INDUCTIVE POWER TRANSFER TECHNOLOGY FOR MOBILE BATTERY CHARGER

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INDUCTIVE POWER TRANSFER TECHNOLOGY FOR MOBILE BATTERY CHARGER

A Thesis presented in partial fulfillment of the exigency for the degree of

Bachelor of Technology in "Electrical Engineering"

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CERTIFICATE

This is to certify that the thesis entitled "**Inductive Power Transfer Technology for Mobile Battery Charger**", produced to the National Institute of Technology, Rourkela by **Mr. Satish Roushan**, **Roll No: 110ee0223** for the award of BACHELOR OF TECHNOLOGY in Electrical Engineering is a bonafide record of research work carried out by him under my supervision and guidance. The thesis which is based on candidate's own work, has not been submitted elsewhere for a degree/diploma.

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<u>Devoted to</u>

My parents

ABSTRACT

Inductive power transfer (IPT) is an application of electromagnetic induction principle. Since electromagnetic induction phenomena is directly proportional to the operating frequency, so as we increase the operating frequency, amount of energy transfer from one coil to another coil will also increase. As our power supply frequency is 50Hz so at this frequency, amount of energy transfer from one coil to another coil will be very less. In this thesis it is shown that, to transfer maximum amount of energy from one coil to another coil, it is necessary to use IPT at high frequency. At high frequency skin effect is more pronounced but there is a resonant frequency where overall efficiency is more in spite skin effect. To increase the power factor of IPT circuit compensated capacitor has used. There are four types of compensated topology but to use the IPT circuit in mobile battery charger primary-series-secondary-parallel (P-S-S-P) is more useful.

CONTENTS

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

TABLE

LISTS OF FIGURES

CHAPTER-1

Introduction

1.1 MOTIVATION

Transfer of wireless power has been used since long time in telecommunications applications. Radio waves, cellular phones and internet Wi-Fi are examples of wireless power transmission. Recently, there is a growing interest towards the innovation of a deeply challenging idea for wireless power applications: electronics utilities without chords. Transmission of the electrical power for utilize it in different other form, a copper wire is used. Sometimes these wires make weird especially when apparatus is small. These wires easily give rise to sparking, short-circuit and it may give dangerous electric shock. Also due to regular use of these wires, it becomes less reliable and lifespan becomes very less. In case of mobile battery charger, mechanical contact is the main reason behind failures of charger [3]. Wireless power transfer technology is the best option to overcome from these types of problems. In this technology, there is no worry about adopter wire. This type of charger is very helpful in carrying charger while we travelled. The invention of new technology and new area of study were the motivations behind the project.

1.2 LITERATURE SURVEY

The topic of Inductive power transfer has been looked upon by many researchers all around the world and presently it is one of the hot topic among the researchers. It has been known that as the distance increases between primary side and secondary side, transfer efficiency decreases and thus a better contactless transfer control mechanism and selection of good quality metal with high mutual coefficient is required. To increase the transfer efficiency compensated capacitors is used in both primary and secondary side.

Grant A. Covic, and John T. Boys, “Inductive power transfer.” Proceeding of the IEEE vol. 101, no. 6, June 2013, have given a detailed historical background, technological issues, and engineering applications of inductive power transfer in their invited paper. The authors had also share their vision and arguments on the engineering challenges and future developments such as battery charger and roadway powered system [5].

Chang-Gyun Kim, Dong-Hyung Seo, Jung-Sik You, Jong-Hu park, and Bo H. Cho, “ Design of a contactless battery charger for cellular phone.” IEEE Transactions on industrial electronics, vol. 48, no. 6, December 2001, have designed a contactless battery charger for cellular phone. In his paper designed optimization has presented and he had also verified his result with experimental results [3].

1.3 OBJECTIVE

The basic objective is to study the fundamentals circuits of inductive power transfer and then modeling of circuit in Matlab environment. And finally implement this circuit in wireless charger for mobile charger.

CHAPTER-2

2.1 INTRODUCTION

Inductive Power Transfer (IPT) Technology is also called Wireless Power Transfer (WPT) Technology. It is the transmission of electrical energy from the electrical source to electrical load without any wire. Inductive Power Transfer technology is very useful in those cases where uses of interconnecting wires are inconvenient, hazardous, or almost impossible. IPT can be used in many applications like hybrid electrical vehicle, medical sensor, laptop charger etc. Indeed, now days IPT uses very frequently in electric vehicle and in medical sensor [2]. IPT was first demonstrated by Nikola Tesla in 1890. However it becomes popular in 20th century. Wireless transmission technology has used in communication system from long time ago like mobile phones, dish TV etc. Frequency used in radio wave is very high i.e. in the range of MHz. But frequency used in IPT used in electrical power application in the range of KHz so that it is not hazardous for human. This thesis presents use of IPT technology in mobile charger application. IPT mobile charger has several advantages over formal mobile charger. One of the most frequent failures in mobile charger is from the mechanical contact. To overcome from this type of problem IPT mobile charger can be used. Working principle behind IPT is electromagnetic induction phenomena. Since, in IPT technology air core is used so conversion efficiency is very low. To increase the efficiency of IPT, both primary and secondary coil should work on the resonant frequency.

2.2 Basic schematic of IPT

Inductive power transfer technology is based on electromagnetic induction phenomena. The basic schematic diagram of IPT [1] is shown in figure-1.

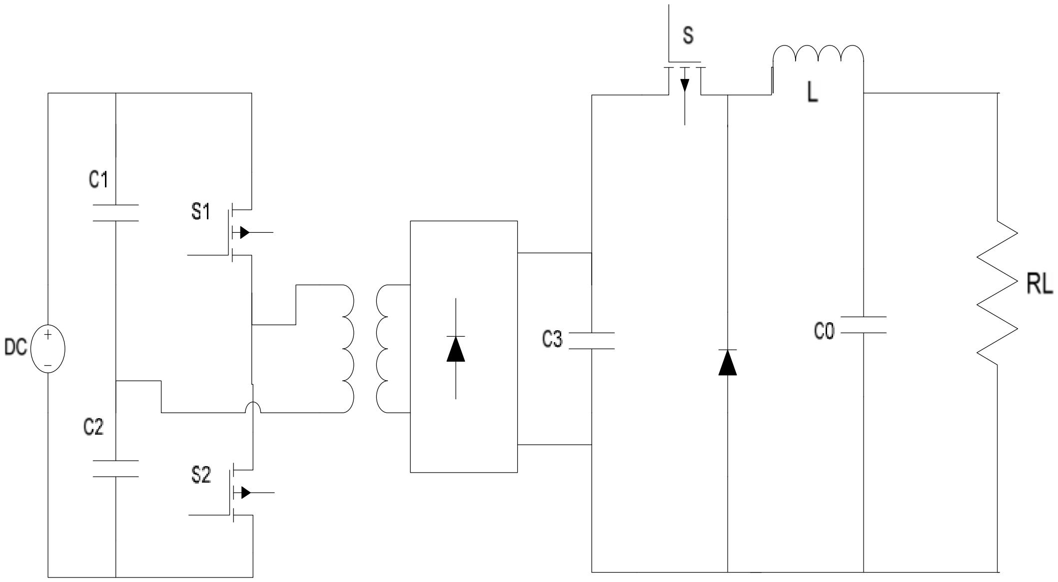


Figure 1-Basic schematic of IPT

A half bridge inverter circuit has used to convert DC voltage to high frequency AC voltage. Between two switches S1 and S2 there is time delay to avoid the simultaneously turning on of both switches [3]. Inverter circuit is used to convert the low frequency voltage into high frequency voltage so that overall power factor and efficiency will be more. Due to the electrical energy is transfer via- magnetic flux coupling over a large air gap between primary and secondary coil, the coupling factor between the primary and secondary coil is very poor.

