and size. However, in high power applications, CPT is not a preferred solution. For this reason, most significant CPT techniques focus on low power applications [12] and portable electronic devices such as wireless toothbrush chargers, wireless cellular phone chargers and biomedical implants [13]. The power transfer interface in [14] is implemented with capacitively coupled matrix pads.

## 2.4 Resonant Inductive Power Transfer

Nikola Tesla pioneered resonant IPT at the beginning of the 20$^{th}$ century. This technique uses two or more resonant tanks that resonate at the same frequency for energy transfer. The short-circuit inductance and resonant capacitors at the secondary coil side form the resonant circuit. When the primary side coil operates at the secondary side resonance frequency, the two sides start resonating at the same frequency and this phenomenon is known as resonance.

## 2.5 Magnetic Resonance Coupling

It works on the principle of coupled-mode theory in which the self-inductance of the coils and the capacitors integrate to form a resonant circuit. The resonance frequency, in this case, is in the kHz-MHz range. This method is suitable for mid-range WPT with efficiency not less than 70-90 %.

A typical MRC WPT system's block diagram [10] is shown in figure 2.3. An MRC has two main parts. one part consists of transmission coils and LC tanks on both sides of the wireless link, whereas the other part consists of the conversion circuits like DC-DC converters, inverter and rectifiers.

Its working principle is quite straightforward. First, an AC supply from the main source is fed to the rectifier and DC-DC converter, which gives the desired DC voltage. After that, a high-frequency inverter is employed to supply the voltage to LC resonator and transmission coils. At the receiver side, it is then rectified to feed the load.

Extensive research has been carried in the field of WPT via MRC. In the subsequent sections, different topologies and techniques used in MRC are discussed.

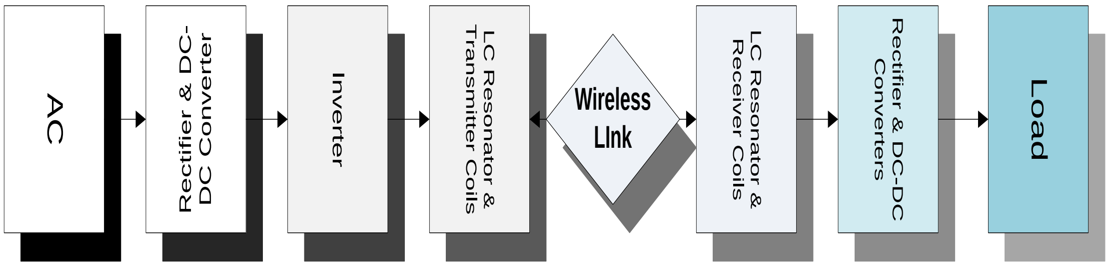


Figure 2.3 Block diagram for MRC Wireless Power Transfer System

## 2.6 Methods for Improving Wireless Power Transfer Performance

Wireless Power Transfer is measured and analyzed by two main factors: Power Transfer Efficiency and Coupling Coefficient. There are many approaches to improve the efficiency of a WPT e.g. impedance transformation, resonance frequency control, load modulation and efficient resonator design Methods.

### 2.6.1 Load Modulation to increase Reflected Resistance

In this method, the effective load resistance is modulated to amplify the loaded quality factor (loaded-Q) and the reflected resistance. The loaded quality factor is the quality factor of the coils when the receiver is connected to the load. In this way, the transmitter to receiver efficiency is improved.

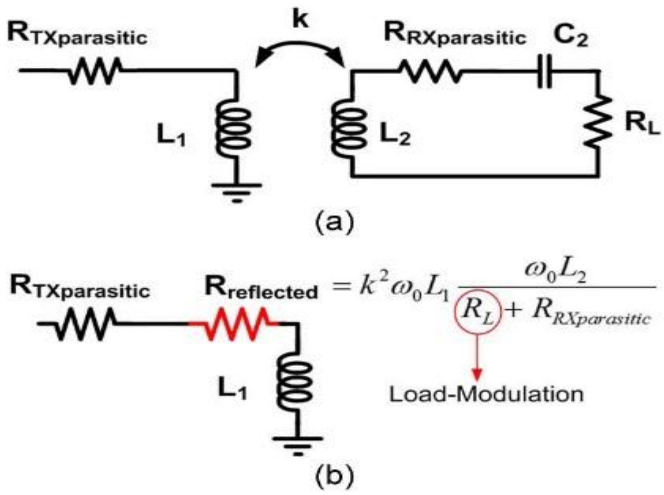


Figure 2.4 Reflected Resistance [15]

