MODELLING OF POWER CONVERTER-WPT SYSTEM BASED ON INDUCTOR CURRENT RIPPLE

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ABSTRAK

Penukar kuasa langkah turun adalah salah satu penukar kuasa yang boleh dilihat dalam kehidupan kita pada masa kini. Penukar langkah turun ialah penukar kuasa arus terus-ke-arus terus yang menurunkan voltan daripada bekalan masukan ke keluarannya sambil menarik arus purata yang kurang. Pensuisan frekuensi dalam reka bentuk penukar langkah turun membantu dalam mengurangkan saiz pengaruh dan mengurangkan riak arus pengaruh. Walaubagaimanapun, ia boleh menyebabkan kehilangan kuasa dan mengurangkan kecekapan akibat kehilangan teras pengaruh. Projek ini membentangkan simulasi kaedah memanfaatkan tenaga riak pensuisan daripada induktor dengan menggunakan Pemindahan Kuasa Tanpa Wayar (WPT) untuk mengimbangi kehilangan teras pengaruh. Dengan menggunakan sistem penukar langkah turun sebagai model, sistem WPT 2-gegelung dan 4-gegelung perlu diganti dengan pengaruh dalam penukar langkah turun. Data dikumpul dengan memanipulasi parameter penukar langkah turun seperti frekuensi, kitaran tugas dan faktor gandingan. Pensuisan frekuensi penukar langkah turun perlu berada dalam frekuensi yang sesuai untuk Buck-WPT beroperasi. Untuk mendapatkan voltan keluaran yang lebih tinggi dalam penukar Buck-WPT, kitaran tugas dan faktor gandingan perlu berada dalam nilai tertentu. Litar Buck-WPT disimulasikan menggunakan Simulink/MATLAB dengan alat yang sesuai untuk litar. Projek ini menyimpulkan dengan mengkaji kesan parameter penukar langah turun terhadap penukar 2-gegelung dan 4-gegelung Buck-WPT.

Istilah indeks- Pemindahan Daya Tanpa Wayar, Penukar Buck, Ripple Arus Induktor, Penukar Daya.

ABSTRACT

Buck power converter is one of the power converters that can be seen in our life nowadays. A buck converter (step-down converter) is a DC-to-DC power converter that steps down voltage from its input supply to its output while drawing less average current. Switching frequencies in buck converter design help in reducing the size of inductor and decrease inductor current ripple. However, it can cause the power loses and decrease efficiency due to inductor core losses. This project presents the simulation of method of harness the switching ripple energy from the inductor by using Wireless Power Transfer (WPT) to compensate the inductor core losses. By using buck converter system as model, 2-coil and 4-coil WPT system need to be replace with the inductor in the buck converter. The data were collected by manipulated parameter of the buck converter such as frequency, duty cycle and coupling factor. The switching frequency of the buck converter need to be in the suitable frequency in order to Buck-WPT to be operate. To obtain higher output voltage in the Buck-WPT converter, duty cycle and coupling factor need to be in certain value. The Buck-WPT circuit is simulate using the Simulink/MATLAB with a suitable tool for the circuit. This project concludes by studies the effect of buck converter parameter toward 2-coil and 4-coil Buck-WPT converter.

Index terms- Wireless Power Transfer, Buck Converter, Inductor Current Ripple, Power Converter.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

LIST OF ABBREVIATIONS

WPT	Wireless Power Transfer
Tx	Transmitter
Rx	Receiver
Buck-WPT	Buck converter with Wireless Power transfer
V	Voltage
A	Ampere
R	Resistance
V_{RMS}	Voltage root mean square
Iwpt	Current of WPT circuit
Iripple	Inductor current ripple
Rload	Resistance of load
Rwpt	Resistance of WPT load

CHAPTER 1

INTRODUCTION

1.1 Project Background

In recent years, the number of potential uses of Wireless power transfer (WPT) technology has increased in number in a variety of fields, including consumer electronics, electric vehicles (EVs), and medical implantable devices (Miller et al., 2014). Inductor current ripple in buck converter is mainly affect by the size of the inductor. The larger size of inductor can reduce inductor current ripple. However, the problem related to design the can be an issues to buck converter design since the bigger inductor size will take some space and cost more (Henry Xie, 2019). Switching frequencies in buck converter design help in reducing the size of inductor and decrease inductor current ripple. However, it can cause the power loses and decrease efficiency due to inductor core losses. The need for a method to harvesting energy from these devices wirelessly has grown. Power converter also been among one of the devices that been explore to merge with WPT. The existing inductor inside the circuit has been use advantages to harness the energy from the power converter(Qahouq & Dang, 2017). In this project, will look at the effect of duty cycle, frequency and coupling factor toward inductor current ripple in 2-coil and 4-coil Buck-WPT converter.

1.2 Problem Statement

Wireless Power Transfer (WPT) systems are increasingly being adopted or considered in new applications such as consumer electronics, electric vehicle charging and energy harvesting through power converter. However, harvesting energy from power converter bring disadvantages as to reach high efficiency, conduction losses and radiated electromagnetic interference (EMI) due to ripple switching. In this project, the analysis of energy harvesting in BUCK-WPT system will further investigate in term of switching ripple of inductor current and the effect of 2-coil and 4-coil wireless power transfer system for converter-WPT system.

1.3 Scope

The main focus in this project is to simulate existing WPT of DC-DC switching power converter. The system will be using inductor in DC-DC switching buck converter as a transmitter (Tx) and put additional circuit with planar coil as receiver (Rx) and load to harvest energy based on switching ripple energy of inductor current. The process of harvest energy based on switching ripple energy of inductor current must not be change the function of buck converter to step-down the voltage-based input voltage and duty cycle.

1.4 Project Objective

The aim of this project is to

- Apply 2-coil and 4-coil WPT inductor in Buck-WPT converter.
- Analyse the transmission efficiency of 2-coil and 4-coil wireless power transfer system for Buck-WPT system.

1.5 Thesis Organization

This thesis is divided into five chapters and appendices. The backdrop of the project in general, the description of the problem, the project goal, the project scopes and limitations, and the thesis organisation are all covered in Chapter 1. The literature study presented in Chapter 2 discusses the buck converter and WPT system. There is also a review of the literature on a mutual inductance that are used in the optimization area of research. The study technique utilised to carry out this project, which is 2-coil and 4-coil, is described in Chapter 3. The result of Buck-WPT converter in manipulate the parameter of the buck converter, will be presented in Chapter 4. The end outcome is to compare the efficiency of Buck-WPT converter for both coils. The project effort is summarised in Chapter 5. It will provide a clear conclusion and suggestions for this research in order to comprehend the optimization for the area study based on buck converter parameter and WPT system.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A conventional inductive WPT system normally includes a transmitter (Tx) side circuit, a Tx coil, a receiver (Rx) coil, and Rx side electronics/load (Kato et al., 2013; Zhong, W. X. Hui, 2015). In most cases, a dedicated DC-DC power circuit is used to drive the Tx coil and produce an oscillating magnetic field in order to transmit wireless energy/power to the receiver. In most cases, a dedicated DC-DC power circuit is used to drive the Tx coil and produce an oscillating magnetic field in order to transmit wireless energy/power to the receiver.

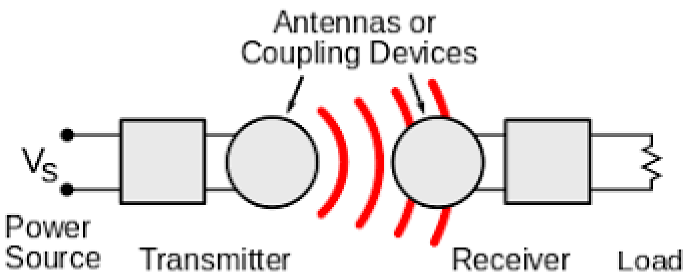

Figure 2.1 Block diagram of wireless power transfer
Source : (Kato et al., 2013; Zhong, W. X. Hui, 2015).

The power inductor is an essential component of the majority of these converters, which bear a current with a DC component and DC switching ripple component.

2.2 Buck Converter

A buck converter is a circuit that converts a direct current input voltage to a lower voltage output voltage(Yusuke Moriwaki, Takehiro Imura, 2011). The rectified AC or other DC supply may be used to generate the DC input. It is beneficial where electrical isolation between the switching circuit and the output is not needed, but where the input is from a rectified AC source, isolation between the AC source and the rectifier may be given by a main isolating transformer. The switch in the circuit is usually a control electronics switch such as a MOSFET, IGBT, or BJT(Zhou et al., 2020). A PWM signal can be used to switch (turn on and off) the switch.

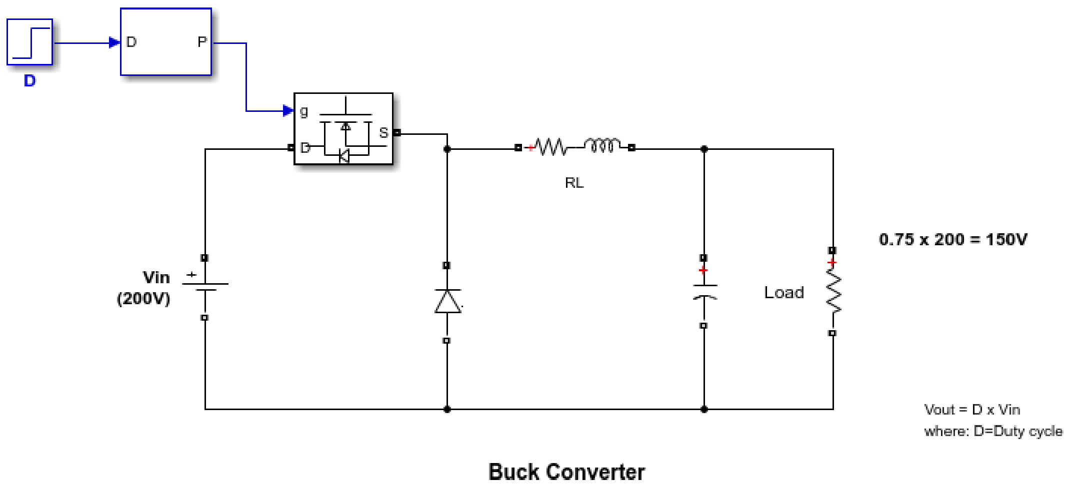

Figure 2.2 Buck Converter Circuit

A low duty cycle indicates that the average voltage seen by the load is low, whereas a high duty cycle indicates that the average voltage is high. The switching transistor between the buck converter's input and output simultaneously turns on and off at a high frequency. The circuit uses the energy stored in the inductor during the on periods of the switching transistor to continue supplying the load during the off periods to ensure a continuous DC output.

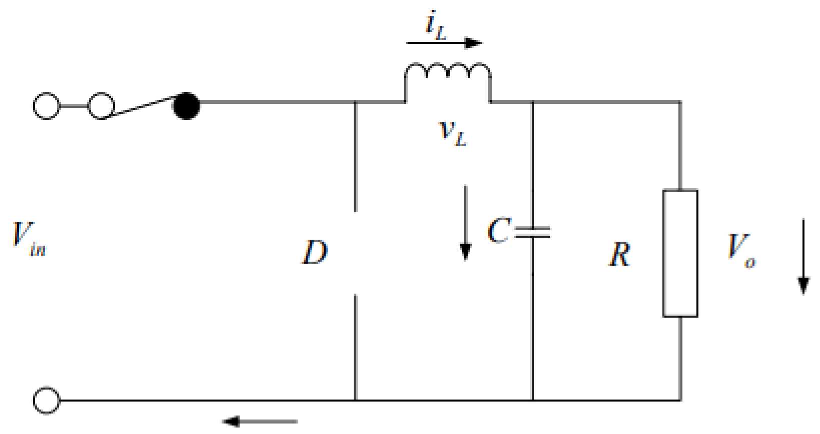

Figure 2.3 Buck converter when switching device is on.

Source: (Rahman, 2007)

When the switching transistor is turned on, it provides current to the load. As energy is also stored in inductor, current flow to the load is controlled, thus the current in the load and the charge on capacitor build up gradually over the 'on' period. As a result, the current in the load and the charge on capacitor steadily increase over the 'on' time. As there will be a significant positive voltage on the diode cathode during the on-time, the diode will be reverse biased and so will not engage in the process.

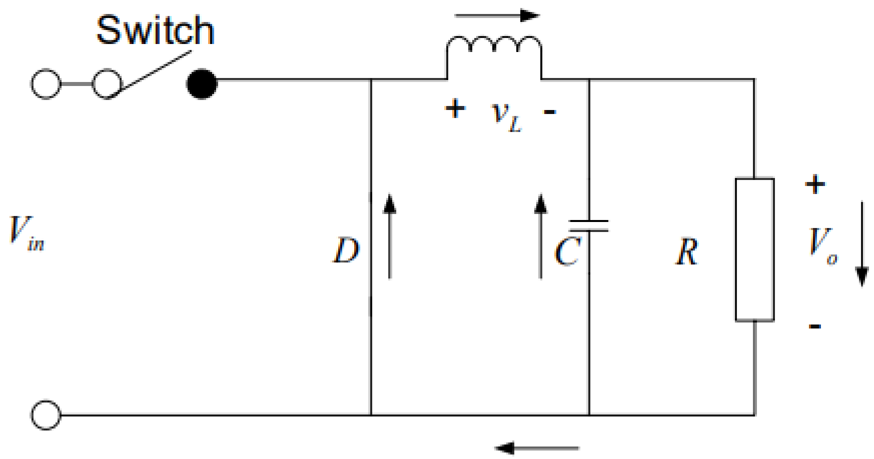

Figure 2.4 Buck converter when switching device is off

Source: (Rahman, 2007)

The energy accumulated in the magnetic field around L1 is released back into the circuit when the transistor turns off, as illustrated in Figure 2.4. The voltage across the inductor (back e.m.f.) is now in the reverse polarity as the voltage across L1 during the 'on' period, and the collapse magnetic field has enough stored energy to keep the current flowing for at minimum part of the time the transistor switch is open.

