I J C T A, 9(16), 2016, pp. 7939-7950

Implementation of Wireless Charging System Using Single Stage Power Conditioning Circuit at Receiver

Ria George[1], Sreekala Manmadhan[2] and Deepa K.[3]

ABSTRACT

Wireless transfer of electric power is being adopted as a viable method of charging portable devices as it makes them safer, raises their mobility and reliability and reduces the cost. Though efficient transmitter driver circuits and optimized coil designs have been developed by researchers in recent years, power conditioning at the receiver side haven't got much attention. To reduce the number of components and the associated losses, the traditional two stage power conditioning should be replaced by an efficient and more compact single stage converter. This paper proposes an efficient wireless charging system based on resonant magnetic coupling that contains single stage boost rectifier at receiver. Single stage rectification and boosting is made possible by the bidirectional conduction ability of MOSFETs. The system is simulated in PSIM software, where overall power transfer efficiency is analyzed for different coupling factors, and different loads. The prototype of the entire system was developed in the laboratory by integrating coils and converters. The two fundamental concepts of power transmission, energy efficiency and transmission distance capabilities are analyzed and the results were found to be quite promising for practical use of this system

Keywords Wireless charging, Single stage boost rectifier, magnetic resonant coupling, inductive loop coils

1. INTRODUCTION

The global electronic industry has undergone a tremendous change in last few decades which lead to innovations in design, process and performance of electronic devices. It has become crucial to make the devices user friendly and efficient. In order to improve system aesthetics, mobility and convenience, conventional method of wired charging is now being replaced with contactless powering techniques. Portable electronics devices which have become an inevitable part of social and economic activities of our daily life can be made more user-friendly, reliable, safe and flexible by removing the traditional cords and wires.

Wireless charging technology is now commercially available for a wide range of applications. According to the data provided by IHS Wireless Power Intelligence Service, the wireless power and charging market is undergoing a rapid growth and is expected to expand further [2]. For power transfer, transmitters and receivers are optimized and customized for different products and applications. Transmitters have been developed for standalone applications, automotives (vehicle charging), airports and transportation, furniture, hospitals and restaurants. Receivers are implemented for portable electronic devices and peripherals, home appliances, vehicles, wearable technology, medical implants etc. Figure 1 shows the current and future market for wireless products as per IHS Wireless Power Intelligence Service.

The contactless transmission of power or energy from a source to load, literally known as Wireless Power Transfer (WPT), can be achieved through different techniques, either far field or near field.

1 Student, *Email: riajoy1991@rediffmail.com*

2,3 Assistant Professor, Dept. of EEE, Amrita Vishwa Vidyapeetham University, Amrita School of Engineering, Amrita University, Bengaluru, India, *Emails: m_sreekala@blr.amrita.edu; deepa.kaliyaperumal@rediffmail.com*

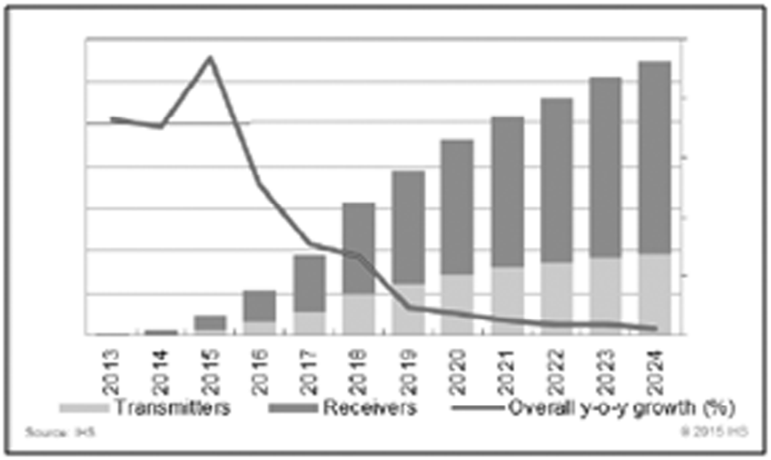


Figure 1: World market for wireless power [2]

Some of the methods used for the wireless transmission of energy are electromagnetic induction, electrostatic induction, electromagnetic radiation, microwave method, laser method and electric conduction. The selection of the technology depends on the various parameters such as required power, transmission distance, medium, application, complexity and cost [3]. Electromagnetic radiation, microwave method and laser method are far-field techniques that require highly directive transmitter and receiver antennas or well-collimated laser beam. A far-field method involves substantial loss of energy to air, and so makes powering electrical equipments but acceptable for data transmission applications [4]. In electrostatic induction or capacitive coupling, the transfer of electric energy is through dielectric medium while electromagnetic induction is a near-field transmission which could be achieved through air [5]. The most common method of wireless power charging is carried out via resonant magnetic induction.

In this work, an improved wireless charging system using magnetic resonant coupling technique is implemented, wherein the two stage power conditioning circuit at the receiver side is substituted by a single stage boost rectifier. This paper discusses the realization of an improvised wireless charging system and investigates the effect of coil design and coupling factor. The paper focuses on hardware implementation and analysis and is comprised of the following sections. Section II points out the current state of technology and examines the existing literatures. Section III discusses about the main components of the system and overview of its working. Section IV provides details about hardware implementation and results. Section V provides various analyses performed on the developed prototype.

2. CURRENT STATE OFWIRELESS CHARGING TECHNOLOGY

Strongly coupled wireless charging systems containing ferrite cores have been deployed in devices such as electric toothbrushes. It requires precise alignment, met through device constraints such as slots or projections, to achieve strong coupling. The design goal is increased safety, as opposed to additional freedom of movement. As the device is designed to operate safely, there exists no conductive path between the device and the charger and also limited freedom of movement. The challenge for a portable electronic device is to reduce or eliminate the use of bulky magnetic materials and operate at high efficiency by providing freedom of movement.