The reflected resistance is the coupling between the transmitter and the receiver, as shown in figure 2.4. The power consumed in reflected resistance is equal to the power delivered from transmitter to receiver [15]. Therefore, the reflected resistance should be very high as compared to the parasitic resistance of the transmitter. So, the reflected impedance at the resonance frequency is calculated as [15]

$$Z_{reflected} = \mathrm{k}\omega_{o}\mathrm{L}_1\left(\frac{\omega_O L_2}{(R_L + \mathrm{R}_{Rxparasitic})}\right) \tag{2.1}$$

$$= \mathrm{K}\omega_O L_1 Q_{Rxseries}$$

Where k is the coupling coefficient between the transmitter and the receiver, $\omega_o$ is the receiver resonance frequency. Whereas the $L_1$ and $L_2$ are the coil inductance of the transmitter and the receiver, and $R_L$ is the load resistance. The $Q_{Rxsereis}$ is the Loaded-Q (Quality factor) of the series resonant receiver which is given by

$$Q_{Rxseries} = \left(\frac{\omega_O L_2}{(R_L + R_{Rxparasitic})}\right) \tag{2.2}$$

Usually, the value of reflected resistance is very small i.e. 0.1 Ohm. For a parallel resonant receiver, the reflected impedance and the Loaded-Q is

$$Z_{reflected} = k\omega_o L_1 \left(\frac{R_L}{(\omega_O L_2)} - j1\right) \tag{2.3}$$

$$= K\omega_O L_1 \left(Q_{Rxparallel} - j1\right) \tag{2.4}$$

$$Q_{Rxparallel} = \left(\frac{R_L}{\omega_O L_2}\right) \tag{2.5}$$

The reflected resistance is d1egraded by an increase in transmitter-receiver distance and by load variation.

### 2.6.2 Impedance Transformation

Impedance matching is an important technique in RF for enhancing the transfer of power to the load. WPT efficiency depends upon the circuit parameters such as $S_{11}$ and $S_{21}$ which are known as the reflected power ratio and transmitted power ratio respectively. Usually, impedance matching involves the matching of the input and the output impedance. It is usually done by inserting a compensating circuit such as the LC circuit.

### 2.6.2.1 Impedance Transformation Using DC-DC Converters

DC-DC converters are an integral part of many wireless power transfer systems. They are mainly used for voltage regulation at the output. But DC-DC converter is also used for power factor correction and buck operation at the transmitter side of WPT. There is another significance of using a DC-DC converter after the rectifier, which is the impedance transformation capability by varying the duty cycle of the converter.

To understand the role of the DC-DC converter in load transformation to increase efficiency, a cascaded boost-buck converter case has been presented. The input impedance of the boost converter is easy to control due to its input current feedback, while buck-converter is mostly used in battery charging applications. So, a cascaded boost-buck converter topology is used. The cascaded boost- buck converter is shown in figure 2.5. Two control modes of cascade boost-buck converter have been analyzed, namely, fixed load control mode and variable load control mode.

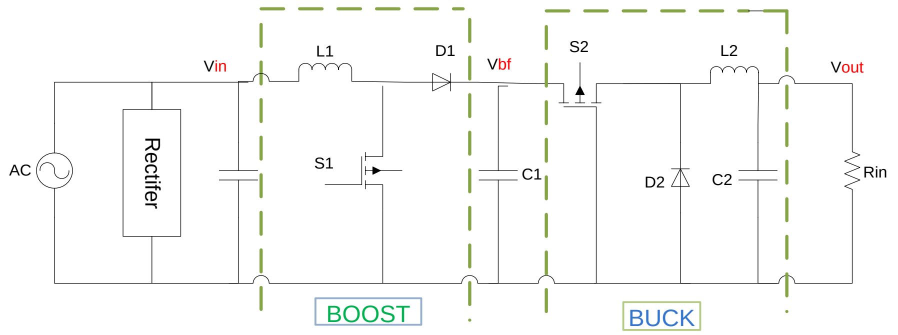


Figure 2.5 DC-DC Converter using Cascaded Boost-Buck topology [16]