2.3 Mathematical description of basic IPT circuit

The mutual inductance M can be expressed as following [1]

$$M = K.\sqrt{L_P \times L_S} \tag{1}$$

Where K is the coupling coefficient which can be expressed as following

$$K = \sqrt{1 - \frac{L_{SC}}{L_{OP}}} \tag{2}$$

Where L_{sc} means the value of measurement inductance from primary side when the secondary side is short- circuited, and L_{op} means the value of measurement inductance from the primary side when the secondary side is open- circuit.

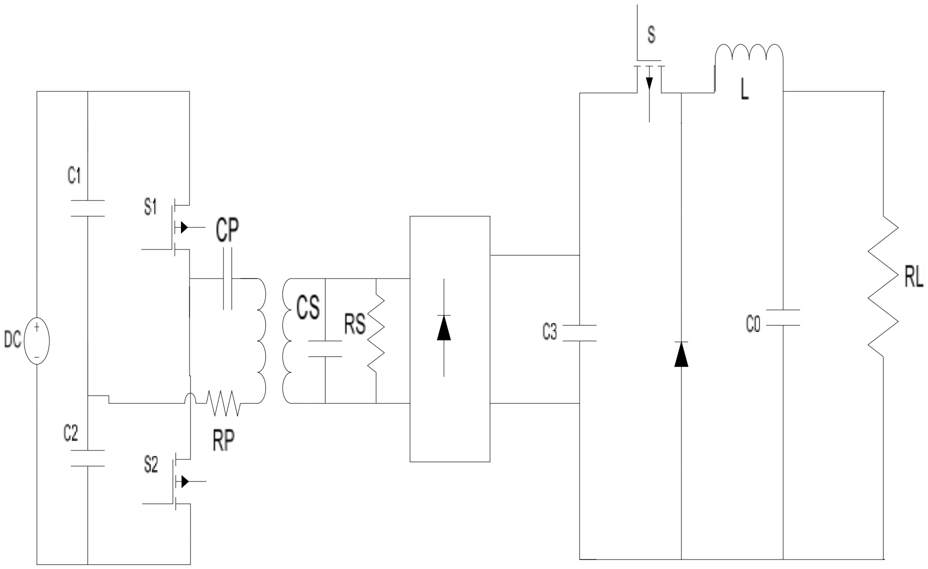


Figure 2- Basic IPT schematic with coupling capacitor

In order to simply the process of analysis, the line resistance of inductor and equivalent series resistance of capacitor will not be considered and resonant capacitor values of the primary side and the secondary side are required to analysis by the following:-

The value of reflection impedance Z_r can be obtained by reflected voltage divided by the primary side current, and can be expressed as following

$$Z_r = -\frac{j\omega M.i_s}{i_p} = \frac{\omega^2 M^2}{Z_s} \qquad (3)$$

Where Z_s is the equivalent impedance of the secondary side parallel resonant, can be expressed as following

$$Z_s = j\omega L_s + \frac{1}{j\omega C_s + {}^{1}/_{R_s}} \qquad (4)$$

Subtitling (4) into (3), we obtain

$$Z_{rs} = \frac{M^2 R_s}{L_s} - j\,\frac{\omega M^2}{L_s} \qquad (5)$$

The equivalent impedance of primary-side can be expressed as following in consideration of the reflected impedance

$$Z_p = \frac{1}{j\omega C_P} + j\omega L_P + \left(\frac{M^2 R_S}{L_S} - j\,\frac{\omega M^2}{L_S}\right) \qquad (6)$$

When the circuit occurs resonance, the primary-side equivalent impedance is purely resistive; therefore the value of the imaginary part is zero, and the primary side resonance capacitor the C_p can be expressed as following

$$C_P = \frac{1}{\omega^2\left(L_P - \frac{M^2}{L_S}\right)} \qquad (7)$$

The resonance capacitor of the secondary side C_S can be obtained by the resonance frequency f_r, expressed as following

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} = \frac{\omega}{2\pi} \tag{8}$$

$$\omega_r = \frac{1}{\sqrt{L_r C_r}} \tag{9}$$

$$C_r = C_s = \frac{1}{\omega_r\, 2.L_s} \tag{10}$$

The inductance value of the primary side and the secondary side can be obtained by the production of the induction coil with core, and decided the resonant frequency. The suitable value of capacitance can be calculated by (7), (10).

Chapter 3

3.1 Compensated topology for IPT

In order to improve the power factor and increase the inductive efficiency, the compensative capacitance can be added. The inductive structure is formed as a resonant circuit to generate the larger magnetic field, and can be classified into four as shown in Fig. 3. The S represents resonant circuit; P represents a parallel resonant circuit [1].

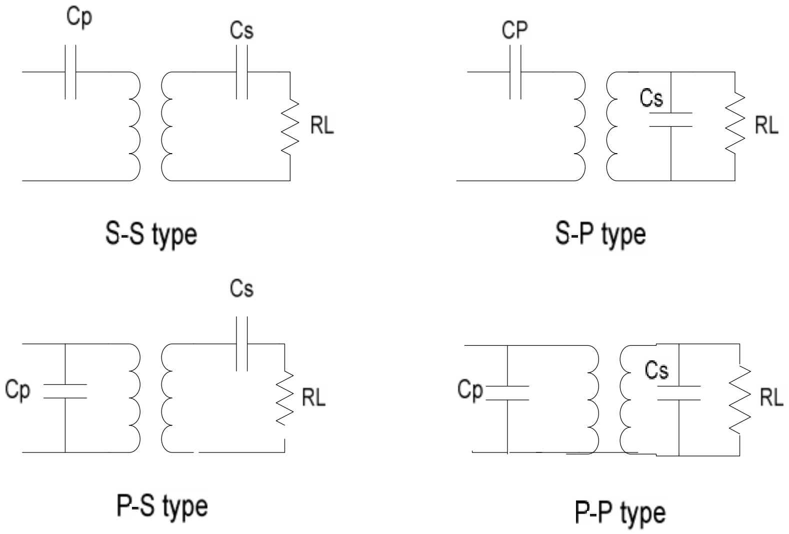
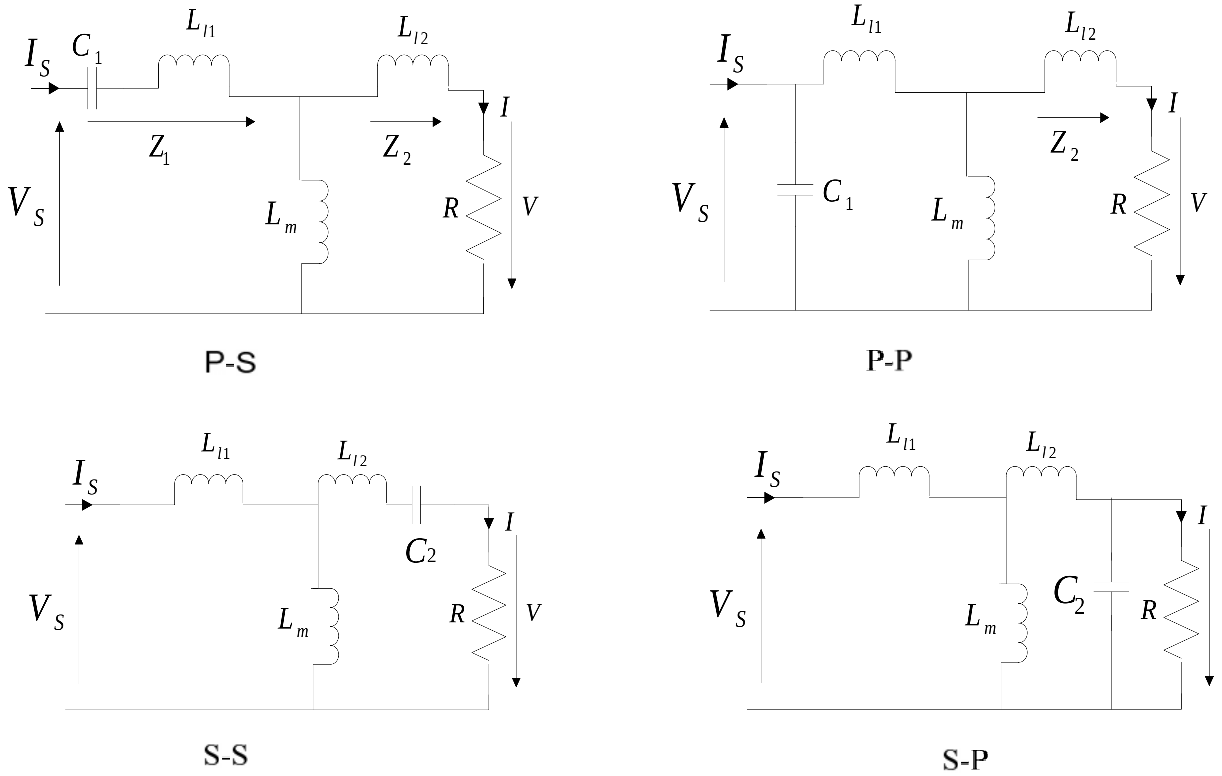