For efficient transfer of power over distances in the order of size of the coil, a large inductive coil can be used which is similar to using large antennas to improve the power transfer efficiency in far-field systems [6]. For any magnetic-field-based near-field wireless power charging system, the maximum transmission distance is limited by two factors, the mutual inductance between the transmitting and the receiving coils and the parasitic resistance of the coils.

Many coil configurations have been reported for midrange transfer. The latest works are based on four-coil approach, utilizing two resonant structures tuned to the same resonant frequency, along with two additional coils coupling with the resonators to serve the function of a matching network [6 - 7]. However, the impedance matching requirement implies that such system has its overall energy efficiency less than 50% as it uses the maximum power transfer principle. The system explained in this paper uses two-coil system in which operating frequency is determined by the resonant capacitor and the inductance of the coils.

Extensive studies have been done on the theoretical and practical aspects of wireless power transfer system in recent years, focusing on of the inductive coil design[8] and optimization of circuits driving the primary coil[9,10]. The use of magnetic induction, tuned circuits and resonance frequency operation in combination has been a common theme in radio and wireless power investigations [11, 12]. Existing works doesn't provide many innovations for the power conditioning circuits at the secondary side of the system. As the load is mostly electronic devices, i.e., DC loads, high frequency and high efficiency rectifiers need to be developed. Traditional half wave or bridge rectifiers are commonly used, wherein voltage drop of the diodes and action of switching causes considerable losses. In case of synchronous rectifiers with bridge configuration, though they provide improved overall efficiency of the system, complexity in control of four switches makes them undesirable, mainly at high resonant frequencies [13]. The traditional rectifiers have non-sinusoidal input current which would result in creating distorted current flow in the secondary coils of the system [14].

The WPT system developed herein comprises of a DC to AC inverter at the source for driving the transmitter coil. The immediate-fields of resonators will be Omni-directional and stationary, exchanging energy over mid-range distances and allows better tolerance in the placement of transmitter and receiver coils. The transmitter and receiver coils are designed by considering the frequency of operation and coil geometry. The proposed system could be employed for charging or powering or simultaneous charging and powering of a variety of electronic devices.

3. IMPLEMENTING WIRELESS POWER TRANSFER SYSTEM - OVERVIEW

The paper explains the implementation of an entire wireless power transfer system by choosing resonant inductive coupling as a means of efficient energy transfer. The authors have already explained the design,

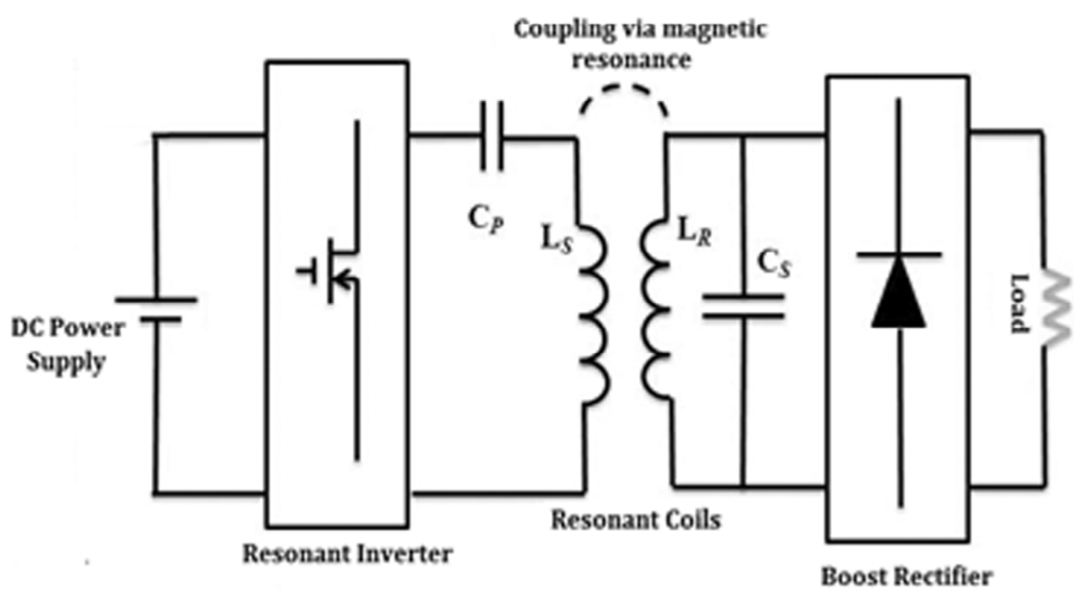


Figure 2: Electrical schematic of the proposed WPT system

state of art and functioning of the system in the reference paper [1]. The hardware developed consists of three main blocks: the coupling coils, transmitter driver circuit and receiver power conditioning circuit. Fig 2 shows the schematic of the entire system, where the receiver side is made more compact by implementing a single stage boost rectifier.

Transmitting energy through magnetic resonant coupling without radiating electromagnetic waves entails creating LC resonance with the aid of the coil loops. The transmitter and receiver coil should be made to resonate at desired frequency. At secondary side, the voltage induced is rectified and boosted by the one-stage converter. The systems drive a resistive load.

3.1. Inductive Link Coils

In WPT systems, loop antennas, i.e., transmitter and receiver are made by winding copper wires on air core. If transmitter is air core, the receiver could be positioned within the core area. The flux linkage and coupling are more effective within the plane of the transmitter and decreases with distance between coils. Effective inductance and capacitance are the factors determining the resonant frequency of the coils. Coil inductance is generated by the loop, whereas, it is required to add capacitance to create resonance at specific frequency. To create resonance, the capacitance required is low for coils with higher diameters.

