ANALYSIS AND COMPARISON OF CLASSICAL COMPENSATION TOPOLOGIES FOR INDUCTIVE POWER TRANSFER FOR ELECTRICAL VEHICLES

A THESIS SUBMITTED TO THE GRADUATE
SCHOOL OF APPLIED SCIENCES
OF
NEAR EAST UNIVERSITY

By
TARK ALTAHR AHMED FARNANA

In Partial Fulfilment of the Requirements for
the Degree of Master of Science
in
Electrical and Electronic Engineering

NICOSIA, 2017

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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Signature:

Date:

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To my family......

ABSTRACT

Wireless transmission of power has been a dream of researchers since Nicole Tesla first revealed the concept. It is a technology that has been realized only recently. There are several applications today that take advantage of this technology and battery charging of electrical vehicles is one of them.

Wireless power transfer systems utilize loosely coupled coils and therefore efficiency of power transfer is expected to be low. The efficiency should be improved by using some kind of compensation topology. The classical compensation topologies include series-series, series-parallel, parallel-series and parallel-parallel connected capacitors and inductors. There are also other topologies such as LLC.

The objective of this thesis is to compare the four classical topologies in terms of their size and performance. A wireless power system has been designed for a 3.3 kW power level and all these topologies were applied in this system by using MATLAB – Simulink. Results show that series-series connected topology is the most proper one among these four.

Keywords: Wireless Power Transfer; Coupling; Compensation

ÖZET

Kablosuz güç aktarımı, Nicola Tesla tarafından fikir ilk olarak ortaya atıldığından beri, araştırmacıların rüyası olmuştur. Teknoloji ancak yakın geçmişte hayata geçirilebilmiştir. Günümüzde, kablosuz güç aktarımı kavramını kullanan pek çok uygulama bulunmaktadır. Elektrikli araçların bataryalarını şarj etme bu uygulama alanlarından biridir.

Kablosuz güç aktarımı gevşek bağlaşımlı sargılar üzerinden gerçekleştirildiğinden güç aktarım veriminin düşük olması beklenir. Verim, kompanzasyon topolojileri kullanılarak arttırılmalıdır. Klasik kompanzasyon topolojileri seri-seri, seri-paralel, parallel-seri ve parallel-paralel bağlı kondansatörler ve endüktörler içerir. Ayrıca LLC gibi farklı kompanzasyon devreleri de bulunmaktadır.

Bu tezin amacı, dört klasik topolojiyi büyüklükleri ve performansları açısından karşılaştırmaktır. 3.3 kW gücünde bir kablosuz enerji transfer sistemi tasarlanmış ve bu klasik topolojiler MATLAB - Simulink üzerinde bu sisteme uygulanmıştır. Sonuçlar, bu topoljiler arasından elektrikli araç uygulamasına en uygun olanın seri-seri bağlantı olduğunu göstermektedir.

Anahtar kelimeler: Kablosuz güç aktarımı; Kuplaj; Topoloji; Kompanzasyon

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LIST OF ABBREVIATION

WPT: Wireless Power Transfer

RLC: Resistor Inductor and Capacitor circuit

KW: Kilowatts

S-S: Series-Series Topology

S-P: Series-Parallel Topology

P-S: Parallel-Series Topology

P-P: Parallel-Parallel Topology

LCL: Primary side CLC, secondary side Series resonant circuit

CLC: Primary side series, secondary side CLC resonant circuit

EMF: Electromotive Force

T(x): Transmitting coil

R(x): Receiving coil

AC: Alternating Current

DC: Direct Current:

CHAPTER 1

INTRODUCTION

1.1 Introduction

Global attention seems to tilt towards wireless technology for electronic devices. This is hugely because of the comfort and ease with which these bands of devices operate. The conventional contact coupling for electromagnetic power transfer seems to be replaced by the loosely coupled coils. This method of power transfer looks easier to work with, in terms of devices that require little or no contact. Devices that benefit through this recent breakthrough are the car charging devices, and the lifts or elevators. These devices benefit the user in many ways amongst which are the low maintenance required and the reliability.

A typical application contains a coil which operates at resonance with a primary coil that may be stationary of fixed. These are two independent mutually coupled coils or systems that produce constant primary current I_p in the coil inductance L_p. this occurs at a specific resonant high frequency that is determined by the RLC circuits of the primary circuit. The model is supported by compensations for the loss of power owing to the air gap losses.

An important part of this model of electronic device, is the need for a thorough theoretical and mathematical analysis of the primary and the secondary systems that make up the entire WPT system. This is important in order to achieve a strong and dynamic design that will stand the tests of time.

The famous tesla experiment that today still promotes more and more research continues to stun the world as more and more findings continues to solve contemporary problems. Tesla experiment proposes the creation of electric field between two coils. Here he proposed the transmission of electric energy from one power source to an electrical load without the necessary contact for activation of charge.

This great idea operates on the principle of matching impedances. Here, the frequency of all the components of the circuit are analyzed, in order to achieve resonant frequency. At this frequency, the soils resonate and conduct. However, some limitations were spotted. The distance between the coils were an issue, as the power transfer was limited. This was a major worry to

Tesla, until His breakthrough in 1919, when he discovered that suitably high frequency, it was possible to make a successful wireless transfer of stable and efficient power. In his words:

“it was clear to me from the very start that successful consummation could only be brought about by a number of radical improvements. Suitable high frequency generators and electrical oscillators had first to be produced. The energy of these had to be transformed in effective transmitters and collected at a distance in the proper receivers. Such a system would be manifestly circumscribed in its usefulness if all extraneous inference were not prevented and exclusiveness secured.” Nikola Tesla (1919).

By this revelation, the breakthrough into a world of wireless power transfer was secured. This ingenious idea has today come to the aid of an ever developing world, as the world seems to look the direction of wireless power transfer for effective transfer of energy and less contact. Considering an office full of wires or a park that charges battery, there would be a clumsy connection of wire if as much as 10 staffs seek to charge their wares. Hence, by implementing the contactless charge of phones and neater work space.

Also, a car park that charges battery, may effectively have self service center with each car owner servicing and fully charging his or her car without having to come down and pull out wires. Here we earn ourselves a neater environment and a seamless transfer of energy to even more than one person at a time, depending on the specifications, rating or capacity of the circuit.

This paper aims to analyses the basic WPT systems using critically looking at the topologies that arise from the compensations of the different cases, depending on the demand of the users.

1.2 Purpose of Research

This research looks to explore power supply Wireless Power Transfer system with analysis in the four major different topologies, with a view to displaying the basic requirements for compensation and simulation of real life challenges in determining the value of the necessary components and compensation required in a basic circuit, depending on the needed output power and the frequency of the power system. It will also serve to analyze the process that leads to achieving resonance in the secondary and primary coil of a prospective WPT circuit.

Furthermore, it will look to expose the critical stages that the design of a conventional WPT must necessarily go through.

1.3 Importance of Research

The importance of this research cannot be over emphasized, because of its basic impact in the world of electronics. It joins the rest of the research world in investigating the endless possibilities that lie in the use of electronics. Amongst other importance.

- The investigation and analysis of the four major topologies for Wireless Power Transfer (WPT) will help to identify the effectiveness of each of them with a view to identifying the most reliable depending on the specifications of an electrical appliance.
- The analysis of the various topologies, will only give an insight into the nature of the circuit, and the real life limitations and setbacks which have to be overcome in order to achieve that much power using loosely coupled coils.
- With millions of views on WPT out there, this research will add its perspective on the specifications and manufacture with current day challenges in order to enforce a much needed improvement in its quality.
- Needless to say that it will help to narrow down the basic questions that require appropriate answers in order to maximize the endless potentials offered through the use of the WPT.
- This publication will help pave the way for future investigation and research therefore redefining the electronic sector and all other connected resources.
- Finally, its research view will serve as a bench mark for further investigation in the endless opportunities that lies in the exploration of this all important topic.

1.4 Literature Review

According to Lentz's law, "a time invariant current in a conductor creates a time invariant magnetic field around it." This principle defines the very method of operation of the primary coil. Hence as current is passed through the conductor or a coil, it would generate similar magnitude of magnetic field in the coil or conductor. Also Faraday proposes that "a secondary loop located in the vicinity of this conductor or coil, will capture its magnetic field and will in turn induce a voltage at the ends of the loop”. At the end of this already formed circuit, a load can be fixed, thus allowing the flow of current. This process defines the method of transference of power without contact

However, according to Chwei-Sen Wang, etc.(2005), before now, good coupling is prerequisite to effective transfer of adequate amount of energy but with the advent of the recent improvements electronic devices, it becomes very possible to transfer even more power across loosely coupled applications, as in the case of wireless battery charging across large air gaps and car charging with no contact.

Lorico (2011), argues that the intensity of the magnetic field decreases relative to distance. That is to say, applications that will require a bit more distance, may not have effective power transfer. With the new development, all these are made possible at very high resonant frequency, specifically the radio frequency, which performs as much as three different basic functions, amongst which are wireless powering or wireless energy transfer.

This can be made possible with the application of different configurations as the design of the circuit goes on. These configurations involve various compensations depending on the surrounding components. That is in order to achieve resonance, the resistances, capacitances and inductances of both primary and secondary circuits must be adequately accounted for. These compensations lead us into the survey of the different topologies.

A. Kurs, A. Karalis (2007) looks into a 60W light bulb with over 40% efficiency. İts coils were set apart for 2 meters, opeating under the principle of magnetic resonance in the induction ciols at very high frequency. Here two identical helical coils were coupled inductively to the sourcecoil which drives the whole system. Kuri talked about the results obtaine and efficiency of the nonradiative power that was transfered.

Cannon**.** B. L (2009) obsereved the resonant frequency that arose from a single coil apparatus. Here the mutual soupling between the coils differed from teh coupled model by the non approximations results. This made his own model more efficient in terms of the high resonant coupling. Here he also showed double induction, from the primary coil to the secondary coil and to the load. This makes the load to be without the secondary coil. Examples of these applications are the multiple mobile recievers. However, the authors figured that the major setback was the adjusting of the capacitances.

Sample, P. A, (2011) tried to tune a wireless system so that a high efficiency of power transfer could be sustained across any distance with the reciever operating within the ambit of the transmitter.concepts such as frequency splitting and operating distance were factors of the model proposed by Sample. The adptive frequency tuning was also used here because of the efficiency variations encountered by the model. While varying the distance of the coil. This model was unique because of the unlimited distance the coil could move arouns, while still transfering power at a efficiency near 70% within the neighbourhood of 70cm.

Rankhamb S.D (2016) considers the losses that occurs during transmission and distribution as one of the major problems plaging WPT. He notes in his review that as the demand for WPT increases, the power generation also does, thereby raising the loses through transmisson because in a typical WPT, the major account of power loss is recorded during transmission, owing to the resistance of the wires used for the grid especially in high voltage transmission. He however noted that this losses could be reduced if the the conductors were strenght composite in over head cases.

1.5 Compensation Topologies Review

Due to these inductance leakages caused by the air-gap between the primary and secondary coils, compensations are recommended for both sides of the coil so as to increase the power transfer efficiency as well as the capacity. The desire to achieve resonance requires the connection of capacitors to both sides of the coil. With only four ways this can be done, we therefore analyze four different topologies as follows. With two newly added topologies.

1.5.1 Series-Series Topology

This topology at the primary coil, helps to reduce the primary voltage and depending on the user demand, the secondary coil, if compensated in series, can help stabilize the output voltage. (Ezhil and Co. Analysis 2014) In this method, the capacitors are connected to the inductance in series in the primary coil and same connection at the secondary coil. This topology is mostly preferred by consumers that require a stable current and mostly because of the unique frequency.

1.5.2 Series-Parallel Topology

This topology has typical structure and compensation as the primary coil of the Series-Series topology, however, at the secondary coil, the capacitor is connected in parallel, thereby supplying a stable voltage output. These compensations are designed for systems with multiple loads like Vehicle systems.

1.5.3 Parallel-Parallel Topology

Here, the capacitors connected in parallel to both the primary and the secondary coils. This produces a very poor performance with a low efficiency. Hence, its less frequent usage.

1.5.4 Parallel-Series Topology

This configuration involves the capacitor in parallel at the primary coil and the capacitor in series at the secondary. Here, the system acts as a current source, but the output power would be reduced due to the parallel connection at the primary. The parallel capacitor at the primary, reduces the current, thereby reducing the magnetic field strength. In addition to the above topologies, review shows a new set of configurations, namely.

1.5.5 CLC_S Topology

This involves a complex form of compensation, where an inductor is connected in-between the coils. This brings about a larger resonant capacity a reduced frequency. Analysis show that the oscillation is difficult to control (LuiJunchuan, wangJingquin& Co. 2015).

1.5.6 LCL_S Topology

Here a capacitor is connected between two inductors. As stated above, these topologies are complex. This however, shows a constant current charging capability. More of the above new topologies are expanded as we go on in the subsequent chapters. The driving force of research into this field for investigation has been, the quest for (Debabani Choudhury, 2015):

- High-density power devices
- Low integrated Circuits,
- High efficiency antennas and
- Innovative circuit architectures

As expected, global attention has been drawn towards WPT, as small and medium corporations have made significant amount of investment in the production of large products that may work effectively through the WPT. This is because the WPT topologies, seems to open the way to a whole different world of electronics that may operate through wireless networks with somewhat high efficiency.

Another sector that seems to catch the wave of new order wireless electronics, is the energy sector. According to Chwei-Sen, the SPS-Topology, would naturally transmit energy from the natural sunlight without the conventional resources used in recent times. These trend of new electronics are built to take over the world, hence the recent attention WPT attracts, ranging from the transmission safety, market value, material engineering, antenna systems to development of the application.

1.6 Content of the Thesis

Wireless power transfer has proven to be a wide topic, whose research areas could take us a whole generation to adequately harness. This is because of the constant findings and endless opportunities it affords our world today. Some of the areas that could spark up possible curiosity and research, have been highlighted earlier in the introduction.

This research will however focus on the steps from the planning, to organization, calculation through to compensation of a potential WPT circuit. To achieve this finite breakdown of the process, different chapters will be used to navigate towards the actual design and simulation with results of the circuit. They are as follows:

Chapter two: will introduce the main topic of wireless power transfer. It will explore the main principles of operation of a typical WPT prototype. Here the mode of operation, ranging from the input DC, to DC conversion to AC, before the induction by the coil and then finally back to the primary coil and onto the secondary side. Tesla’s idea of induction using loosely coupled soils would be reviewed, and its contemporary applications deliberated on, thereby establishing a connection with his work and possibly showing the evolution of wireless power transfer since his time.

This chapter will also browse through the various applications in our contemporary times with a view to determining the possible future applications depending on the current energy needs of an ever evolving world.

We will then proceed to introduce the different topologies and their basic applications. Here, all possible topologies in the public domain will be assembled and treated to a surface review, highlighting the differences in their circuit depending on their compensations, as the demand from end users may vary.

Chapter three: will dive deep into the world of compensations. Here we will deliberate on the reasons for compensation, and the role each component part plays in each of the compensation topologies. This will be done, believing that an in-depth understanding of the reasons for compensations, will give us a clue firstly, of what component is lacking or required at each of the times and will also go ahead to help us determine the value or rating of that component for the purpose of compensation.

Here the different four major topologies and others, (that is: Series-Series, Series-Parallel, Parallel-Parallel, and Parallel-Series, plus a range of others), would be analyzed critically towards understanding the differences in the output, the effect of each of the compensations and the uses of each of them. This would help us understand the topologies distinctively and also help us to plan our circuit, as demand may require.

The other topologies may not be fully detailed because of its less importance in the field of WPT today. These ones will however be criticized and analyzed to show the distinctive features and possibly determine the reason for its less impact and application today.

Chapter four: will head straight into the main method for our design. Here the Simulink will be used to set up a simple circuit containing all the necessary materials for conversion, induction and onward transference of power to the end user.

We will do an analysis and calculation to determine the value of the components used to achieve the needed 3.3KW of power. Here all L & C values for all Four compensation topologies would be calculated to be able to adequately put elements with rating into the circuit for onward design and simulation. Then, all four basic compensation technologies would be sampled and designed. The Simulink will then be used to simulate and the results would be gotten.

After the simulation, the results of the simulation would be collected, with adequate maps and diagrams where necessary. They would be analyzed and commented on. Then a brief comparison would be done to ascertain the differences in the parts and the most effective for selected situations.

Finally, **Chapter Five:** will conclude this research by drawing a conclusion from the design and the results from the simulation to be able to add voice to the advancement of wireless power transfer.

Here, the results will be compared with the models obtainable in other researches, and specific uses for the different topologies would be discussed, depending on the amount os current it supplies and or voltage it can supply.

CHAPTER 2

BACKGROUND AND OVERVIEW

A car park that charges battery, may effectively have self service center with each car owner servicing and fully charging his or her car without having to come down and pull out wires. Here we earn ourselves a neater environment and a seamless transfer of energy to even more than one person at a time, depending on the specifications, rating or capacity of the circuit.

2.1 Principles of Operation of WPT

While it has been globally maintained that tightly coupled coils are the basis for power transfer, Consistent research in this field have revealed that power can be transferred by loosely coupled coils even more efficiently. With distance as the only factor that classifies this method of power transfer as shown in Figure 2.1, laws have divided the transmission into two main types, depending on the distance of the inductive coils or the material of transmission(Kh, Yusmarnita, and Jamal 2015).

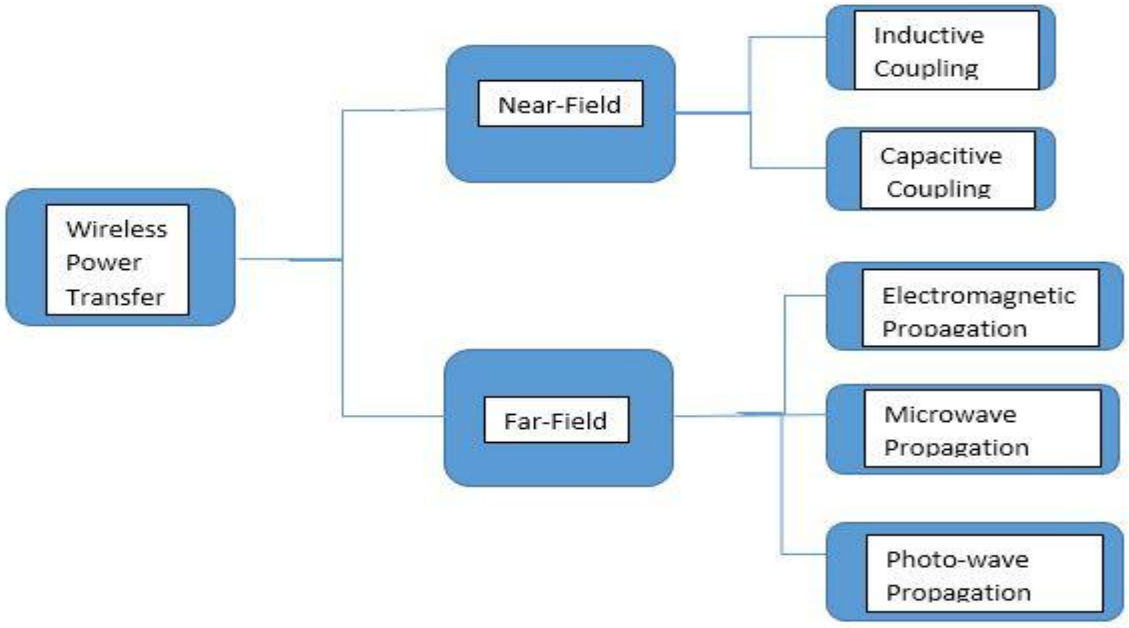

Figure 2.1: Resultant classes of Wireless Power Transfer

According to Lentz's law, "a time invariant current in a conductor creates a time invariant magnetic field around it." This principle defines the very method of operation of the primary coil(Farid 2015). Hence as current is passed through the conductor or a coil, it would generate similar magnitude of magnetic field in the coil or conductor. From the Figure 2.1, it is clear that any electromagnetic source will produce both Electric field and magnetic field. The resultant classes show a variation in terms of distance, which is also an indication of the strength of the magnetic field produced as shown in Figure 2.2.

