Proceedings of IOE Graduate Conference, 2017
Volume: 5 ISSN: 2350-8914 (Online), 2350-8906 (Print)

Analysis and Optimization of Magnetic Resonant Wireless Power Transfer System

Ashutosh Timilsina [a], Binay Paudyal [b], Beni Nepali [c], Jenesha Devendra Kunwar [d], Arbind Kumar Mishra [e], Sharad Kumar Ghimire [f]

[a, b, c, d, e] *Department of Electrical Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*
[f] *Department of Electronics & Computer Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal*
Corresponding Email: [1] ashutoshtimilsina@gmail.com, [2] binay@pcampus.edu.np

Abstract

Wireless Power Transfer (WPT) has a great potential to improve the quality of life of people with downside being low efficiency of the system. This requires special attention in design and optimization of the system. This paper presents a novel approach for WPT using class E inverter. The wireless power system setup with transmitter and receiver were simulated and a prototype was developed. The prototype was tested at different frequency and the effect was analyzed. The paper consists of the details and analysis of the WPT system and also design optimization technique has been presented which can make the system more efficient and economic.

Keywords

Class E Resonant Inverter – Frequency Splitting – Resonance – Optimization – Wireless Power Transfer

1. Introduction

Wireless Power Transfer was first successfully demonstrated by Nikola Tesla in 1890s [1]. Safe and reliable methods of wireless electric energy transmission have been explored only since the past decade. As of now, the concept of WPT has successfully been applied in Inductive chargers (cell-phones, toothbrush chargers), SmartCards, Electric Vehicles, medical devices and also in Solar Power Satellites [2, 3, 4, 5, 6]. With the development of magnetically coupled resonators, higher range and efficiency of the WPT system has been realized [2, 3, 7, 8]. WPT could be the preferred technology for the future since it brings forward the possibility of eliminating the use of wires and bulky cable altogether [9].

A crude version of wireless power transfer could be understood from a transformer model which consists of a source in one circuit and a load in another circuit that are electrically insulated.The source coil is supplied an alternating current. If the source and load circuit are placed extremely close to each other then the power could be transmitted simply by induction. Power transferred through this method obviously decreases by drastically as the distance among the circuits (or just the inductor coils) increases. However, if the two circuits are resonating, with addition of capacitor to the circuitry, then the distance through which the power can be transferred can be increased. Depending upon the method used for power transfer, WPT methodologies can be categorized on the basis of their range of power transfer into near field and far-field techniques [3]. Near-Field/Non-radiative technique includes inductive coupling, capacitive coupling, magnetic resonance coupling and magnetodynamic coupling whereas Far-field or radiative technique consists of Microwave and Laser based WPT.

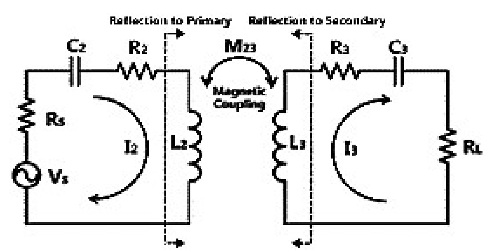

Figure 1: Two coil Model of Wireless Power Transfer

Inductive coupling, most widely used currently, is efficient only in close proximity transferring small power (around 5W for a distance of 5-10 cm) [3].