3.2. Primary coil driver circuit

As the current driving the primary coil need to be sinusoidal, the coils must be operated at resonance. To achieve this, primary coils are driven by Class D type H-bridge resonant. The single phase bridge circuit has two legs of switches, each leg consisting of an upper switch and a lower switch and the junction point of the upper and lower switches is the output point of that particular leg. Fig 3 shows the circuit diagram of the series resonant inverter that drives the primary coil. The effective capacitance and impedance is considered and the coil is represented by a series RLC load in the circuit,

3.3. Single Stage Boost Rectifier at receiver side

In this work, single stage boost rectifier, as shown in figure 4 is employed at the receiver side. Rectification and boosting in single stage is made possible by the bidirectional current conduction ability of the MOSFET.

Compared to two-stage conventional circuit, this converter is more compact. The series diode in the boost converter and DC side inductor is removed from the conventional topology. As MOSFETs S1 and S2 are driven by same pulse, their gate legs are referred to the same ground. When the pulses for both MOSFETs are high, one switch conducts forward whereas the other conducts in opposite direction, in each half cycle. When the gate is driven by low pulses, both the MOSFETs enter OFF mode and circulation current will be

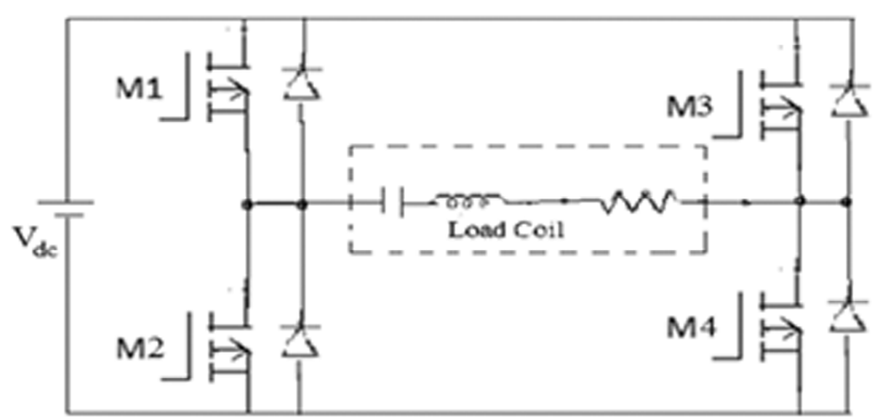


Figure 3: Series resonant DC/AC inverter at the primary side

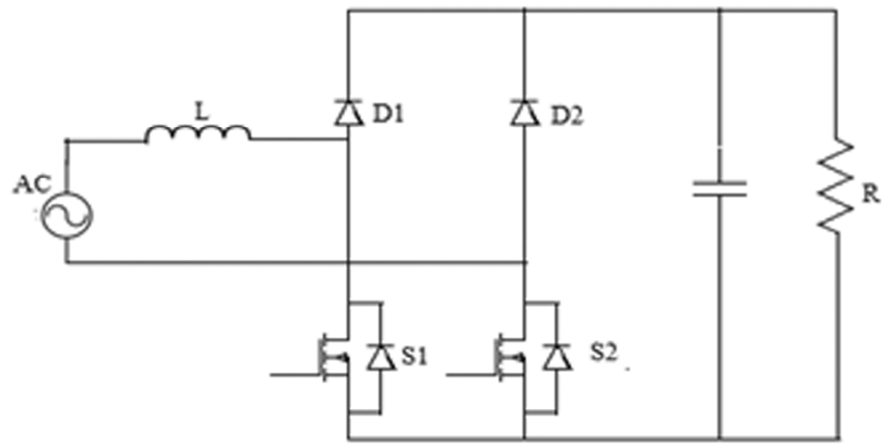


Figure 4: Single stage boost rectifier circuit

restricted by body diodes which are connected anti-parallel to the switches. In order to maintain the desired output voltage, the duty cycle is varied accordingly. The operational specifications and working modes of the boost rectifier circuit is explained in previous work [1].

4. HARDWARE IMPLEMENTATION AND RESULTS

The wireless charging system using magnetic resonant coupling was designed, simulated in PSIM software and implemented practically in the laboratory. A step-by step approach was followed in developing the whole system. Initially the transmitter and receiver coils were made out of copper wires and were experimented to find the resonant frequency by using a function generator block. Then the prototype was made by integrating a single phase inverter, transmitter coil, receiver coil and boost rectifier circuit.

The transmitter coil is driven by a single phase inverter operating at 300 kHz switching frequency. Pulses for the inverter switches were obtained from Motor Control PWM module of dsPIC30f4011. Figure 5 shows the pulses generated through dsPIC30f4011.

Also the boost rectifier circuit at the receiver side has to be operated in synchronism with the receiver coil signal. For that, the converter switches are driven by pulses obtained from analog IC- SG3525, so that the duty cycle and frequency could be varied in real-time. Figure 6 shows the output pulses obtained from SG3525.