In the fixed load mode, the constant duty cycle is applied. Let, $D_1$ and $D_2$ are the duty cycles of Boost and buck converter respectively [16]. Then Input Impedance is given by:

$$R_{IN} = R_L \frac{(1 - D_1)^2}{{D_2}^2} \quad (2.6)$$

In the variable control mode, constant duty cycle control mode is not applied due to the varying characteristics of load impedance. Instead, a feedback control mode is applied with the measurement of three signals. These signals are input voltage $V_{IN}$, Input current $I_{IN}$ and buffer capacitor voltage $V_{BC}$. The boost converter duty cycle $D_1$ is used to maintain the ratio of $V_{IN}$ to $I_{IN}$, whereas $D_2$ use to make $V_{BC}$ higher than the $V_{IN}$ [16].

$$R_{IN} = \frac{(1 - D_1) * V_{bf}}{P_{IN}} \quad (2.7)$$

#### 2.6.2.2 Impedance Transformation Using Passive Circuits

Using passive resonant circuits or coils for impedance matching is a very common approach. Different placements of the passive circuits have been suggested. An LCC circuit has been inserted in the transmitter circuit in [17]. Similarly, an LC circuit is inserted after the rectifier on the receiver side in [18] and before the rectifier in [19]. In the four-coil WPT system [20], two extra magnetically coupled coils are placed between the transmitter and receiver resonators. This technique provides two additional mutual inductance terms for impedance matching. Manual positioning of the intermediate coils in the four-coil system with respect to the transmitter and the receiver can enhance the power transfer efficiency. The techniques in [18]-[20] are based on the maximum power transfer theorem that requires impedance matching with the power source. These approaches are usually not preferred for medium and high power applications like EVs due to the power loss in source resistance. Therefore, it is preferable for low power systems like biomedical implants.

### 2.6.3 Resonance Frequency Control

Resonant frequency control is a widespread method for voltage regulation and hence the PTE. Because if the coupled coils are not tuned to the resonant frequency, the PTE will greatly be reduced. In [21], the frequency splitting phenomenon occurs at 10 MHz operating frequency, with the maximum transmission coefficient bifurcates at the critical coupling. In the over-coupled region, the excessive coupling between the coils results in frequency splitting, producing low transmission coefficients. On the other hand, a small amount of power is transferred from the primary resonator to the secondary resonator in the under-coupled state due to the weak coupling coefficient. It is difficult to operate and maintain the WPT system at the critical coupling. According to changed operating circumstances such as the changed coupling coefficient; some system parameters i.e. inductance, capacitance and resistance should be adjusted to achieve the high transmission coefficient. Therefore, in turn, it gives high efficiency. Hence, in this way, the PTE can be improved by selecting the suitable resonance frequency and the critical coupling point for this specific resonance frequency.

In [22], they used a phase-locked loop (PLL) system to track the resonant frequency. Figure 2.6 shows the block diagram for the PLL. First of all, output voltage ($V_o$) is compared with the reference square wave which produces $V_d$. Where $V_d$ is the voltage difference between input and output. This $V_d$ is filtered to give linearized feedback voltage ($V_f$) which is equal to the phase difference. Then the resonant frequency is tuned until the $V_f$ is zero.

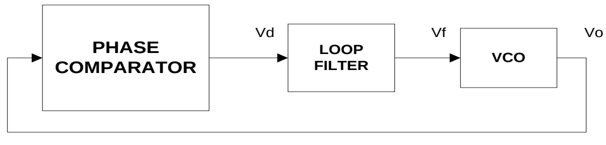


Figure 2.6 PLL (Phase Locked Loop) block diagram [22]

Similarly, in [23], the author described the frequency splitting phenomenon which occurs due to the strong coupling. Due to the critical coupling between the closely placed transmitter and receiver, the frequency characteristics curve splits into two halves. Then the frequency is tuned usually by selecting the lower peak of the two split peaks to increase the PTE.

### 2.6.4 Winding AC Resistance Reduction

The most significant losses in the WPT system is the conduction losses of the coils due to the proximity and skin effect. So, in order to minimize these losses, the AC resistance of the coils must be reduced. In [24], the AC resistance of the coils is minimized by choosing the Litz wire of suitable dimensions. AC resistance of the compensating capacitor is also considered to reduce the parasitic resistance of the coil. By using Litz wire, the skin effect can be ignored as in [24]. While in [25], Litz wire is designed for electric vehicle's WPT system using aluminium by considering all the losses such as proximity effect, skin effect and dc losses. Therefore, by analyzing the design of previous researchers, it is highly desirable to use Litz wire as a coil winding to reduce losses.