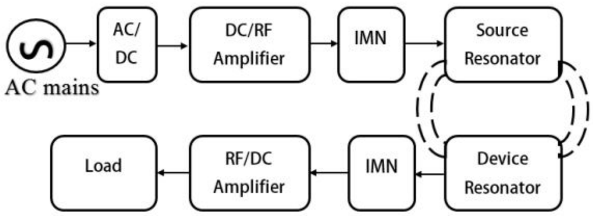

Figure 2: Block diagram of the system

Inefficiency of inductive coupling for increased energy-transmitting distances led to the application of resonance to the already existing inductive technique which would simply use an inductor and a capacitor, connected in series or parallel resonating on a certain frequency [7]. The resonators resonating at same frequency exchange energy efficiently with minimum losses to the surrounding [2, 3, 4]. This method is Magnetic Resonant Wireless Power Transfer System. This system can significantly achieve greater range in WPT and hence termed as "mid-range" distance, as the WPT system ranging for longer distances are also possible. Long range wireless power transfer based on microwave was also successfully implemented by William C. Brown in 1960s. The size and the cost increases significantly for the microwave based WPT, should the transmitted power be raised. Hence this system is improbable for consumers as of now and the current focus of research is the method of Magnetic Resonant WPT proposed by Soljacic and team [3]. This method has realized the highest efficiency possible until now (about 70-90%.) However, the operation frequency of the system was required to be at a higher range to achieve this efficiency [6]. The operating frequency of the system is generally made on ISM radio band, which is internationally reserved band for Industrial, Scientific and Medical purposes except for telecommunications to avoid interference with communication signals and the reserved frequencies for the ISM bands are 6.78 MHz and 13.56 MHz [5, 10].

Even though such system consists of four coils: two coils each in transmitter and receiver loop, this paper studies only the two coil type. Benefit of using four-coil instead of two coil structure is that the source can be matched by varying the mutual inductance of source coil and transmitting coil and the load is matched by varying the mutual inductance of load coil and receiving coil [4]. Four coil structure itself accommodates the Impedance Matching Mechanism for the system eliminating the need for separate Impedance Matching Network. The basic circuit diagram of the proposed system is shown in Fig 1 which consists two LC circuits (*resonators*) as transmitter and receiver circuitry. The oscillating magnetic field is generated by transmitter coil due to presence of inductor and capacitor. Fig 2 shows outline of the project. The power input from wall socket is rectified and amplified to higher frequency which is then transmitted wirelessly to receiver, where, the signal is again rectified and supplied to the load. Section 3 gives the details of methodology used in this project. Section 3.1 consists of simulation details of the project followed by section 3.2, which depicts the hardware fabrication of the project. At last the results and analysis are presented in 4.

2. Theoretical Overview

A wireless power system, as in wireless communication, consists essentially of two parts "transmitter" and "receiver" devices. The transmitter generates the oscillating, time-varying electromagnetic field from the input power with a coupling device whereas a similar coupling device is utilized in receiver which converts thus obtained electromagnetic field into the electric current as required to operate an electrical load. The resonating objects transmit energy very efficiently with each other while the non-resonant objects have very weak interaction with each other [6, 8]; which is the reason why these system are very efficient. This technology has been extensively used to supply power wirelessly to the consumer electronics and is useful in medical and military applications as well [6]. For further understanding of the theory behind the wireless power transfer, details on self and mutual inductance, skin depth and resonance must be understood.

2.1 Self and Mutual Inductance

Inductance is the property of a current carrying conductor to resist the change in current. This property is also referred to as self-inductance. According to Oersted's Law, the steady current flowing through a conductor creates magnetic field around it whereas the ac flowing through that conductor creates a time varying magnetic field. This law devises the relationship between electricity and magnetism. Faraday's Law of Electromagnetic Induction states that the time varying magnetic field in one coil can induce electromotive force on nearby coil. On the basis of this law, to realize Wireless Power Transmission using two coils the supply must be AC. This law also presents another important property in case of two separate inductors called mutual inductance. Mutual Inductance is defined as the property of two coils to be magnetically linked with each other so as the change in current in one coil affects the current and voltage in another coil. Simplified mutual inductance for co-axial coils can be deduced as given in equation 2 [4]. The self-inductance (L) of a coil is given by equation 1 whereas the mutal-inductance(M) between two coils is given by equation 2 [5].

$$L = N^2 \mu R \left[ln\left(\frac{8R}{a}\right) - 2 \right] \tag{1}$$

where,
N= Number of Turns, μ = Relative Permeability, R = Radius of Coil, a = Radius of the Cross-Section of Coil

$$M_{12} = \mu\sqrt{r_1 r_2 \left[\left(\frac{2}{k} - k\right) K - \frac{2}{k} E \right]} \tag{2}$$

where,
r_1 and r_2 are radii of the coaxial coils, k is the Coupling Coefficient between two coils, K is the First Elliptical Integral and E is the Second Elliptical Integral

The amount of inductive coupling or the mutual inductance between two coils is governed by a fractional coefficient that varies from 0 to 1, indicating zero as no coupling to 1 or maximum coupling. This coefficient is called Coupling Coefficient and is symbolized by k and is given by equation 3.