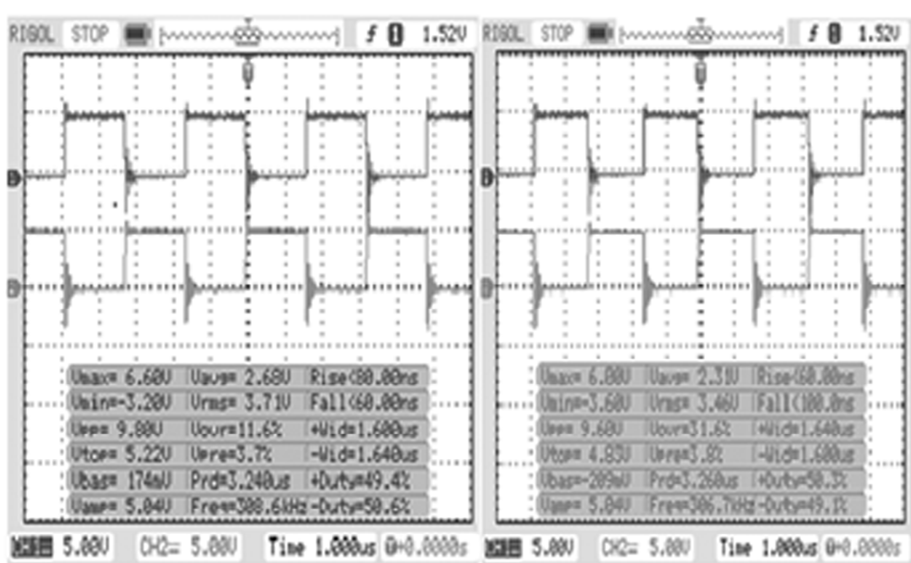


Figure 5: Complementary pulses from dsPIC30f4011

Transmitter and receiver coils are the major components of the WPT system. Physical design of inductive coils and their orientation with respect to each other are important as they have direct impact on inductive link circuit and power delivery. For hardware implementation in the laboratory, the transmitter coil is cylindrically wound with air core. The distribution of flux lines is uniform throughout the coil in air medium. Design parameters include the type of wire used, the diameter and number of turns. Receiver coil is wound as a single layer so that the windings can cut maximum flux lines from the transmitter. The transmitter coil geometry ensures effective transmission over greater distances, while the receiver geometry ensures maximum flux linkage, thereby making the system effective.

Fig. 7 shows the transmitter and receiver coils, with 7 turns in cylindrical shape and with 75 turns in concentric manner respectively. While experimenting with the coils using function generator as driver and without adding series or parallel capacitors, were found to resonate at a frequency of 1.3 MHz. After appending the capacitors, resonant frequency comes down to 300 kHz.

Resonant frequency, switching frequency and load quality factor are the parameters considered for designing the passive elements of the converter. The quality factor of series- loads circuit is kept high to obtain sinusoidal current and duty ratio of switching pulse is 50%. The input for the inverter is 30V DC and

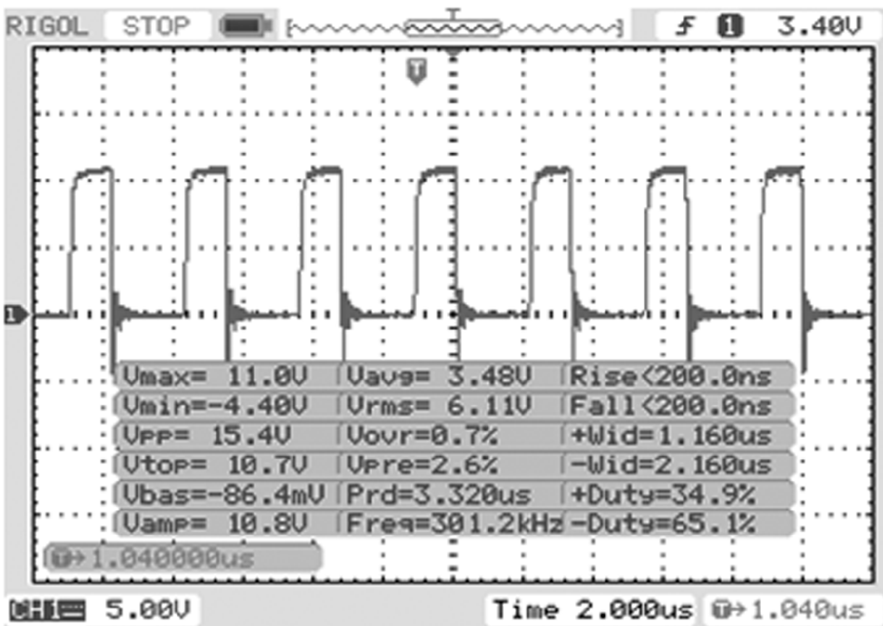
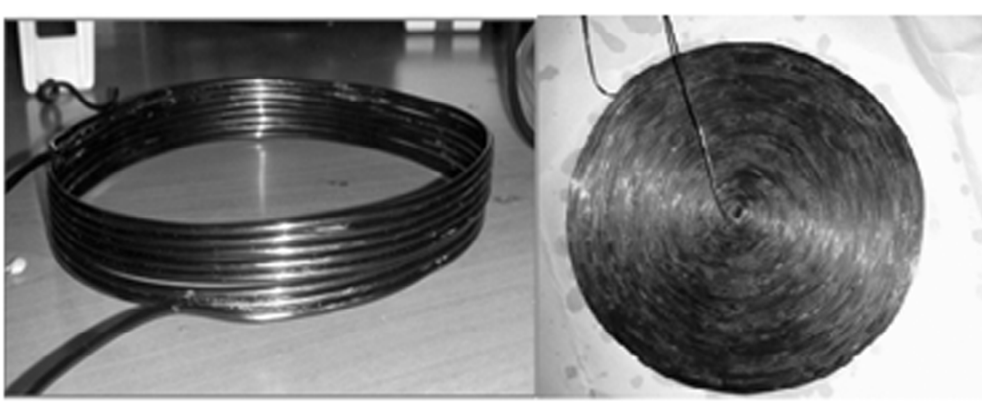