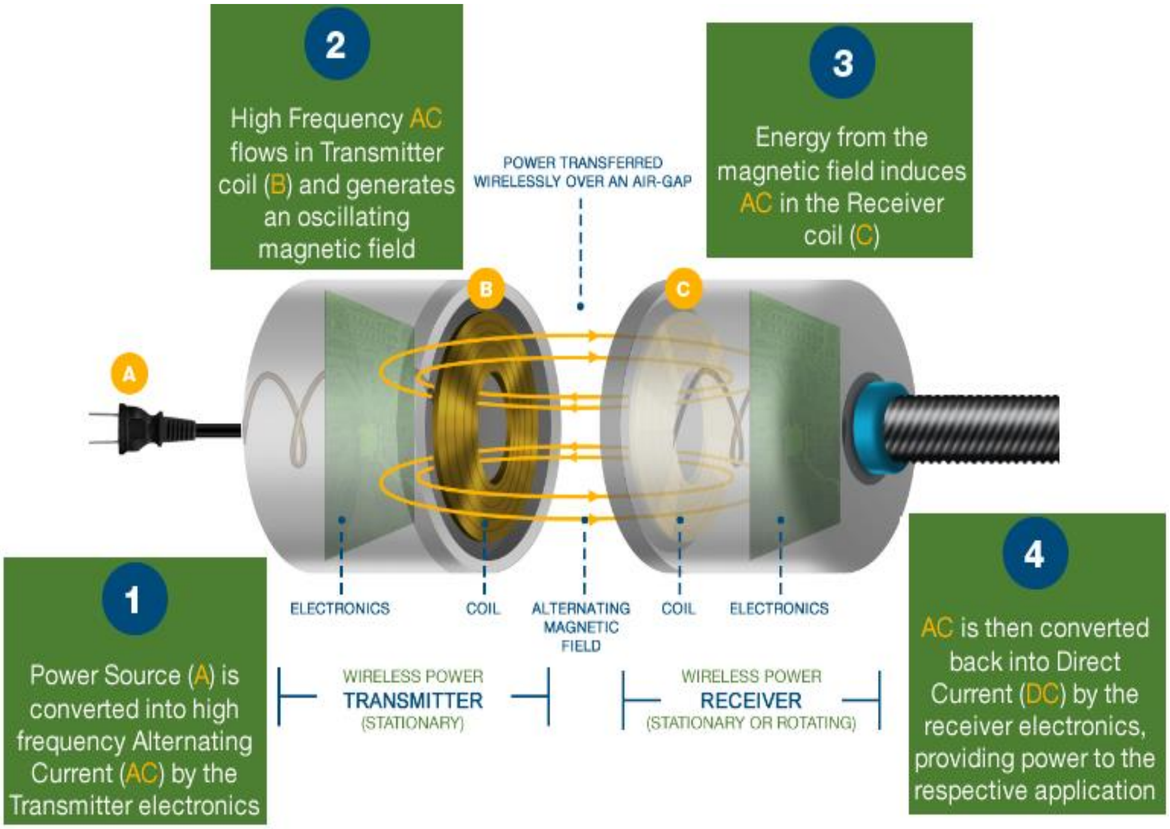

Figure 2.2: Wireless Power Transfer Processes

Within a radius of a wavelength as shown in Figure 2.3, the magnetic field is said to be near field, while outside that region is Far-field.

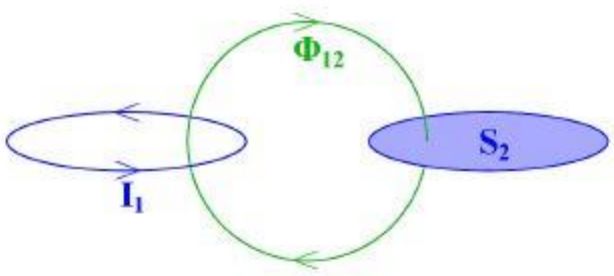

Figure 2.3: Changing magnetic field generated by a changing current in a conductor. Cedelof, Mikael. (2012).

Also Faraday proposes that “a secondary loop located in the vicinity of this conductor or coil, will capture its magnetic field and will in turn induce a voltage at the ends of the loop”. At the end of this already formed circuit, a load can be fixed, thus allowing the flow of current(Farid 2015). This process defines the method of transference of power without contact. These induction and transmission processes are supported by the Maxwell’s equations, which goes as follows:

$$\oiint_s E.ds = \frac{Q}{\varepsilon_0} \qquad (2.1)$$

$$\oiint_s B.ds = 0 \qquad (2.2)$$

$$\oiint_c E.dl = \frac{-d\Phi_B}{dt} \qquad (2.3)$$

$$\oiint_c B.dl = \mu_0(\mathrm{I} + \varepsilon_0 \frac{d\Phi_B}{dt}) \qquad (2.4)$$

Where equation (2.1) deals with the relationship between the charges and the electrical field produced, (2.2) indicates a closed loop situation with no sources, (2.3) Here we find a slightly equal but opposite magnetic flux changing with time and (2.4) Further simplification of equation (2.3), gives us a relationship between current and the magnetic field.

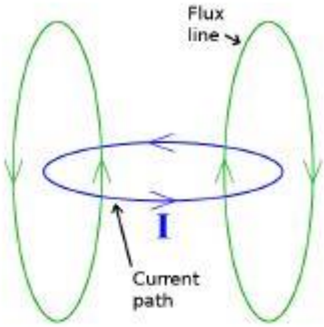

Figure 2.4: The secondary loop in the vicinity. Cedelof, Mikael. (2012).

Study have shown that coils operating within the near field, have a higher frequency in circuits. This is the case because of reduced electrical and magnetic field with respect to distance from the source of propagation as shown in Figure 2.4. Within this field length, a higher diffraction is recorded which helps to achieve more penetration. With the new development, all these are made possible at very high resonant frequency, specifically the radio frequency, which performs as much as three different basic functions, amongst which are wireless powering or wireless energy transfer.

2.2 Wireless Power Transfer

The magnitude of a magnetic field produced by the copper coil B(r) is inversely proportional to the distance from the center of the coil to the field point. Therefore, the field strength B is proportional the current flowing through the coil(Hong, Yang, and Won 2017). When another copper coil R(x) is brought into the field of this original coil T(x), through the laws of electromagnetic induction, R(x) conducts, provided, R(x) is within the range of the magnetic field produced by the T(x) and the current flowing through the T(x) is Alternating Current. Hence the magnetic field generated by the R(x) on R(x) at a distance x, is

$$B = \frac{\mu_0 N I a^2}{2(a^2 + d^2)\frac{3}{2}} \tag{2.5}$$

N= Number of turns

I = T(x) current

A = radius of T(x)

D = distance between T(x) and R(x)

Here, the mutual generated flux becomes, $B = \iint_s \ BdS$

Where B is the magnetic flux density, and S is the area of R(x) surface.

The time variant current in the T(x) produces a magnetic flux in the R(x), thus inducing an electromotive force, ε. According to Faraday, this EMF, ε produced is proportional to the negative rate of change of the magnetic flux, hence,

$$\varepsilon = -\frac{d\varphi}{dt} \tag{2.6}$$

And for N loops, the EMF becomes

$$\varepsilon = -N\frac{d\varphi}{dt} \tag{2.7}$$

Where φ is the magnetic flux.

Here, the EMF in R(x) id the current driving the secondary circuit. The magnetic field, however, is in the opposite direction to the flux. Hence power is seamlessly transferred from T(x) to R(x).

Following the principle of self-inductance,

$$\varepsilon = -L\frac{dl}{dt} \tag{2.8}$$

Where,

$$L = \frac{N\varphi}{l} \tag{2.9}$$

In the case of two coils with mutual inductance,

$$\varepsilon = -M\frac{dl}{dt} \tag{2.10}$$

Where M is the mutual inductance of both T(x) and R(x). We say, that the EMF on the coil is proportional to the mutual inductance of the T(x) and R(x). this is given by ;

$$M = K\sqrt{l_1 l_2} \tag{2.11}$$

K = K-coupling or coupling coefficient

L_1 and L_2 are the inductances of the coils

From the above equations, it is obvious that the Voltage or EMF in R(x) is a factor of the current and the voltage of T(x)

2.2.1 Quality Factor (Q)

Quality factor this is the inductance and resistance ratio of a coil. It is an important determinant of the energy that is transmitted in a WPT system, and consequently the efficiency of the entire system(Kim et al. 2011). The Quality factor is given by

$$Q = \frac{\omega L}{R} \tag{2.12}$$

Here, ω is the frequency of the system, while L represents the inductance of the coil

Need for High frequency the Q factor is proportional to ω hence an increase in Q factor means a high efficiency. This however continues for a while until, the peak when it decreases. The higher the Q factor, the narrow the bandwidth. All these factors set the maximum frequency at;

$$\eta = \frac{K^2 Q_1}{\left(1 + \sqrt{1 + K^2} Q_1 Q_2\right)^2} \tag{2.13}$$

Here K = coupling coefficient

Q_1 and Q_2 are the Q factors for T(x) and R(x)

In a potential system, the number of turns of a coil is very significant in achieving adequate magnetic flux density, B.

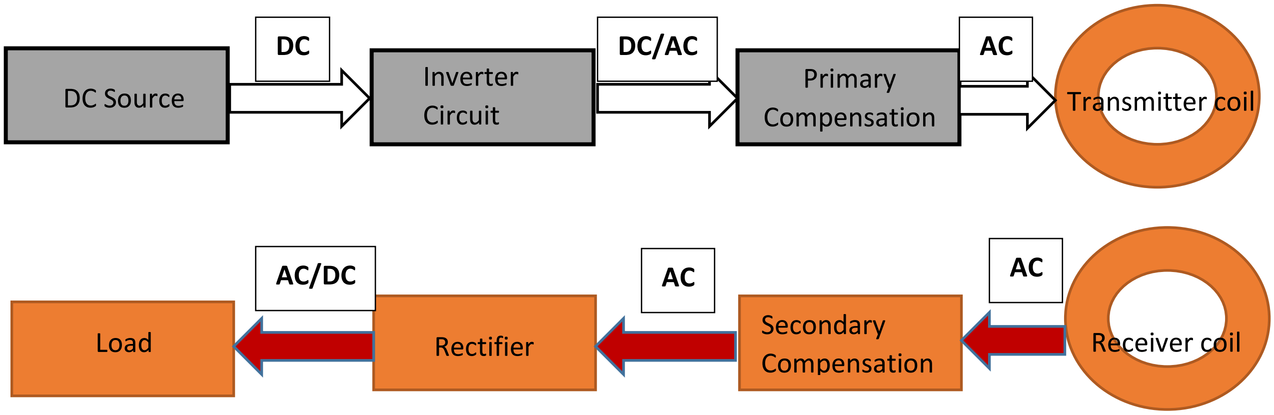

Figure 2.5: Block diagram of a basic WPT power flow

Basically, as shown above, the WPT operates with two coils operating at resonant frequency, accepting only AC and transmitting AC at the secondary coil. The block diagram as shown in Figure 2.5 is used to analyze the basic formation of the flow of power through the circuit.

From the above stages, a DC voltage is fed into the input, but because of the working principles of the induction coils, which only conduct with AC, an inverter made up of four mosfets is used to convert the DC to AC. After the conversion, due to leakages that may arise in the process of conduction, compensations are made(Pevere et al. 2015). The compensations include the connection of capacitors in series or in parallel, as the case may be. The compensations also help the make up for RLC resonance of the circuit, which is a basic requirement for a transference of power at high frequency.

The Transmitter coil is then energized with current, which induces an EMF in the coil. This concept is known as the self-induction. The changing electric field induced in the Transmitter coil, is highly transferable, only in the presence of a similar coil, whose circuit is operating at same frequency as the transmitter circuit(Vinge 2015).

A secondary coil brought in the vicinity of the field produced by the transmitter coil conducts this EMF produced by the Transmitter coil. This EMF is however AC, which has to be converted to DC for consumer or transmission purposes. Hence the need for a rectifier which only allows the flow of current in one direction. The output of the rectifier the supplies DC which is suitable for direct load or any form of consumer usage.

At the end of the block, sometimes, harmonic distortions are recorded, which may bring about fluctuation of the output and supply/ it may also be dangerous to house hold appliances or any form of load. Therefore, there is the need for filtering and smoothening of the output current in some cases. This is usually done by connecting a high series inductance to the rectifier output.

The resultant output becomes a constant voltage or current source as the case may be or according to the demand of the consumer.

2.3 Compensations

In a typical WPT system, the primary for improvement of the input power factor and the secondary systems need to be compensated in order to transfer a high amount of power. This compensation may involve resistances, capacitances and or inductances.

Some of the weaknesses of the WPT includes the leakages, magnetic inductances and high operating frequency range of 10KHz to 100KHz which leads to low power factor and sometimes, high inductive power. These weaknesses can lead to massive system losses. The solutions to these losses that may be incurred, amongst others, involves the connecting of capacitors to the circuit, as the case may require.

This can be made possible with the application of different configurations as the design of the circuit goes on. These configurations involve various compensations depending on the surrounding components(Hou et al. 2015)(W. Zhang and Mi 2016). That is in order to achieve resonance, the resistances, capacitances and inductances of both primary and secondary circuits must be adequately accounted for. These compensations lead us into the survey of the different topologies.

Due to these inductance leakages caused by the air-gap between the primary and secondary coils, compensations are recommended for both sides of the coil so as to increase the power transfer efficiency as well as the capacity(Guo and Jegadeesan 2012). The desire to achieve resonance requires the connection of capacitors to both sides of the coil. With only four ways this can be done, we therefore analyze four different topologies as follows. With two newly added topologies.

2.3.1 Series-Series Topology

This topology at the primary coil, helps to reduce the primary voltage and depending on the user demand, the secondary coil, if compensated in series, can help stabilize the output voltage. In this method, the capacitors are connected to the inductance in series in the primary coil and same connection at the secondary coil(W. Zhang and Mi 2016). This topology as shown in Figure 2.6 is mostly preferred by consumers that require a stable voltage and mostly because of the unique frequency.

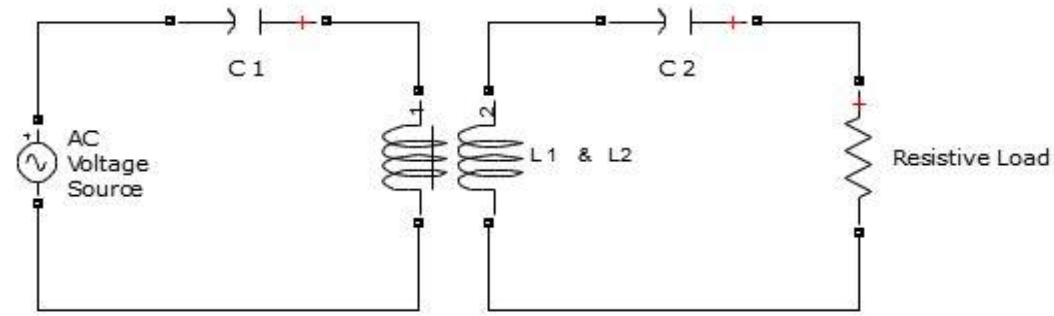

Figure 2.6: Series-Series topology

2.3.2 Series-Parallel Topology

This topology has typical structure and compensation as the primary coil of the Series-Series topology as shown in Figure 2.7, however, at the secondary coil, the capacitor is connected in parallel, thereby supplying a stable current output(W. Zhang and Mi 2016; Cho et al. 2013). These compensations are designed for systems with multiple loads like Vehicle systems.

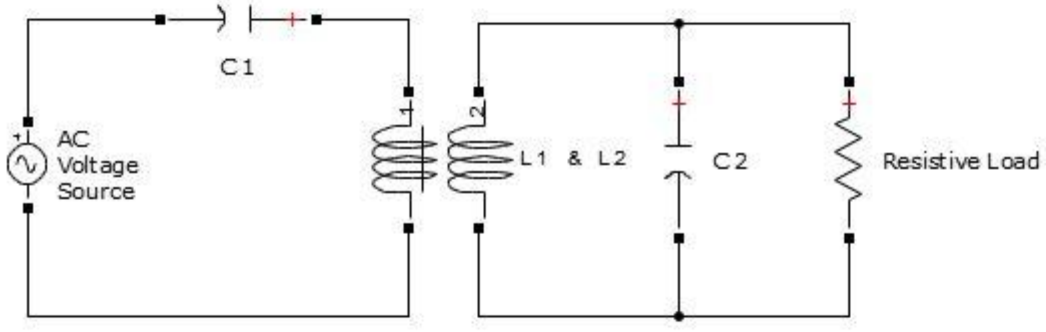

Figure 2.7: Series-Parallel Topology

2.3.3 Parallel-Parallel Topology

Here, the capacitors connected in parallel to both the primary and the secondary coils as shown in Figure 2.8. This produces a very poor performance with a low efficiency. Hence, its less frequent usage.