$$k = \sqrt{\frac{4 r_1 r_2}{(r_1 + r_2)^2 + d^2}} \tag{3}$$

where,
r_1 and r_2 are radii of the coaxial coils,
k is the Coupling Coefficient between two coils

2.2 Resistance and Skin Depth

Resistance is the property of a material to resist the current flowing through it. Its value is different for ac and dc current and for high frequency ac, the Ohmic Resistance of the coil is

$$R_0 = \sqrt{\frac{\mu_0 \omega}{2\sigma}} \frac{l}{4\pi\alpha} \tag{4}$$

where,
μ_0 is he permeability of the air or vacuum
$\omega = 2\pi f$ is the angular frequency
$\sigma = 5.96x10^7$
$l$is the length of the coil
α is the core length/(core diameter + coil diameter)
Also for high frequency ac signal, the skin effect is considerably high and the skin depth (δ) up to which the current can penetrate is given by the equation 5. The skin depth decreases with increase in frequency of the signal. For $f > 10MHz$, the skin depth is ≈20 μm [5].

$$\delta = \sqrt{\frac{2}{\omega\sigma\mu}} \tag{5}$$

2.3 Resonance and Magnetic Resonance Coupling

Resonance is a phenomenon which involves the energy oscillating between two modes in a system. For a particular frequency referred as *Resonant Frequency*, the amplitude of oscillation is largest. Resonance is achieved in electrical circuit in form of electromagnetic resonance consisting of circuit of inductor (L) and capacitor (C) either in series or in parallel. In a circuit with single inductor and capacitor connected in series the energy oscillates at the resonant frequency between the inductor and the capacitor. The energy stores in magnetic field of the inductor and the energy stored in electric field of capacitor is exchanged at resonant frequency, given by equation 6 [6].

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{6}$$

Integral with resonance is the term *Quality Factor* (Q-factor) which is a measure of energy stored in the resonating circuit *i.e.* higher the Q factor, lower is the rate of energy loss in the circuit and the oscillations die out more slowly [5, 6]. The expression for Q-factor is

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} = \frac{\omega L}{R} \quad (7)$$

Magnetic Resonance Coupling refers to the electro-magnetically coupled antenna (resonators) which are tuned at the same resonating frequency and can be coupled to transmit power wirelessly to a distance greater than normal inductive coupling only [5, 6].

3. Methodology

WPT system in this study has been implemented on the basis of previously existing analysis and models of magnetic resonance coupling while determining the optimum performance characteristics of the system. The study also considers the hardware implementation of system proposed in [5] with an aim to develop a working model of WPT system. The theories were thoroughly studied at first followed by development of rough sketch of the project. The rectifier was simulated and fabricated alongside the class E inverter for generating high frequency output. The antennas were studied, designed and then fabricated. The components were then connected and subjected to different supply and frequencies. The outputs obtained and challenges faced are discussed further in Section 4. The simulations for the study of the system were done in LTSpice and Advanced Design Software (ADS) whereas the Printed Circuit Boards (PCBs) were designed using PCB designing softwares, PCB Wizard and KiCad. The circuits thus prepared were used to develop the prototype for the proposed system of mid-range WPT. The detailed methodology is presented here.

3.1 Simulation

The simulations were performed for the inverter and the two coil model. Simulation for inverter was performed in LTSpice, whereas the two coil model was simulated in Advanced Design System (ADS). Both of these simulations are described here.

3.1.1 Rectifier

Two types of bridge rectifier are used in WPT system, one operating at power frequency in input side and another operating at high frequency in load side. The electrical circuit for both rectifiers is same, only difference between them is the use of different types of diode.