Figure 6: Gate drive pulses for boost rectifier from SG3525



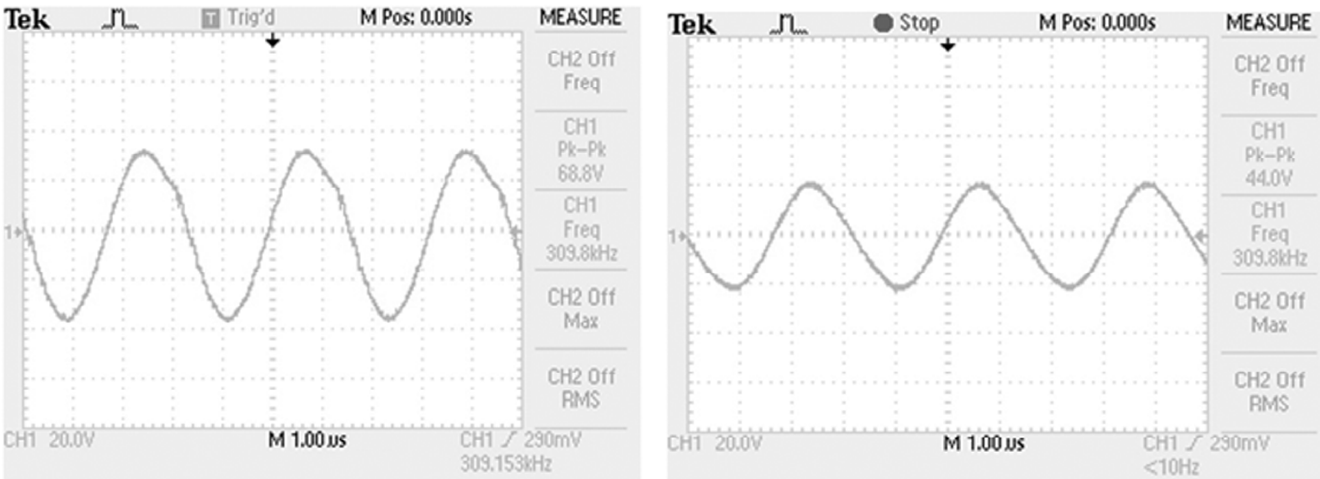
(a) (b)

Figure 7: (a) Transmitter coil and (b) Receiver coil

the output obtained is 34V (Amax) AC when transmitter coil of 19µH is kept as load. Figure 8 gives the voltage waveforms at both the coils.

The receiver coil, 150 µH with series resonant capacitors is connected to the single stage boost rectifier circuit to act as the source. 22Kû, 1W resistor was kept as the load and at minimum distance between transmitter and receiver coil, the voltage across load is 96V (shown in figure 9).

Figure 10 shows the hardware implementation of the proposed WPT system in the laboratory. The system can be used to charge low power devices, e.g. mobiles, laptops etc. The rating of mobile phones is approximately 3.5V, 1000mA. The device can be connected to the system through a voltage divider circuit using voltage regulator.



(a) **(b)**

Figure 8: (a) Output voltage of the inverter across the primary coil and (b) Voltage across the receiver coil