Current then flows through the circuit via the load and D1, which is now forward bias, due to the back e.m.f. from L1. The charge stored in C1 becomes the main source of current once the inductor has returned a significant portion of its stored energy to the circuit and the load voltage begins to decline. This maintains current flowing through the load until the next 'on' phase begins.

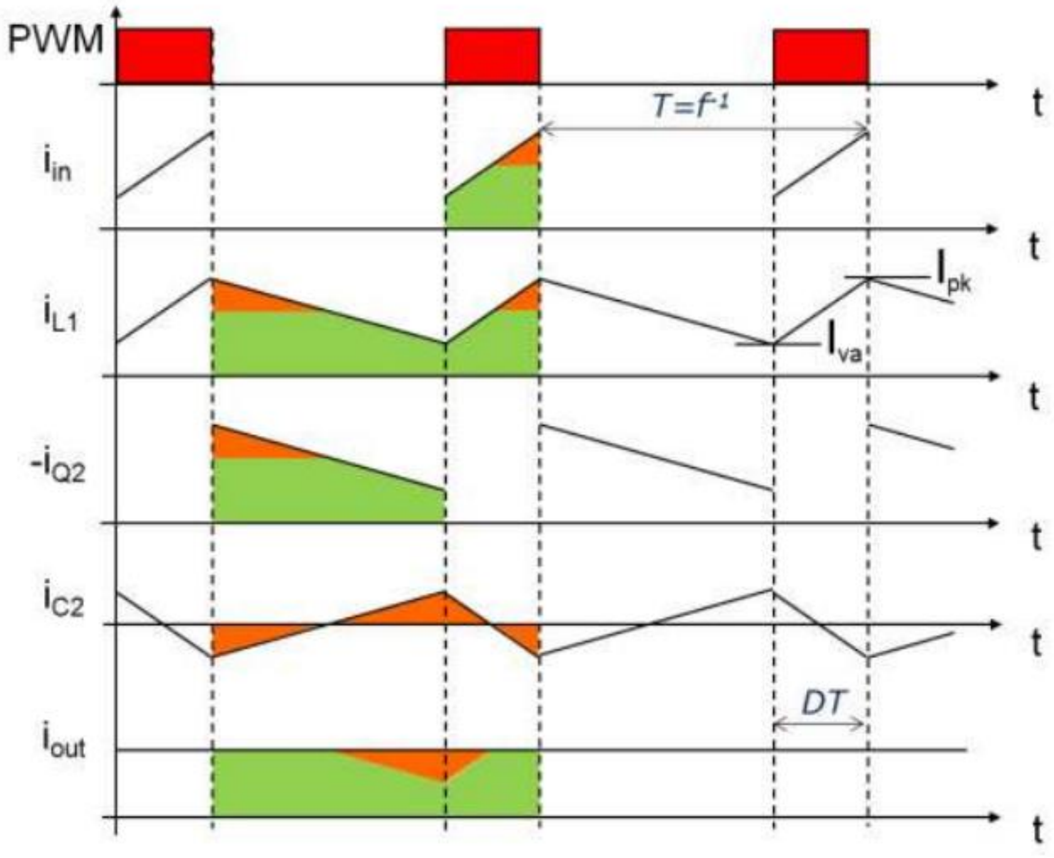

Figure 2.5 Output waveform of Buck converter
Source: (Jens Ejury, 2013)

The calculation of the buck converter can be expressed as equation 2.1 until 2.4

$$V_{out} = D \times V_{in} \quad 2.1$$

$$I_{max} = \left(\frac{1}{R} + \frac{(1 - D)}{2Lf}\right) \quad 2.2$$

$$I_{min} = \left(\frac{1}{R} - \frac{(1 - D)}{2Lf}\right) \quad 2.3$$

$$\Delta I_L = \frac{(V_{in} - V_{out}) \times D}{f \times L} \quad 2.4$$

2.3 Wireless Power Transfer 2-coil and 4-coil system

The two-coil design directly links the power supply and load to the Tx and Rx. In contrast, in four-coil designs, Tx and Rx are magnetically attached to the additional drive loop and load loop, which are linked to the power supply and load, respectively. Four-coil system achieves larger high efficiency range and shows higher misalignment tolerant capability compared with two-coil system(Zhigang Dang & Abu Qahouq, 2015). At any misalignment point, the efficiency of a four-coil system is greater than the efficiency of a two-coil system. When misalignment = 300 mm, the two-coil system achieves 35 % efficiency, while the four-coil system gets 72 % efficiency, which is nearly twice as high as the two coil system efficiency. When there is lateral misalignment, it may be stated that a four-coil system has a larger high efficiency range than a two-coil system.

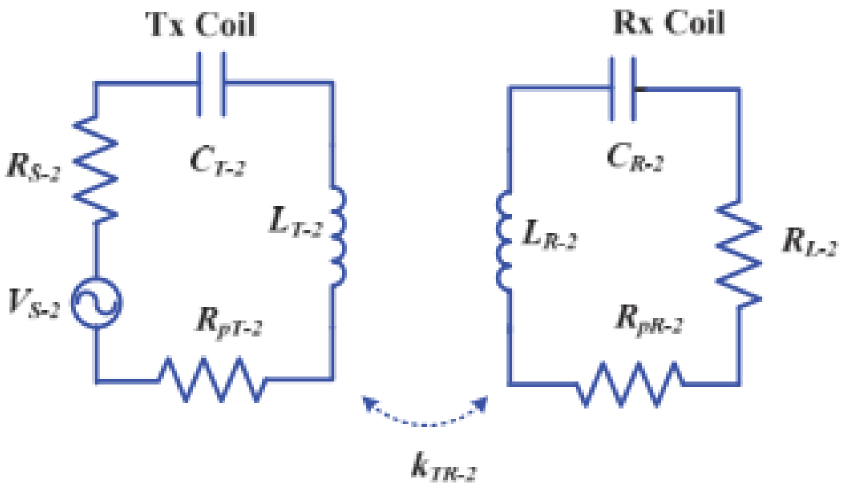

Figure 2.6 WPT system of 2-coil transmission
Source: (Zhigang Dang & Abu Qahouq, 2015)

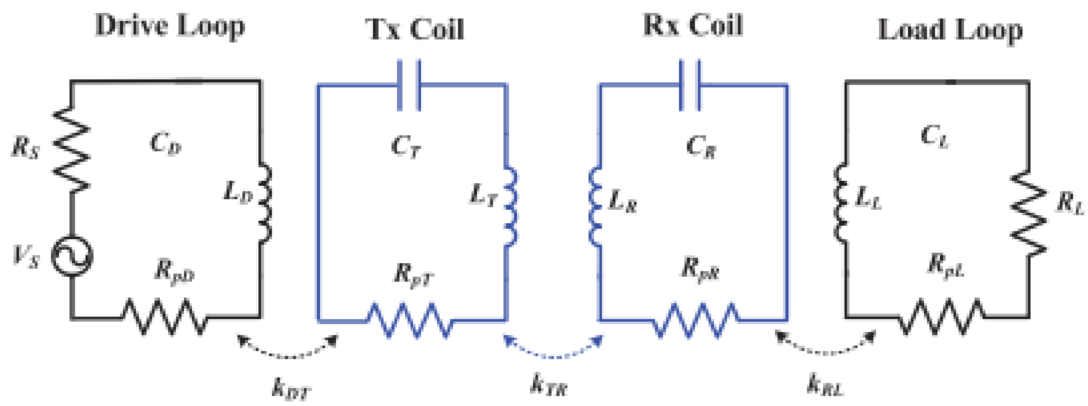

Figure 2.7 WPT system of 4-coil transmission
Source: (Zhigang Dang & Abu Qahouq, 2015)

2.3.1 Wireless Power Transfer of Series LC and LLC (2-coil and 3-coil WPT) system

A series LC resonance operation may be used to acquire the output power and voltage when the distance between the transmitter and the receiver is more than 2 mm due to a critical coupling condition. The output voltage is larger than one under the critical coupling situation and is unaffected by load variation (Yi, 2020). Furthermore, when the distance between the transmitter and the receiver is less than 2 mm due to an excessive coupling condition, a series LLC resonant operation is appropriate for recovering output power with high efficiency. Due to the low switching loss of semiconductor devices in MOSFETs and diodes, the series LLC resonant operation achieves greater efficiency in the over coupling situation than in the critical coupling situation. The LLC resonance operation can be a good solution to compensate the low efficiency in over coupling inductive WPT.

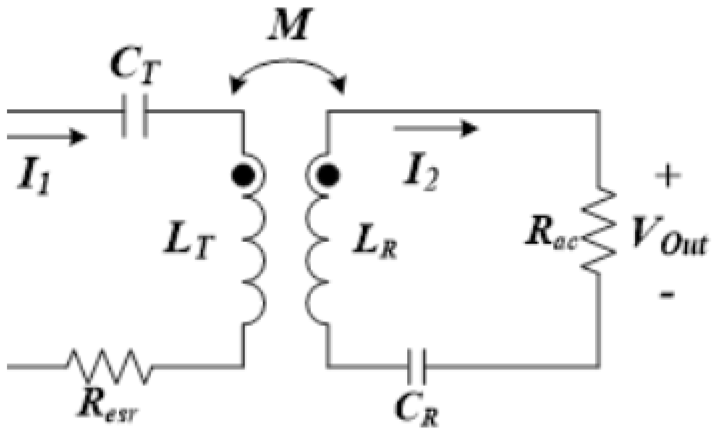

Figure 2.8 LC resonance circuit.
Source: (Yi, 2020)

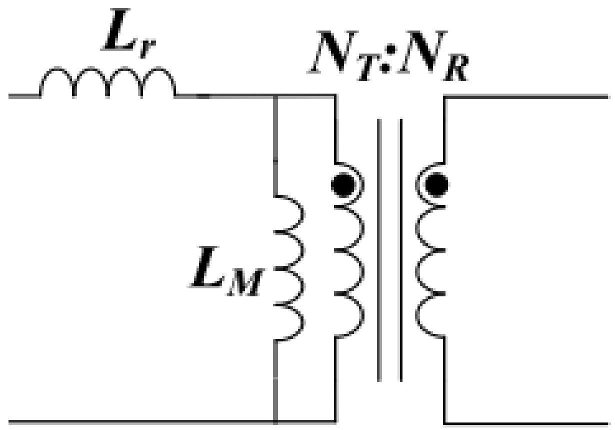

Figure 2.9 LLC resonance circuit.
Source: (Yi, 2020)

2.4 Impedance Matching

One of the challenges in achieving wireless power transfer (WPT) is the increase in reflected power caused by load variation and displacement. Reflected power causes a loss in the power source, resulting in a decrease in power transfer efficiency(Kato et al., 2013). Reflected power rises due to impedance mismatch. Reflected power causes loss in the source which causes distorted waveforms, so it should be minimised to achieve high performance power transfer(Yusuke Moriwaki, Takehiro Imura, 2011). As a result, impedance matching circuits become critical for achieving high performance wireless power systems. In the past, an impedance matching circuit was built with a variable capacitor and an inductor. However, the matching time is too slow for energy transfer in systems with rapid load variance, such as capacitors and motors. The duty cycle and the relationship between input and output power can be used to measure the impedance value. A DC/DC converter converts dc voltage from one level to another. Through controlling the duty cycle of the switching MOSFET, the DC/DC converter behaves like a variable impedance circuit.

2.5 Switching Ripple Inductor

Switching frequency have a significant impact on power loss in a buck converter(Henry Xie, 2019). In a buck converter, an inductor and a capacitor create a low-pass filter. The LC filter's corner frequency is always set to a low value in order to reduce switching ripple(Huang et al., 2016). The inductor will store energy while the switch is turned on and release energy when the switch is turned off. In theory, the load current should travel through the inductor, requiring a sufficient area of winding wire. If a smaller ripple factor or higher inductance is desired, more winding turns are required, resulting in a larger inductor size. The greater the inductance L, the smaller the capacitance C, resulting in the same output voltage ripple. However, an inductor that is too large results in a high volume and a high cost.

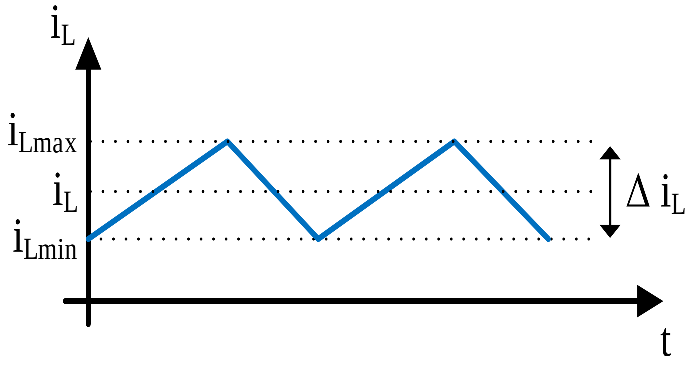

Figure 2.10 Output of current ripple

Source: (Jens Ejury, 2013)

$$\Delta_{iL} = i_{Lmax} - i_{Lmin} \quad 2.5$$

Switching frequencies can help reducing the size of inductor in the design of buck converter. By increase the switching frequency, the ripple of inductance current and capacitance voltage reduces but it can cause to increase the power loss of the buck converter.

2.6 Coupling factor

The mutual inductance of two coils is described as the induced emf in one coil opposing the change in current and voltage in the other coil. Due to the obvious change in magnetic flux, the two coils are magnetically connected. The magnetic field or flux of one coil interacts with the magnetic field or flux of another coil. M signifies for this. Because of the changes in magnetic flux, the current flowing in one coil causes the voltage in another coil to rise. The mutual inductance and current change are directly proportional to the quantity of magnetic flux coupled to the two coils.