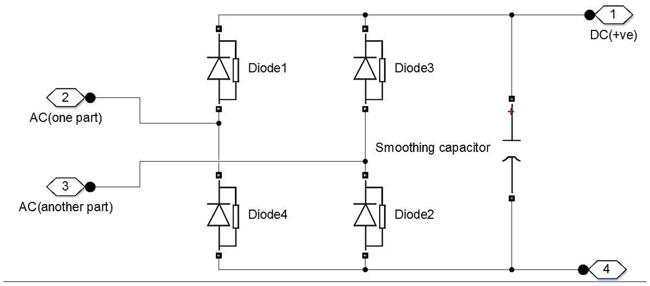

Figure 3: Bridge rectifier simulated in MATLAB

Table 1: Parameters for Class E Inverter for simulation in LTSPice for 120KHz

Inverter Parameters	Theor. Values	Pract. Values
Ls	6.02 mH	5.3 mH
Cs	76.59 nF	100 nF
L1	16.4 μ H	85 μ H
C1	43.86 nF	43 nF

For input side rectifier, the voltage is stepped down to 9 V using step down transformer and the rectifier converts AC into ripple DC voltage. Using smoothing capacitor, nearly constant DC output is fed to the class E resonant inverter.

3.1.2 Class E Resonant Inverter

Class E Resonant Inverter is a high frequency inverter that uses only one switching device and produces nearly sinusoidal output for a DC input [9, 11]. The design of a Class E Resonant Inverter consists of a series inductor (Ls), a shunt capacitor (Cs), a switch or a transistor, a load network (L1-C1) and load as depicted in Fig 4. Its benefit is that the power loss incurred in the circuit is very less and use of a single switching device reduces switching losses significantly [12]. The output frequency is determined by the pulse frequency given to the gate of MOSFET (or switching device). For better simulation results, the inverter was simulated in LTSpice instead of MATLAB. The design of Class E Resonant Inverter is made on the basis of a set of empirical formula presented in [12, 13] to calculate the value of components which are shown in table 1.

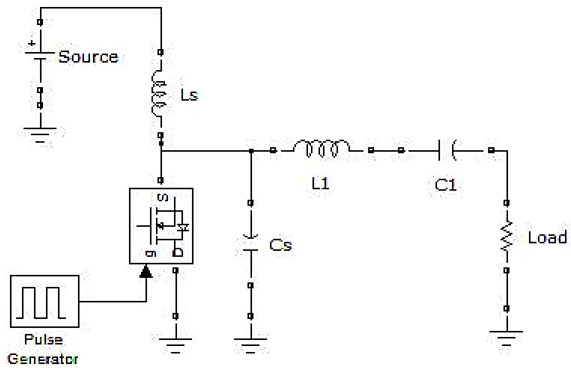

Figure 4: Simulation schematic of Class E Resonant Inverter

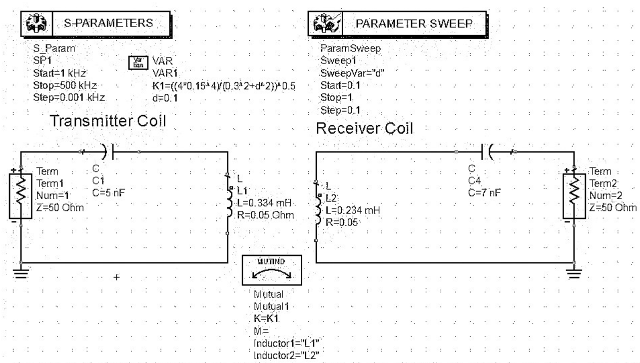

Figure 5: Simulation of Two Coil Model of Resonant-WPT in Electromagnetic simulation tool ADS

From the simulation in LTSpice, the output voltage obtained is 9 V peak ac with peak value of current 1.2 A and frequency 120 KHz for a load of 7.3 Ohm.

3.1.3 Antenna

Magnetic Resonant Coupling for WPT uses two resonators called *antenna* to transfer power wirelessly. Transmitting and receiving sides resonate at the same resonant frequency as the frequency of output of the Class E resonant Inverter. Simulation with known parameters for two coil WPT system was simulated in ADS as shown in figure 5.