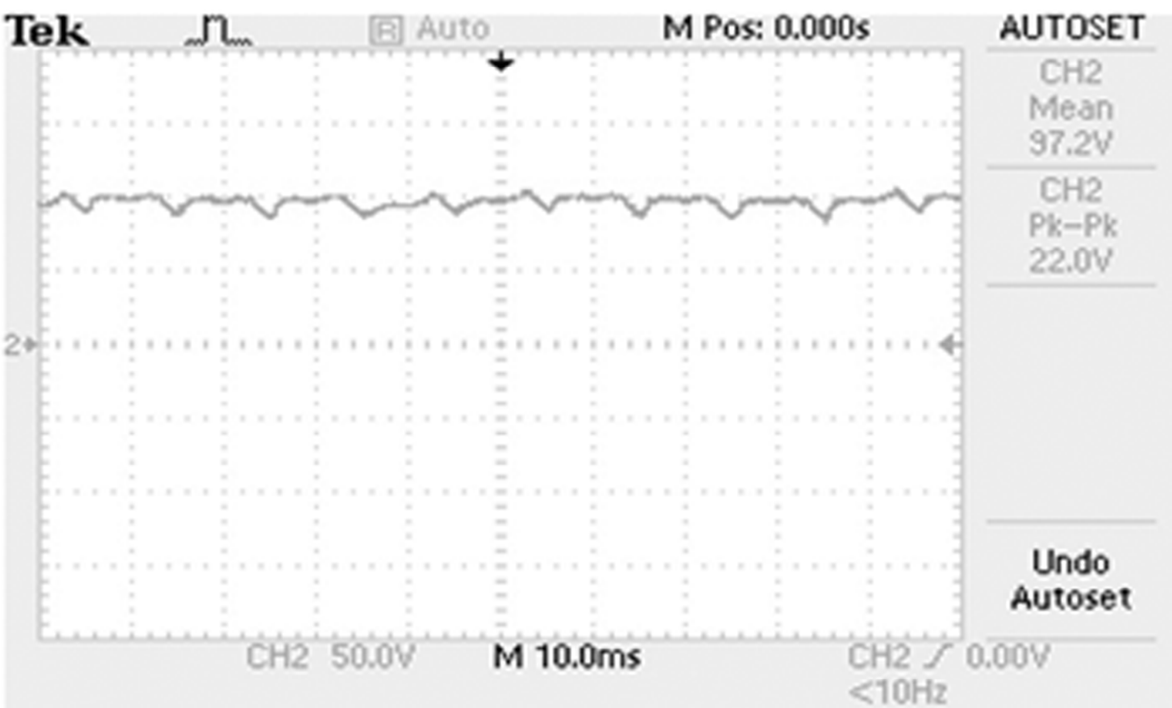


Figure 9: Output of the single stage boost rectifier

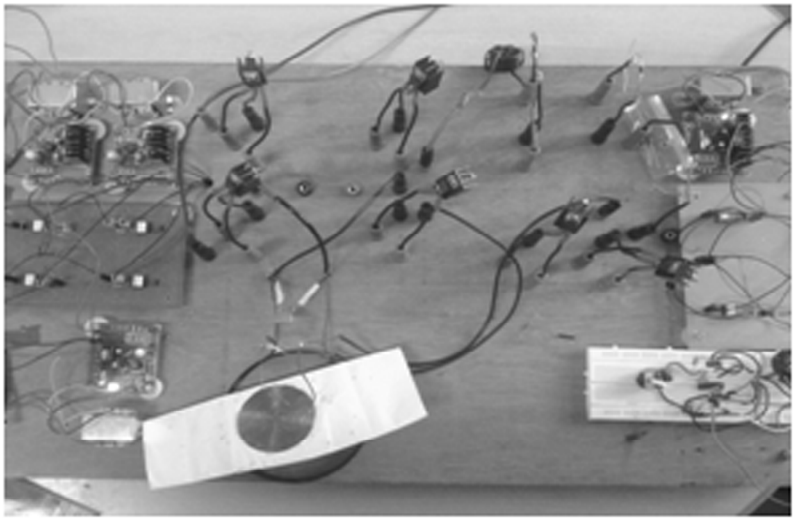


Figure 10: Hardware implementation of the whole system

5. EXPERIMENTAL ANALYSIS ON THE PROTOTYPE

During the process of hardware development and after the implementation of the prototype, various analyses were done towards the improvisation and optimization of the system. The results provide useful data for optimization of inductive links and prove the efficiency of single stage boost rectifier for wireless charging applications.

5.1. Effect of coupling capacitors

After making the coils, they were experimented for resonance. Transmitter coil was excited with sine wave from function generator and receiver coil output was observed. It was found that the receiver gives pure sine wave voltage at a transmission frequency of 1.3MHz.Table 1 shows the voltage across the receiver coil at various distances without using coupling capacitors

A coupling capacitor of 10nF is connected parallel to the transmitter coil. The receiver coil is coupled with 33nF capacitor. After connecting the coupling capacitors, the transmitter and receiver coils were

Table 1
Voltage at receiver coil without coupling capacitors

Resonant frequency = 1.3 MHz	
Distance	*Voltage across receiver*
1 cm	50.8 V
5 cm	45 V
10 cm	12.4 V
15 cm	5.60 V

Table 2
Voltage at receiver coil with coupling capacitors

Resonant frequency = 290.8 kHz (LC resonance)	
Distance	*Voltage across receiver*
1 cm	16V
5 cm	8 V
10 cm	2V

found to resonate at 290 kHz. Table 2 shows the voltage across the receiver coil at various distances after using coupling capacitors. The system can be operated at lower frequencies and considerable voltage is induced at receiver coil at moderate distance.

5.2. Effect of number of turns and diameter of coils

The geometry and orientation of the coils could be optimized for increasing the amount of power transferred and thereby improving the efficiency of the system. Two receiver coils, as shown in figure 11, were made with different number of turns, and were tested for induced voltage by using the same primary coil. One was with 50 concentric turns and the other was with 75 turns. It was found that the second one with larger diameter could make more flux utilization and there by induce a higher voltage.

5.3. Effect of change in input voltage

The whole system was analyzed for change in input voltage. As the input increases the output at the load also increases. Table 3 shows the effect of input voltage on the system.

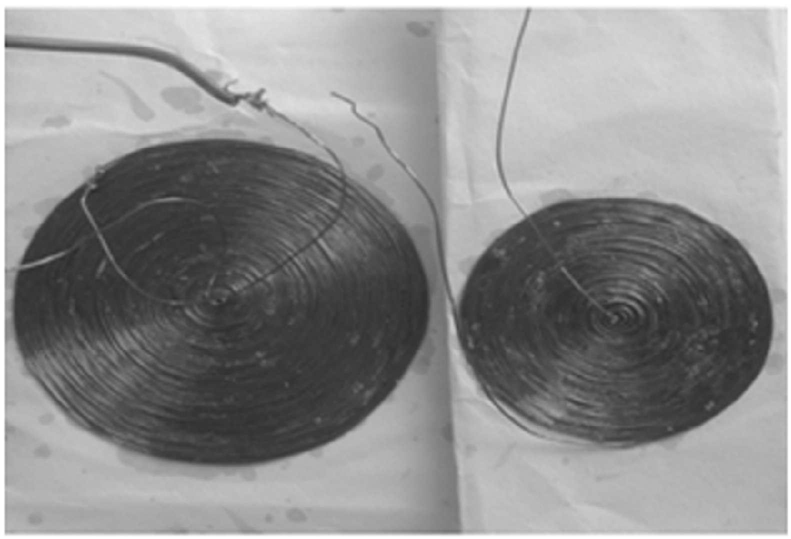


Figure 11: Receiver coils of different number of turns

Table 3
Output of the system with change in input voltage

Input voltage (DC)	Output of the inverter Vmax (AC)	Voltage at the receiver Vmax (AC)	Output of the boost rectifier (DC)
5 V	3.2 V	3 V	10 V
10 V	12.3 V	7 V	22.7 V
15 V	14.5 V	12.4 V	47.2 V
20 V	21.3 V	16.2 V	64.6 V
25 V	26.2 V	22.1 V	83.2 V
30 V	34.4 V	26.4 V	97.6 V

5.4. Normal bridge rectifier vs. Boost rectifier circuit

Usually, power conditioning at receiver side is obtained by rectifying the AC voltage at using traditional half wave or bridge rectifiers and then feeding it into a boost converter to deliver required power to a portable electronic load. This two stage system may be inefficient and reduce the power received by the load. Fig 12 shows the circuit containing two stage converter used for power conditioning at the receiver side.