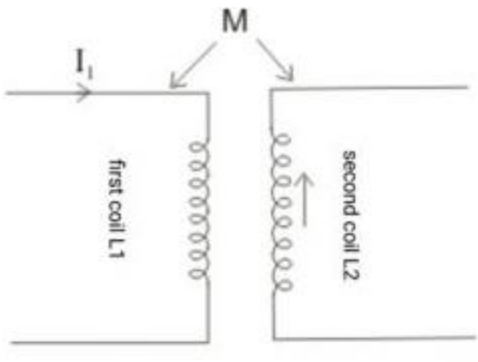

Figure 2.11 Mutual Inductance between two coil.
Source: (Jaeger & Cantillon-Murphy, 2018)

When the current in L1 varies over time, the magnetic field changes as well, causing the magnetic flux in the second coil L2 to change. An EMF is induced in the first coil L1 as a result of the magnetic flux change. EMF is also induced in the second coil by the rate of change of current in the first coil. As a result, EMF is induced in both the L1 and L2 coils. M can be calculated as equation 2.6

$$M = \sqrt{L1 \times L2} \qquad 2.6$$

2.7 Coupling Coefficient

The coupling coefficient, represented as 'k,' is the proportion of magnetic flux connected to the two coils to the total magnetic flux between the coils. The open circuit to real voltage ratio and the ratio of magnetic flux acquired in both coils are used to calculate the coupling coefficient. Because the magnetic flux of one coil links with that of another. The coupling coefficient describes an inductor's inductance. When the coefficient coupling k = 1, the two coils are firmly connected. As a result, all of one coil's magnetic flux lines cut all of the turns of the other coil. As a result, the arithmetic mean of the self-inductances of two coils is the mutual inductance. When the inductances of two coils are equivalent (L1=L2), the mutual inductance among them equals the inductance of a single coil.

Coupling factor between coils can be expressed as a number between 0 and 1. There is no inductive coupling between the coils if the coupling value is 1. There is a maximum or full inductive coupling between the coils if the coupling factor is 0. The inductive coupling is expressed in terms of 0 and 1, not percentages. If k=1, the two coils are completely linked. If k>0.5, the two coils are strongly connected. If k<0.5, the two coils are loosely linked. The following equation 2.7 should be used to get the coefficient coupling factor between the two coils:

$$M = k\sqrt{L1 \times L2} \qquad 2.7$$

2.8 K-chart

The initial part of a research activity is planning. It includes identifying problems and themes, establishing objectives, identifying deliverables and milestones, and establishing a timeframe. Clarity in planning will result in smoother research progress, even if part of the study objectives must be revised. An effective planning tool should be able to smooth the way. A K-chart is composed of several components: Issues, Methodologies, Results, and a Time Line.(Mohd Khazani et al., 2006) A K-chart simply classifies the topics within the topic under investigation from broad to detail. The general problems are put at the top of the Tree diagram and are subdivided into many specific concerns (sub-problems) under it. The concerns are then classified as broad, complimentary, or targeted. However, as the layer of difficulties becomes deeper and more particular, so do the challenges for literature reviews.

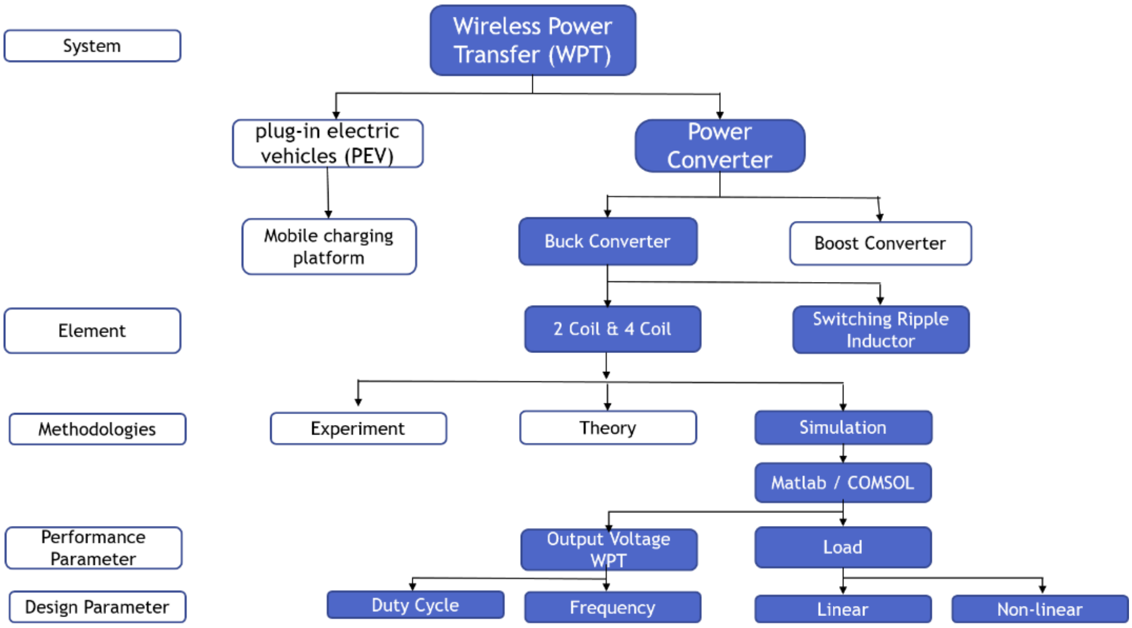

Figure 2.12 K-Chart Studies of WPT effect toward power converter

CHAPTER 3

METHODOLOGY

3.1 Introduction

The steps and process to complete the project is explained in this chapter is using the MatLab/Simulink software to simulate the effect of design parameter toward Buck-WPT converter.

3.2 Flow Chart

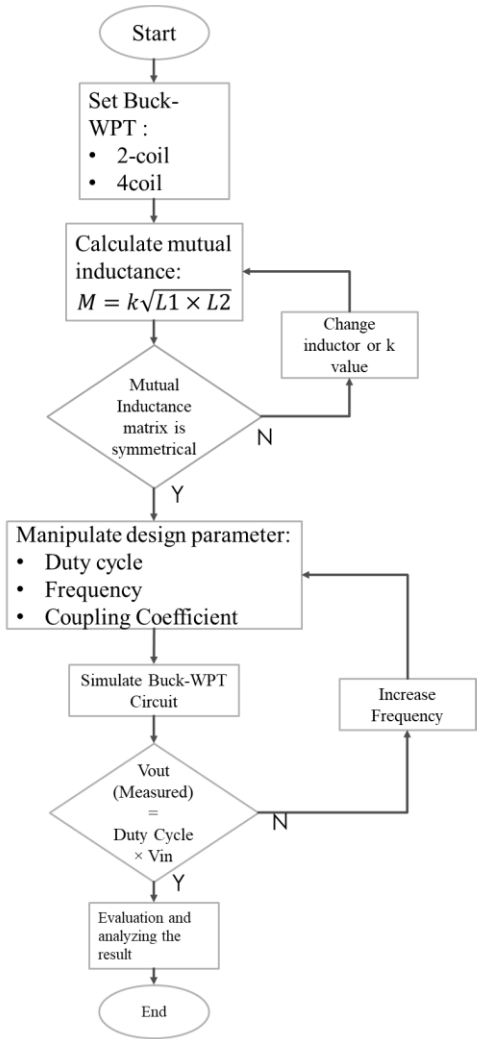

Figure 3.1 Flowchart of design parameter in Buck-WPT converter.

Figure 3.1 shown the flowchart of Buck-WPT converter in determining the efficiency of Buck WPT converter by manipulate parameter of buck converter. This project needs to be set in whether 2-coil or 4-coil by replacing inductor with mutual inductor in buck converter to demonstrate effect of inductor ripple current toward buck converter and WPT load. Mutual inductance needs to be calculated along with the coupling factor in order to simulate the losses of coil. Mutual inductance in the coil must be symmetrical and if the mutual inductance is not symmetrical, the inductor and coupling factor need to be change until it symmetrical. Then the parameter of Buck-WPT converter such as coupling factor, duty cycle and frequency is varied to studies its effect toward load. After parameter has been set, the circuit need to be simulated in Simulink and monitor its voltage at Rload. If the output voltage of the load does not equal with the calculation, the switching frequency need to be increase.

3.3 Buck-WPT converter circuit

In this simulation, buck converter is use to demonstrate and simulate the application of WPT. To apply the WPT circuit into the buck converter, the inductor of the buck converter will be replace with the mutual inductor to act as planar coil or inductor. All the parameter has been reconsider apply inside the circuit to suit with the WPT circuit. In this circuit it has 2 load which is wired load that connect with buck converter and WPT load that show the WPT output.

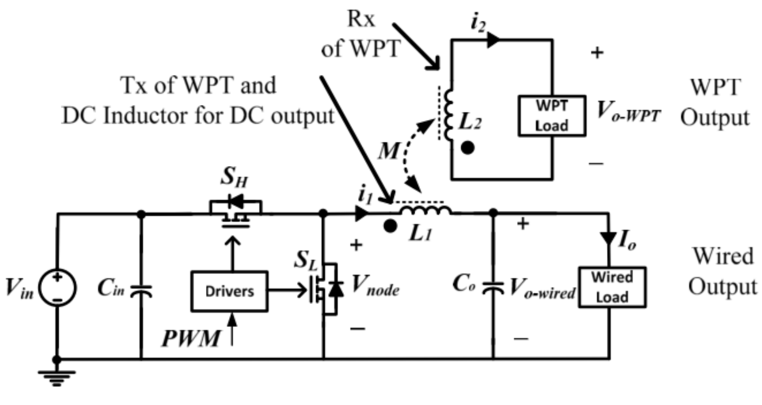

Figure 3.2 Illustration diagrams of proposed Buck-WPT system
Source: (Qahouq & Dang, 2017)

By refer to Figure 3.2, the circuit has been constructed to study the output of the Buck-WPT system.

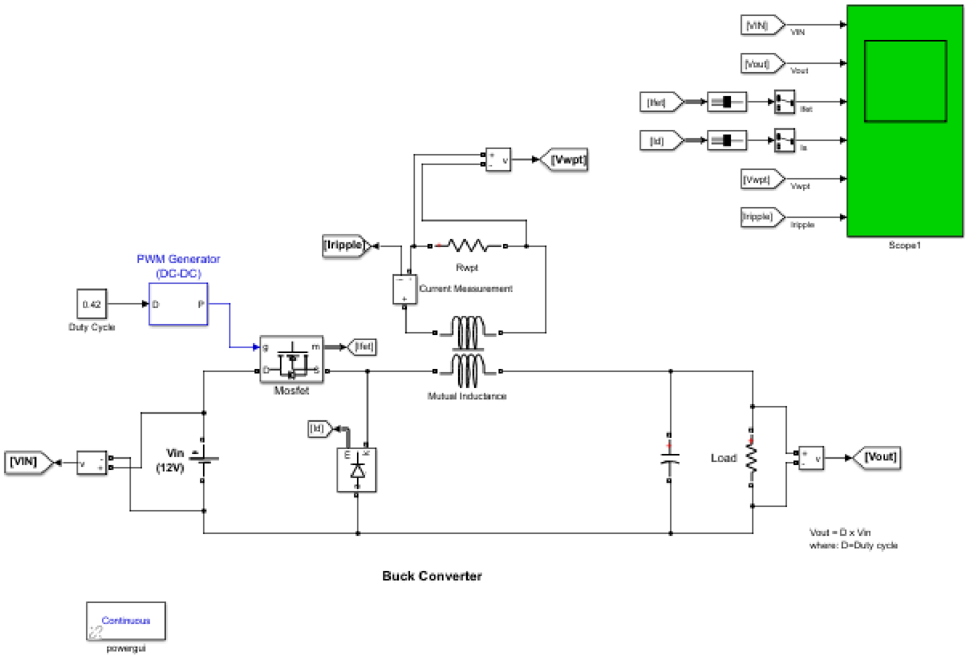

Figure 3.3 Buck-WPT circuit in SIMULINK.

3.3.1 2-coil Buck-WPT Converter

By using mutual inductance as inductor in simulate the WPT in the buck converter, 2-coil and 4 coil mutual inductance are added to study the effect of inductor current ripple toward load at WPT and buck converter. 2-coil WPT-Buck Converter using 2 coil as transmitter (Tx) from buck converter and receiver (Rx) at WPT load to simulate inductor current transfer between two coil.