3.2 Prototype Development and Design Detail

A prototype was developed considering each block of Fig 2. KiCAD tool was used to design the schematics for circuit involved which were then fabricated into

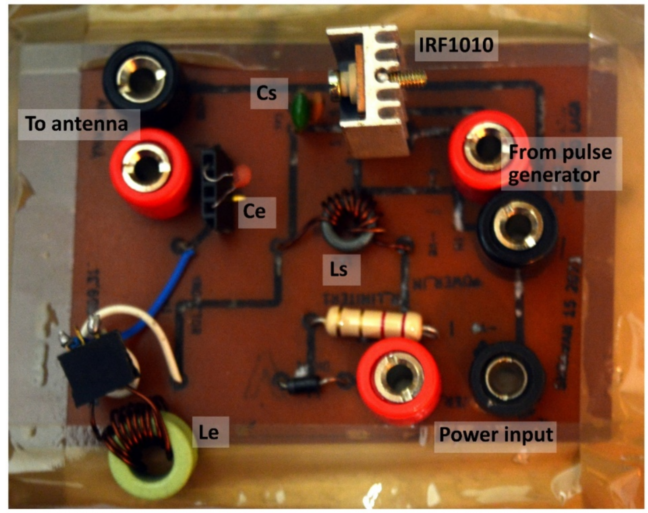

Figure 6: PCB Design for Class E Inverter for 120 KHz frequency

Table 2: Design Parameters for Antenna

Antenna Coil	No. of Turns	Radius of the Coil cm	Height of the Coil cm	L mH	f KHz	C nF
Source	300	3	1.3	5.34	120	0.33
Load	200	3	1.5	7.9	120	0.22

PCBs. Bridge Rectifier was fabricated with 1N4007 power diodes which converted 230 V ac to 30 v dc then regulated by 7809 Linear Voltage Regulator IC. Class E resonant inverter was developed as in figure 6. High frequency MOSFET IRF1010E was used as switching device. The inductor in class E inverter and corresponding capacitor value was determined with precision for given frequency. Table 1 shows the variation between theoretical and practical values of parameters of class E inverter. For the transmitting and receiving antenna (or resonators), copper wire of SWG 16 was used. Table 2 consists the design parameters for the antenna constructed. The values of capacitor used for antenna design were selected based on approximate standard rating of capacitor available. The receiver end also had another rectifier, with 1N4142 type diodes for high frequency .

All the components were integrated and One of the coils was fixed and the other was moved so as to vary the distance between the coils. Fig 7 shows the lab setup for the prototype testing.

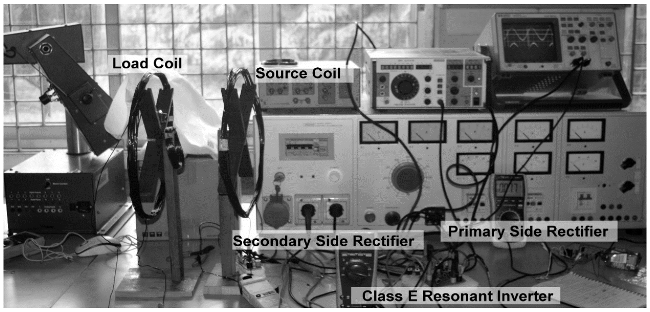

Figure 7: Hardware Setup for prototype testing

4. Results and Performance Analysis

With the available inductors and capacitors, two coil model was designed and again simulated in ADS, which can be utilized to determine the S-parameters of the entire system. The S-parameters gives the results of electrical properties of the network such as gain and return loss.To determine the S- parameters, matched load conditions are used considering the system to be a two port network with terminations of 50 Ohms, which is normal port impedance for RF circuits. Fig 5 shows the setup of the two coil model simulated in ADS. After sweeping the value of coupling coefficients by varying the coil to coil distance (d) from 0.1 meter to 1 meter. It was observed that considering matched load conditions, resonance occurred at approximately 121 KHz as seen in figure 8. The system was thereafter re-simulated considering the standard value of capacitor available, here, 5 nF instead of 5.267nF in the transmitter coil and 7 nF instead of 7.517 nF in the receiver coil.Fig 9 shows the result obtained from the simulation in ADS. From the plot of magnitude of S(2,1) versus frequency, maximum forward gain for varying values of distances was determined. With the updated values of capacitance, the resonance frequency shifted to approximately 124.5 KHz. The markers m4, m5, and m6 denote forward gains at 120 KHz at a distance of 10cm, 20cm and 1 m respectively. Maximum and minimum forward gains at 120 KHz reduced to 85.9% and 33% at coil to coil distances of 10 cm and 1 m respectively. This shows that the maximum efficiency of the system is achieved when there is resonance and the efficiency reduces for other frequencies. The efficiencies obtained are for matched loads and the efficiency will decrease if the impedances are different. In other words, Impedance Matching must be done to improve the efficiency of the