## 2.7 System Architectures

Coils are an essential and crucial part of a typical WPT system. The number of coils, the turns number of each coil and winding resistance plays an important role in the performance [24]of a WPT system. The quality factor (Q) shows how efficient the coil in transferring power. While Q is the ratio of the energy stored to the energy dissipated in the coil. Depending on the application and the power requirements, different WPT topologies have been used. They are discussed in detail in the next subsections.

### 2.7.1 Two Coil Wireless Power Transfer System

The most basic and simple architecture of WPT is a two-coil system shown in Figure 2.7 which is used in most medium-efficiency and short-range applications. A two-coil MRC-WPT was analyzed and characterized [26] with an estimated efficiency of 76 % at 40 W. Similarly, another two-coil maximum efficiency point tracking system [27] is devised through a matching network and AC-DC converters. In [27] [26], two-coil wireless power transfer systems are developed using MRC. Increasing the number of coils has disadvantages as well as increase the losses and make the system cost-expensive.

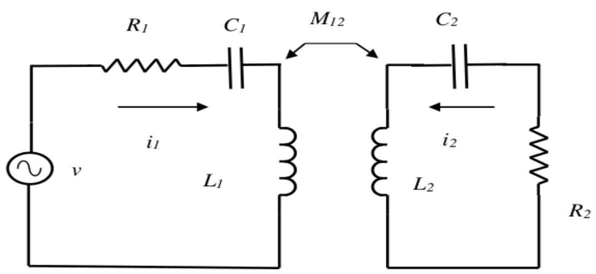


Figure 2.7 Lumped circuit model for a typical two coil WPT system [28]

### 2.7.2 Three Coil Wireless Power Transfer System

Usually, the three-coil system is designed to enhance the performance of loosely coupled MRC-WPT systems. An equivalent circuit diagram for the three-coil WPT system is shown in figure 2.8. In many applications, inserting a third coil changes the resonance frequency but enhances the coupling between the transmitter and receiver. To reduce the loading effect in the biomedical implantable devices, a three-coil WPT system [7] is preferable. It consists of two layers of printed spiral resonator coils and load loops on each side of FR4. These printed spiral coil (PSC) resonators are designed and fabricated on the side of implantable devices. Similarly, a three-coil system for load-independent output-current and voltage [29] is developed which shows better performance and long-range with respect to its counterpart two-coil system.

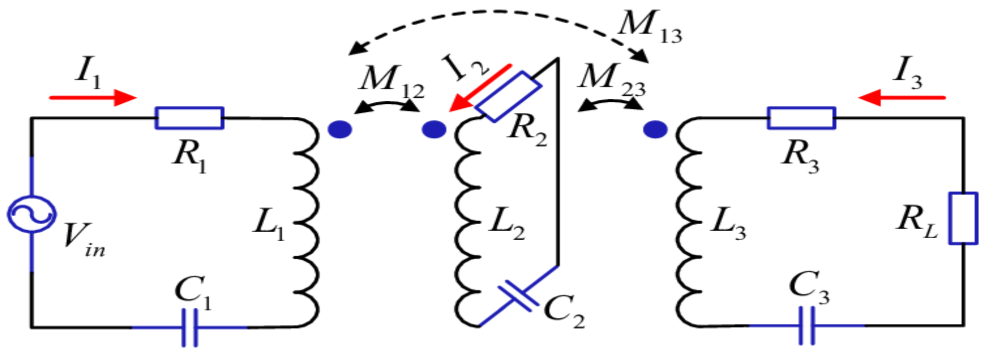


Figure 2.8 Circuit diagram for three coil WPT system [30]

### 2.7.3 Four Coil Wireless Power Transfer System with Source and Load Coils

The most commonly used WPT architecture after two-coil is a four-coil wireless power transfer system. Usually, a two-coil system is modified to the four-coil system by inserting source and load loops at the transmitting and receiving side respectively. Circuit analysis of the four-coil system using Scattering-Parameter [5] is done with an efficiency of 80% with first and second coils as a source and load transforming loops, as shown in figure 2.9 given below. Instead of using the three-coil system for biomedical implants, in [2] the authors used the four-coil WPT system for deep brain stimulation (DBS) for reducing the loading effect. By using FR4 (flame retardant composite material) and printed spiral coils (PSCs), they achieved efficiencies of 19.1% and 14.8% through the air and 11.7% and 7.7% through tissue at the 10-mm gap.