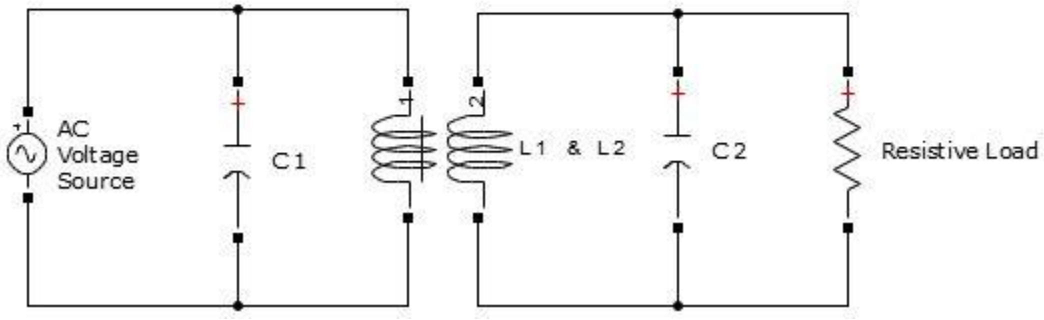

Figure 2.8: Parallel-Parallel topology

2.3.4 Parallel-Series Topology

This configuration involves the capacitor in parallel at the primary coil and the capacitor in series at the secondary. Here, the system acts as a Voltage source, but the output power would be reduced due to the parallel connection at the primary(Cho et al. 2013). The parallel capacitor at the primary, reduces the current, thereby reducing the magnetic field strength as shown in Figure 2.9.

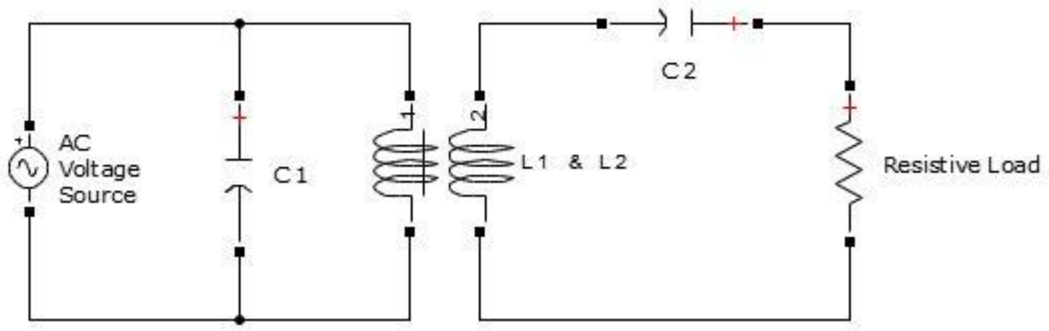

Figure 2.9: Parallel-Series topology

In addition to the above topologies, review shows a new set of configurations, namely.

2.3.5 CLC_S Topology

This involves a complex form of compensation, where an inductor is connected in-between the coils. This brings about a larger resonant capacity a reduced frequency. Analysis show that the oscillation is difficult to control. Two types of CLC topology formation have so far emerged. These include.

- Primary side CLC, secondary side Series resonant circuit as shown in Figure 2.10

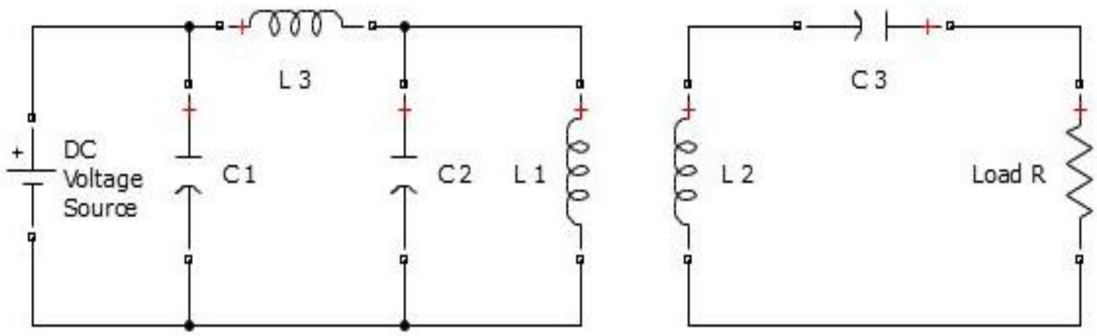

Figure 2.10: CLC topology

- Primary side series, secondary side CLC resonant circuit here, the only function of the C_3 capacitor is to regulate the impedance angle of the system as shown in Figure 2.11.

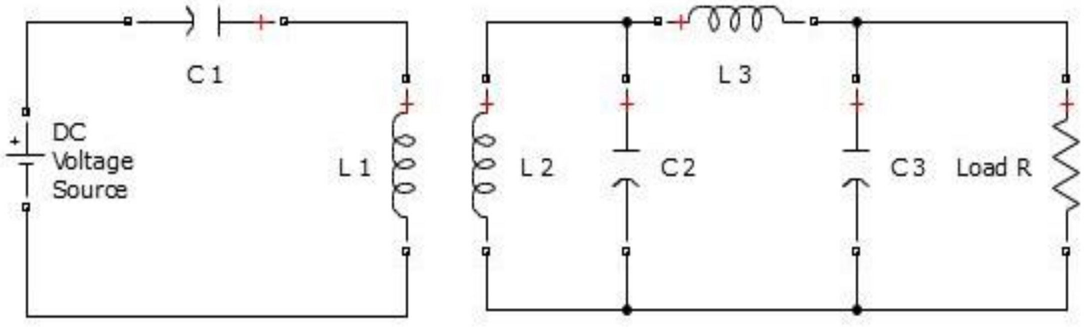

Figure 2.11: CLC topology

2.3.6 LCL_S Topology

Here a capacitor is connected between two inductors. As stated above, these topologies are complex. This however, shows a constant current charging capability. Here, the primary coil current is often kept constant, and the primary configuration helps to reduce the harmonic distortion that may arise from the inverter as shown in Figure 2.12.

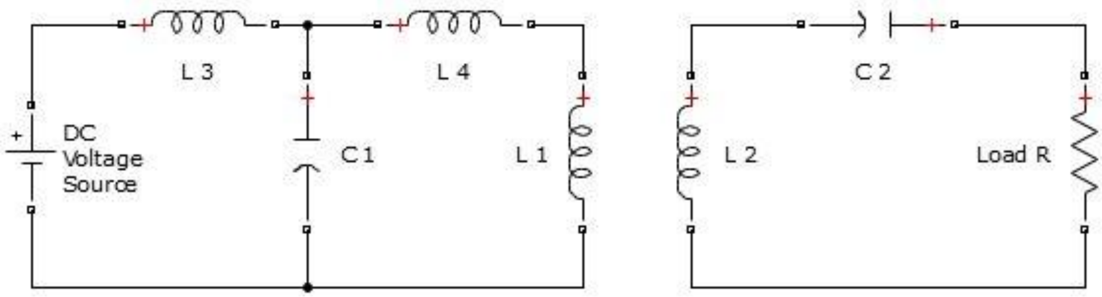

Figure 2.12: LCL topology

More of the above new topologies are expanded as we go on in the subsequent chapters.

The driving force of research into this field for investigation has been, the quest for:

- High-density power devices

- Low integrated Circuits,
- High efficiency antennas and
- Innovative circuit architectures

As expected, global attention has been drawn towards WPT, as small and medium corporations have made significant amount of investment in the production of large products that may work effectively through the WPT. This is because the WPT topologies, seems to open the way to a whole different world of electronics that may operate through wireless networks with somewhat high efficiency.

Another sector that seems to catch the wave of new order wireless electronics, is the energy sector. According to Chwei-Sen, the SPS-Topology, would naturally transmit energy from the natural sunlight without the conventional resources used in recent times(Wang, Covic, and Stielau 2004; Wang, Stielau, and Covic 2005; Song et al. 2015). These trend of new electronics are built to take over the world, hence the recent attention WPT attracts, ranging from the transmission safety, market value, material engineering, antenna systems to development of the application.

CHAPTER 3

3.1 Compensation Topologies and Analysis

The choice of topology is largely dependent on the specific needs or specification of the required user. As stated in the previous chapter, the four main topologies, have specific uses based on their outputs and stability. Here we will take a deeper look into the various peculiarities of the four major topologies, with a view to highlighting their various differences and uses in modern times. We will also throw light on the two new topologies stated at the end of chapter two.

Near accurate choices for topology usage can be said to be based on some general rules, as follows(Cho et al. 2013):

- For system with varying load, the Series- Series or the Series-Parallel is preferred, due to its independence on load (Resistive Load).
- Also for system with varying magnetic coupling, would require the Series-Series compensation, whose primary and secondary capacitance do not depend on the Mutual inductance or the magnetic coupling.
- With fixed load and steady coupling, the system with more efficient secondary compensation is preferred.
- Very high and obvious internal capacitance of the coil requires parallel compensation systems for adequate account of the internal capacitance.

3.1.1 Series-Series Compensation

Here, at resonant frequency, and fixed capacitances at the primary and secondary compensation, the varying voltage and current mathematically sums up to the source voltage. During simulation of this system, the total impedance of the circuit is reduced to the barest minimum with the frequency and rises afterward as the frequency rises. The primary and secondary current is expected to peak at frequency resonance. This causes the efficiency to rise with corresponding rise in frequency(Aditya and Williamson 2014; Cho et al. 2013; Hong, Yang, and Won 2017). These qualities make the series- series as shown in Figure 3.1 compensation more desired because of its dependence and stable output supply.

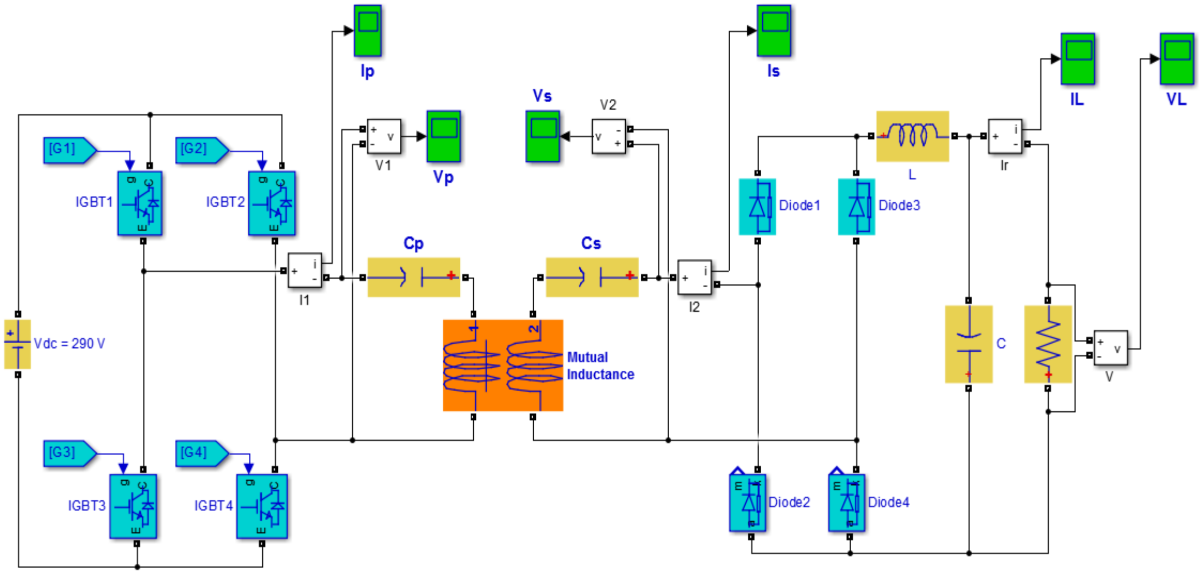

Figure3.1: Series- Series compensation

At the operating frequency, the series capacitor, C_p compensates coil 1 (L_1), to produce a steady voltage as the input voltage V_{dc}. Hence,

$$C_p = \frac{1}{(\omega_0^2 L_1)} \tag{3.1}$$

Since the voltage of the coil $V = V_{dc}$

$$I_l = -\frac{1}{j\omega_0 M} V_{dc} \tag{3.2}$$

At the secondary side, the capacitor, C_s compensates coil 2 (L_2), so as to efficiently optimize power transfer of V_{dc}.

Hence,

$$C_s = \frac{1}{(\omega_0^2 L_2)} \tag{3.3}$$

Not in anyway ignoring the contribution of the impedance, it can be noted that, a high resistant load, R_L, forces the input current to rise, and subsequently transfer the same I_L to the output.

Thus

$$Z_{tot} = \frac{(\omega_0 M)^2}{R_L} \tag{3.4}$$

The power becomes

$$P_{ss} = \left(\frac{V_{dc}}{\omega_0 M}\right)^2 R_L \tag{3.5}$$

3.1.2 Series- Parallel Compensation

Here, similar occurrences as with the series-series, are noticed. That is, the rise and rise of the secondary and primary current and resultant rise in efficiency of the system. It however, possesses higher power than that of Series-series, owing to the reduced total impedance in the Series-Parallel system as shown in Figure 3.2.

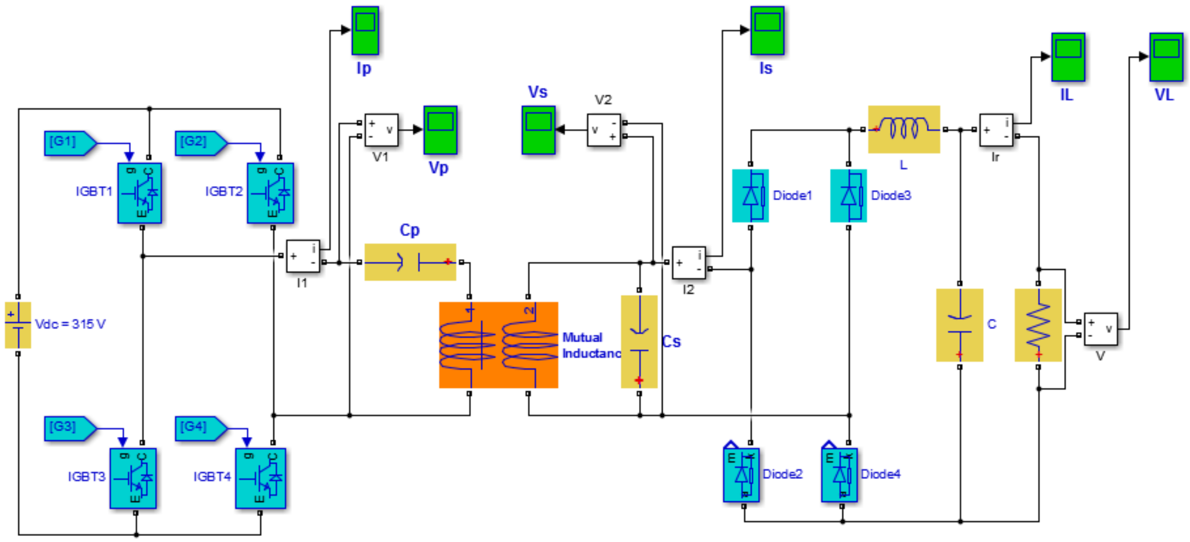

Figure 3.2: Series- Parallel compensation

We know that

$$K = \frac{M}{\sqrt{L_1 L_2}} \tag{3.6}$$

In this topology, the C_s is placed in parallel, which provides a current path parallel to $R_{L.}$ there is therefore a difference between the input current and the load current. The new capacitances for primary and secondary compensation becomes,

$$C_p = \frac{1}{\left(\omega_0^2 L_1 (1 - K^2)\right)} \tag{3.7}$$

And

$$C_s = \frac{1}{(\omega_0^2 L_2)} \tag{3.8}$$

Since the Series-Parallel, behaves as a voltage source, the output voltage (V_{out}) is independent of the load, hence,

$$\frac{V_{out}}{V_{dc}} = \frac{1}{\omega_0^2 M C_s} = \frac{L_2}{M} = \frac{1}{K}\sqrt{\frac{L_2}{L_1}} \tag{3.9}$$

Thus making the total impedance

$$Z_{tot} = \frac{\omega_0^2 M^2 R_L C_s}{L_2} = \left(\frac{M}{L_2}\right)^2 R_L \tag{3.10}$$

The power becomes

$$P_{sp} = \left(\frac{L_2 V_{dc}}{M}\right)^2 \frac{1}{R_L} \tag{3.11}$$

3.1.3 Parallel-Parallel Compensation

For this system, the total impedance reaches peak at resonant frequency. The secondary current reaches peak too, because of the primary current source peaking. This brings about very high losses, and consequently produces low efficiency in the system as shown in Figure 3.3.

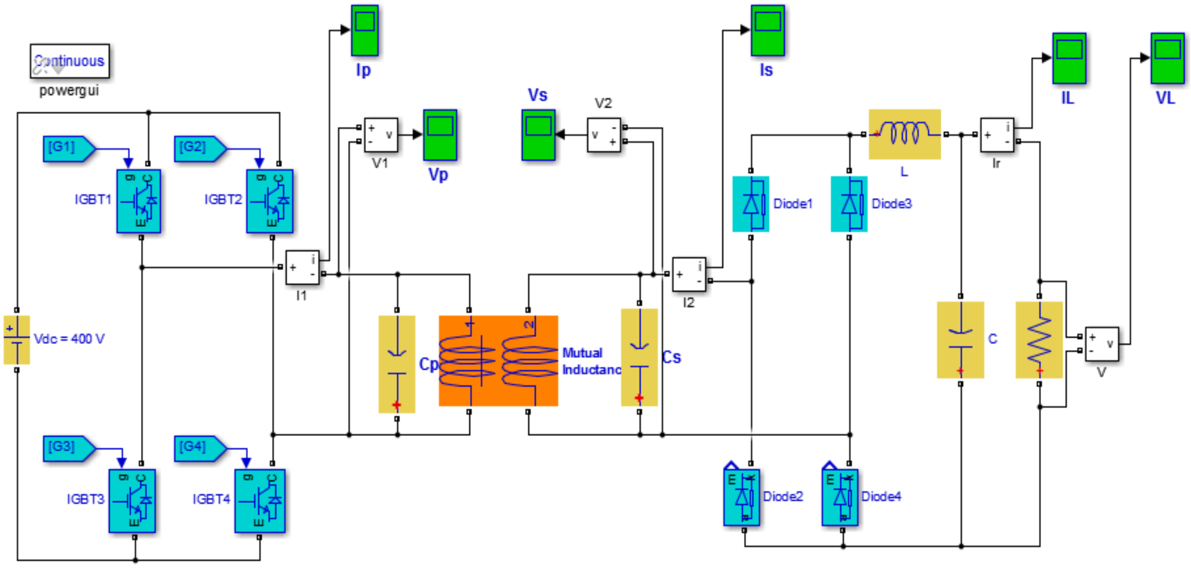

Figure 3.3: Parallel-Parallel compensation

Here, the total impedance, seen through Voltage/Current converter, becomes

$$Z_{tot} = \frac{-j\omega_0 M^2}{L_2} + \frac{\omega_0^2 M^2 R_L C_s}{L_2} = -j\omega_0 \frac{M^2}{L_2} + \left(\frac{M}{L_2}\right)^2 \tag{3.12}$$

The capacitances become

$$C_p = \frac{1}{\left(\omega_0^2 L_1 (1 - K^2)\right)} \tag{3.13}$$

And

$$C_s = \frac{1}{(\omega_0^2 L_2)} \tag{ 3.14}$$

The voltage is then structured by

$$\frac{V_{out}}{V_{dc}} \frac{K}{1 - K^2} X \frac{R_L}{j\omega_0 \sqrt{L_2 L_1}} \tag{3.15}$$

The power becomes

$$P_{pp} = \left(\frac{K^2 V_{dc}}{(1-K^2)\omega_0 M}\right)^2 R_L \qquad (3.16)$$

3.1.4 Parallel-Series Compensation

With the impedance peaking at resonant frequency, only a current source would bring about maximum power transfer. Typical with Parallel compensated sources, the primary system provides that high current source which brings about the needed high power transfer(Hong, Yang, and Won 2017). This occurs as the secondary current reaches peak at resonant frequency. A high efficiency is also expected with this system as shown in Figure 3.4.