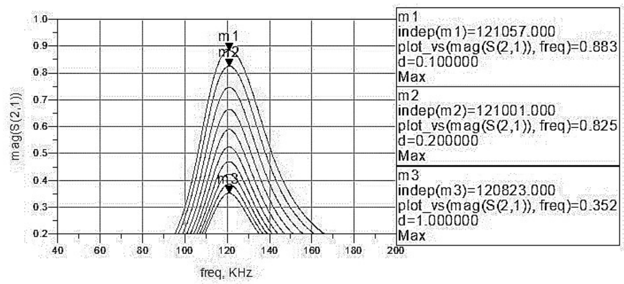

Figure 8: : S-parameter vs. Frequency along with Varied Coupling Factor (Distance) for the theoretical values of capacitor

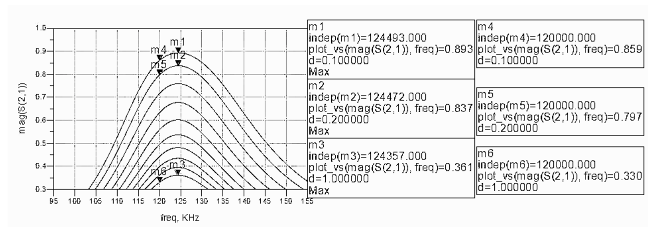

Figure 9: : S-parameter vs. Frequency along with Varied Coupling Factor (Distance) for the circuit of Fig5

WPT system. Hence, the Impedance Matching Network is essential in these systems in hardware realization so that the efficiency of the system can be increased. This study does not include such Impedance Matching Network due to which the prototype efficiency observed was lower than expected. Fig 10 depicts the output waveform obtained from Class E Resonant Inverter that was of 7 V peak magnitude (2V less than expected from simulation). It is also evident that the output waveform is purely sinusoidal, a unique feature of this inverter.

After the whole system was set up, it was first subjected to 56 KHz frequency. The transferred power, obtained power and efficiency of this case is shown in figure 11. It is clear that for 56 KHz which is way away from resonant frequency for the designed system, the efficiency fell steeply as the distance increased.System was then subjected to 120 KHz frequency. The transferred power, obtained power vs distance and efficiency vs distance curve is shown in figure 13 and 12 respectively for different loading conditions. In all cases, i.e. for specific voltage input and frequency, the power transfer efficiency between two magnetically coupled resonators decreased with increase in distance due to decreased coupling between resonators.