In a conventional boost converter topology, the diode is kept in series with the path of power flow which causes voltage drop and reduces reliability by increasing power loss. Also it is required to specially design the dc-side inductor to carry dc current as well as the ripple current which is of high frequency. At all instants the power flow path contains three semiconductor device drops.

The voltage boosting capability of the single stage boost rectifier was proved by comparing its output with the DC output obtained from normal diode bridge rectifier. The rectifier circuit was made using FR306 diodes and 1μF filter capacitor. The receiver coil voltage is given as input to the rectifier circuit and output was observed. The load connected to both the circuits was 22Kû. At minimum distance, the output voltage at boost rectifier circuit is 96V, whereas at diode rectifier is 35 V. Figure 13 shows the circuits developed for comparison and figure 14 shows the output waveforms .Also table 4 provides the results of analysis.

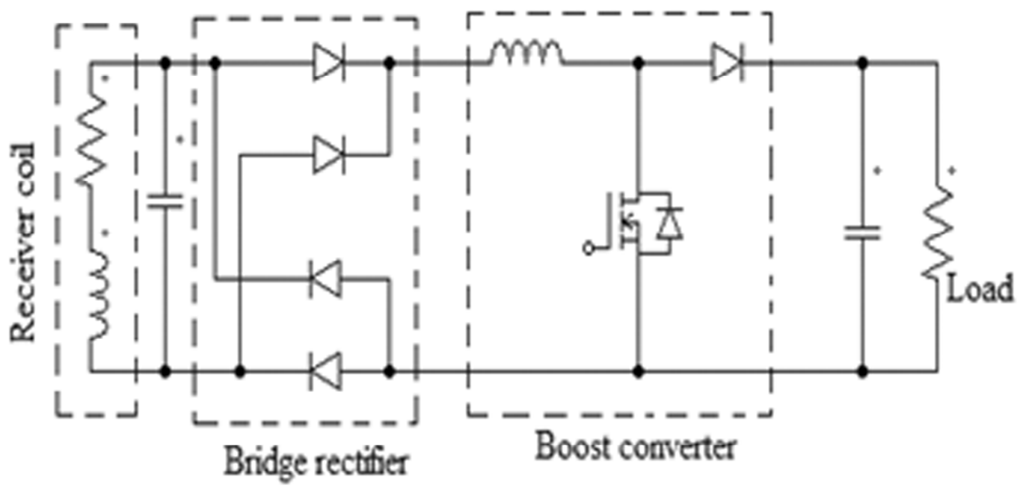


Figure 12: Conventional two stage circuit with rectifier and boost converter at receiver side

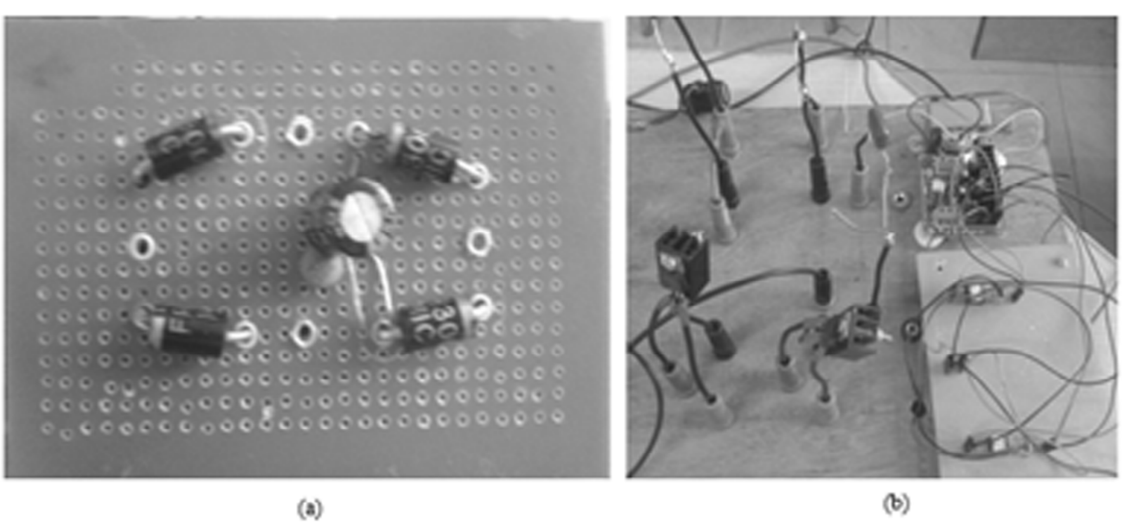
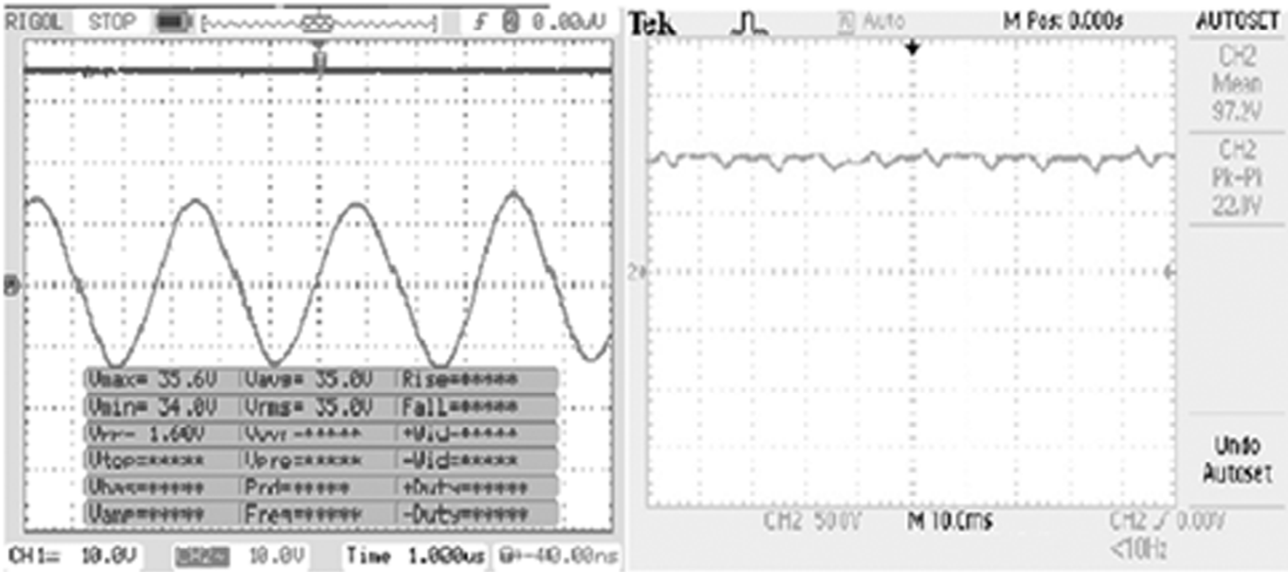