Figure 3-Different types of multi-resonant circuit

When the circuit operating at a resonant frequency, capacitive impedance and inductive impedance will be canceled out with each other in the circuit. Therefore, the voltage and current can be in phase, and the regarded as a purely resistive circuit. That is, when the resonance occurs, the impedance is minimum, input current is maximum and waveform close to sinusoidal, a resonance voltage on the inductive coil is greater. When the circuit is operated in the resonant frequency, the secondary side may have the highest output voltage, which can avoid the low voltage of the secondary side of induction. Based on the above considerations, the architecture of the coupling circuit chooses S-P, shown in Fig.-2.

3.2 Single-Resonant Compensation topology for IPT

There are two main fundamental capacitive topologies to compensate the reactive power, which are series and parallel compensation. This is used on each side of IPT circuit as shown in Fig. 4. In this figure, it is illustrated that these fundamental capacitive topologies in their equivalent circuits can be modeled as its T equivalent circuit model [11] and the load with the rectifier circuit can be modeled as resistance of value R. In this equivalent circuit all parameter which is in the secondary is transferred to the primary side of equivalent circuit.



P-S

P-P

S-S

S-P

Figure 4- Single-resonant compensation topology

3.3 Mathematical analysis of single-resonant topology

In fig.4 (P-S) T model circuit in the air-core mutual inductor, the equivalent leakage impedance with inductance value of L_{1l}, L_{2l} and the magnetizing impedance of inductance value of L_m is written as K, L_1, L_2 [11].

$$L_1 = N\frac{\varphi_1}{\mathrm{i}} \tag{11}$$

$$L_{l1} = N\frac{(\varphi_1 - \varphi_{12})}{\mathrm{i}} \tag{12}$$

$$K = \frac{\varphi_{12}}{\varphi_1} \tag{13}$$

$$L_{l1} = (1 - \mathrm{K})L_1 \tag{14}$$

$$L_{l2} = n^2(1 - \mathrm{K})L_2 = L_{l1} \tag{15}$$

$$L_m = \mathrm{K} * L_1 \tag{16}$$

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} \tag{17}$$

$$\omega_n = \frac{\omega}{\omega_0} \tag{18}$$

$$Q_n = \frac{\omega_n L_1}{R} \tag{19}$$

$$Z_1 = \frac{-\mathrm{j}}{\omega C_1} + \mathrm{j}\omega L_{l1} \tag{20}$$

$$Z_2 = \mathrm{j}\omega L_{l2} = \mathrm{j}\omega(1 - K)L_1 \tag{21}$$

$$Z_m = \omega K L_1 \tag{22}$$

$$M_V = \left|\frac{V}{V_S}\right| \tag{23}$$

$$M_I = \left|\frac{I}{I_S}\right| \tag{24}$$

$$M_V = \left|\frac{Z_m R}{Z_1 Z_m + Z_2(Z_1 + Z_m) + R(Z_1 + Z_m)}\right| \tag{25}$$

$$M_I = \left|\frac{Z_m}{Z_m + Z_2 + R}\right| \tag{26}$$

In general in actual circuits, ratio of voltage from primary to secondary to be consideration to get the actual M_V & M_I. Hence for easy mathematical analysis, it is assumed to be equal to 1. PF of any resonant circuits implies that the how much useful power extract from apparent power. Hence PF is define by equation (27) given below.

$$pf = \frac{P_{out}}{P_{in}} = \frac{VI}{V_s I_s} = M_V M_I \tag{27}$$

Voltage gain and current gain of all four is shown in table-I

Table-I: Voltage gain and current gain of single-resonant circuit of IPT

P-S	$\sqrt{L_{l1}C_1}$	$1\Big/\sqrt{\left\{\left[1+\frac{1-K}{K}\left(1-\frac{1}{\omega_n}\right)\right]^2+\omega_n^2Q_n^2\left[1-K+\frac{1-K}{K}\left(1-\frac{1}{\omega_n}\right)\right]^2\right\}}$	$\frac{1}{\sqrt{K\left(1+\frac{1}{Q_n^2\omega_n^2}\right)}}$
P-P	$\sqrt{L_{l1}C_1}$	$\frac{1}{\sqrt{\left[K^2+\omega_n^2Q_n^2(1-K)^2\left(\frac{1}{K}-K\right)^2\right]}}$	$\frac{1}{K\sqrt{\left[\frac{1}{\omega_n^2Q_n^2}\left(1-\frac{\omega_n^2}{1-K}\right)^2+\left(1-\omega_n^2(1+K)\right)^2\right]}}$
S-S	$\sqrt{L_{l2}C_2}$	$\frac{1}{\sqrt{\left[\frac{1}{K^2}+\omega_n^2Q_n^2(1-K)^2\left(1+\frac{1}{K}\left(1-\frac{1}{\omega_n^2}\right)\right)^2\right]}}$	$\frac{1}{\sqrt{\left\{\left[K+(1-K)\left(1-\frac{1}{\omega_n^2}\right)\right]^2+\frac{1}{Q_n^2\omega_n^2}\right\}}}$
S-P	$\sqrt{L_{l2}C_2}$	$\frac{1}{\sqrt{\left[\omega_n^2Q_n^2\left(\frac{1-K}{K}\right)^2+\left(\frac{1}{K}-\left(1+\frac{1}{K}\right)\omega_n^2\right)^2\right]}}$	$\frac{1}{K\sqrt{\left[1+\frac{1}{Q_n^2\omega_n^2}\left(1-\frac{\omega_n^2}{1-K}\right)^2\right]}}$

3.4 Multi-Resonant Compensations topology of IPT

Fig. 5 shows the four multi-resonant compensation topologies. Multi-resonant compensation topology is better for mobile battery charger application.