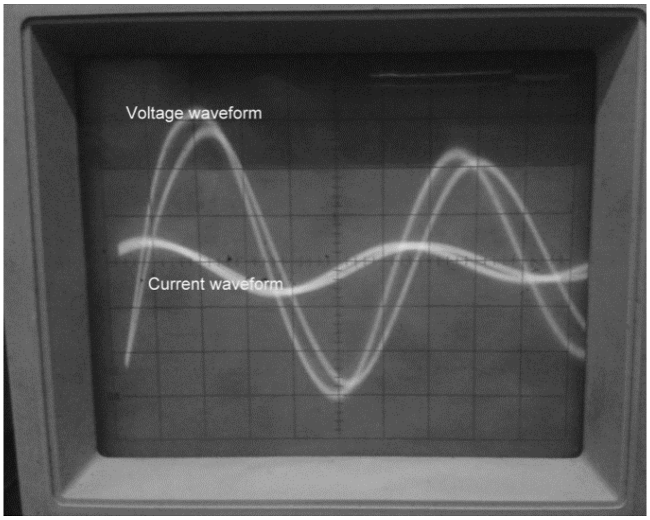

Figure 10: Output of Class E inverter for 120KHz and 9V input

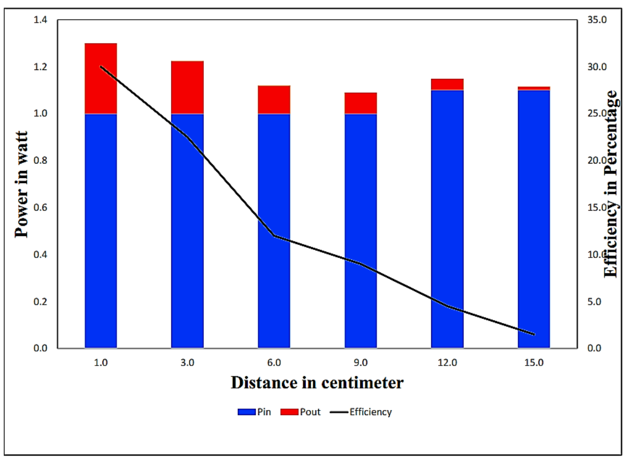

Figure 11: Results obtained for 56 KHz

4.1 Frequency Splitting

As the two coils were brought closer than 4 cm, the efficiency decreased instead of increasing. This is due to the frequency splitting phenomena. As the distance between two coils is reduced to a critical distance (in this case around 4 cm), the resonant frequency curve splits into two different frequencies above and below the actual resonant frequency (see figure 14 which reduces the efficiency of the system significantly. The major causes of this phenomenon are dominant role of source internal resistance in efficiency and the dramatic increase in the mutual inductance between two coils at closer distances [5, 14]. This leads to increase in imaginary part of input impedance which represents the power exchanged between source and the source coil where as decrease in real part of the input impedance which is proportional to the power transferred.

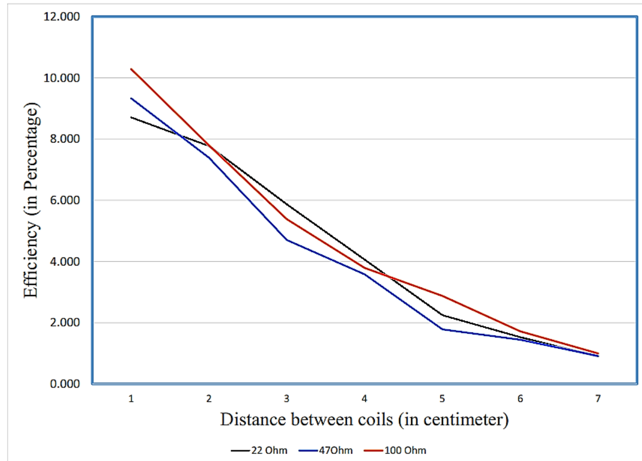

Figure 12: Efficiency vs Distance for 120KHz

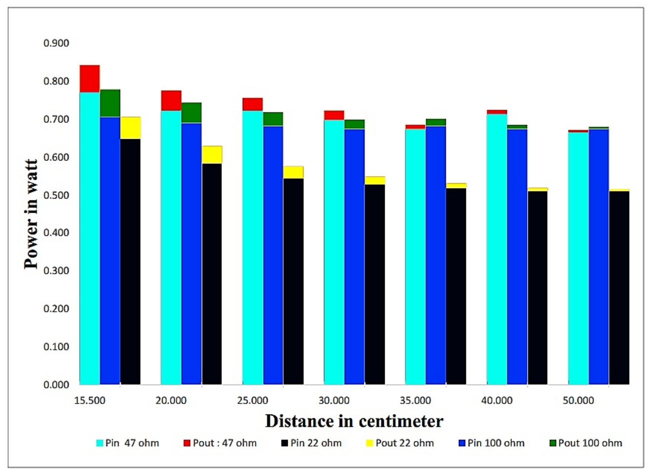

Figure 13: P_{in}, P_{out} vs Distance for 120KHz

4.2 Design Optimization

The effect of misalignment between antennas was observed and it was found, as expected, that when the coils are aligned co-axially, the efficiency is maximum and as the angle between the axes of two coils is made perpendicular, there is practically no coupling between the coils. It was also noted that alike other high frequency applications, impedance matching was the major parameter to be considered in WPT [8]. In our case, load and source impedance mismatch was major cause for reduction in efficiency as the reflection of the signal becomes higher compared to the transmission of

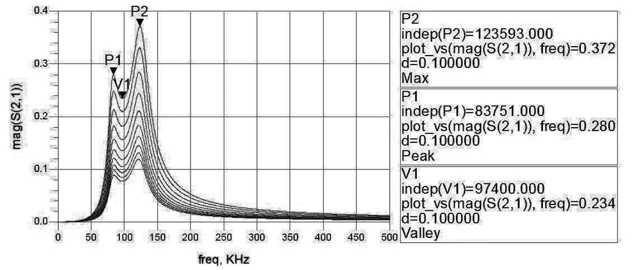

Figure 14: Frequency Splitting Phenomenon

the signal[10]. For higher efficiency, the design of the system was also changed to LCC topology as referred in [5], which resulted in slight increase in efficiency of the system. Further optimization technique were also referred from [8].