Figure 13: (a) Conventional bridge rectifier and (b) Boost rectifier circuits made in laboratory



(a) (b)

Figure 14: (a) Input and output of diode rectifier (b) Output of bridge rectifier

Table 4
Comparison of outputs of diode rectifier and boost rectifier

Distance between transmitter and receiver coils	*Diode rectifier outpu t(DC)*	*Boost rectifier output (DC)*
0 cm	35 V	96.5 V
2cm	31.3V	84.6V
4 cm	24 V	59 V
6 cm	18.2 V	32.4V
8 cm	13 V	25 V
10 cm	7.3 V	14.2V
12 cm	5 V	8 V
14 cm	1.2 V	3 V

6. CONCLUSION

An Efficient wireless charging system for portable devices is developed by substituting the conventional converters with single stage converter. Effective coil design and compact converter could be practically used in wireless charging devices. Converter was analyzed through experiments and effects of different parameters studied and presented proves that the power can be transferred safely over an air gap and also through any non-metal object which might exist between the coils i.e. wood, plastic, granite. Addition of extra or larger transmitters could improve the range of power transfer.

REFERENCES

[1] Ria George, M. Sreekala, K. Deepa, “Single stage boost rectifier for wireless charging of portable devices through magnetic resonant coupling”. Advances in Intelligent systems and computing, Volume 394, pages 443-452, February 2016, Volume 394, pages 443- 452, February 2016.

[2] David Green, “Is 2015-breaking year for wireless power”, Wireless power Report-2015,Part of wireless power intelligence service, IHS technology.

[3] Benjamin L. Canno, James F. Hoburg, Daniel D. Stancil “Magnetic resonant coupling as a potential means for wireless power transfer to multiple small receivers”, *IEEE Transactions on Power Electronics*, vol. 24, pp. 7, July 2009.

[4] G. Covic and J. Boys. “Modern trends in inductive power transfer.” IEEE Journal of Selected Topics in Power Electronics, pp. 28–41, July 2013.

[5] Erin M. Jason D. Heebl, Carl, and A.Grbic.”A study of wireless non-radiative power transfer systems using resonant shielded loops.” *IEEE Transactions on Circuits and Systems I*, volume 59, pages.2125 – 2136, September 2012.

[6] S. Raju, R. Wu, M. Chan, and C. P. Yue. “Modeling of mutual coupling between planar inductors in wireless power applications.” *IEEE Transactions on Power Electronics*, vol. 29, pp.481–490, January 2014.

[7] M. Budhia, G.A. Covic, and J.T. Boys.”Design and optimization of circular magnetic structures for lumped inductive power transfer systems.” *IEEE Transactions on Power Electronics*, vol. 26, pp.3096–3108, Nov. 2011.

[8] Duk Soo , Jong Yu Tae-Dong, Kyoung-Sub. “Dual Resonance Frequency Selective Loop of Near-Field Wireless Charging and Communications Systems for Portable Device”. *IEEE Microwave and Wireless Components Letters* ,Volume: 25, Issue 9, pp. 624-626, September 2015.

[9] Rohan Dayal, Kumar Modepalli, Leila Pars, “A new optimum power control scheme for low-power energy harvesting systems” *IEEE Transactions on Industrial applications*, vol. 49, pp. 6, December 2013.

[10] J. Huh, S.W. Lee, W.Y. Lee, G.H. Cho, and C.T. Rim. Narrow-width inductive power transfer system for online electrical vehicles. *IEEE Transactions on Power Electronics,* vol. 26, p. 12, December 2011.

[11] Huber L,Yungtaek Jang, Jovanovic M.M, “Performance evaluation of bridgeless PFC boost rectifiers” *IEEE Transactions on Power Electronics*, vol. 23, pp.1381-1390, May 2008.

[12] R Kuo, Riehl, Anand, Jenshan L. “In-Vehicles Wireless Charging System for Portable Devices.” Vehicular Technology Conference (VTCFall), 2015 IEEE;DOI: 10.1109/VTCFall.2015.7390995, pp. 1-3, Sept 2015.

[13] Robert L.S, “A comparison of half-bridge resonant converter topologies”, *IEEE Transactions on Power Electronics*, vol. 3, p. 2, April 1999.

[14] Enjeti. P.N., Martinez R., “A high performance single phase ac to dc rectifier with input power factor correction.” IEEE conf. on Applied Power Electronics and Exposition(APEC), pp.190-195, March 1993.