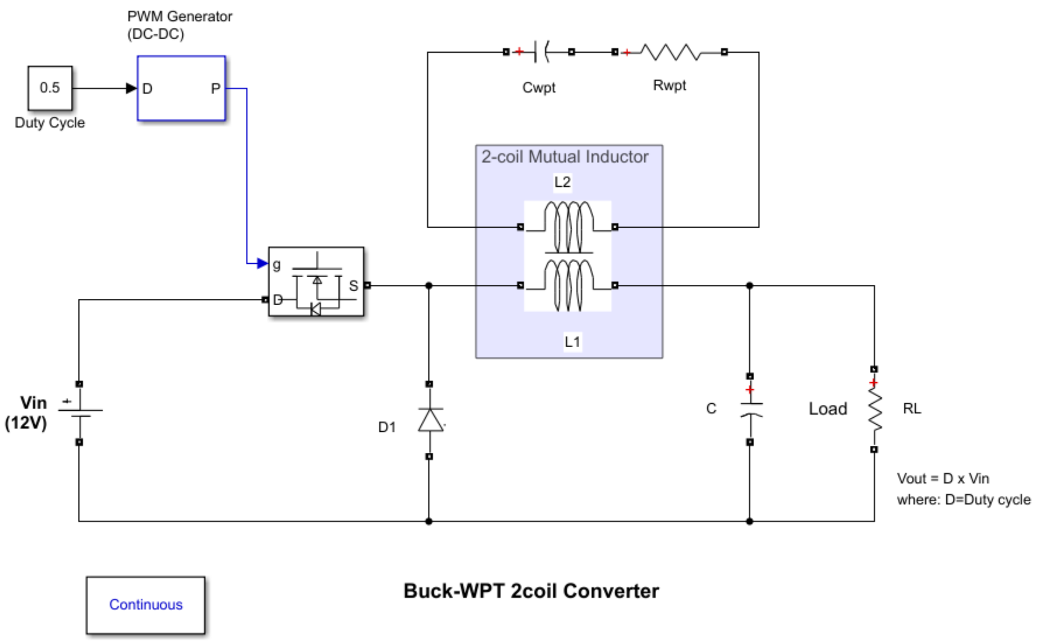

Figure 3.4 2-coil Buck-WPT circuit

In the Simulink, mutual inductance value must be put in the form of the inductance matrix. 2-coil mutual inductance require 2-by-2 matrix. Mutual Inductance that produce between the coil can be expressed as equation 3.1.

$$M = k\sqrt{L1 \times L2} \quad 3.1$$

The mutual inductance M represent by the square root of the inductor with coupling factor. Mutual inductances indicate the form of magnetic coupling between two inductors or coils.in terms of the self-inductance of each coil. The calculation inside of mutual inductance must be include the coupling factor to demonstrate the losses of the coil.

$$M_{2-COIL} = \begin{bmatrix} L1 & M_{12} \\ M_{21} & L2 \end{bmatrix} \quad 3.2$$

$$M_{2-COIL} = \begin{bmatrix} L1 & k\sqrt{L1 \times L2} \\ k\sqrt{L2 \times L1} & L2 \end{bmatrix}$$

$$= \begin{bmatrix} 3 & 2.6 \\ 2.6 & 9 \end{bmatrix}$$
$$= [3\ 2.6, 2.6\ 9\ ]$$

Inductance matrix of 2-coil must be put as equation 3.2 and the calculation of the M must be according to self-inductance of the coil. The result of the mutual inductance matrix calculation must be put in linear before change the mutual inductance matrix in Simulink.

3.3.2 4-coil Buck-WPT Converter

4-coil Buck WPT converter is a system that merge the buck converter with the 4-coil WPT system. The input coil L1 in the buck converter, the transmitting coil L2, the receiver coil L3, and the load coil L4 form the 4-coil WPT system.

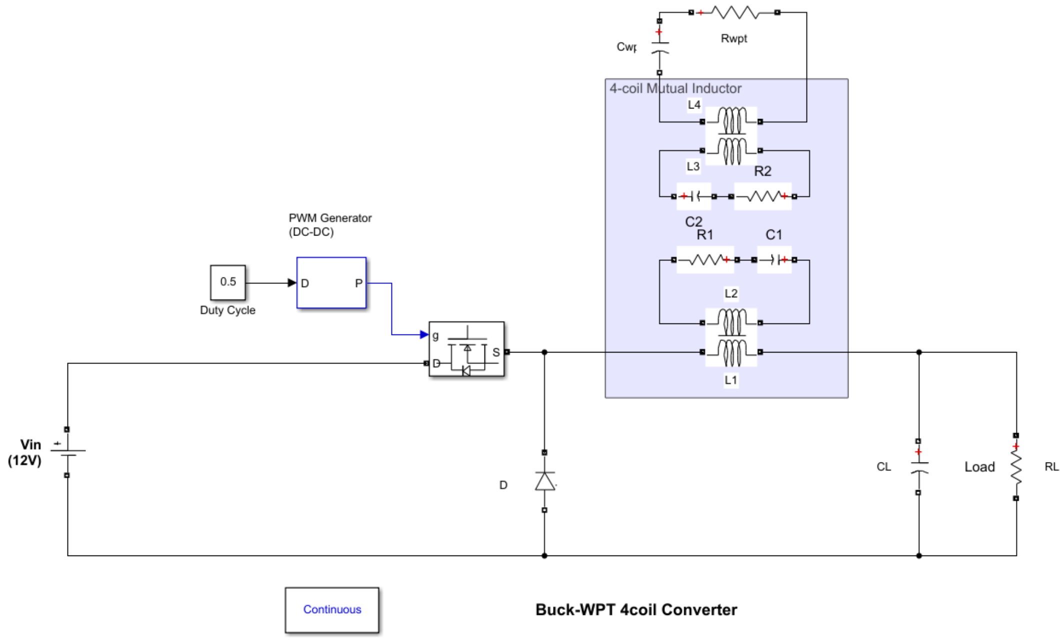

Figure 3.5 4-coil buck-WPT circuit

In the Simulink, mutual inductance value must be put in the form of the inductance matrix. 4-coil mutual inductance require 4-by-4 matrix. Mutual inductance that produces between the coil can be expressed as equation 3.1

$$M_{4-COIL} = \begin{bmatrix} L1 & M_{12} & M_{13} & M_{14} \\ M_{21} & L2 & M_{23} & M_{24} \\ M_{31} & M_{32} & L3 & M_{34} \\ M_{41} & M_{42} & M_{43} & L4 \end{bmatrix} = \begin{bmatrix} 3 & \sqrt{3\times 6} & \sqrt{3\times 6} & \sqrt{3\times 9} \\ \sqrt{3\times 6} & 6 & \sqrt{6\times 6} & \sqrt{6\times 9} \\ \sqrt{3\times 6} & \sqrt{6\times 6} & 6 & \sqrt{6\times 9} \\ \sqrt{9\times 3} & \sqrt{9\times 6} & \sqrt{9\times 6} & 9 \end{bmatrix} = \begin{bmatrix} 3 & 4.24 & 4.24 & 5.2 \\ 4.24 & 6 & 6 & 7.35 \\ 4.24 & 6 & 6 & 7.35 \\ 5.2 & 7.35 & 7.35 & 9 \end{bmatrix}$$	3.3

Inductance matrix of 4-coil must be put as equation 3.3 and the calculation of the M must be according to self-inductance of the coil. Mutual inductance matrix of 4-coil must be symmetrical to simulate mutual inductance in Simulink. The result of the mutual inductance matrix calculation must be put in linear before change the mutual inductance matrix in Simulink.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discussed the relationship between the Buck-WPT system and the inductor current ripple.

4.2 Output Waveform

4.2.1 Duty Cycle

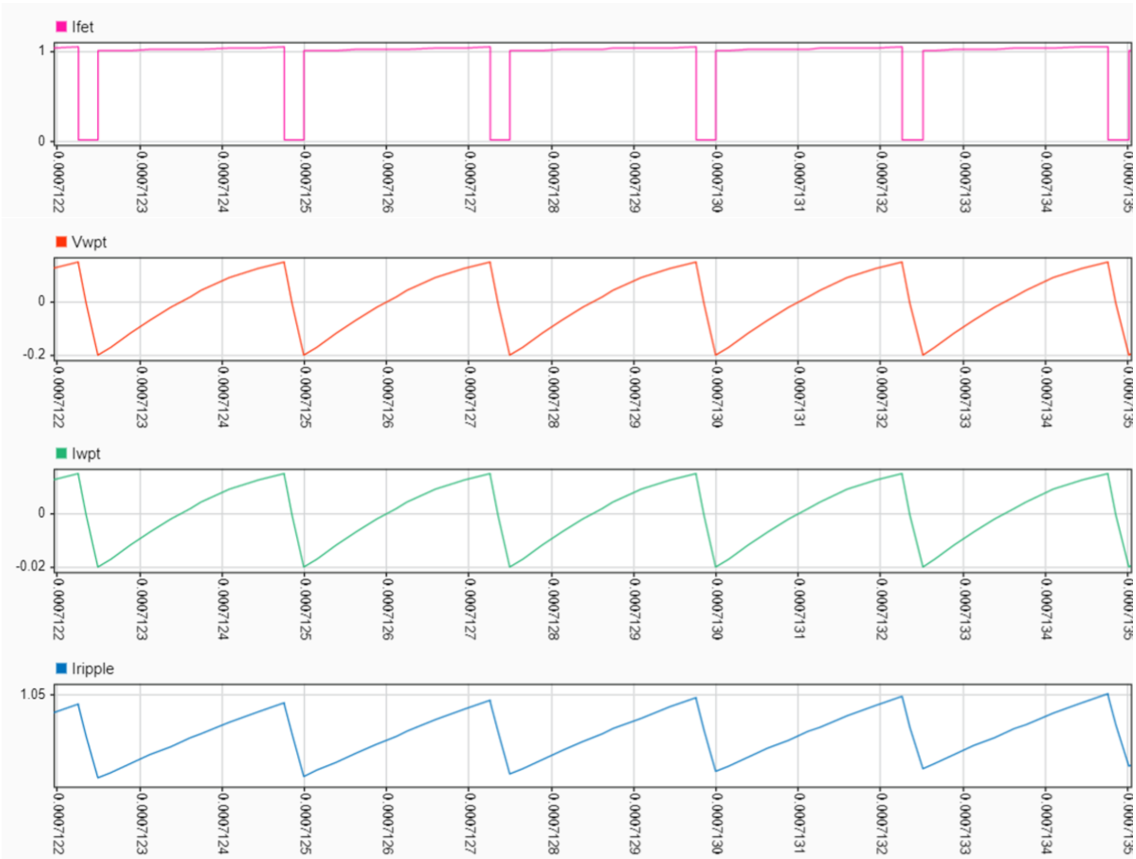

Figure 4.1 Output waveform of 2-coil Buck-WPT converter at D = 0.9.

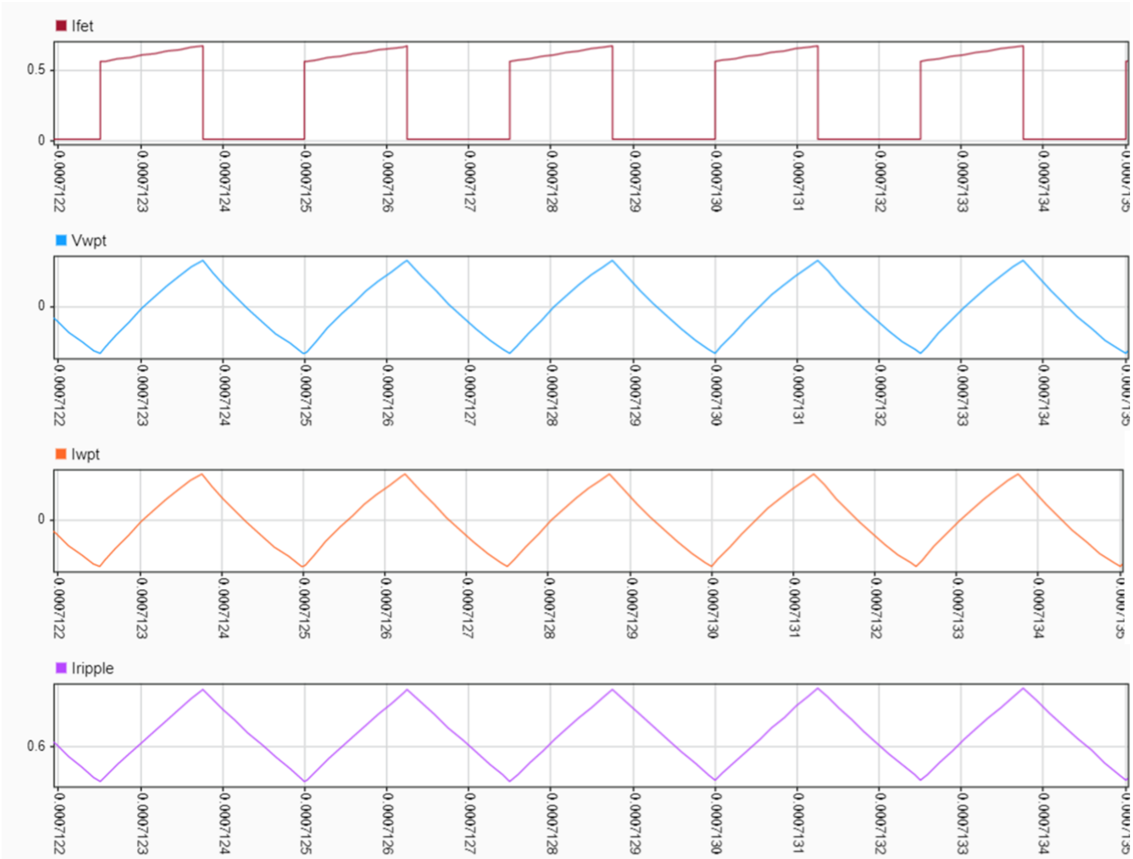

Figure 4.2 Output waveform of 2-coil Buck-WPT converter at D = 0.5.

The duty cycle be main factor in determining the output of WPT. During transistor in switch on period, the current is supplied to the load by the switching transistor when it is turned on. Current that flow to the load of buck converter will be store as energy in inductor. In this phase, store energy in the L1 will produce flux energy that transmit from coil L1 to L2. The current of WPT (Iwpt) and inductor current ripple (Iripple) will increase at the same time.

During transistor in switch off period, energy that stored inside the inductor will begin to release through the circuit of buck converter. Flux inside the L1 will start to decrease as the stored energy begin to release to the circuit. As the the flux decrease the current produce at Iwpt also will be decrease.

The output voltage of Rwpt of 0.5 duty cycle is higher than 0.9 duty cycle. When Buck-WPT duty cycle is set to 0.5, the period of transistor switching is same for on and off period resulting inductor store and release energy within the same period compared to when Buck-WPT is set to 0.9 duty cycle.