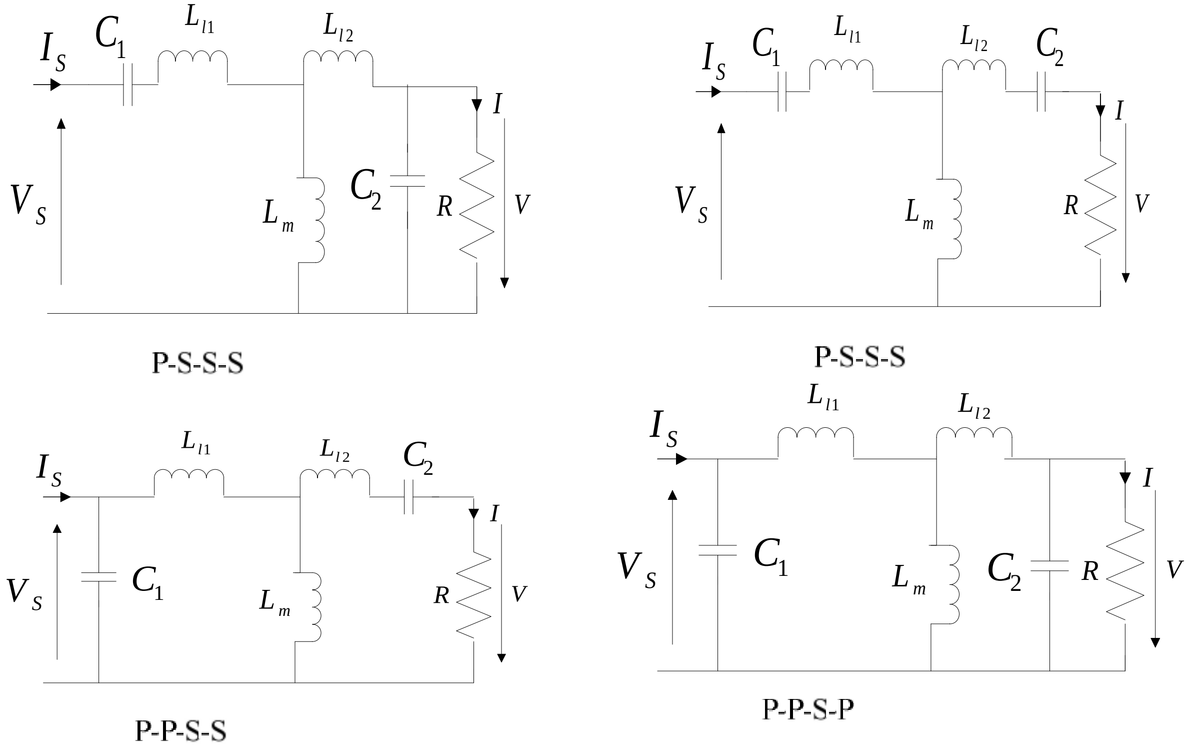


Figure 5- Multi-resonance compensation topologies.

Similar mathematical analysis has done [11] but in this thesis only value of voltage gain and current gain has given.

TABLE-II: Voltage gain and current gain of multi-resonant compensation circuit of IPT

	M_V	M_I
P-S-S-S	$\dfrac{1}{\sqrt{\left\{\frac{1}{K^2}\left(1-\frac{1-K}{\omega_n^2}\right)^2+\omega_n^2Q_n^2(1-K)^2\left[1-\frac{1}{\omega_n^2}+\left(\frac{1}{K}-\frac{1-K}{K\omega_n^2}\right)\left(1-\frac{\alpha}{\omega_n^2}\right)\right]^2\right\}}}$	$K\Big/\sqrt{\left\{\left[1-(1-K)\frac{\alpha}{\omega_n^2}\right]^2+\frac{1}{\omega_n^2Q_n^2}\right\}}$
P-S-S-P	$K\alpha\Big/\sqrt{\left\{\omega_n^2Q_n^2(1-K)^2\alpha^2\left(K+1-\frac{1}{\omega_n^2}\right)^2+\left[1+\alpha-(1+K)\omega_n^2-\frac{1-K}{\omega_n^2}\right]^2\right\}}$	$K\Big/\sqrt{\left[1+\frac{\omega_n^2-(1-K)\alpha}{\omega_n^2Q_n^2K(1-K)\alpha}\right]}$
P-P-S-S	$1\Big/\sqrt{\left[\frac{1}{K^2}+\omega_n^2Q_n^2(1-K)^2\left(1+\frac{1}{K}\left(1-\frac{\alpha}{\omega_n^2}\right)\right)^2\right]}$	$K\Big/\sqrt{\left\{\left[K+(1-K)\left(1-\frac{\alpha}{\omega_n^2}\right)-(1+K)\omega_n^2+\alpha\right]^2+\frac{1}{\omega_n^2Q_n^2}\left(1-\frac{\omega_n^2}{1-K}\right)^2\right\}}$
P-P-S-P	$\alpha\Big/\sqrt{\left[\omega_n^2Q_n^2\alpha^2\left(\frac{1}{K}-K\right)^2+\left(\frac{\alpha}{K}-\frac{1+K}{K}\omega_n^2\right)^2\right]}$	$K(1-K)\alpha$ $1\Big/\sqrt{\left\{(1-K)^2\alpha[(1+K)\omega_n^2-1+\alpha]^2+\frac{\omega_n^2}{Q_n^2}\left[(1+K)\omega_n^2-\alpha-1+\frac{(1-K)\alpha}{\omega_n^2}\right]^2\right\}}$

From table-II we can observe that the IPT circuit which is compensated both side have more impact on PF that is the PF of multi resonance circuit is more than the single resonance circuit.

Chapter 4

4.1 circuit parameter calculation

The parameter of circuit used in the simulation analysis can be calculated by chapter 2, the parameter are shown in table III.

TABLE III: Value of circuit parameter of IPT at resonant frequency

Resonant parameters	**Parameter value**
L_p	0.8µH
L_s	0.4µH
C	25µF
C_1	25uf
Lop	83.025µH
L_{SC}	16.828µH
M	0.394µH
F_r	50KHz

4.2 Matlab simulation of IPT for mobile battery charger application

Full bridge inverter circuit has used as inverter circuit for simulation of IPT. Pulse generator is used to trigger the IGBT switches. Magnitude of DC supply voltage is 10V and magnitude of output AC voltage is 6V peak.