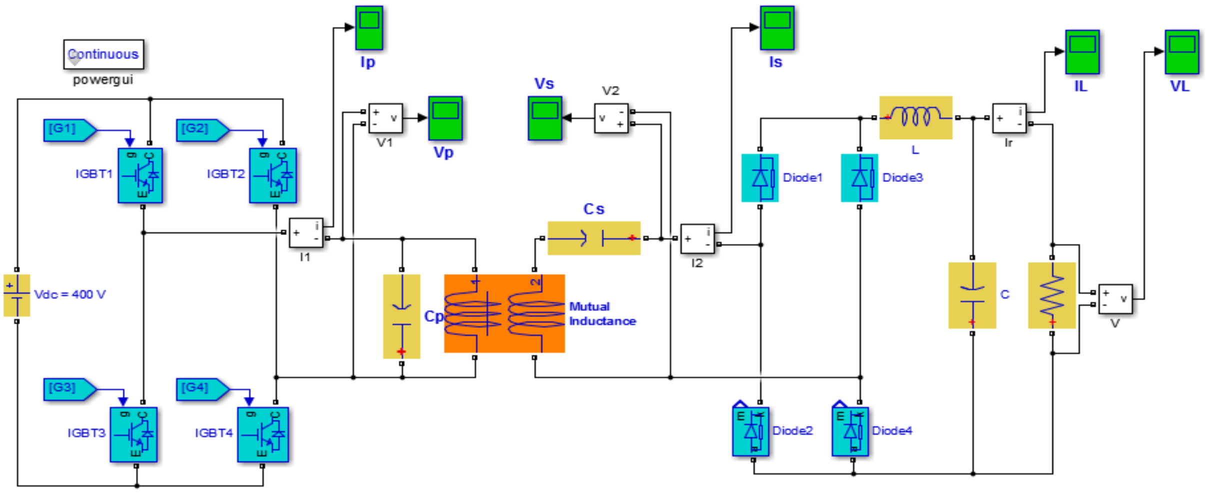

Figure 3.4: Parallel- Series compensation

Here, the impedance seen in the voltage/Current converter becomes

$$Z = \frac{\omega_0^2 M^2}{R_L} \qquad (3.17)$$

The capacitance for a full compensation becomes

$$C_p = \frac{1}{(\omega_0^2 L_1)} \tag{3.18}$$

And

$$C_s = \frac{1}{(\omega_0^2 L_2)} \tag{3.19}$$

The entire system tends to have a voltage behavior, hence the output voltage becomes by

$$\frac{V_{out}}{V_{dc}} = \omega_0^2 M C_p = \frac{M}{L_1} = K\sqrt{\frac{L_1}{L_2}} \tag{3.20}$$

The power becomes,

$$P_{ps} = \left(\frac{K^2 V_{dc} L_2}{M}\right)^2 \frac{1}{R_L} \tag{3.21}$$

Table 3.1: circuit characteristics of the various topologies

Topology	**Designd for**	**Power Factor (Small air gap)**	**Power Factor (Large air gap)**	**Resonance Impedance**	**Efficiency**
Series-Series (SS)	Voltage Source	Low	Very High	Low	Very High
Series-Parallel (SP)	Current Source	Low	High	Low	Medium
Parallel-Series (PS)	Voltage Source	High	Medium	High	Medium
Parallel-Parallel (PP)	Current Source	Very High	Medium	High	High

CHAPTER 4

4.1 Methodology

To design the recommended topology, the MATLAB Simulink is needed. Using the Simulink, the power Library is opened, then, direct current is passed through an inverter circuit, to convert the direct current to Alternating current(Li et al. 2016). The emerging AC is then passed through the primary side of a conducting coil (Mutually coupled coils). while the resulting induced current on the secondary side is received and converted to Direct current using the full wave bridge inverter. A resistive load is connected to the Direct current output produced by the inverter(Kong et al. 2005). This helps to balance the circuit, and quantify the output properties of the designed circuit.

Towards simulating an efficient system, a thorough evaluation of the various parts of a potential inductive power transfer system. To do this, we simulate the inverter circuit, which is made up of a DC source, four IGPT/diodes and a resistive load, as shown in Figure 4.1.

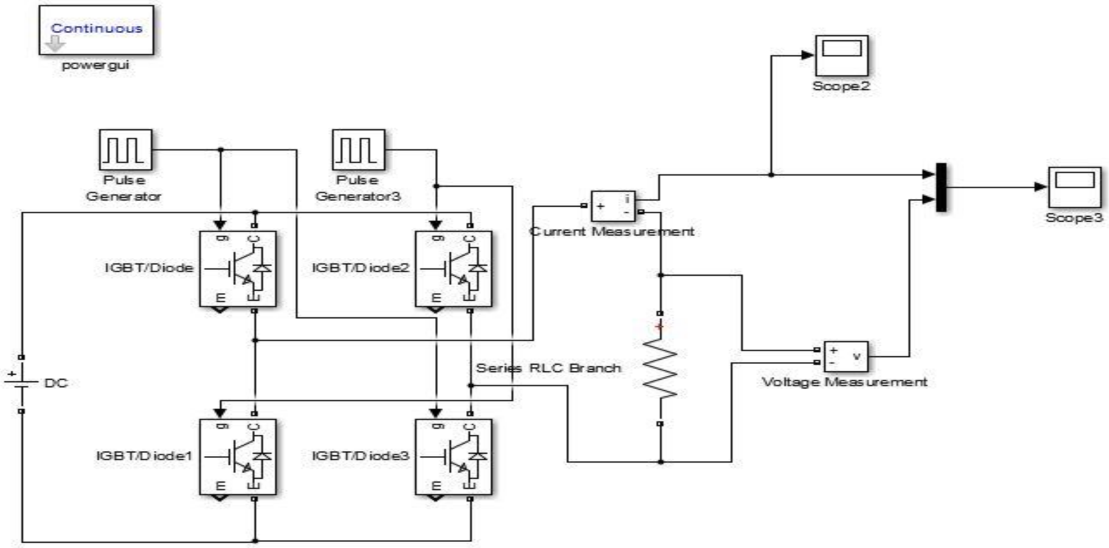

Figure 4.1: Inverter test circuit

The circuit in the Figure 4.1 shows full-wave bridge inverter consisting of four IGBT/diodes, pulse generators and resistive loads. As stated earlier, the materials here are randomly chosen, without specific values for them. The idea was to ensure that all smaller circuits function effectively when put together(Song et al. 2015). As show in the Figure 4.1, the pulse generators help to modulate the output signals, by introducing visible undulations in form of square waves. The resistance at the end of the circuit serves a load, to analyze, adjust and manipulate the circuit properties until a balance is gotten with the required output power achieved.

Next, the inductive coil, which is the most important member of an inductive circuit is added and run for compatibility(Li et al. 2016). The new circuit is as show below.

These periodic and circuit by circuit testing helps to prevent complications at the completion stage. Typical inductive circuit construction always encounters compatibility issues and or non-responsive systems. During this kind of situation, it becomes difficult to locate the main fault of the non-responsiveness or error messages which may arise. Hence, pre-tested smaller parts of the system help to identify and track errors that may arise at the end of the construction, so as to pay more attention to those items. The new circuit becomes as follows in Figure 4.2.

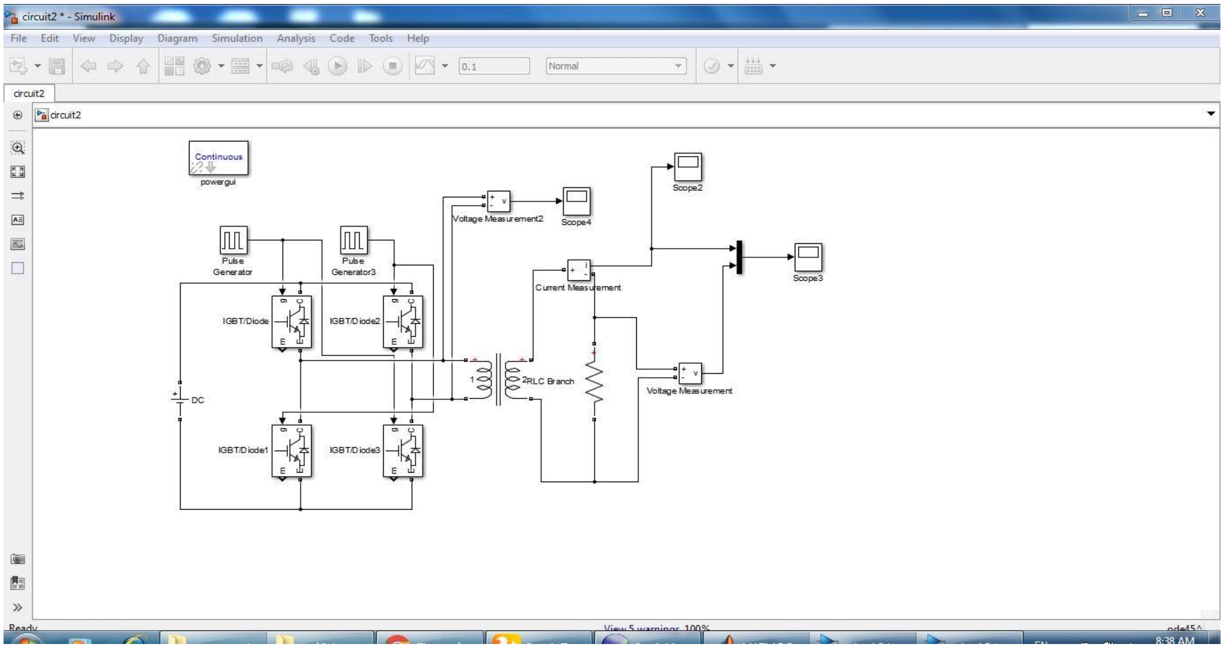

Figure 4.2: Inductor coil test circuit

At this point, the system is observed for consistency. During simulation of this circuit, the output is expected to drop, due to the change in transmission media. The inductive coil comes with issues such as air-gap losses, coupling coefficient, internal resistance etc. these factors are mainly instigated by the air-gap between the coils. Therefore, compensations should be made along the line, in order the balance the circuit requirements in the process.

Another advantage of this part by part testing of the circuits, is the fact that it helps to determine the major components that influence the final output power. The major parameters in the design of and inductive circuit are:

- Internal resistance of the inverter
- The voltage supplied
- Load voltage
- Load power
- Load resistance
- Winding of coils (secondary and primary)
- Maximum operating frequency
- Resistance of coils
- Compensations
- Overall capacitance, Inductance and Resistance of the system

The next stage of the test is addition of the inductor coils for transmission. Here, the coil is added and simulated with a resistive load, to test for compatibility and compliance. The resulting circuit is as follows.

As shown in Figure 4.2, just a little modification on the previous inverter stage of the test. The test is also meant to check the successful transmission of induced current from primary to secondary coil. The output voltage is then measured across a resistive load.

It is important to state that during these test simulations, the measured output values are not significant to the final results, as they are meant to ensure that all attached elements are correctly functioning. At this stage, it is easy to Figure out any non-compatible element and check for errors or unexpected leakages in the transmission that may cause irregular and inconsistent results(Guo and Jegadeesan 2012; Vinge 2015).

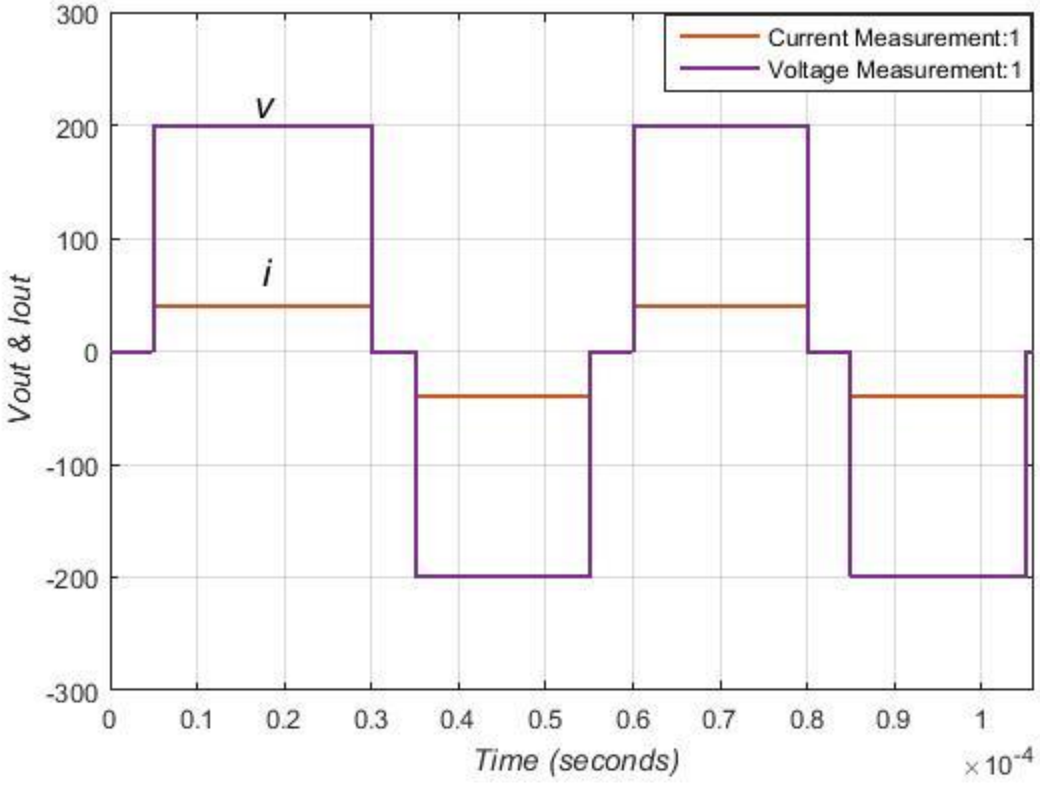

Figure 4.3: Inductor test circuit output

Figure 4.3 shows results from the simulation of Figure 4.2. It displays perfect square wave of induced current measured at the secondary circuit. It receives same 200V transmitted across the resistive load. This is an indication that at calculated inductances and capacitances, the secondary circuit will produce expected outputs without much errors.

4.1.1 Coil Design

Designing the coil requires that the inductances of the coil needed to generate the required output is already calculated. The inductances, are calculated based on the current, voltage and required power of the circuit. The frequency is another factor that can be used to regulate the output power. These factors are analyzed and fine-tuned until the required power is achieved(Guo and Jegadeesan 2012; Vinge 2015; Song et al. 2015; H. Zhang et al. 2016). At the required power, the current density is evaluated for compatibility with the system. This is done to ensure that the current density does not exceed the limit of the coil, as this responds adversely to the smooth running of the system.

The coil is central to the smooth running of the circuit, hence, determining the composition and value of its properties is very paramount. First, we consider the power, voltage and current relationship in the coil.

We know that, in order to get less than 1MHz frequency at resonance in the inductance coils, the capacitance and the inductance have to be larger than that of higher frequency ones. Therefore, coils with radius, 11.861cm are used. These are wound with 13 & 12.9 turns for the primary and secondary turns each. These parameters amount to $20.6\mu H$& $18.6\,\mu H$ for the primary and secondary inductance respectively.

Applying the following formulas

$$L = \frac{N^2 \mu A_c}{l_c} \tag{4.1}$$

Where N = number of turns

μ = permittivity of the coil

l= length of he coil

A = area of the coil

the Flux linkage Ψ is a very important factor in calculating coil parameters in terms of design. The coil, L is given by dividing the flux linkage with the current I.

$$L = \frac{\Psi}{I} \tag{4.2}$$

To generate a mutual inductance, the primary current is passed through the primary coil. During this process, the flux linkage is recorded as Ψ_{11}, the secondary current is also run through the secondary coil, and the flux linkage is saved as Ψ_{22}. When this process is repeated simultaneously with both coils, the mutual inductance is gotten by obtaining the total flux linkage for each of the coils, $\Psi_1 \; and \; \Psi_2$.

$$M = \frac{\Psi_1 - \Psi_{11}}{I_2} = \frac{\Psi_2 - \Psi_{22}}{I_1} \tag{4.3}$$

Mathematically, this results to

$$M = \frac{\Psi_{21}}{I_2} = \frac{\Psi_{12}}{I_1} \tag{4.4}$$

Primary side Impedance

Where

Z_C =capacitive resistance

Z_L=inductive resistance

Z_S= series resistance,

When the primary side is compensated in series, the total resistance becomes

$Z_1 = Z_C + Z_L + Z_S$

For the primary side compensation, we have,

$$Z_1 = \frac{Z_C(Z_L + Z_S)}{Z_C + Z_L + Z_S} \tag{4.5}$$

Secondary Impedances

Where

Z_C =capacitive resistance

Z_L=inductive resistance

R_{LOAD}= load resistance

Using the above resistances for the secondary side, we have that the total impedance in the secondary side when connected in series compensation, becomes

$Z_2 = Z_C + Z_L + R_{LOAD}$

While for the secondary side, the parallel combination becomes

$$Z_2 = Z_L + \frac{1}{\frac{1}{Z_C} + \frac{1}{R_{LOAD}}} \tag{4.6}$$

4.1.2 Induced Voltage

Using Ohm's law, the induced voltage is proportional to the current flowing through the coil, while the resistance is kept constant. Therefore, using the above formula, we have that for series compensation:

$$I_1 = \frac{U_1}{Z_S} \tag{4.7}$$

For parallel compensation:

$$I_L = \frac{U_1}{Z_L + Z_S} \tag{4.8}$$

While the input voltage is kept constant, voltage is induced on the secondary side. This also lead to a series compensated secondary side acting as a voltage source while the parallel side acts like a current source. This induced voltage is given by

$$U_{LOAD} = \frac{M}{L_2} I_L \tag{4.9}$$

The operating frequency of about 20 kHz determines the capacitances and he inductances of circuit parameters.at this frequency, the circuit resonates and there is current interaction between the coils, therefore it is essential that the RLC analysis of each of the coils has to add up at 20 kHz.