4.2.2 Inductor Current Ripple

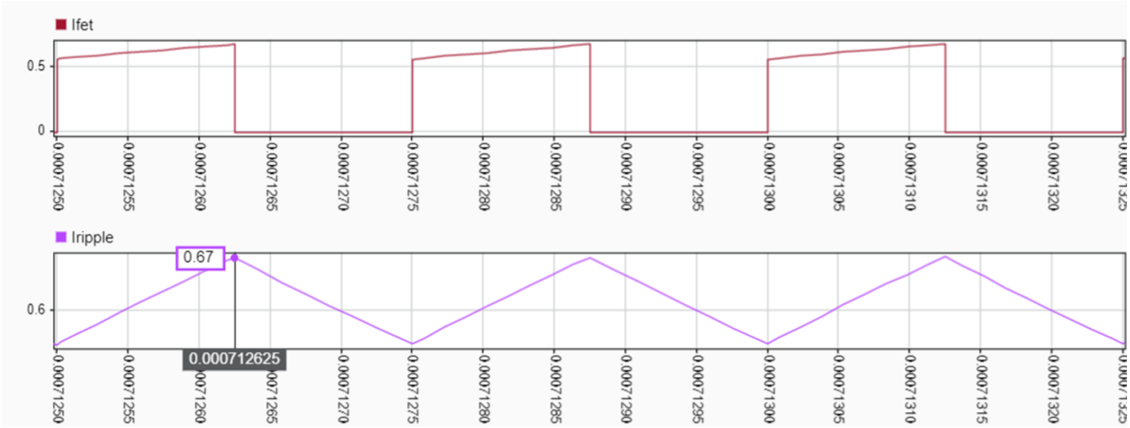

Figure 4.3 Inductor current ripple in 2-coil Buck-WPT converter

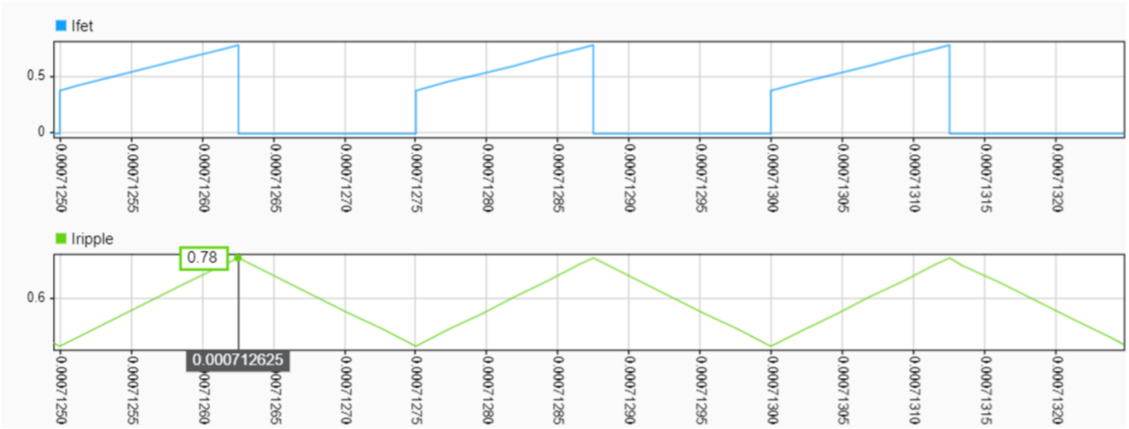

Figure 4.4 Inductor current ripple in 4-coil Buck-WPT converter

Figure 4.3 shown the inductor current ripple in 2-coil Buck-WPT converter whereas inductor current ripple in 2-coil Buck-WPT converter is shown in Figure 4.4. Both of the WPT circuit parameter is fixed and the output waveform is taken by using Simulink software. Inductor current ripple in 4-coil Buck-WPT converter is measured at 0.78A whereas 2-coil Buck-WPT converter reach 0.67. Inductor current ripple in 4-coil Buck-WPT converter is higher to be compared to 2-coil Buck-WPT converter due to additional loop at 4 coil WPT. The additional 2 loop in 4-coil WPT has increase the mutual inductance cause the inductor current ripple also increase.

4.3 Result and Analysis for Duty Cycle.

4.3.1 Data Collection

The process of data collection in 2-coil Buck-WPT converter in depth analysis of duty cycle was carried out by varied the duty cycle from 0.1 until 0.9. The parameter of 2-coil Buck-WPT converter was fixed such as parameter Table 4.1 to observe the output.

Table 4.1 Parameter of the 2-Coil Buck-WPT Converter(Duty cycle)

Vin	12 V
Frequency	4 MHz
L1	3μH
L2	9 μH
C	10 μF
Rwpt	10Ω
Rload	10Ω
k	0.5

Data collected in Table 4.2 was collected by varied the duty cycle. Load efficiency for Rload and Rwpt was calculated in this table.

Table 4.2 Data obtain by varied duty cycle in 2-coil Buck-WPT converter

Duty cycle	V_{Rload}(V)	V_{wpt} (V)	P_{in}(W)	P_{Rload}(W)	P_{Rwpt} (W)
0.9	10.8	0.1065	12.3	11.66	0.001139
0.8	9.6	0.189	10.31	9.214	0.003588
0.7	8.4	0.2487	8.445	7.055	0.006199
0.6	7.2	0.2842	6.708	5.183	0.008069
0.5	6	0.2956	5.11	3.599	0.008727
0.4	4.8	0.2836	3.663	2.304	0.008047
0.3	3.6	0.2474	2.384	1.296	0.006129
0.2	2.4	0.1879	1.301	0.5759	0.003539
0.1	1.2	0.1065	0.4612	0.144	0.001117

Data collection in 4-coil Buck-WPT converter in depth analysis of duty cycle was carried out by varied the duty cycle from 0.1 until 0.9. The parameter of 4-coil Buck-WPT converter was fixed to observe the output. The parameter of buck converter can be follow as Table 4.3.

Table 4.3 Parameter of the 2-Coil Buck-WPT Converter(Duty cycle)

Vin	12 V
Frequency	4 MHz
L1	3µH
L2, L3	6 µH
L4	9 µH
C	10 µF
Rwpt	10Ω
Rload	10Ω
k	0.5

Table 4.4 shows the data obtain in 4-coil Buck-WPT converter when its duty cycle was varied. The efficiency of Rload and Rwpt was calculated for further analysis.

Table 4.4 Data obtain by varied duty cycle in 4-coil Buck-WPT converter

Duty cycle	V_{Rload}(V)	V_{wpt} (V)	P_{in}(W)	P_{Rload}(W)	P_{Rwpt} (W)
0.9	10.8	0.06452	12.3	11.66	0.000416
0.8	9.6	0.1115	10.34	9.214	0.001243
0.7	8.4	0.145	8.494	7.055	0.002103
0.6	7.2	0.1643	6.779	5.183	0.002699
0.5	6	0.17	5.194	3.599	0.002889
0.4	4.8	0.1637	3.751	2.304	0.002681
0.3	3.6	0.1428	2.461	1.296	0.002039
0.2	2.4	0.1091	1.358	0.5759	0.00119
0.1	1.2	0.06151	0.4094	0.144	0.000378

4.3.2 Analysis

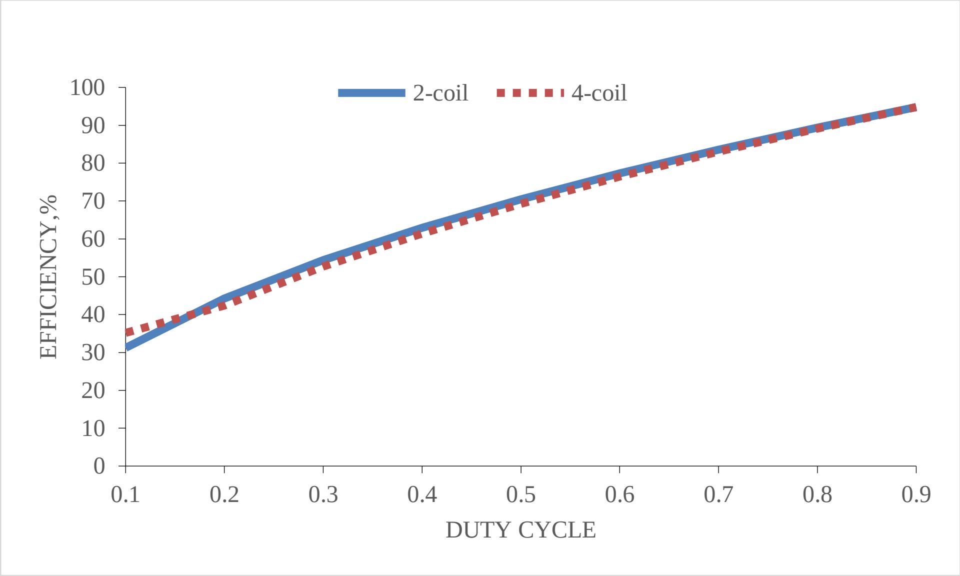

Figure 4.5 Efficiency of Rload between 2 coil and 4 coil against duty cycle

As the duty cycle increase, the efficiency the Rload also increase for both coils. However, 4-coil Buck WPT converter at duty cycle 0.1 has higher efficiency than 2-coil-Buck WPT converter. Duty cycle at 0.1 achieve 30%.and achieve up to 90% when duty cycle is set to 0.9. As the duty cycle is increase, the efficiency of Rload also increase. Varied the duty cycle in Buck-WPT converter does not seem to change the efficiency of the Rload for both coils.

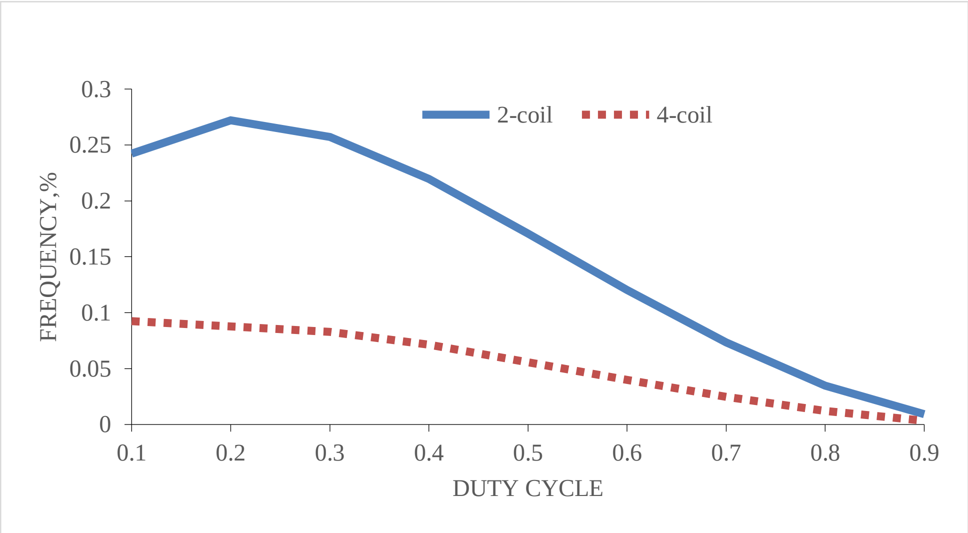

Figure 4.6 Efficiency Of RWPT Between 2 Coil And 4 Coil Against Duty Cycle

The efficiency of Rwpt for 2-coil Buck-WPT Converter is high at duty cycle 0.1 and 0.2 but drop until 0.9. This is the result when input power of buck converter is increase as the output power also increase when duty cycle increase. However, the output power of Rwpt increase in low increment resulting from the output power of Rwpt is too low compared to input power of buck converter when duty cycle is set to 0.9.

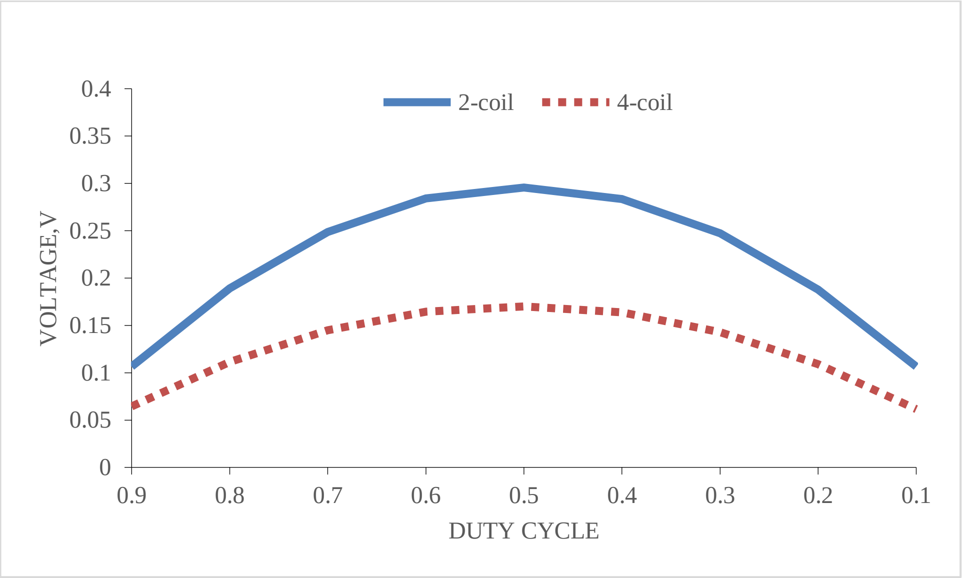

Figure 4.7 Output Voltage of Rwpt Between 2-Coil And 4-Coil Against Duty Cycle

Figure 4.7 shows that output voltage of Rwpt achieve the same trend for both 2-coil and 4-coil. Both 2-coil and 4-coil Buck-WPT reach peak voltage at duty cycle at 0.5 although output voltage of 4-coil Buck-WPT converter lower voltage compare to2-coil Buck-WPT converter output voltage of Rwpt is affected by switching period of the transistor. At D= 0.5 inductor able to store and release energy due to has the same period when transistor is switch on and off. The store energy in the inductor is lower during $0.1 \leq D \geq 0.4$ due to has less period of the transistor when it's on resulting there are low magnetic field in the inductor.