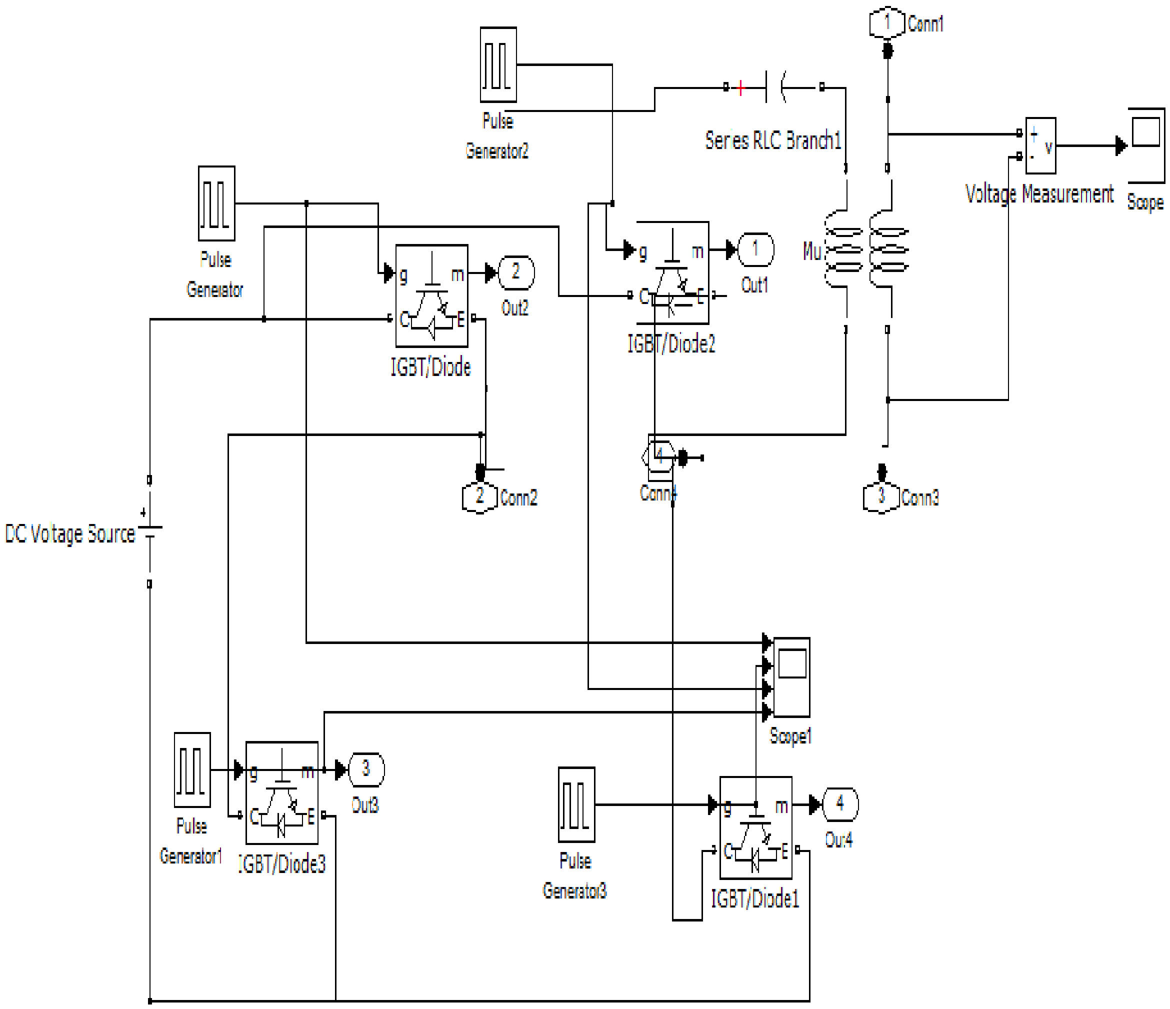


Figure 6 (a)-Simulink model with compensated capacitors

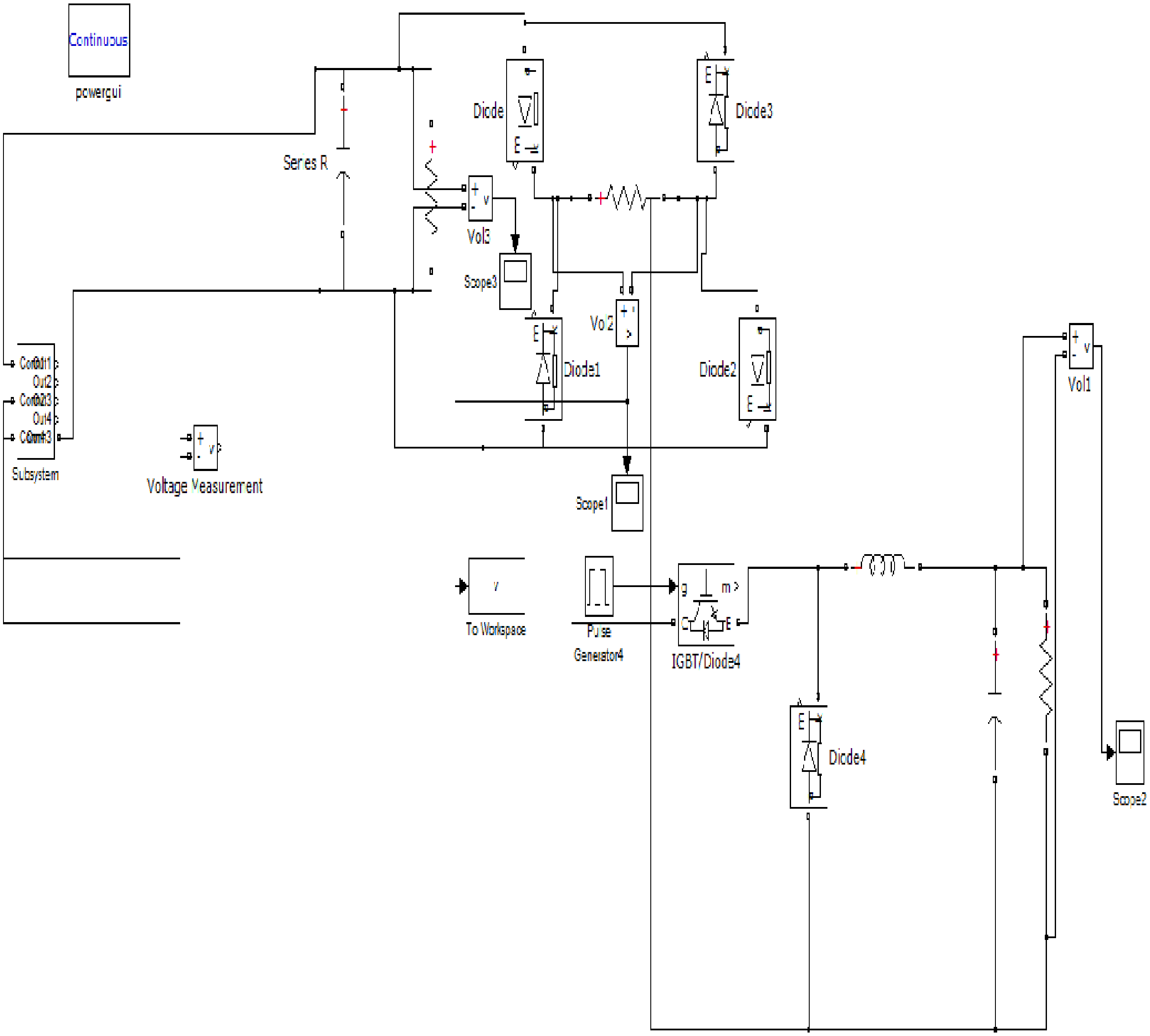


Figure 6(b) - Schematic of IPT including rectifier circuit

4.3 Simulation result

IPT for mobile charger application has simulated in simpower of MATLAB. Circuit parameter for this circuit has used from 4.1 chapter. In inverter circuit switch S1 & S2 operate simultaneously and S3 & S4 operates simultaneously. 5V amplitude voltage has given to the pulse generator and 50KH frequency has used.