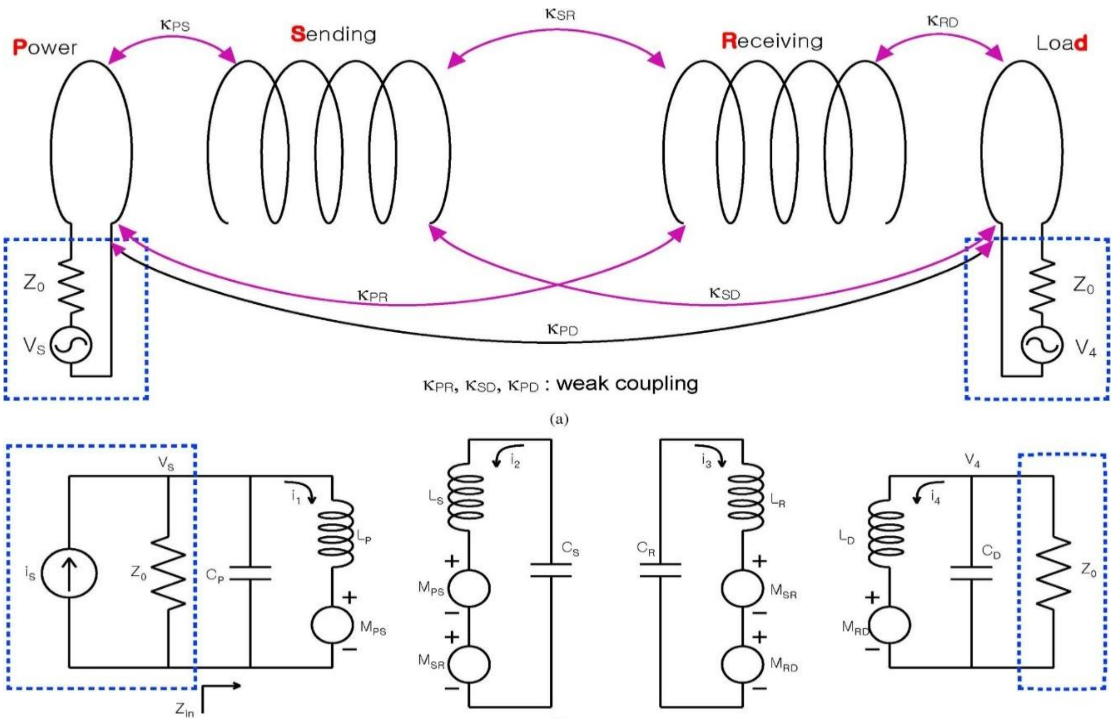


Figure 2.9 Schematic of a Conventional 4-Coil wireless energy-transfer system using coupled magnetic resonance [31]

### 2.7.4 Four-Resonator Coil Wireless Power Transfer System

Usually, most of the researchers have adopted the conventional four-coil WPT system with the first and the second coil acting as a source and load impedance transformation coils. It is mostly done for efficiency improvement, and to increase the transmission distance. Using resonator (high Q coils) instead of using source and load coils is very rare. A transmitter and receiver consisting of two strongly coupled resonators acting as intermediate boosters for both transmitter and receiver are reported in [6]. Intermediate boosters have strong coupling (k) with transmitter and receiver i.e. around 0.4-0.5.

## 2.8 Applications of Wireless Power Transfer System

WPT has a wide range of applications, from portable electronic devices to the charging of electric vehicles. Depending upon the application and its requirements, i.e. transmission distance, power level and efficiency, different WPT techniques are used for various applications. The most widely used technique for short-range high power applications such as EV charging is IPT. MRC is mainly used in midrange and mid-power applications such as mobile and laptop charging.

### 2.8.1 Wireless Power Transfer for Electric Transit Applications

In this section, the background and current status of WPT and deployment of IPT technologies by academia and Industry around the world have been discussed. Conductix IPT Technology is a German company that started in 1996 has developed an IPT charging system in 2014 [32]. The system has power transfer efficiency exceeding 90% with a typical power level of 60 kW. Moreover, it has an air-gap between primary and secondary coils is 4-cm. Korea Advanced Institute of Science and Technology (KAIST) has developed an Online Electric Vehicle (OLEV) green concept for wireless charging of electric vehicles. OLEV means that EVs will be charged while moving on the road. When the vehicle moves over the coil, it is triggered by the position sensor and starts transferring power to the vehicle side pick-up coil [32]. The system is operated by 200 A current and 20 kHz with 60 kW of power transferred to the load. Figure 2.10 shows the Wireless Charging Pad with Primary Coil for Stationary Charging of Electric Vehicles. The charging pads in figure 2.10 are embedded in the utility hole cover. Also, the following technologies contributed to the electrification of the public transit system.