4.4 Result and Analysis for Frequency.

4.4.1 Data Collection

Table 4.5 Data obtain by varied frequency in 2-coil Buck-WPT converter

Freq, kHz	V_{Rload}(V)	V_{wpt} (V)	P_{in}(W)	P_{Rload}(W)	P_{Rwpt} (W)
4000	6	0.2956	5.125	3.598	0.00873
5000	6	0.2329	5.118	3.598	0.005442
6000	6	0.1928	5.115	3.598	0.003716
7000	6	0.1649	5.113	3.598	0.002716
8000	6	0.1446	5.112	3.598	0.002094

Table 4.6 Parameter of the 2-Coil Buck-WPT Converter(Frequency)

Vin	12 V
Duty cycle	0.5
L1	3µH
L2	9 µH
C	10 µF
Rwpt	10Ω
Rload	10Ω
k	0.5

The depth analysis for frequency in 2-coil Buck-WPT Converter used parameter at Table 4.6. The efficiency of load will be calculated from data collected in Table 4.5 from varied the frequency.

Table 4.7 Data obtain by varied frequency in 4-coil Buck-WPT converter

Freq, kHz	V_{Rload}(V)	V_{wpt} (V)	P_{in}(W)	P_{Rload}(W)	P_{Rwpt} (W)
4000	6	0.17	5.194	3.599	0.002889
5000	6	0.1377	5.158	3.599	0.001896
6000	6	0.1154	5.138	3.599	0.001331
7000	6	0.09947	5.126	3.599	0.000995
8000	6	0.08837	5.119	3.599	0.000781

Table 4.8 Parameter of the 4-Coil Buck-WPT Converter(Frequency)

Vin	12 V
Duty cycle	0.5
L1	3µH
L2	9 µH
C	10 µF
Rwpt	10Ω
Rload	10Ω
k	0.5

The depth analysis for frequency in 4-coil Buck-WPT Converter has been follow the parameter at Table 4.8. The efficiency of load will be calculated from data collected from varied the frequency in Table 4.7.

4.4.2 Analysis

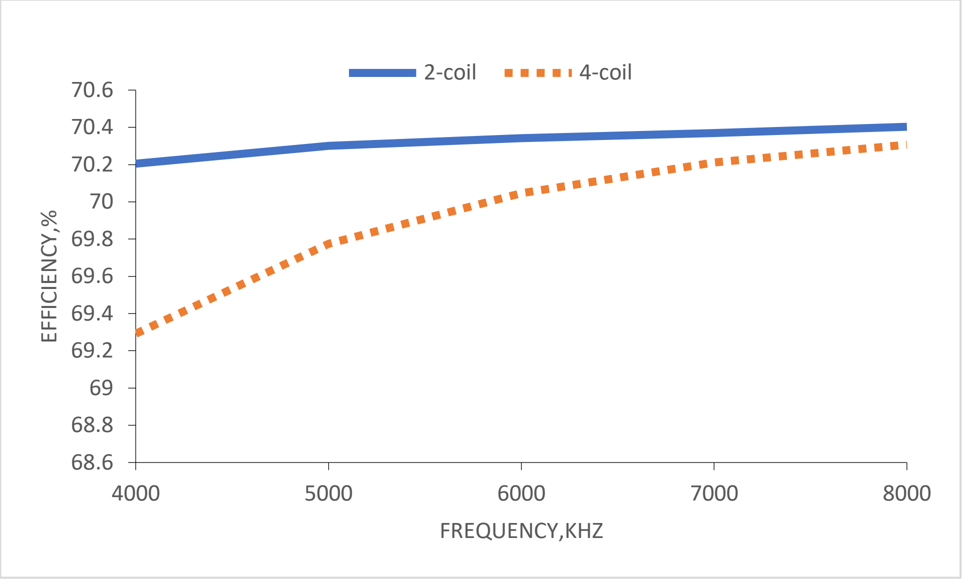

Figure 4.8 Efficiency of Rload between 2-coil and 4-coil against Frequency

Figure 4.8 shows that the efficiency of Rload for 4-coil Buck-WPT converter is gradually increase from 4000 kHz until 8000 kHz. The higher the frequency of the 4-coil Buck-WPT converter the nearer reach efficiency of Rload in 2-coil. 4-coil Buck-WPT converter require high frequency to operate the buck converter. The output voltage of the load in the buck converter will not match the output voltage of the buck converter if the frequency is lower than 4000 kHz in the 4-coil Buck-WPT converter.

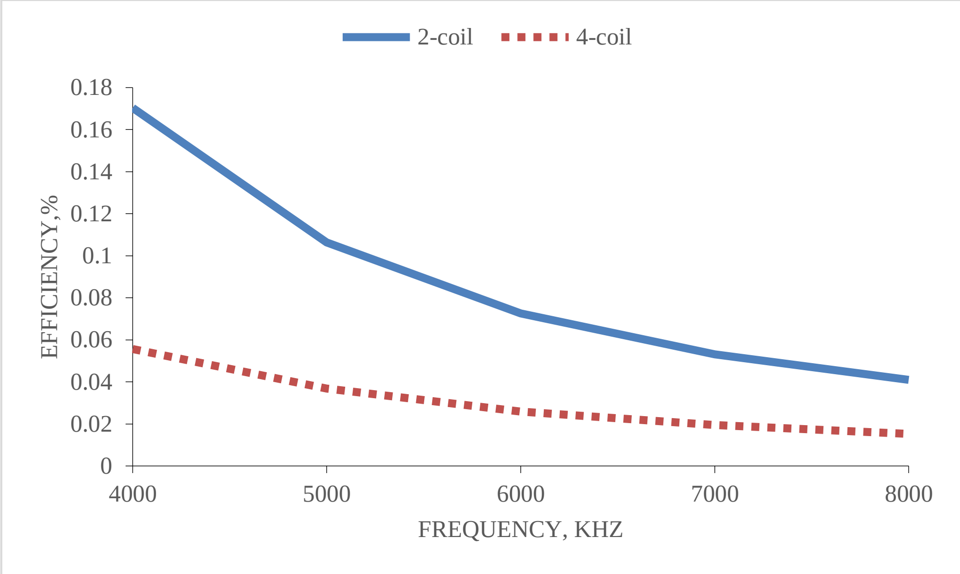

Figure 4.9 Efficiency of Rwpt between 2-coil and 4-coil against frequency

The efficiency of Rwpt for 2-coil and 4-coil Buck-WPT Converter decline as the switching frequency increase as shown in Figure 4.9. When the switching frequency is increased with fixed inductance, the inductor ripple current and the output voltage ripple is decreased. It will lead to higher switching losses and low efficiency. High switching frequencies can cause inductor core losses, which can lead to even greater efficiency losses.

4.5 Result and Analysis for Coupling Factor

4.5.1 Data Collection

The depth analysis of the coupling factor in 2-coil Buck-WPT converter was carried out by calculate the inductance matrix inside the mutual inductance. The value of inductance is fixed whereas coupling factor, k is varied from 0.05 until 0.5 to simulate fractional value of the total flux linkage between the coils. The parameter of the circuit is set as shown in Table 4.9. The result simulation was collected and calculate its efficiency in Table 4.10 for further analysis.

Table 4.9 Parameter of the 2-Coil Buck-WPT Converter(Coupling Factor)

Vin	12 V
Frequency	4 MHz
L1	3μH
L2	9 μH
C	10 μF
Rwpt	10Ω
Rload	10Ω
D	0.5

Table 4.10 Data obtain by varied coupling factor in 2-coil Buck-WPT converter

Coupling Factor,k	V_{Rload}(V)	V_{wpt} (V)	P_{in}(W)	P_{Rload}(W)	P_{Rwpt} (W)
0.05	6	0.02203	5.111	3.599	4.8466E-05
0.1	6	0.044	5.111	3.599	0.00019689
0.15	6	0.06748	5.111	3.599	0.0004547
0.2	6	0.09165	5.112	3.599	0.0008389
0.25	6	0.1175	5.113	3.599	0.001378
0.3	6	0.1454	5.114	3.599	0.002111
0.35	6	0.176	5.116	3.599	0.003095
0.4	6	0.2104	5.118	3.599	0.004422
0.45	6	0.2947	5.121	3.599	0.006231
0.5	6	0.2956	5.125	3.599	0.00873

The depth analysis of the coupling factor in 4-coil Buck-WPT converter was carried out by calculate the inductance matrix inside the mutual inductance. The value of inductance is fixed whereas coupling factor, k is varied from 0.05 until 0.5 to simulate fractional value of the total flux linkage between the coils. The parameter of the circuit is set as shown in Table 4.11.Then all the simulate data when varied the coupling factor will be collected and calculate its efficiency as shown in Table 4.12.

Table 4.11 Parameter of the 2-Coil Buck-WPT Converter(Coupling Factor)

Vin	12 V
Frequency	4 MHz
L1	3µH
L2, L3	6 µH
L4	9 µH
C	10 µF
Rwpt	10Ω
Rload	10Ω
Duty Cycle	0.5

Table 4.12 Data obtain by varied coupling factor in 4-coil Buck-WPT converter

Coupling Factor,k	V_{Rload}**(V)**	V_{wpt} **(V)**	P_{in}**(W)**	P_{Rload}**(W)**	P_{Rwpt} **(W)**
0.05	6	0.01965	5.129	3.599	0.0000386
0.1	6	0.03679	5.131	3.599	0.0001349
0.15	6	0.05213	5.134	3.599	0.0002718
0.2	6	0.06684	5.137	3.599	0.0004467
0.25	6	0.08157	5.142	3.599	0.0006654
0.3	6	0.09649	5.148	3.599	0.000931
0.35	6	0.1122	5.156	3.599	0.001259
0.4	6	0.1291	5.165	3.599	0.001667
0.45	6	0.1484	5.178	3.599	0.002202
0.5	6	0.17	5.194	3.599	0.002889

4.5.2 Analysis

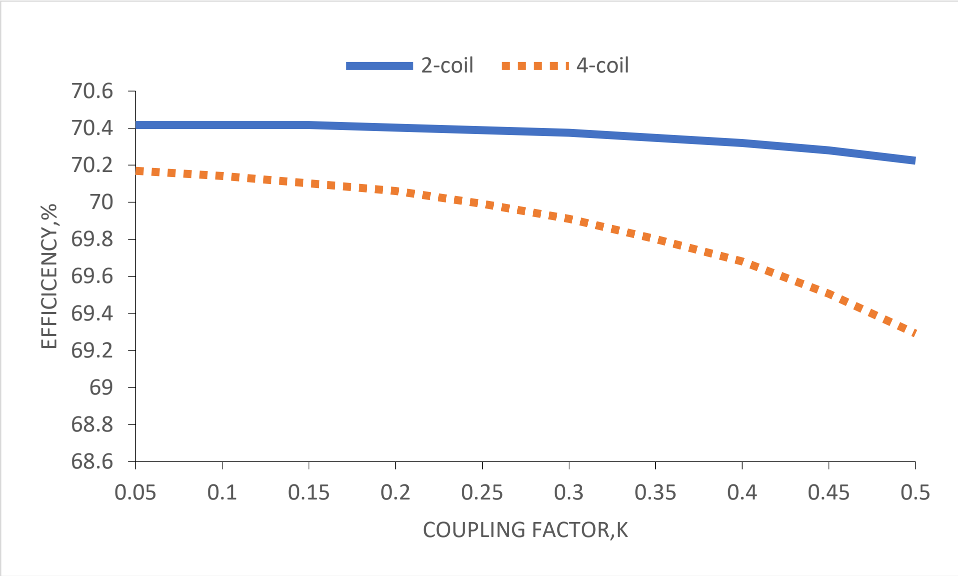

Figure 4.10 Efficiency of Rload between 2-coil and 4-coil against coupling factor

Figure 4.10 shows the efficiency of Rload between 2-coil and 4-coil when coupling factor is varied. The efficiency of Rload for 2-Coil Buck-WPT converter is able to maintain from k=0.05 until k=0.25 and drop its efficiency at k=0.3. The efficiency of Rload for 4-Coil Buck-WPT is decrease when coupling factor is increase. As the coupling factor is increase near to the value of unity (k=1) in mutual inductance, magnetic flux between the inductance will increase resulting the efficiency of Rload will decrease. 4-coil Buck-WPT converter has shown an obvious decline in efficiency of Rload due to increase of flux between the 4-coil.

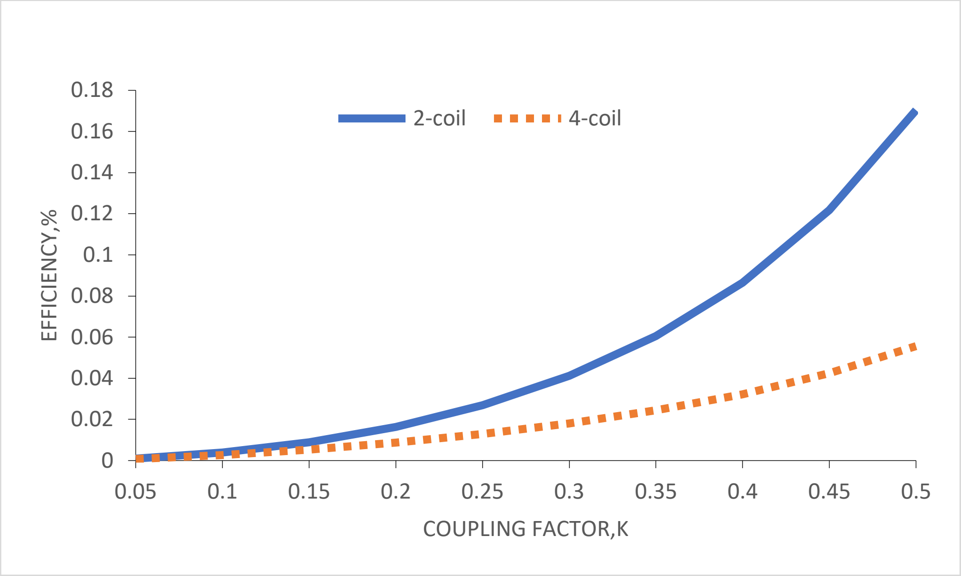

Figure 4.11 Efficiency of Rwpt between 2 coil and 4 coil against coupling factor

As the coupling factor near the value 1 which is unity within mutual inductance, there will be low loss due to leakage. Figure 4.11 presents rapid increase when the coupling factor is increase for both coil Buck-WPT converter. 2-coil Buck-WPT converter has higher efficiency of Rwpt than 4-coil Buck-WPT converter due to 4-coil WPT has more loss in efficiency in term of current leakage.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The method of harness energy from the inductor in buck converter has been study in this project. Replaced the inductor with planar coil or inductor can generate a WPT through the buck converter system. Both 2-coil and 4-coil WPT inductor were determined by calculating the mutual inductance and coupling factor, k. Both 2-coil and 4-coil WPT were simulated as mutual inductor in Simulink.