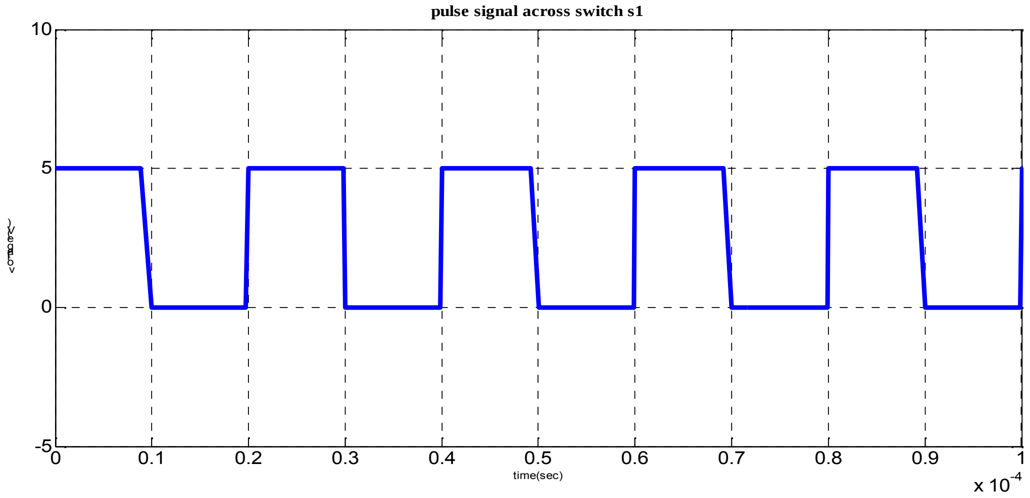


Figure 7(a) - Pulse signal across switch S1 & S2

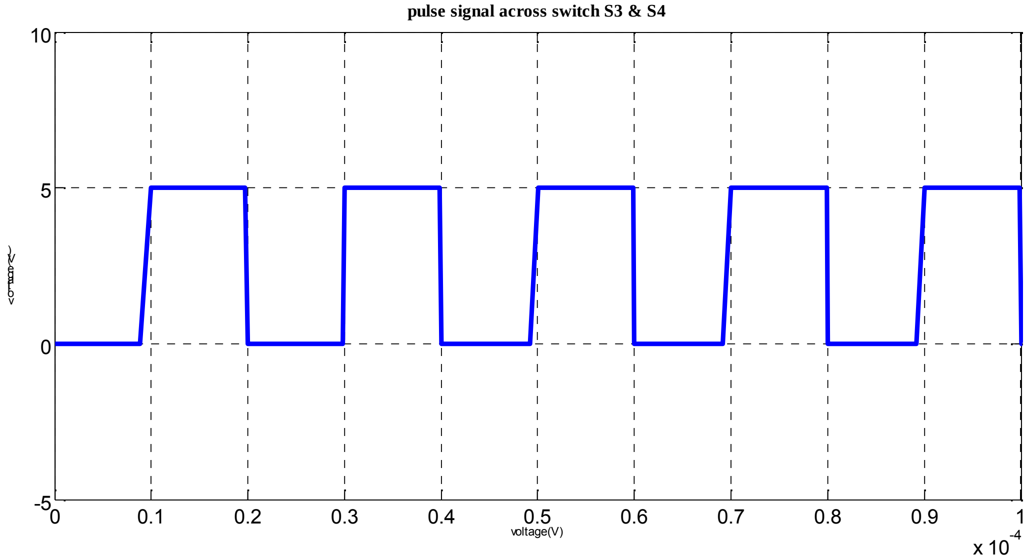


Figure 7(b) - Pulse signal across switch S3 & S4

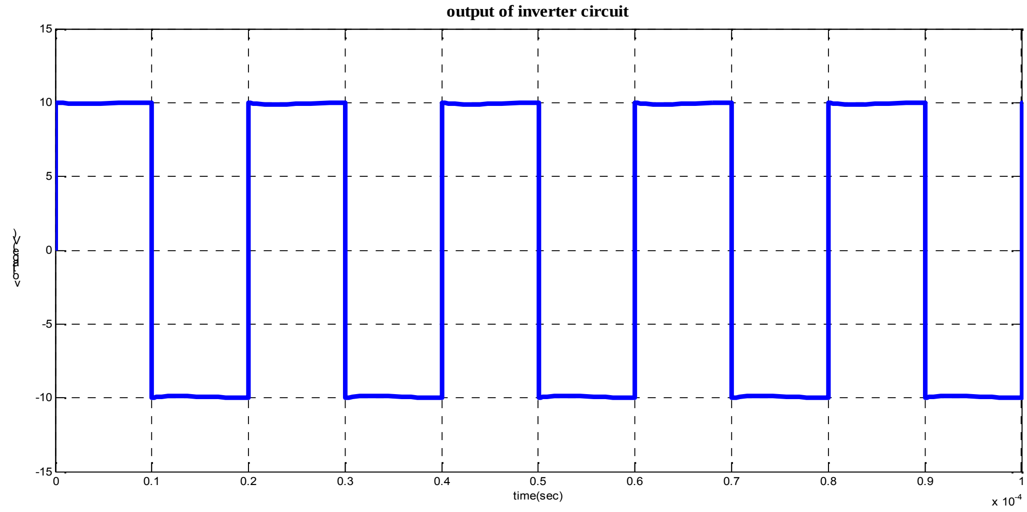


Figure 7(c) - Output voltage waveform of inverter circuit

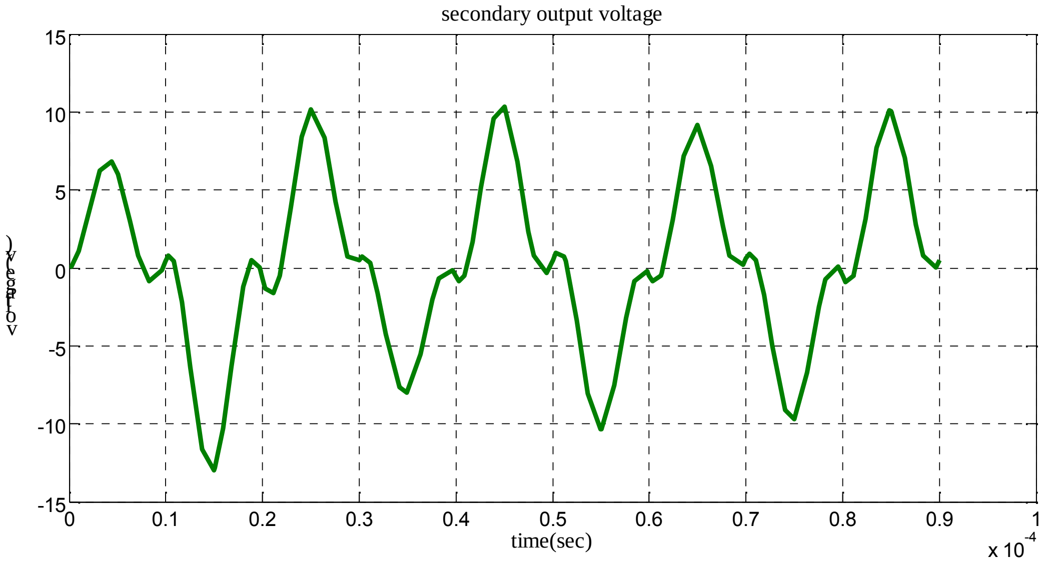


Figure 7(d) - Secondary output voltage of air core transfer

DC input voltage to inverter circuit has given whose magnitude is 10V. Ouput voltage of secondary side of air core transformer is 6V. This voltage is given to the full bridge rectifire circuit whose output voltage waveform is shown in fig. 7(e).