Hence if:

$$\omega^2 = \frac{1}{L_1 C_1} \tag{4.10}$$

We know that

$$\omega = 2\pi f \tag{4.11}$$

Then, it follows that

$$f = \frac{1}{\sqrt{(2\pi)^2 L_1 C_1}} \tag{4.12}$$

From the above equations, at the resonant frequency of 20 kHz, we need $3.074\mu F$ and 3.40 μF for the primary and the second circuits consecutively.

This design makes the system to switch at resonant frequency of 20kHz, this is within the range of the IGBT diodes and the Rectifier circuit.

The Q-factor seems to be strengthened by a low capacitance, and a high inductance is capable of producing that. This subsequently produces a larger parasitic resistance in the end.

4.2 WPT Compensation Designs

4.2.1 Series – Series Compensation

This topology at the primary coil as shown in Figure 4.4, helps to reduce the primary voltage and depending on the user demand, the secondary coil, if compensated in series, can help stabilize the output voltage. In this method, the capacitors are connected to the inductance in series in the primary coil and same connection at the secondary coil. This topology is mostly preferred by consumers that require a stable current and mostly because of the unique frequency.

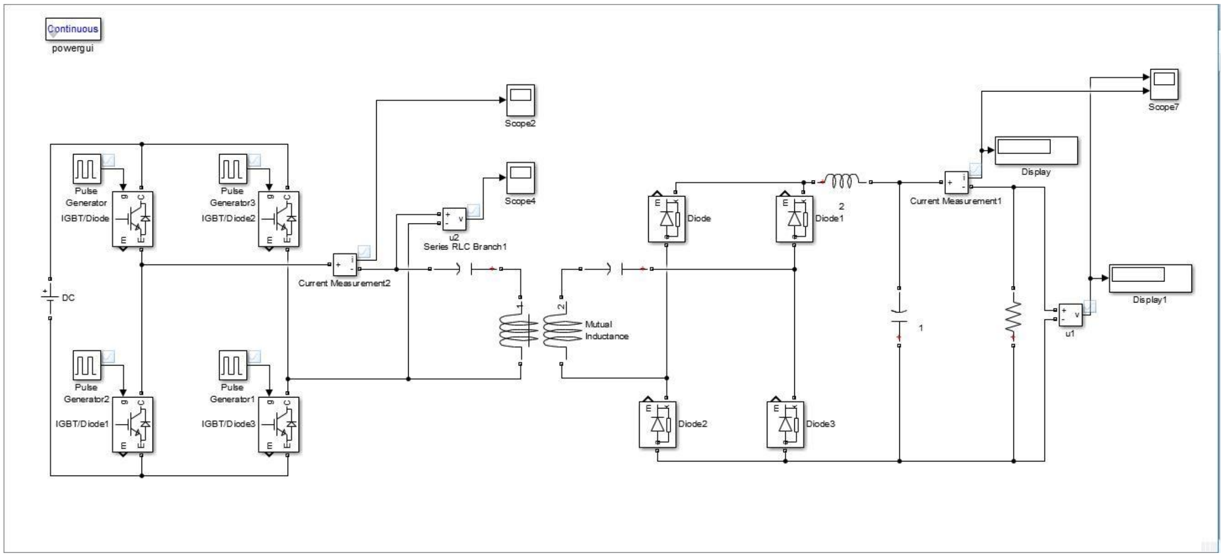

Figure 4.4: Series – Series Compensation

Table 4.1: Input and Output properties of Series-Series Compensation topology

Series - Series Compensation	
Circuit Components and Parameters Values	
Power MOSFET	NMOS IRF510
Operating Frequency (KHz)	20
Input DC supply (V)	310
Primary Inductance (mH)	1.06
Secondary Inductance (µH)	18.6
Primary Capacitor (nF)	59.7
Secondary Capacitor (µF)	3.40
Load Resistance (Ω)	1.7

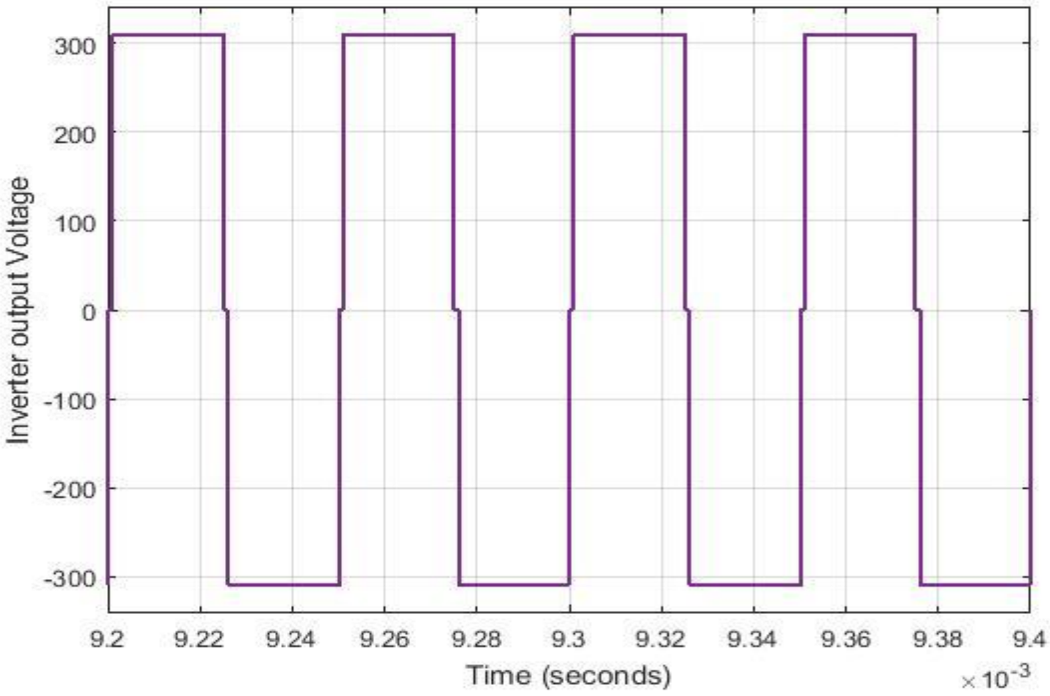

Figure4.5: Inverter output voltage

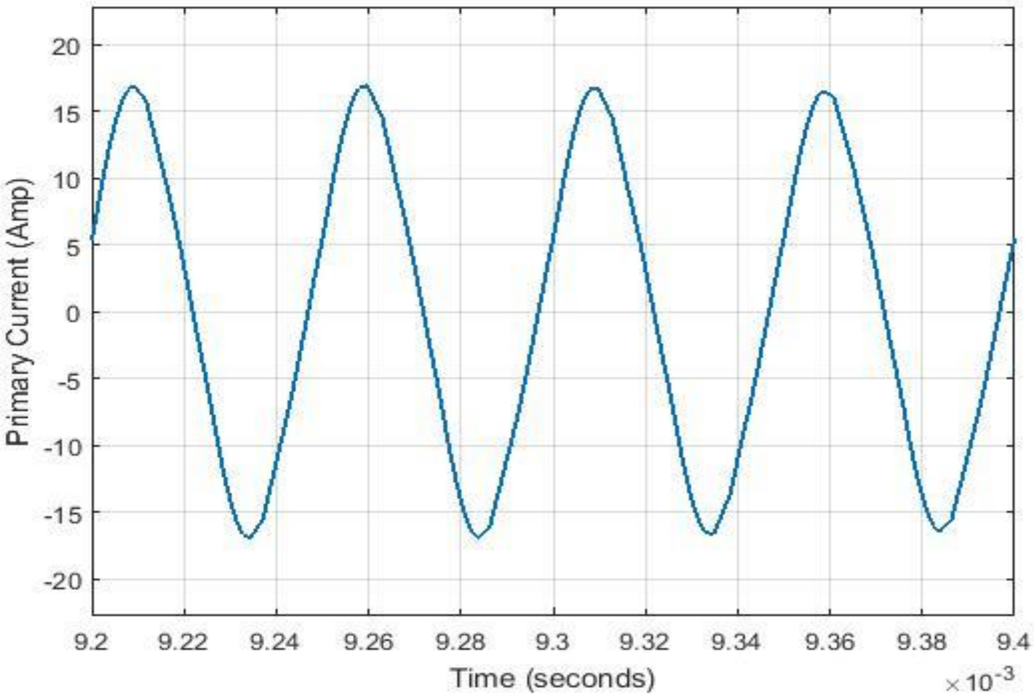

Figure 4.6: primary current

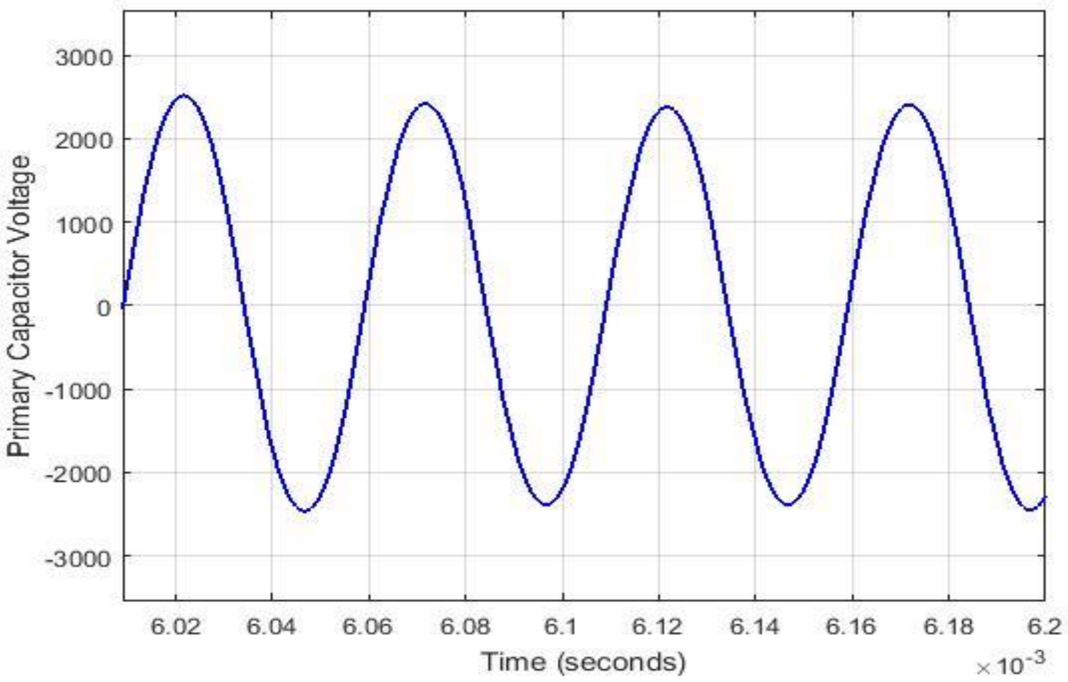

Figure 4.7: Primary capacitive voltage

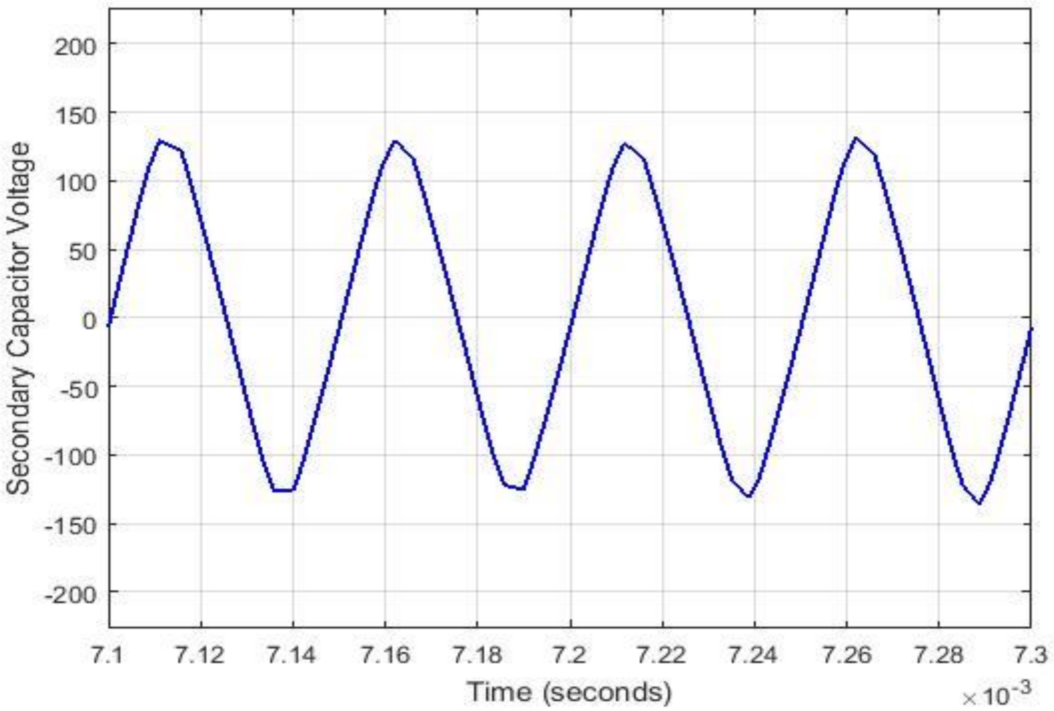

Figure 4.8: Secondary capacitive voltage

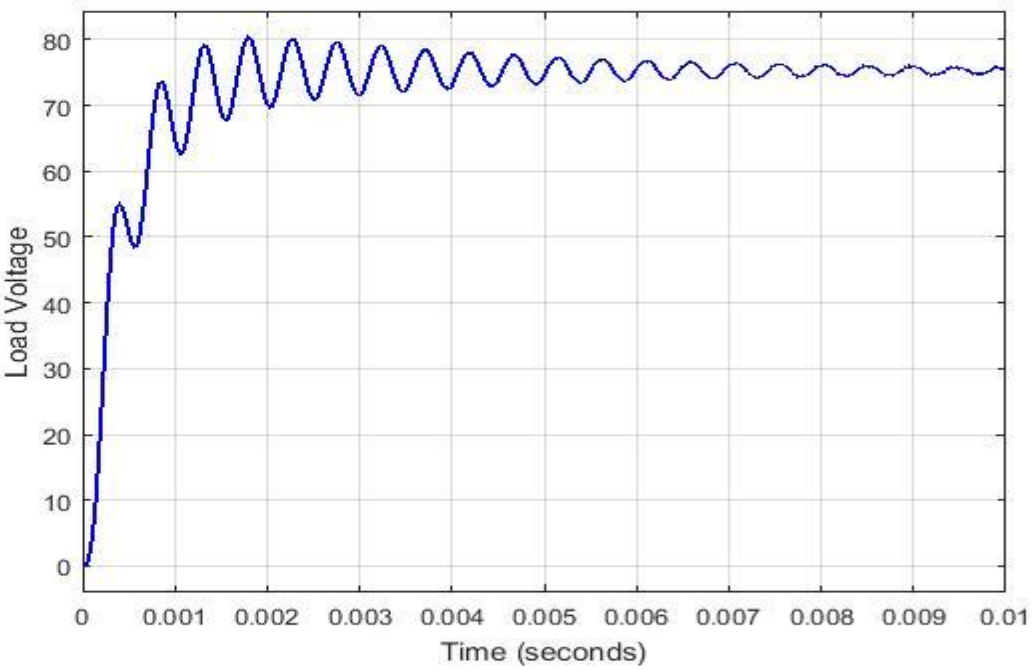

Figure 4.9: Load voltage

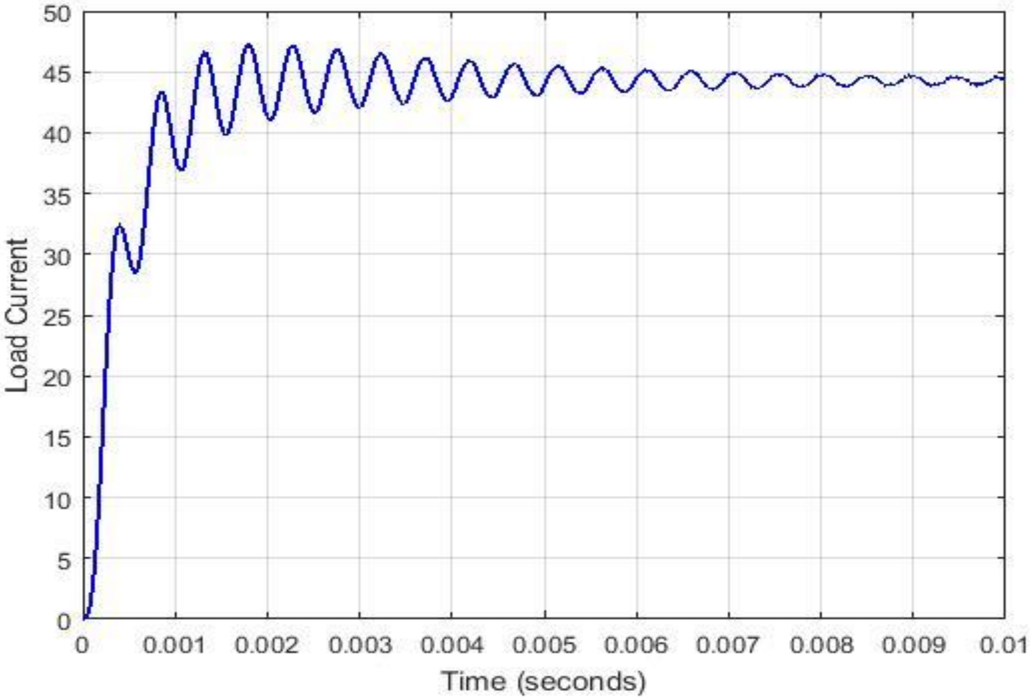

Figure 4.10: Load Current

4.2.2 Series – Parallel Compensation

This topology has typical structure and compensation as the primary coil of the Series-Series topology, however, at the secondary coil, the capacitor is connected in parallel, thereby supplying a stable voltage output. These compensations are designed for systems with multiple loads like Vehicle systems as shown in Figures 4.11.