The transmission of efficiency of 2-coil and 4-coil Buck-WPT system was analysed. At high frequency range between 4 Mhz until 8 Mhz, the 2-coil produce up to 0.17% efficiency and the 4-coil produce 0.06% efficiency. Duty cycle is important in determining output voltage of the WPT system. Output voltage produces at 2-coil and 4-coil reach it peak at ~~when~~ D = 0.5. However, the efficiency of Rwpt is declining from D = 0.1 until D = 0.9 caused by transistor switching period. The higher the coupling factor inside the mutual inductance, the higher the Rwpt efficiency. The loss of efficiency in the mutual inductor due to current leakage and position between the coils can be reduced when the coupling factor, k is closer to 1.2-coil Buck-WPT converter has better performance in term efficiency compared to 4-coil Buck-WPT converter cause by 4-coil has low performance toward transistor switching and require high switching frequency to be operated.

5.2 Recommendation

Although the project is successful in finding the best coil for Buck-WPT converter, the efficiency of 2-coil Buck-WPT converter still only able to transfer certain amount of current from inductor current ripple. High frequency in the Buck-WPT converter is among the reason 2-coil Buck-WPT converter unable to produce higher efficiency in the WPT load. The frequency range between 20kHz to 60kHz is recommendable for further study of this circuit. The WPT circuit in Buck-WPT converter also can be improved to achieve higher efficiency. Thus, more studies can be done in future by focusing in WPT circuit.

REFERENCES

Henry Xie, E. G. (2019). *How the Switching Frequency Affects the Performance of a Buck Converter*. 1–8.

Huang, W., Member, S., Qahouq, J. A. A., & Member, S. (2016). *Input Voltage Ripple Based Sensorless Current Sharing Auto-Tuning Controller for Multiphase DC-DC Converters*. *9994*(c). https://doi.org/10.1109/TIA.2016.2570205

Kato, M., Imura, T., & Hori, Y. (2013). Study on maximize efficiency by secondary side control using DC-DC converter in wireless power transfer via magnetic resonant coupling. *World Electric Vehicle Journal*, *6*(4), 858–862. https://doi.org/10.3390/wevj6040858

Miller, J. M., Onar, O. C., & Chinthavali, M. (2014). *Primary Side Power Flow Control of Wireless Power Transfer for Electric Vehicle Charging*. https://doi.org/10.1109/JESTPE.2014.2382569

Mohd Khazani, A., Nur Riza, M. S., Nordin, J., Ahmad Samsuri, M., A. Rahim, A. T., & Mohd Faizal, Z. (2006). K-Chart: A Tool for Research Planning and Monitoring. *Journal of Quality Measurement and Analysis*, *2*(1), 123–129. https://www.academia.edu/2977536/K-Chart_a_tool_for_research_planning_and_monitoring

Qahouq, J. A. A., & Dang, Z. (2017). Investigation and simulation model results of high density wireless power harvesting and transfer method. *Conference Proceedings - IEEE Applied Power Electronics Conference and Exposition - APEC*, 3095–3099. https://doi.org/10.1109/APEC.2017.7931139

Yi, K. H. (2020). Output voltage analysis of inductive wireless power ttransfer with series lc and llc resonance operations depending on coupling condition. *Electronics (Switzerland)*, *9*(4). https://doi.org/10.3390/electronics9040592

Yusuke Moriwaki, Takehiro Imura, Y. H. (2011). Basic Study on Reduction of Reflected Power Using DC/DC Converters in Wireless Power Transfer System via Magnetic Resonant Coupling. *IEEE*, 0–4.

Zhigang Dang, & Abu Qahouq, J. A. (2015). Range and misalignment tolerance comparisons between two-coil and four-coil wireless power transfer systems. *2015 IEEE Applied Power Electronics Conference and Exposition (APEC)*, *2015-May*(May), 1234–1240. https://doi.org/10.1109/APEC.2015.7104505

Zhong, W. X. Hui, S. Y. R. (2015). Maximum energy efficiency tracking for wireless power transfer systems. *IEEE Transactions on Power Electronics*, *30*(7), 4025–4034. https://doi.org/10.1109/TPEL.2014.2351496

Zhou, Z., Zhang, L., Liu, Z., Chen, Q., Long, R., & Su, H. (2020). Model Predictive Control for the Receiving-Side DC-DC Converter of Dynamic Wireless Power Transfer. *IEEE Transactions on Power Electronics*, *35*(9), 8985–8997. https://doi.org/10.1109/TPEL.2020.2969996

Jaeger, H. A., & Cantillon-Murphy, P. (2018). Distorter characterisation using mutual inductance in electromagnetic tracking. *Sensors (Switzerland)*, *18*(9), 1–25. https://doi.org/10.3390/s18093059

Jens Ejury. (2013). *Buck Converter Design Note*.

Rahman, M. S. (2007). *Buck Converter Design Issues Master thesis performed in division of Electronic Devices*.

Yi, K. (2020). Output Voltage Analysis of Inductive Wireless Power Ttransfer with Series LC and LLC Resonance Operations Depending on Coupling Condition. *Electronics*, *9*(4), 592. https://doi.org/10.3390/electronics9040592

APPENDIX A

wpt_BuckConverter2

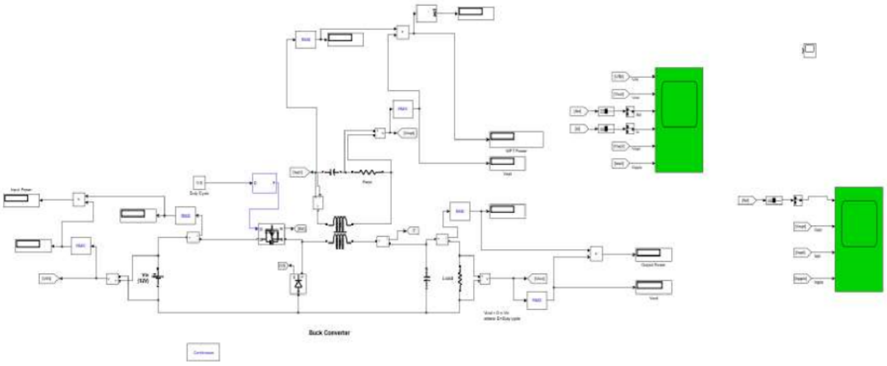

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Table of Contents

List of Tables

Model - wpt_BuckConverter2

Full Model Hierarchy

1. wpt_BuckConverter2

Simulation Parameter	Value
Solver	VariableStepAuto
RelTol	1e-4
Refine	1
MaxStep	1e-4
MaxOrder	5
ZeroCross	on

[more info]

System - wpt_BuckConverter2

Description.

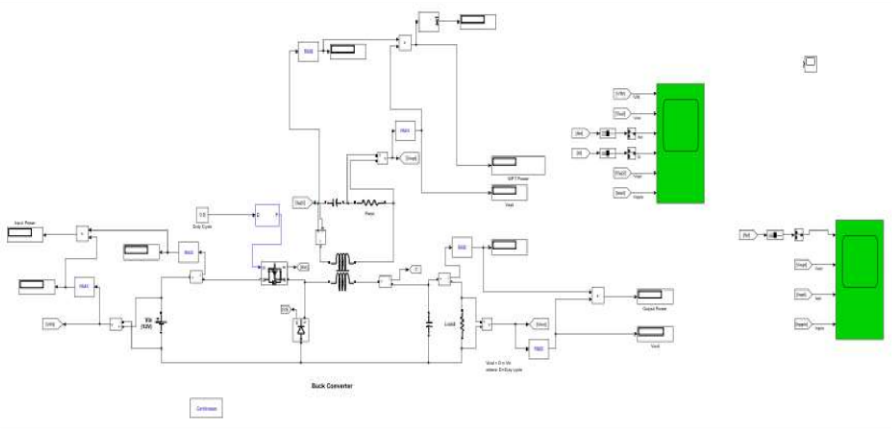

Table 1. BusToVector Block Properties

Name
Bus to Vector
Bus to Vector1
Bus to Vector2

Table 2. Constant Block Properties

Name	Value	Out Data Type Str	Lock Scale	Sample Time	Frame Period
Duty Cycle	0.9	Inherit: Inherit from 'Constant value'	off	inf	inf

Table 3. Current Measurement Block Properties

Name
Current Measurement
Current Measurement1
Current Measurement2
Current Measurement3

Table 4. DC Voltage Source Block Properties

Name	Amplitude	Measurements
Vin (12V)	12	None

Table 5. Diode Block Properties

Name	Ron	Lon	Vf	IC	Rs	Cs	Measurements
Diode1	1e-3	0	0	0	inf	inf	on

Table 6. Display Block Properties

Name	Format	Decimation	Floating
Display2	short	1	off
Display4	short	1	off
Display6	short	1	off
Display7	short	1	off
Display8	short	1	off
Input Power	short	1	off
Output Power	short	1	off
Vout	bank	1	off
Vwpt	short	1	off
WPT Power	short	1	off

Table 7. From Block Properties

Name	Goto Tag	Icon Display	Goto Blk Name	Goto Blk Location	Defined In Blk
From	Vout	Tag	Goto2	wpt_BuckConverter2	do not delete this gain
From1	VIN	Tag	Goto3	wpt_BuckConverter2	do not delete this gain
From12	Id	Tag	Goto	wpt_BuckConverter2	Demux, Demux
From2	Vwpt	Tag	Goto4	wpt_BuckConverter2	do not delete this gain
From3	Iwpt	Tag	Goto5	wpt_BuckConverter2	do not delete this gain
From4	Ifet	Tag	Goto1	wpt_BuckConverter2	Demux, Demux

Name	Goto Tag	Icon Display	Goto Blk Name	Goto Blk Location	Defined In Blk
From5	Vwpt	Tag	Goto4	wpt_BuckConverter2	do not delete this gain
From6	Iwpt	Tag	Goto5	wpt_BuckConverter2	do not delete this gain
From7	Iripple	Tag	Goto6	wpt_BuckConverter2	do not delete this gain
From8	Ifet	Tag	Goto1	wpt_BuckConverter2	Demux, Demux

Table 8. Goto Block Properties

Name	Goto Tag	Icon Display	Tag Visibility	From Blk	From Blk Location	Used By Blk
Goto	Id	Tag	local	From12	wpt_BuckConverter2	Selector
Goto1	Ifet	Tag	local	From8, From4	wpt_BuckConverter2, wpt_BuckConverter2	Selector1, Selector2
Goto2	Vout	Tag	local	From	wpt_BuckConverter2	Scope1, Product, Product, Product1, Product
Goto3	VIN	Tag	local	From1	wpt_BuckConverter2	Scope1, Product, Product, Product1, Product
Goto4	Vwpt	Tag	local	From5, From2	wpt_BuckConverter2, wpt_BuckConverter2	Scope2, Scope1, Product, Product, Product1, Product
Goto5	Iwpt	Tag	local	From6, From3	wpt_BuckConverter2, wpt_BuckConverter2	Scope2, Scope1, Product, Product, Product1, Product
Goto6	Iripple	Tag	local	From7	wpt_BuckConverter2	Scope2

Table 9. Mean Block Properties

Name	Freq	Vinit	Ts
Mean1	100e3	1	0

Table 10. Mosfet Block Properties

Name	Ron	Lon	Rd	Vfd	IC	Rs	Cs	Measurements
Mosfet	1e-3	0	1e-3	0	0	inf	inf	on

Table 11. Mutual Inductance Block Properties

Name	Type Of Mutual	Number Of Windings	Inductance Matrix	Resistance Matrix	Measurements
Mutual Inductance	Generalized mutual inductance	2	[3 2.6; 2.6 9] * 1e-6	[0 0 ; 0 0]	None

Table 12. PSB option menu block Block Properties

Name	Simulation Mode	Iterations	Frequencyindice	Pbase	Err Max	Units V	Units W	Function Messages	Echomessages	Current Source Switches	Disable Snubber Devices	Disable Ron Switches	Disable Vf Switches	Display Equations	Methode	X0stat
powergui	Continuous	50	0	100e6	1e-4	kV	MW	off	off	off	off	off	off	off	off	blocks

Table 13. PWM Generator (DC-DC) Block Properties

Name	Fsw	Ts
PWM Generator (DC-DC)	4000e3	0

Table 14. Product Block Properties

Name	Inputs	Multiplication	Collapse Mode	Collapse Dim	Input Same DT	Out Data Type Str	Lock Scale	Rnd Meth	Saturate On Integer Overflow
Product	2	Element-wise(.*)	All dimensions	1	off	Inherit: Inherit via internal rule	off	Floor	off
Product1	2	Element-wise(.*)	All dimensions	1	off	Inherit: Inherit via internal rule	off	Floor	off
Product2	2	Element-wise(.*)	All dimensions	1	off	Inherit: Inherit via internal rule	off	Floor	off

Table 15. RMS Block Properties

Name	True RMS	Freq	RMSInit	Ts
RMS	on	100e3	0	0
RMS1	on	100e3	0	0
RMS2	on	300e3	0	0

Name	True RMS	Freq	RMSInit	Ts
RMS3	on	100e3	0	0
RMS4	on	100e3	0	0
RMS5	on	100e3	0	0