1) Wireless Advanced Electric Vehicle Electrification (WAVE)

2) Qualcomm HaloIPT

3) WiTricity

4) Eaton HEVO and Momentum Dynamic

5) ORNL (Oak Ridge National Lab)

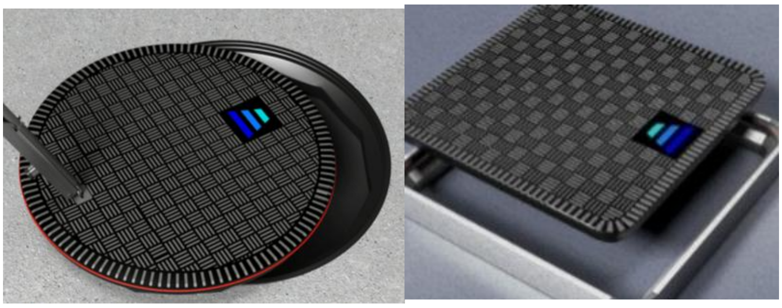

Figure 2.10 Wireless Charging Pad with Primary Coil for Stationary Charging of Electric Vehicles [32]

In the United States, the Chattanooga Area Regional Transportation Authority (CARTA), in partnership with the center for energy, transportation and environment (CETE) has developed an IPT system to charge a 30-foot long electric bus. The primary transmitter coil has a power transfer capacity of 60 kW at 20 kHz. It can charge a 30-foot long bus in 3-minutes [32].

In Germany, the PRIMOVE IPT technology shown in figure 2.11, has been demonstrated in Mannheim to charge a 12-meter solo electric bus and two 18-meter e-buses. The charging pad has a power capacity of 200 kW. Similarly, in the Netherlands, a Volvo 86-passenger electric bus has been recharged by IPT technology by 120 kW power transfer modules embedded in the parking pad. The e-bus has the mechanical lowering system for the pickup coil for maximizing transfer efficiency. The asea brwon bovery (ABB) Ltd. in Switzerland is testing an articulated e-bus operating from city-to-airport by using the flash charging concept. The bus is recharged at the stops by an overhead charger which sends charging bursts of 400 kW every 15-seconds.

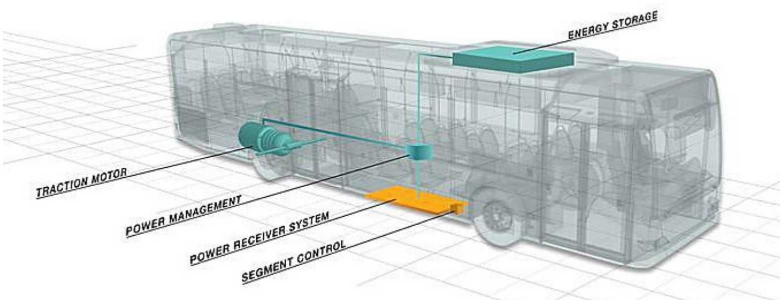


Figure 2.11 Electric Bus Model for German PRIMOVE IPT Technology [32]

Hino bus in Japan has developed and tested a fleet of hybrid electric buses; equipped with lithium-ion batteries and receptor coils to recharge them by pavement embedded coils on a 4.2 km long route. Another Waseda Electric Microbus-4 (WBM-4) was recharged by an inductive coil embedded in the road pavement with a 1.4 cm air gap and having an efficiency of 92%. The KAIST OLEV IPT system has been developed, tested and deployed in the city of Gumi, South Korea. The size of the rechargeable battery in The KAIST OLEV IPT system is 1/5 times the typical e-bus battery and it operates on a 24 km long route.

### 2.8.2 Wireless Power Transfer System for Biomedical Implantable Devices

Since WPT has gain popularity in many fields including transportation, sensor networks and most importantly in medical implantable microsystems (MIMS). A block diagram for MIMs is shown in figure 2.12. Extensive research is being performed in a broad range of biomedical applications such as artificial heat, wireless video capsule endoscopy and visual prosthesis. Medical implantable devices have certain limitations when applying WPT such as frequency, size and reliability of WPT and these parameters should be optimized for MIMS. Among the type of WPT,