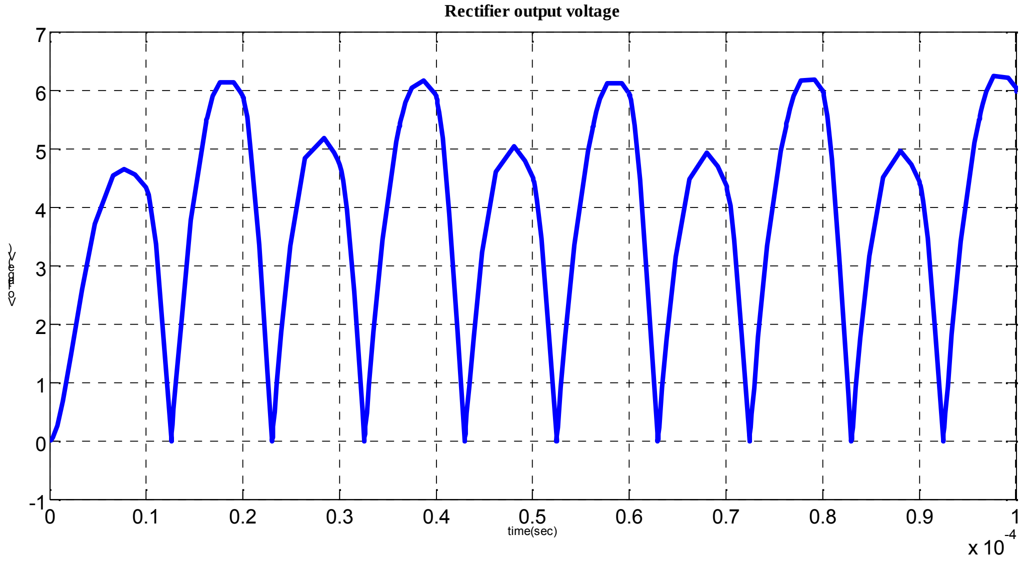


Figure 7 (e) - Rectifier output voltage waveform

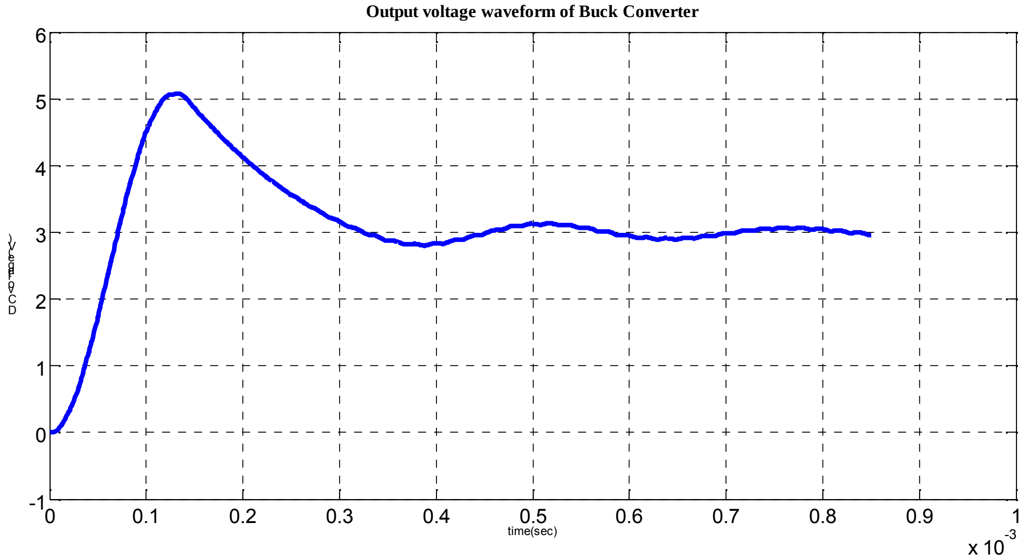


Figure 7(f) - DC output voltage waveform

Voltage waveform of other type of compensated topology is shown in figure 8. Here only secondary output voltage of air core transformer has shown.

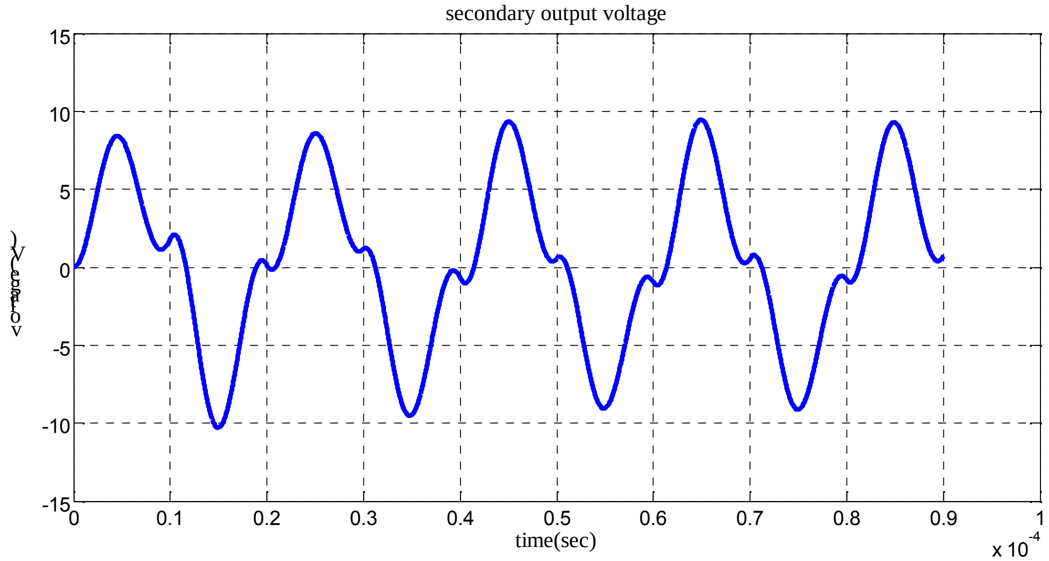


Figure 8(a) - Output waveform of parallel-parallel compensated capacitor circuit

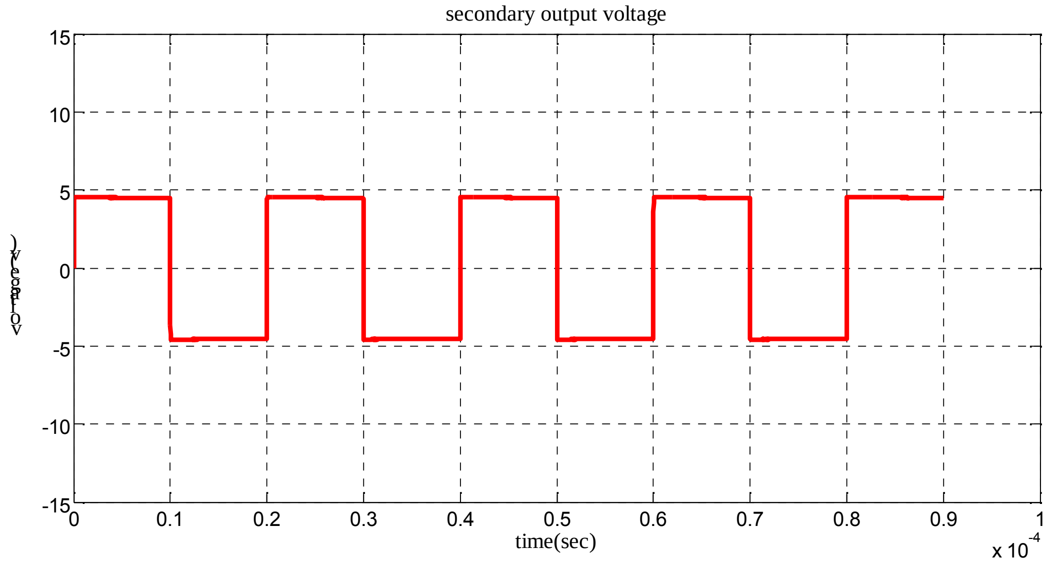


Figure 8(b) - Output waveform of parallel-series compensated capacitor circuit.

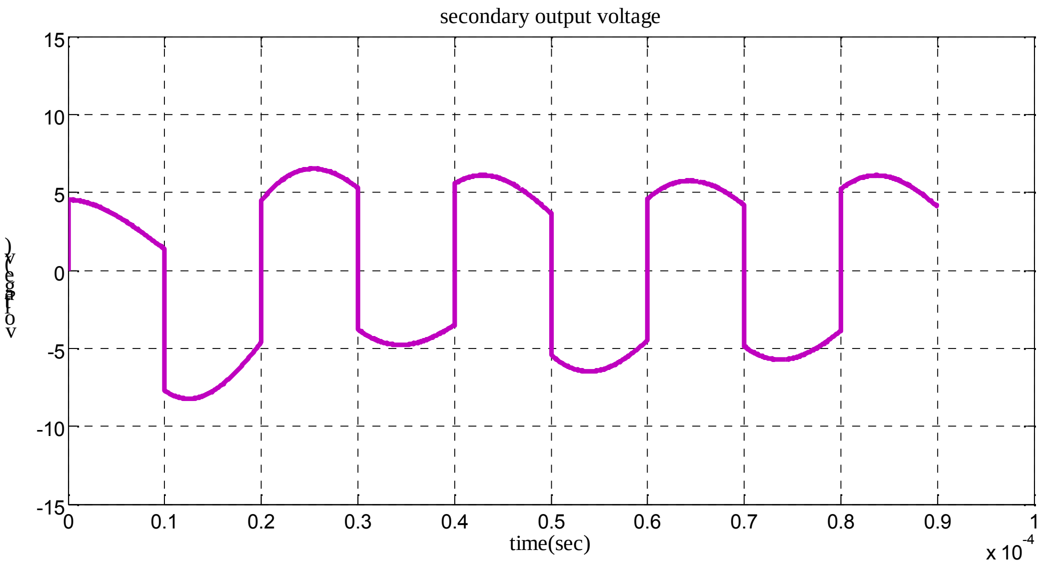


Figure 8(c) - Output voltage waveform of series-series compensated capacitor circuit.