Table 16. Selector Block Properties

Name	Number Of Dimensions	Index Mode	Index Option Array	Index Param Array	Output Size Array	Input Port Width	Index Options	Indices	Output Sizes
Selector	1	One-based	Index vector (dialog)	1	1	2	Index vector (dialog)	1	1
Selector1	1	One-based	Index vector (dialog)	1	1	2	Index vector (dialog)	1	1
Selector2	1	One-based	Index vector (dialog)	1	1	2	Index vector (dialog)	1	1

Table 17. Series RLC Branch Block Properties

Name	Branch Type	Resistance	Measurements
Load	R	10	None
Rwpt	R	10	None
Series RLC Branch1	C	1e-4	None
Series RLC Branch2	C	1e-4	None

Table 18. Voltage Measurement Block Properties

Name
Voltage Measurement
Voltage Measurement1
Voltage Measurement2

Appendix

Table 19. Block Type Count

BlockType	Count	Block Names
From	10	From, From1, From12, From2, From3, From4, From5, From6, From7, From8
Display	10	Display2, Display4, Display6, Display7, Display8, Input Power, Output Power, Vout, Vwpt, WPT Power
Goto	7	Goto, Goto1, Goto2, Goto3, Goto4, Goto5, Goto6
RMS (m)	6	RMS, RMS1, RMS2, RMS3, RMS4, RMS5
Series RLC Branch (m)	4	Load, Rwpt, Series RLC Branch1, Series RLC Branch2
Current Measurement (m)	4	Current Measurement, Current Measurement1, Current Measurement2, Current Measurement3
Voltage Measurement (m)	3	Voltage Measurement, Voltage Measurement1, Voltage Measurement2
Selector	3	Selector, Selector1, Selector2
Scope	3	Scope, Scope1, Scope2
Product	3	Product, Product1, Product2
BusToVector	3	Bus to Vector, Bus to Vector1, Bus to Vector2
PWM Generator (DC-DC) (m)	1	PWM Generator (DC-DC)
PSB option menu block (m)	1	powergui
Mutual Inductance (m)	1	Mutual Inductance
Mosfet (m)	1	Mosfet
Mean (m)	1	Mean1
Diode (m)	1	Diode1
DC Voltage Source (m)	1	Vin (12V)
Constant	1	Duty Cycle

APPENDIX B

wpt_BuckConverter_4coil_drive_loop

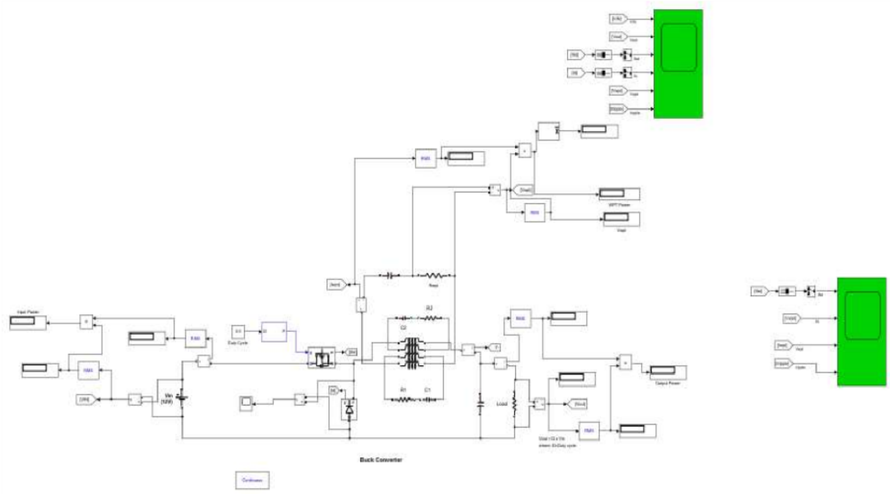

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Table of Contents

List of Tables

Model - wpt_BuckConverter_4coil_drive_loop

Full Model Hierarchy

1. wpt_BuckConverter_4coil_drive_loop

Simulation Parameter	Value
Solver	VariableStepAuto
RelTol	1e-4
Refine	1
MaxStep	1e-4
MaxOrder	5
ZeroCross	on

[more info]

System - wpt_BuckConverter_4coil_drive_loop

Description.

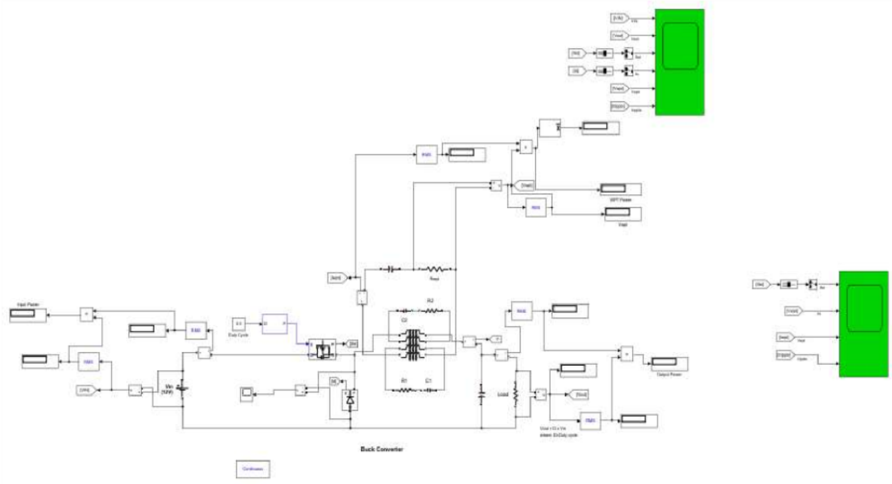

Table 1. BusToVector Block Properties

Name
Bus to Vector
Bus to Vector1
Bus to Vector2

Table 2. Constant Block Properties

Name	Value	Out Data Type Str	Lock Scale	Sample Time	Frame Period
Duty Cycle	0.5	Inherit: Inherit from 'Constant value'	off	inf	inf

Table 3. Current Measurement Block Properties

Name
Current Measurement
Current Measurement1
Current Measurement2
Current Measurement3

Table 4. DC Voltage Source Block Properties

Name	Amplitude	Measurements
Vin (12V)	12	None

Table 5. Diode Block Properties

Name	Ron	Lon	Vf	IC	Rs	Cs	Measurements
Diode1	1e-3	0	0	0	inf	inf	on

Table 6. Display Block Properties

Name	Format	Decimation	Floating
Display1	short	1	off
Display2	short	1	off
Display3	short	1	off
Display4	short	1	off
Display6	short	1	off
Display7	short	1	off
Display8	short	1	off
Input Power	short	1	off
Output Power	short	1	off
Vwpt	short	1	off
WPT Power	short	1	off

Table 7. From Block Properties

Name	Goto Tag	Icon Display	Goto Blk Name	Goto Blk Location	Defined In Blk
From	Vout	Tag	Goto2	wpt_BuckConverter_4coil_drive_loop	do not delete this gain
From1	VIN	Tag	Goto3	wpt_BuckConverter_4coil_drive_loop	do not delete this gain
From10	Ifet	Tag	Goto1	wpt_BuckConverter_4coil_drive_loop	Demux, Demux
From12	Id	Tag	Goto	wpt_BuckConverter_4coil_drive_loop	Demux, Demux
From2	Vwpt	Tag	Goto4	wpt_BuckConverter_4coil_drive_loop	do not delete this gain
From3	Iripple	Tag	Goto6	wpt_BuckConverter_4coil_drive_loop	do not delete this gain
From4	Vwpt	Tag	Goto4	wpt_BuckConverter_4coil_drive_loop	do not delete this gain
From7	Iwpt	Tag	Goto5	wpt_BuckConverter_4coil_drive_loop	do not delete this gain
From8	Ifet	Tag	Goto1	wpt_BuckConverter_4coil_drive_loop	Demux, Demux
From9	Iripple	Tag	Goto6	wpt_BuckConverter_4coil_drive_loop	do not delete this gain

Table 8. Goto Block Properties

Name	Goto Tag	Icon Display	Tag Visibility	From Blk	From Blk Location	Used By Blk
Goto	Id	Tag	local	From12	wpt_BuckConverter_4coil_drive_loop	Selector
Goto1	Ifet	Tag	local	From8, From10	wpt_BuckConverter_4coil_drive_loop, wpt_BuckConverter_4coil_drive_loop	Selector1, Selector3
Goto2	Vout	Tag	local	From	wpt_BuckConverter_4coil_drive_loop	Scope1, Product, Product, Product1, Product, Display2
Goto3	VIN	Tag	local	From1	wpt_BuckConverter_4coil_drive_loop	Scope1, Product, Product, Product1, Product
Goto4	Vwpt	Tag	local	From4, From2	wpt_BuckConverter_4coil_drive_loop, wpt_BuckConverter_4coil_drive_loop	Scope2, Scope1, Product, Product, Product1, Product
Goto5	Iwpt	Tag	local	From7	wpt_BuckConverter_4coil_drive_loop	Scope2, Product, Product, Product1, Product
Goto6	Iripple	Tag	local	From9, From3	wpt_BuckConverter_4coil_drive_loop, wpt_BuckConverter_4coil_drive_loop	Scope2, Scope1

Table 9. Mean Block Properties

Name	Freq	Vinit	Ts
Mean	100e3	1	0

Table 10. Mosfet Block Properties

Name	Ron	Lon	Rd	Vfd	IC	Rs	Cs	Measurements
Mosfet	1e-3	0	1e-3	0	0	inf	inf	on

Table 11. Mutual Inductance Block Properties

Name	Type Of Mutual	Number Of Windings	Inductance Matrix	Resistance Matrix	Measurements
Mutual Inductance1	Generalized mutual inductance	4	[3 2.121 2.121 2.598; 2.121 6 3 3.674; 2.121 3 6 3.674; 2.598 3.674 3.674 9]* 1e-6	[0 0 0 0 ; 0 0 0 0 ; 0 0 0 0 ; 0 0 0 0]	Winding currents

Table 12. PSB option menu block Block Properties

Name	Simulation Mode	Iterations	Frequencyindice	Phase	Err Max	Units V	Units W	Function Messages	Echomessages	Current Source Switches	Disable Snubber Devices	Disable Ron Switches	Disable Vf Switches	Display Equations	Methode	X0stat
powergui	Continuous	50	0	100e6	1e-4	kV	MW	off	off	off	off	off	off	off	off	blocks

Table 13. PWM Generator (DC-DC) Block Properties

Name	Fsw	Ts
PWM Generator (DC-DC)	4000e3	0

Table 14. Product Block Properties

Name	Inputs	Multiplication	Collapse Mode	Collapse Dim	Input Same DT	Out Data Type Str	Lock Scale	Rnd Meth	Saturate On Integer Overflow
Product	2	Element-wise(.*)	All dimensions	1	off	Inherit: Inherit via internal rule	off	Floor	off

Name	Inputs	Multiplication	Collapse Mode	Collapse Dim	Input Same DT	Out Data Type Str	Lock Scale	Rnd Meth	Saturate On Integer Overflow
Product1	2	Element-wise(.*)	All dimensions	1	off	Inherit: Inherit via internal rule	off	Floor	off
Product2	2	Element-wise(.*)	All dimensions	1	off	Inherit: Inherit via internal rule	off	Floor	off

Table 15. RMS Block Properties

Name	True RMS	Freq	RMSInit	Ts
RMS	on	100e3	0	0
RMS1	on	300e3	0	0
RMS2	on	300e3	0	0
RMS3	on	100e3	0	0
RMS4	on	100e3	0	0
RMS5	on	100e3	0	0

Table 16. Selector Block Properties

Name	Number Of Dimensions	Index Mode	Index Option Array	Index Param Array	Output Size Array	Input Port Width	Index Options	Indices	Output Sizes
Selector	1	One-based	Index vector (dialog)	1	1	2	Index vector (dialog)	1	1
Selector1	1	One-based	Index vector (dialog)	1	1	2	Index vector (dialog)	1	1
Selector3	1	One-based	Index vector (dialog)	1	1	2	Index vector (dialog)	1	1

Table 17. Series RLC Branch Block Properties

Name	Branch Type	Capacitance	Setx 0	Measurements
C1	C	10e-9	off	None
C2	C	10e-9	off	None
Load	R	400e-6	off	None
R1	R	400e-6	off	None
R2	R	400e-6	off	None
Rwpt	R	1e-6	off	None
Series RLC Branch1	C	10e-6	off	None
Series RLC Branch2	C	0.01e-6	off	None

Table 18. Voltage Measurement Block Properties

Name
Voltage Measurement
Voltage Measurement1
Voltage Measurement2
Voltage Measurement3

Appendix

Table 19. Block Type Count

BlockType	Count	Block Names
Display	11	Display1, Display2, Display3, Display4, Display6, Display7, Display8, Input Power, Output Power, Vwpt, WPT Power
From	10	From, From1, From10, From12, From2, From3, From4, From7, From8, From9
Series RLC Branch (m)	8	C1, C2, Load, R1, R2, Rwpt, Series RLC Branch1, Series RLC Branch2
Goto	7	Goto, Goto1, Goto2, Goto3, Goto4, Goto5, Goto6
RMS (m)	6	RMS, RMS1, RMS2, RMS3, RMS4, RMS5
Voltage Measurement (m)	4	Voltage Measurement, Voltage Measurement1, Voltage Measurement2, Voltage Measurement3
Current Measurement (m)	4	Current Measurement, Current Measurement1, Current Measurement2, Current Measurement3
Selector	3	Selector, Selector1, Selector3
Scope	3	Scope, Scope1, Scope2
Product	3	Product, Product1, Product2
BusToVector	3	Bus to Vector, Bus to Vector1, Bus to Vector2
PWM Generator (DC-DC) (m)	1	PWM Generator (DC-DC)
PSB option menu block (m)	1	powergui
Mutual Inductance (m)	1	Mutual Inductance1
Mosfet (m)	1	Mosfet
Mean (m)	1	Mean
Diode (m)	1	Diode1
DC Voltage Source (m)	1	Vin (12V)
Constant	1	Duty Cycle