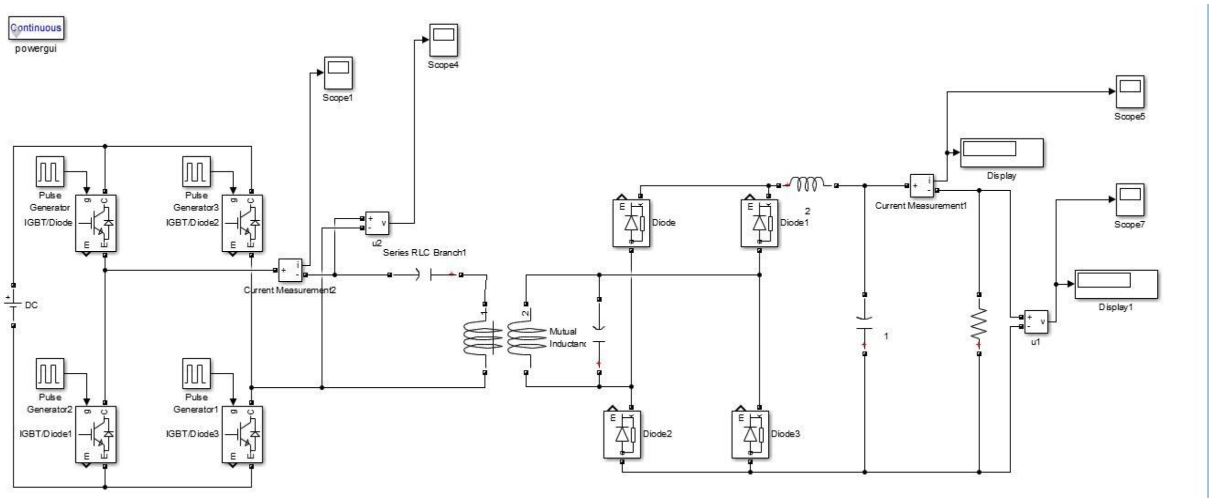

Figure 4.11: Series – Parallel Compensation

Table 4.2: Input and Output properties of Series-Parallel Compensation topology

Series – Parallel Compensation	
Circuit Components and Parameters Values	
Power MOSFET,	NMOS IRF510
Operating Frequency (KHz)	20
Input DC supply (V)	310
Primary Inductance (mH)	1.06
Secondary Inductance (µH)	18.6
Primary Capacitor (nF)	7.11
Secondary Capacitor (µF)	3.40
Load Resistance (Ω)	1.7

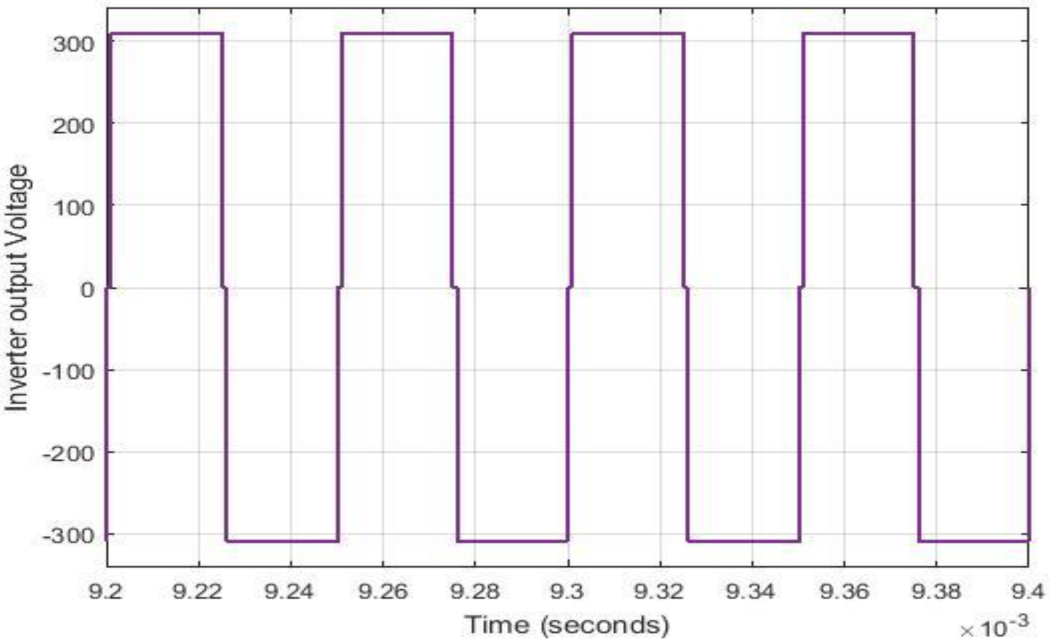

Figure 4.12: Inverter Voltage

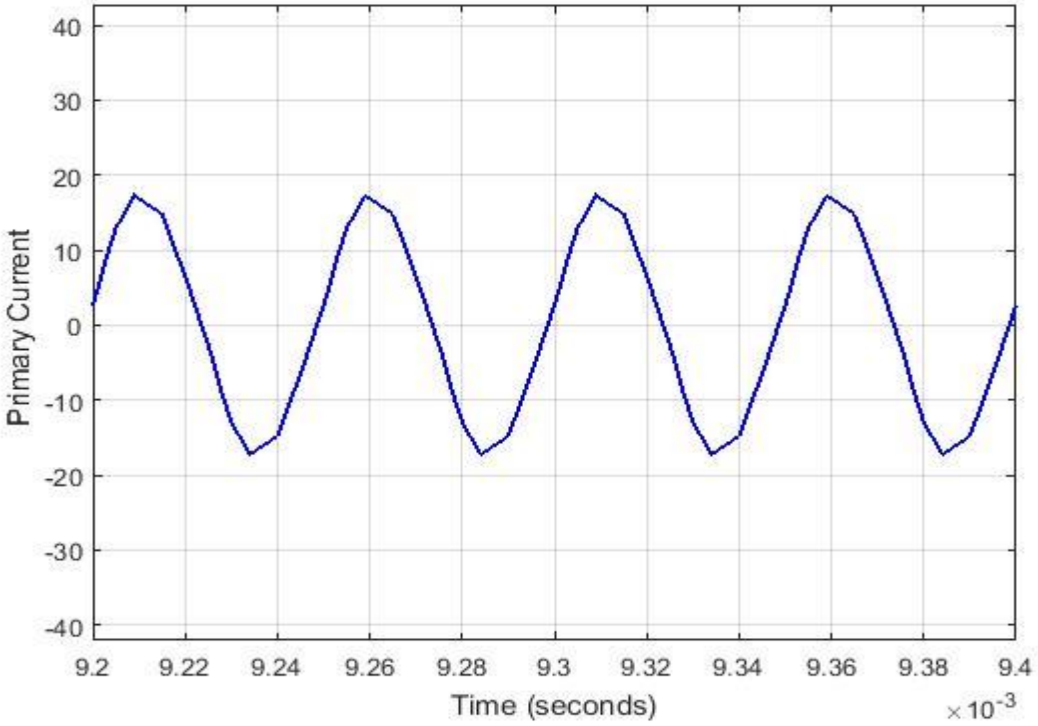

Figure 4.13: Primary Current

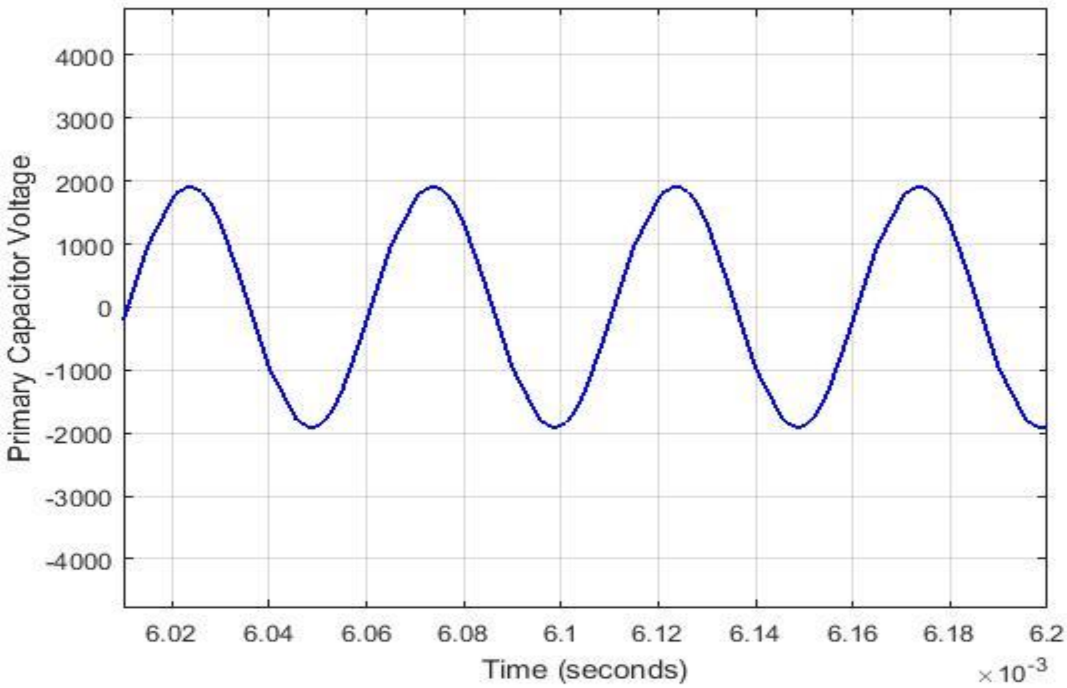

Figure 4.14: Primary Capacitive Voltage

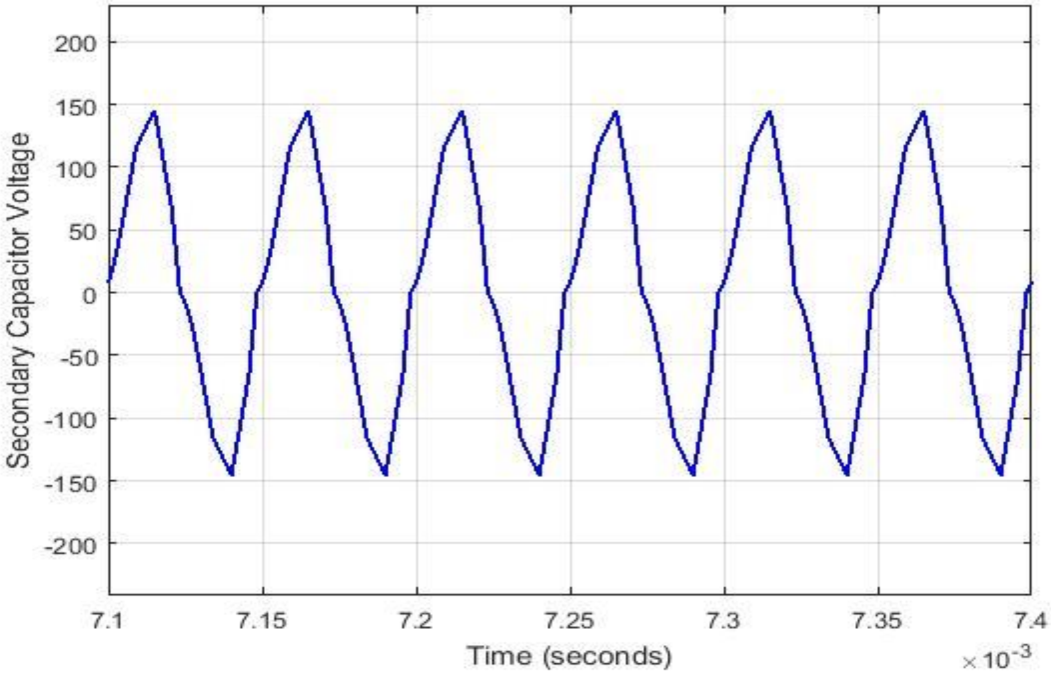

Figure 4.15: Secondary Capacitive Voltage

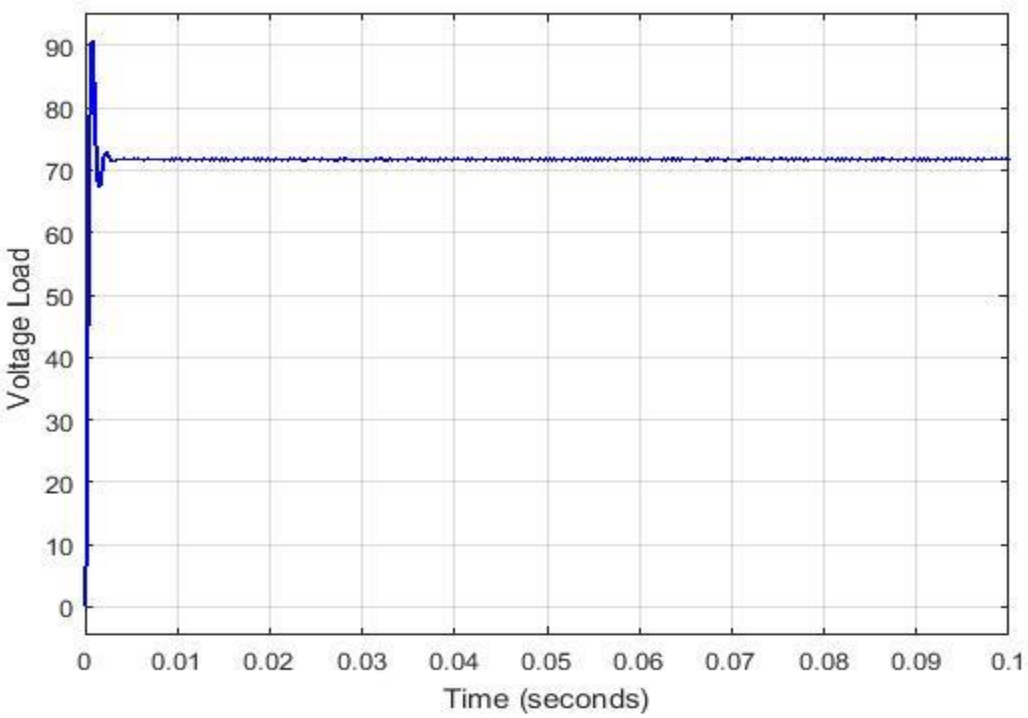

Figure 4.16: Load Voltage

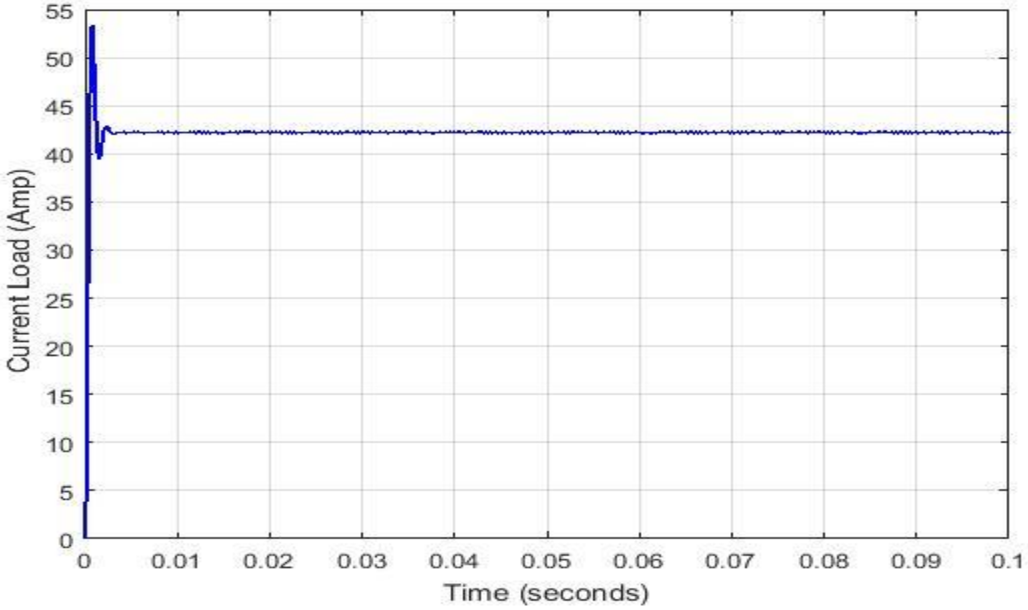

Figure 4.17: Load Current

4.2.3 Parallel – Series Compensation

This configuration involves the capacitor in parallel at the primary coil and the capacitor in series at the secondary. Here, the system acts as a current source, but the output power would be reduced due to the parallel connection at the primary as shown in Figures 4.18. The parallel capacitor at the primary, reduces the current, thereby reducing the magnetic field strength.