From above graph we can see that for mobile battery charger application series parallel compensated topology is more suitable.

4.4 Hardware design

For hardware design two inductor coil is made by trial and error of the same value as written in chapter 4.1. First using to inductor coil without any compensated capacitor and at high frequency electromagnetic induction phenomena is seen. Since there is no coupling capacitor hence amount of energy transfer is very less. But when we use the compensated capacitor then amount of energy transfer is about the same value as we saw in simulation.

Figure 9 (a) - Experimental setup for IPT

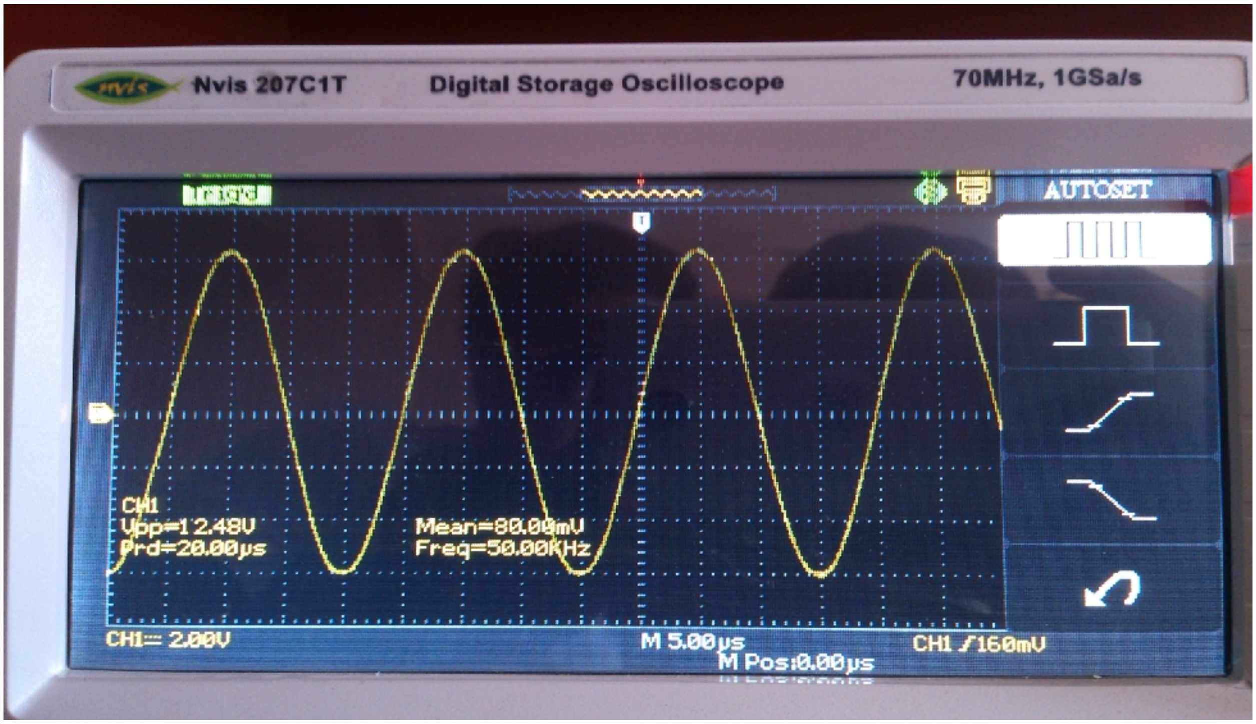


Figure 9 (b) - Input voltage to the primary inductor coil.

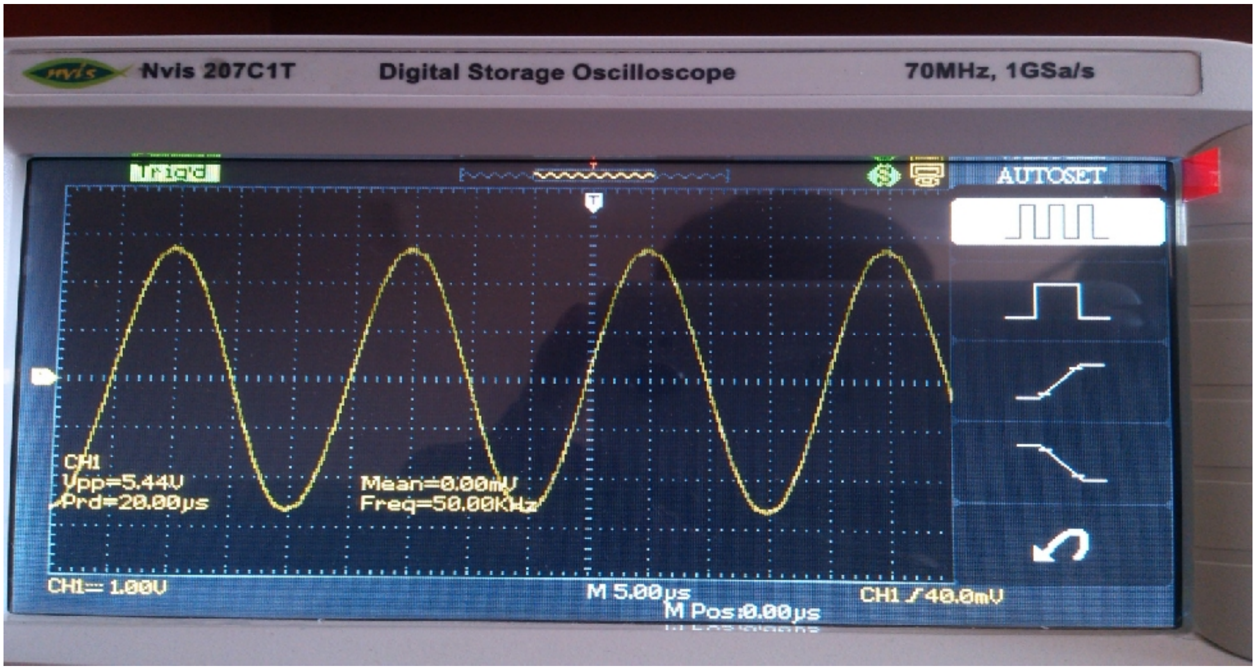


Figure 9(c) - Output voltage waveform at resonance.

Chapter 5

Conclusion

The inductive power transmission system applied to a mobile battery charger is proposed. From simulation analysis, it can be observed that output waveforms is not as much good as we required, so a suitable compensated circuit is required to improve the output voltage waveforms and efficiency of power transfer circuit. There are four main type of compensated topology, each has its own advantages & disadvantages [6]. Choice of compensated topology depends upon circuits' application. Mathematical analysis of compensation circuit gives the information about each topology has different equivalent impedance hence it's has effect on efficiency on circuit and on output voltage waveform.

Future work

The future work deals with finding ways to charge mobile battery without any charger chord. The distance between mobile and battery can be extended up to 1m. Closed loop buck converter can be realized to get desired regulated DC output voltage. Dynamic wireless battery charger may also be designed. To get maximum energy transfer efficiency a suitable structure of inductor coil will be made.

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