5. Conclusion

Based on existing theory of two-coil type magnetic resonant WPT, design analysis and optimization was carried out to evaluate the feasibility of WPT system based on its performance and characteristics. From the simulation and practical results, it was noted that Impedance Matching and design optimization is the key to improving the efficiency of such system. Furthermore, it can also be concluded that by decreasing the distance between two resonators to a critical distance will result in frequency splitting phenomenon which further reduces the efficiency of the system. The analysis presented in this paper is helpful for detailed and in-depth understanding of the magnetic resonant based WPT.

6. Recommendation for Future Works

WPT with four coil model could cope up the impedance matching problem to some extent. Use of Vector Network Analyzer could help for problem diagnosis. Increasing frequency range is also suggested and in case of hardware, “Manhattan Prototyping” system for high frequency PCB design is highly recommended.

Acknowledgments

The authors express their gratitude to Deepak Shrestha for providing laboratory for the prototype setup, Dinesh Baniya Kshatri for his incessant supervision and Atul Rauniyar for providing the necessary data.

References

[1] Nikola Tesla. The transmission of electrical energy without wires. *Electrical World and Engineer*, 1905.

[2] A Kurs, A Karalis, R Moffatt, J D Joannopoulos, P Fisher, and M Soljacic. Wireless power transfer via strongly coupled magnetic resonances. *Science Express*, 317:83–86, 2007.

[3] S S Valtchey, E N Baikova, and L R Jorge. Electromagnetic field as the wireless transporter of energy. *Facta Universitatis*, pages 171–181, 2012 2012.

[4] Ajay Kumar Sah and Arun Kumar Timilsina. Design of wireless power transfer system via magnetic resonant coupling at 13.56 mhz. In *Proceedings of IOE Graduate Conference*, volume 1, pages 202–210.

[5] Ajay Kumar Sah. Analysis and optimization of wireless power transfer link. Bachelor thesis, Department of Electronics and Computer Engineering, Institute of Engineering, Pulchowk Campus, November 2014.

[6] M P Kesler. Highly resonant wireless power transfer :safe, efficient and over distance. Technical report, 2013.

[7] Muhummad H Rashid. *Power Electronics: Circuits, Devices and Applications*. Pearson Publishers, 2013.

[8] Xiu Zhang, S L Ho, and W N Fu. Analysis and optimization of magnetically coupled resonators for wireless power transfer. *IEEE Transactions on Magnetics*, 48, 2012 2012.

[9] Ashutosh Timilsina, Beni Nepali, Binay Paudyal, and Jenesha Devendra Kunwar. Design and performance analysis of highly efficient class e resonant inverter. *Zerone*, 1:14–17, 2016 2016.

[10] Huy Hoang and Franklin Bien, editors. *Maximizing Efficiency of Electromagnetic Resonance Wireless Power Transmission Systems with Adaptive Circuits*. 2012.

[11] Ashutosh Timilsina, Beni Nepali, Binay Paudyal, and Jenesha Devendra Kunwar. Wireless power transfer via strongly coupled magnetic resonance. Bachelor thesis, Department of Electrical Engineering, Institute of Engineering, Pulchowk Campus, August 2016.

[12] N O Sokal. Class-e rf power amplifiers. *QEX*, pages 9–20, 2001 2001.

[13] J I Agbinya. *Wireless Power Transfer*. River Publishers, Denmark, 2012.

[14] Yiming Zhang, Zhengming Zhao, and Kainan Chen. Frequency-splitting analysis of four-coil resonant wireless power transfer. *IEEE Transactions on Industry Applications*, 50, 7 2014.