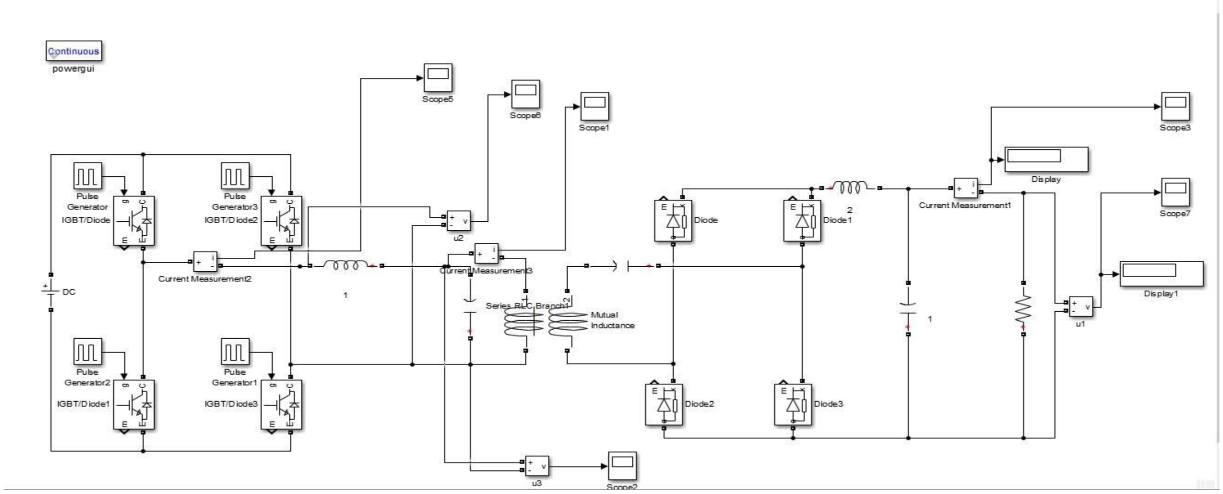

Figure 4.18: Parallel – Series Compensation

Table 4.3: Input and Output properties of Parallel-Series Compensation topology

Parallel – Series Compensation	
Circuit Components and Parameters Values	
Power MOSFET,	NMOS IRF510
Operating Frequency (KHz)	20
Input DC supply (V)	310
Primary Inductance (mH)	1.06
Secondary Inductance (µH)	18.6
Primary Capacitor (nF)	55.8
Secondary Capacitor (µF)	3.40
Load Resistance (Ω)	1.25

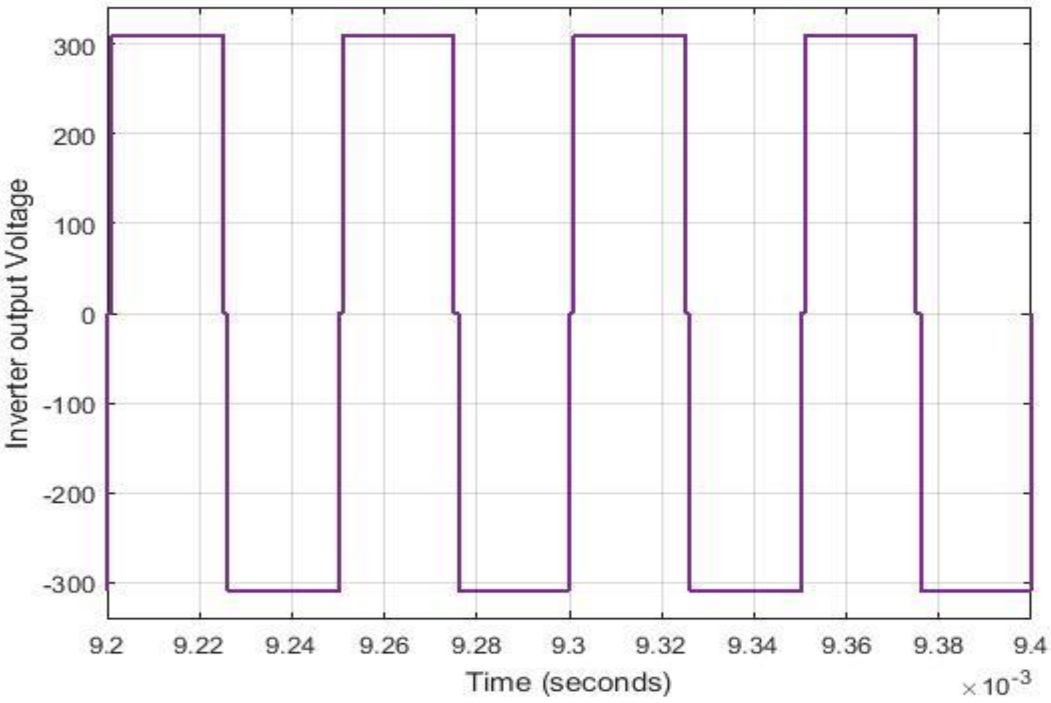

Figure 4.19: Inverter output voltage

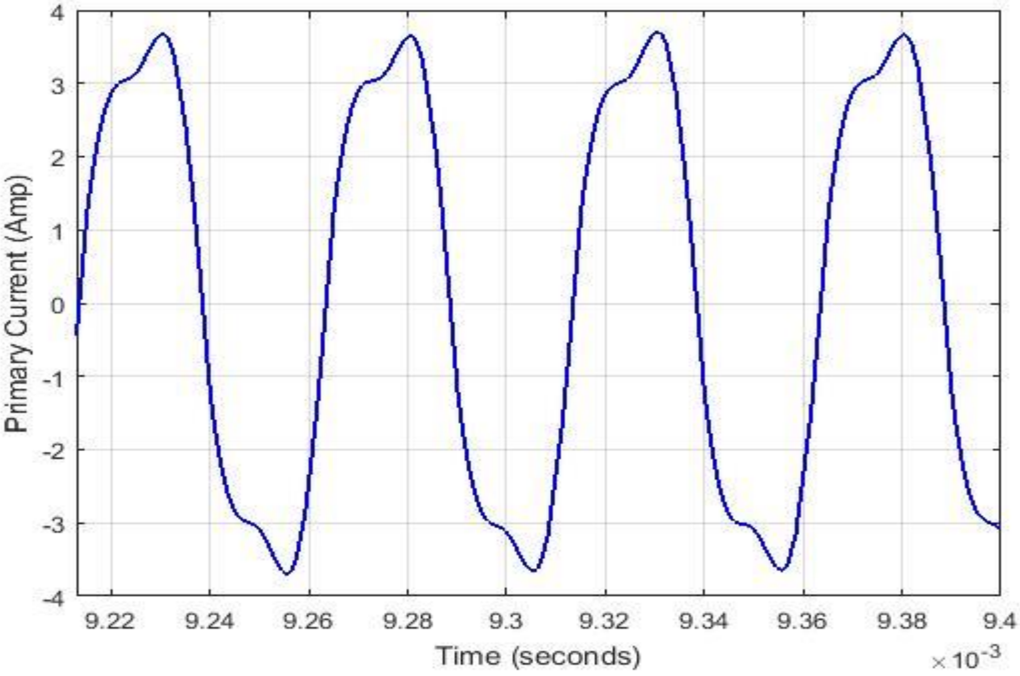

Figure 4.20: Primary Current

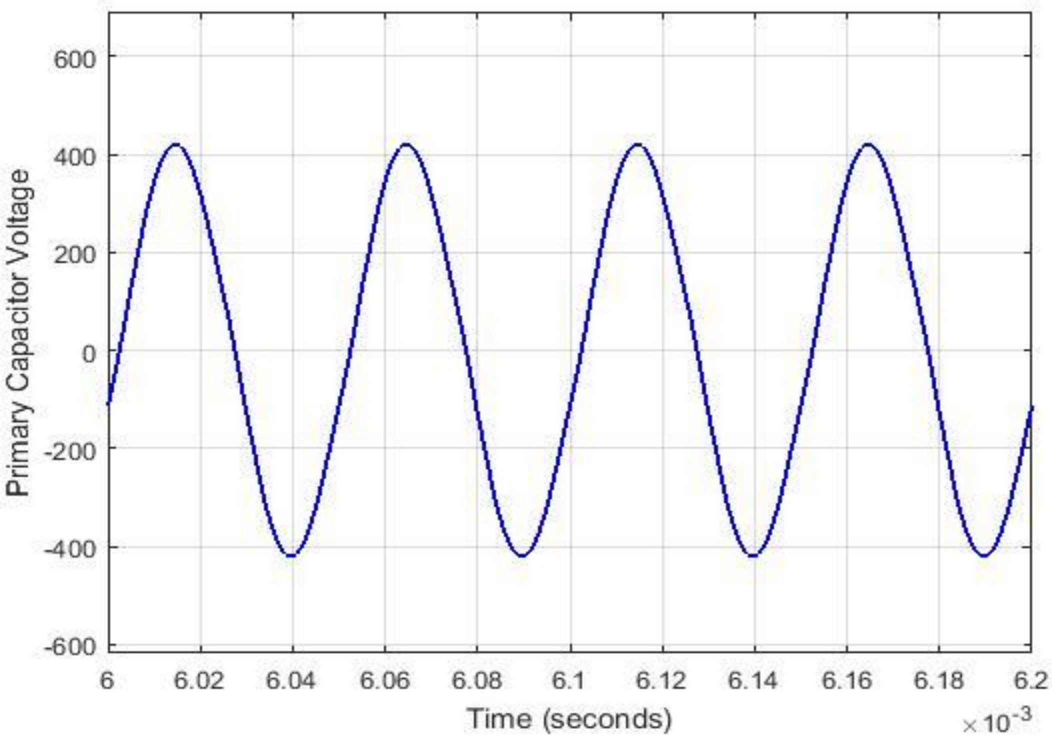

Figure 4.21: Primary Capacitive Voltage

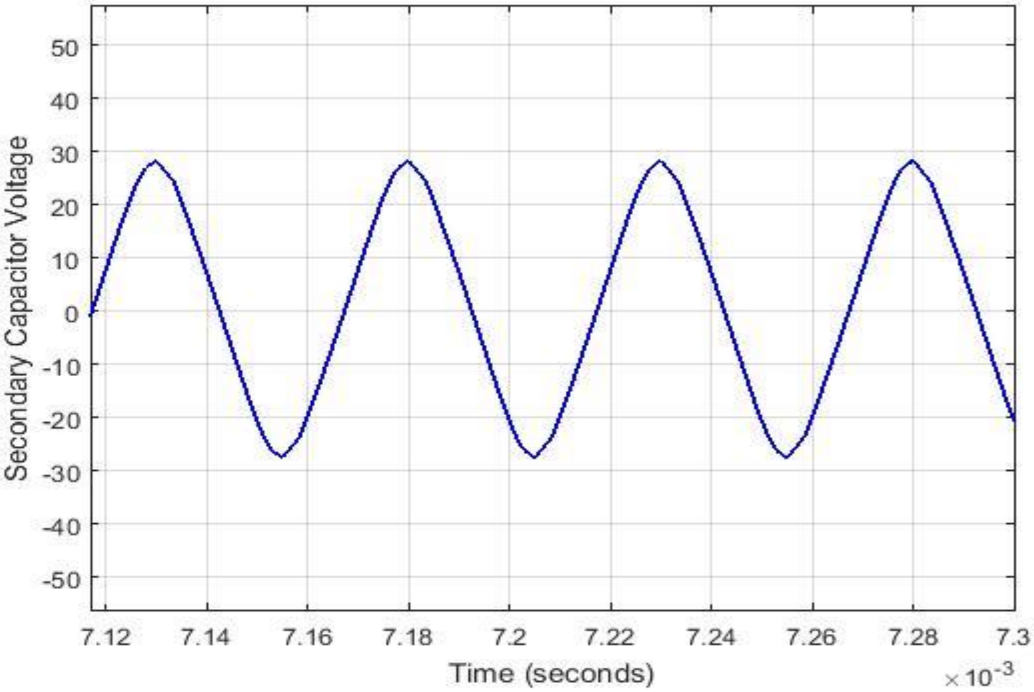

Figure 4.22: Secondary Capacitive Voltage

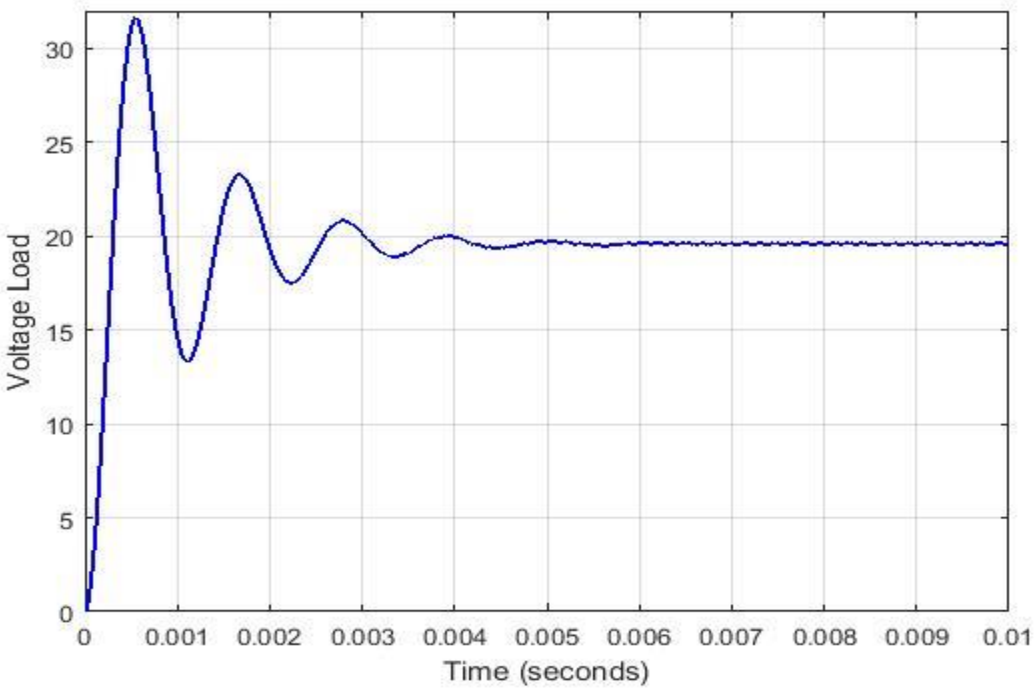

Figure 4.23: Load Voltage

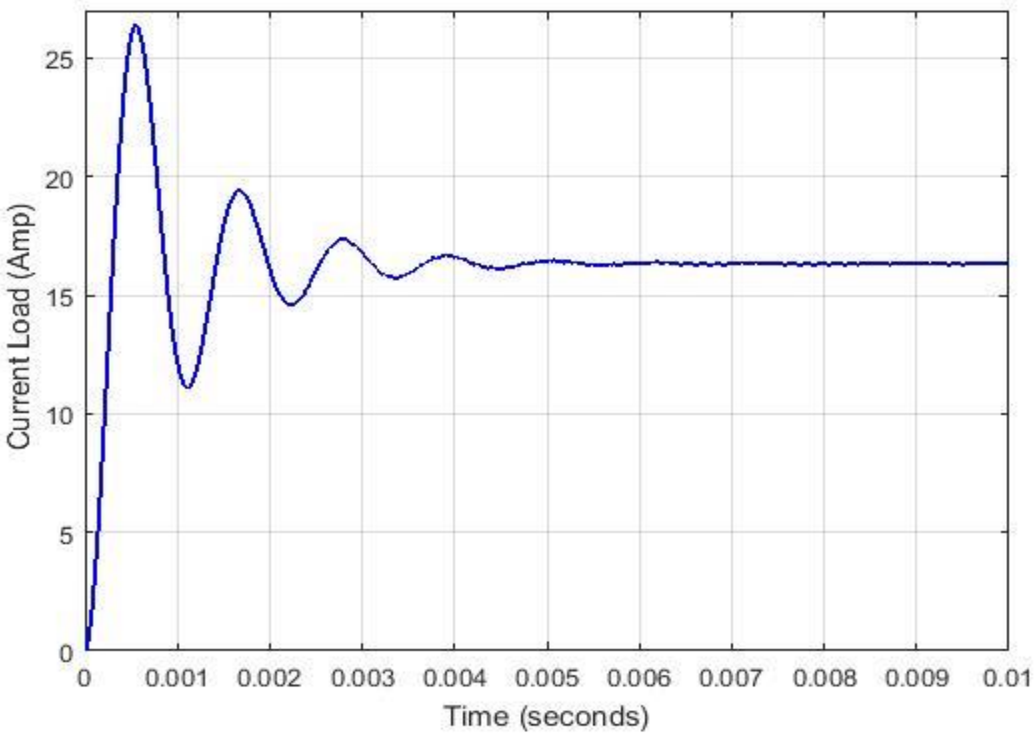

Figure 4.24: Load Current

4.2.4 Parallel – Parallel Compensation

Here, the capacitors connected in parallel to both the primary and the secondary coils as shown in Figures 4.25. This produces a very poor performance with a low efficiency. Hence, its less frequent usage.

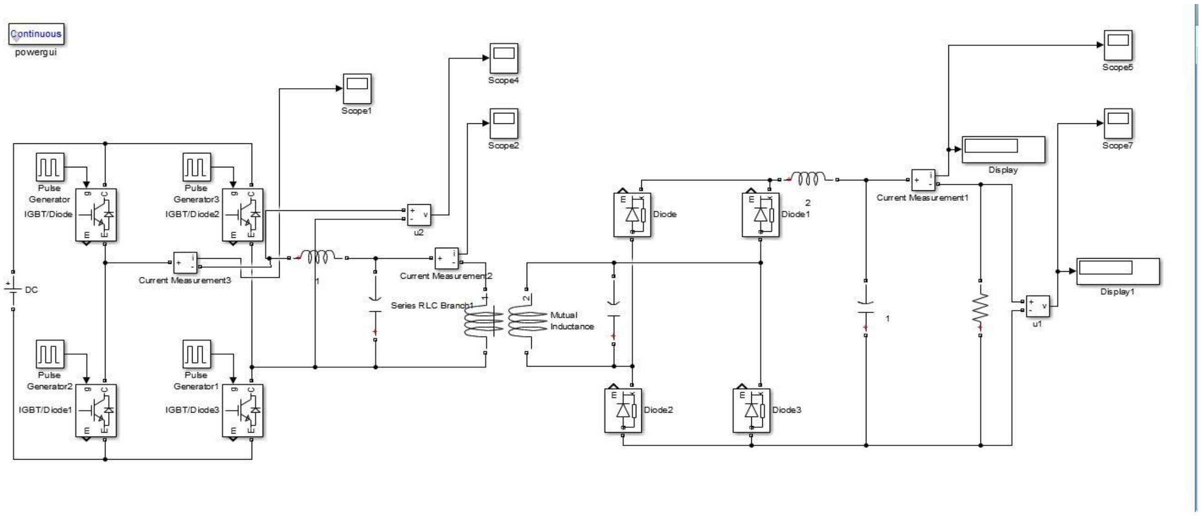

Figure 4.25: Parallel – Parallel Compensation

Table 4.4: Input and Output properties of Parallel-Parallel Compensation topology

Parallel – Parallel Compensation	
Circuit Components and Parameters Values	
Power MOSFET,	NMOS IRF510
Operating Frequency (KHz)	20
Input DC supply (V)	400
Primary Inductance (mH)	1.06
Secondary Inductance (µH)	18.6
Primary Capacitor (nF)	59.7
Secondary Capacitor (µF)	3.40
Load Resistance (Ω)	1.25

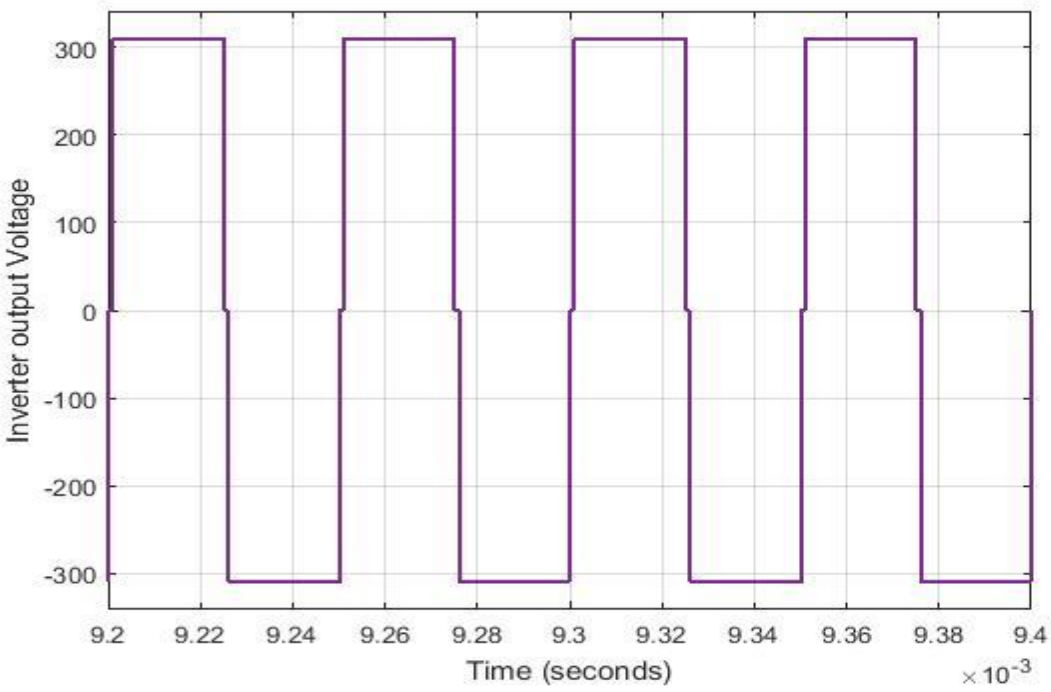

Figure 4.26: Inverter output voltage

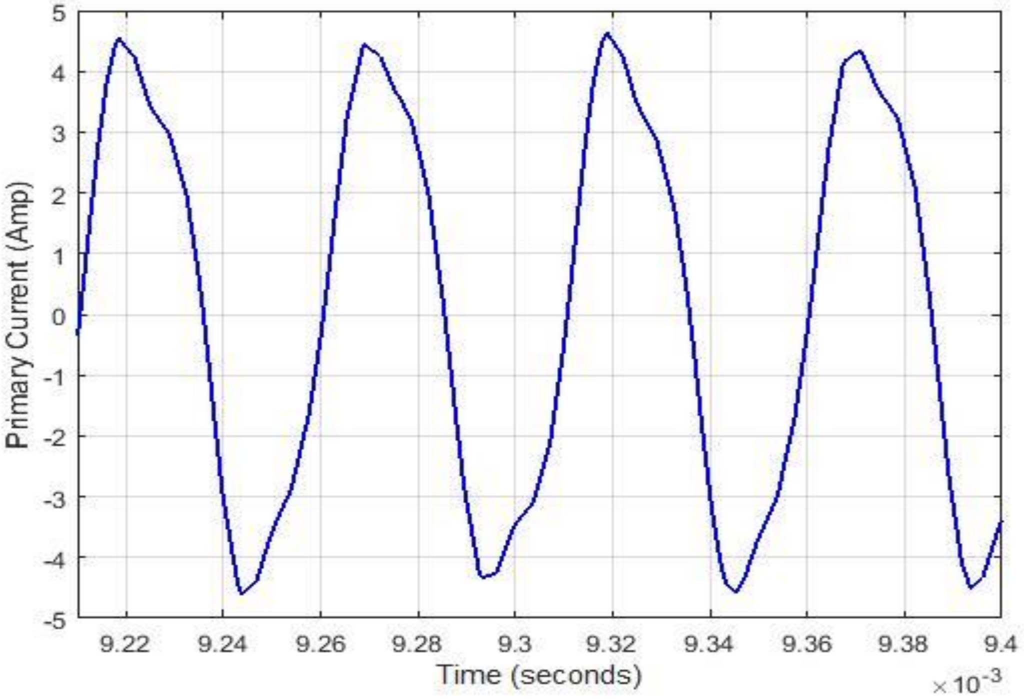

Figure 4.27: Primary current

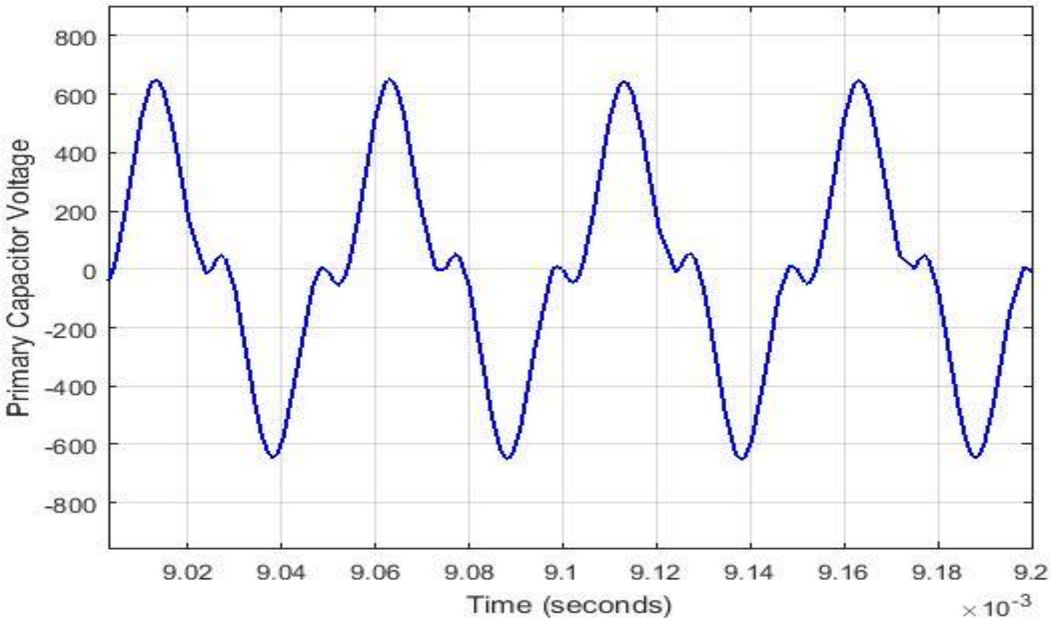

Figure 4.28: Primary Capacitive Voltage

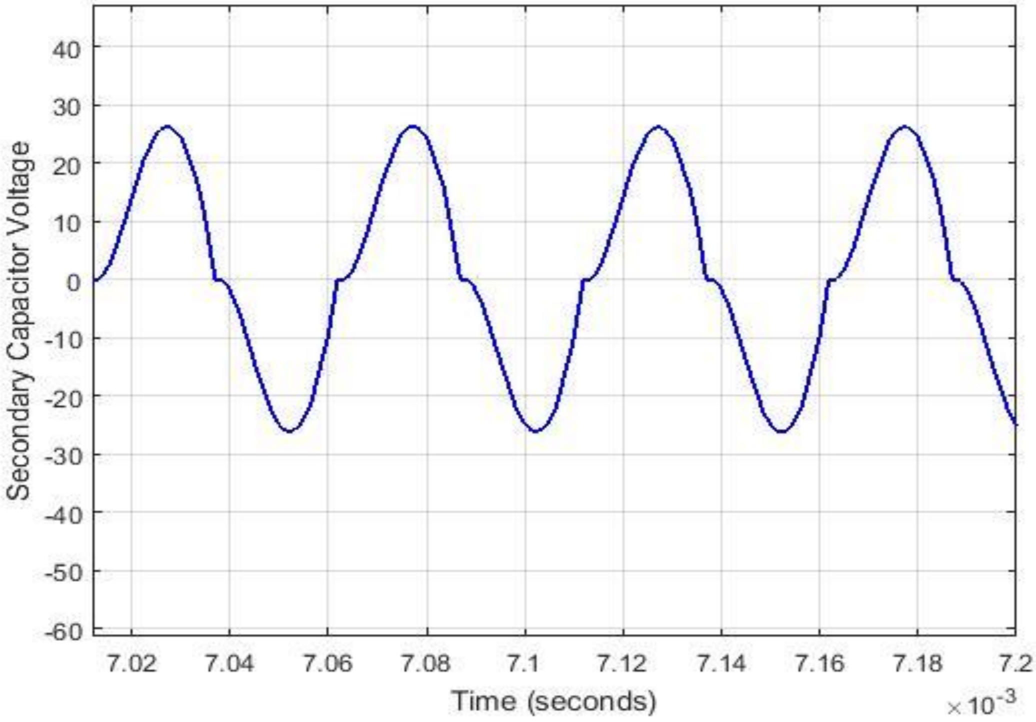

Figure 4.29: Secondary Capacitive Voltage

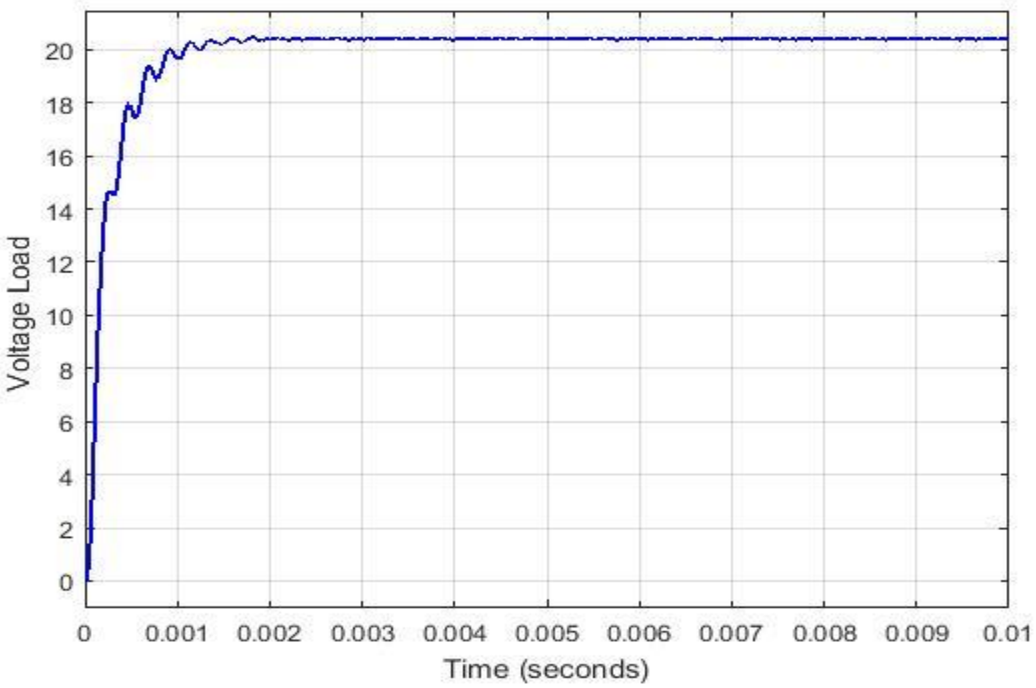

Figure 4.30: Load Voltage

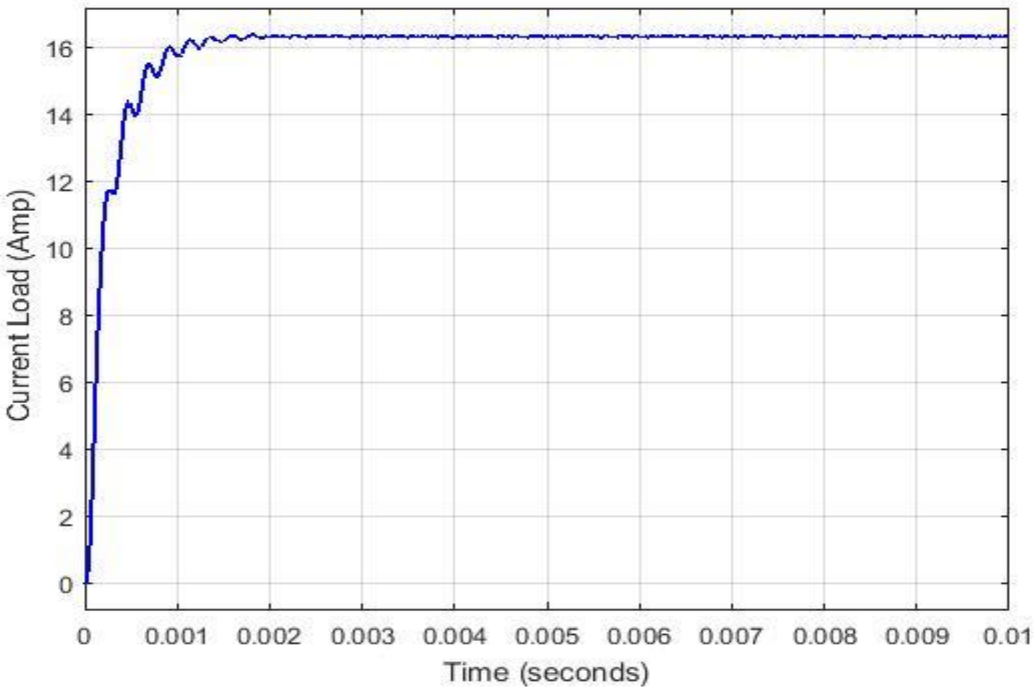

Figure 4.31: Load Current

4.3 Comments

In the above compensations, the change in self-inductances increases as a result of reactive currents of the entire system. These also lead to more losses as far as the system is concerned. It is also noticed that the efficiency of the entire system decreases in the order of the four topologies. At the Series-Series level, the system just requires a normal voltage to produce as much voltage on the secondary side. Its usage becomes efficient because of the high voltage it presents. At almost 1700V, hence when designing the circuit, the choice of a correct and appropriate capacitor is very important. The series-parallel is similarly high. The primary side capacitor stands at a high value of 1400V, almost as high as series-series voltage. But the secondary side is quite low. This places a priority on the choice of primary capacitance While at the Parallel – Parallel the system can only generate a little voltage because it becomes a current source. The efficiency and the usage is not as it is with the Series – Series topology. That is not to say, apart from Series – Series topology, there are no import usage to the other topologies. Other topologies have specific requirements. For low current usage and low voltage usage. As shown in Fıgure 4.28 and Figure 4.29 the capacitive voltage seems reduced at 290V at the primary side and 20V while the Parallel-parallel topology shows a high primary voltage of 460V and a small secondary voltage of 20V.

The operating frequency seems to be a very important tool. This was shown during the simulation. By varying the frequency, the amplitude of the output current reduces, at increased frequency, but increases at reduced frequency, especially with the Series – Series and the Parallel – Parallel. Doing this just requires periodic adjusting of the resonant capacitances in order to maintain the resonant balance of the system.

4.4 Comparisons

As described in the compensation topologies above, the Series-Series compensation seems to be different from the others in several ways. The high voltage and current makes it preferred for power supply. The high voltage and current results in high power factor and high efficiency. This makes the Series-Series preferred compared to the other topologies.

The Series-Parallel requires varying of the secondary capacitance, as against the primary capacitance of the Series-Series. This brings about constant voltage for the output in both Series-Parallel and Parallel Series topologies.

In terms of power factor and output power, the Series-Series ranks highest. The efficiency is highest in the Series-Series topology. This is due to the high output power. Other properties of the compensation topologies are compared as shown in the Table 4.5.

Table 4.5: Comparison of the Topologies

Compensations Comparison				
Topology	S-S	S-P	P-S	P-P
Operating Frequency (KHz)	20	20	20	20
Output voltage (V)	73.2	71.7	19.6	20.35
Output Current (A)	43.1	42.2	16.33	16.3
Primary Capacitor Voltage (V)	1700	1400	290	460
Secondary Capacitor Voltage (V)	90	100	20	20
Input voltage (V)	310	310	310	310
Input current (A)	10.66	10.81	1.7	1.63
Primary coil inductance (mH)	1.06	1.06	1.06	1.06
Secondary coil inductance (μH)	18.6	18.6	18.6	18.6
Mutual coil inductance (μH)	56.16	5.616	5.616	5.616
Primary Coil self-impedance (Ω)	0.65	0.65	0.65	0.65
Secondary coil self-impedance (Ω)	0.11	0.11	0.11	0.11
Load Resistance (Ω)	1.7	1.7	1.25	1.25
Primary Capacitance (nF)	59.7	71.1	55.8	59.7
Secondary Capacitance (μF)	3.40	3.40	3.40	3.40
Efficiency (%)	95	90	60	65

The topologies of the compensations are basically measured by the performances of the secondary resonance type. That is to say that the type of secondary resonance has a significant effect on the efficiency of the entire circuit. The primary resonance influences only the primary circuit. Because of this, we will consider the behavior of the Series-Series and the Series - Parallel.

The series method has a better power transfer efficiency than the parallel side when the frequency operation is beyond the normal operating frequency. It is noticed that the series-series connection performs better with smaller load. At simulation, the primary capacitance of the S-S compensates for the self-inductance of the primary side. This helps to adjust the zero angle frequency of the load model to equal the secondary resonant frequency, thereby operating at maximum frequency.

The parallel method supplies a larger voltage while the series method provides more current than voltage. The parallel side also shows high sensitivity to varied load. This is noticed at frequencies higher than the normal operating frequency.

The P-P circuit displays a very unpredictable output sequence. With efficiency well below 60%, it seems to require a kind of controller for both primary and secondary. This will help in adjusting the circuit components, to ensure resonance when brought together.

CHAPTER 5

5.1 Conclusions and Recommendations

The simulation of all four topologies has exposed the strengths and the weaknesses of the topologies. Generally, as indicated in the previous chapter, entire performance of the circuit in terms of power and efficiency is largely determined by the compensation on the secondary side of any topology. Hence it is easy to see that the efficiency decreases in the order of S-S, S-P, P-S and P-P.

The choice of charging options in the case of battery charging is therefore dependent on the power rating of the device to be charged and the compensation of the circuit to be charged. A car to be charged at will preferably be charged using the S-S compensation or the S-P because of the high power output, while a small device will require a smaller power like the P-P or the P-S.

As much as a high frequency produces high efficiency, it is also found that high frequencies could also bring about high coil resistances, and could also result in switching losses. We also find that the cost of building a system operating at high frequency could be costly, because of the cost of high frequency capacitors used in the compensation. Hence, the design may operate an opportunity cost or a trade-off between the cost and efficiency. Also keeping the power and the efficiency as high may require some good and efficient electronic devices. Specifically, for the transistors, the components made of silicon will attract better working system in terms of the power, voltage and the current.

For seamless working relationship between the primary and the secondary side, a controller is recommended. This device may be responsible for starting and stopping the device when needed. This may be required just before application of this technology in systems like vehicles and or motors. By using the controllers, the system is electronically stopped by stopping the transfer of power from the primary side.

The usage of the wireless power transfer system is not restricted to vehicles or motors alone, it could also find applications in the house hold appliances like the charging ports for phones and other electronic devices that may require power for usage. Here, a central port may be located in the house without wire connections, devices brought around the region of the system coverage can be charged automatically.

Application in offices will reduce the clumsy nature of wires around the office. Printers and systems could find resonance in connection. That is, without wires around the place, the frequencies of the devices can be matched, so that a user of the central printer can communicate with the printer while in his office. This can be done with any device, as long as it is able to match the operating frequency of the coil in the printing device.

In a nut shell, there are endless usages to the world of wireless power transfer. Also endless world of researches in the field. In the nearest future, we expect wireless usage of power in absolutely everything that relates to power transfer.

It is however necessary to check the standardization in the area of wireless power transfer technology. The exact size of the coil, the frequency and resistance must be taken into consideration. This is needful to be able to meet international standard. This is because the charging solutions must be in accurate relations with the devices.

5.2 Future Works

As more and more revelations continue to unveil in the field of wireless power transfer, more prospects continue to open up for exploration. The world of wireless power transmission seems endless as new topologies are researched and implemented. This leaves a world unlimited applications at least for the possible future.

The research has shown the complications involved in simulating the P-P and the P-S topologies. Obviously, the components will require modification so as to achieve a stable output. Hence future work will involve critical analysis of these two compensation with a view to improving the power and efficiency.

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