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Design of a Non-Ideal Buck Converter

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Abstract - *This report focused on the design of a buck (step down) converter which has a range of input voltages received from Lithium polymer battery (LiPo) and constant output voltage that supply a Lead acid battery (LA). The design is based on given specifications as well as takes into account the non-idealities of all components. The changeability of input voltages govern the switching frequency and the duty ratio to maintain a constant output performance i.e. voltage, current, and power. The first stage of the design is about a non-ideality modeling of the components and the theoretical calculations. Then, Simulation using Pspice software carried out to validate the operation of the buck converter circuit. The performance and efficiency analysis which covers the non-idealities effects with related waveforms of output voltage, current and power are discussed.*

Key Words: Buck , Losses, Duty ratio, Ripple, Switch

1. INTRODUCTION

DC-DC converters (also known as choppers) in power electronic systems are the circuits which convert the system voltages from one DC level to another DC level that can be step-down, step-up, or to regulate the output voltage level [1]. The choppers are employed in a wide range of applications for the power ranging from watts (mobile phones), through kilowatts (dc motor drives) to megawatts (traction vehicles). The DC choppers are classified into main two types namely; isolated and non-isolated. A non-isolated DC-DC converter has a dc path between its input and output. On the other hand, a transformer is used for an isolated DC-DC converter to eliminate the dc path between its input and output. There are three common types of non-isolated DC-DC converter known as buck, boost and buck boost. The buck converter is the most basic DC-DC converter topology. It is widely used in the industry to convert a higher input voltage into a lower output voltage. The Buck converter has two mode of operation; the continuous conduction mode (CCM) where inductor current that remains positive throughout the switching period and discontinuous conduction mode (DCM) where the inductor currents returning to zero during each period [2]. Fig. 1 shows the inductors current waveforms for CCM and DCM. This design project concentrate on design a Buck converter operates in CCM considering non-idealities properties of components. The buck converter used to charge a lead acid battery with constant energy.

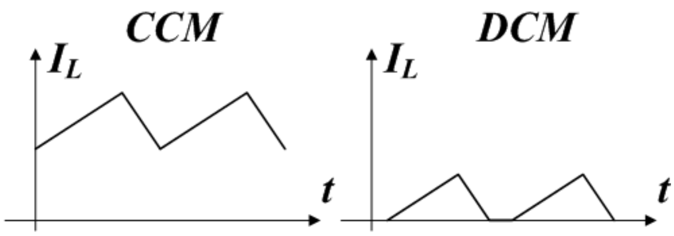

Fig. 1: The waveforms of Buck Converter's CCM and DCM modes.

2. METHODOLOGY

The approach that used in this design is based on theoretical calculations that consider the effects of non-idealities characteristics to estimate the circuit parameter values as referred to the modeled realistic buck converter circuit diagram as shown in Fig. 2. All variables as well as selection of components are described in details in Section III. Then, simulation works are carried out by using Pspice program to validate the operation and performance of the buck converter circuit. Performance and efficiency analysis and the key waveforms such as voltage, current and power are shown and discussed by taken into account for all non-ideal components used in the buck converter circuit.

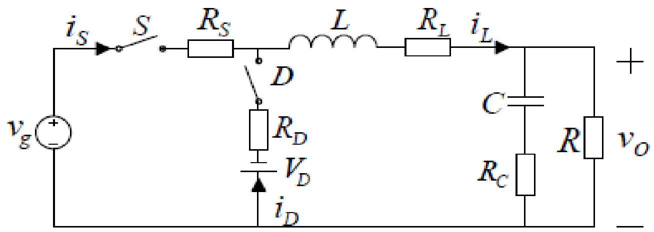

Fig. 2: The circuit diagram of non- ideal buck converter.

2.1 Design Specification

In this design project, a non-isolated buck converter operates in continuous conduction mode (CCM) is designed. The performance in terms of output voltage, current and output power is estimated. However, the effects of non-idealities due to components are observed. The design specifications are given as follows:-

- Input supply : 350 Vdc high voltage LiPo battery
- Output voltage : 48 Vdc Lead acid battery.
- Output power : 400 W
- Output voltage ripple : < 5%

The satisfaction of analysis the real case buck converter is depend on decent modeling of components and the effects of non-idealities variable. For sick of design such realistic buck converter, some variables have been considered and investigated. Such as The following non-ideal characteristics:

- The on-resistance of the MOSFETs RDS(on).
- Diode voltage drop V_f.
- Inductor winding resistance r_L.
- Equal series resistance of capacitor (ESR).

The key point of analyzing the buck converter is to study the voltage and current in inductor during each cycle D and (1-D) where D indicates the cycle in which the switch is closed and (1-D) indicates the cycle in which the switch is open.

2.2 Design Calculations and Considerations

The theoretical calculation is performed at the steady state operations of the buck converter in continuous conduction mode based on typical principal waveforms. Besides, the highest input voltage which is 350V is used to derive the system components. Consequently, The lowest input voltage used by varying the switching frequency and duty ratio for the same components. In result, there will be two duty ratios and two switching frequencies. The high switching frequencies will increase the power loss in the switch. The Increased power loss in the switch produces more heat. This will decrease the converters efficiency and require a large heat sink. Nonetheless, the size of inductor and capacitor will be decrease. Typical switching frequencies are above 20 kHz, and may they extend into the megahertz range. Some designers prefer about 500 kHz to be the best settlement [3]. The switching frequency used in this design selected to be 300 KHz as middle ground of the two above considerations.

2.2.1. Load Resistor R_L and output Current I_o

Since the output voltage and power are given we can calculate the output current and load resistance as follow:

$$R_L = \frac{V_o^2}{P_o} = \frac{48^2}{400} = 5.76\ \Omega$$

$$I_o = \frac{P_o}{V_o} = \frac{400}{48} = 8.33\ Amp$$

2.2.2. Duty Ratio (D)

The key to the analysis for determine the Duty ratio is to examine the inductor current and inductor voltage first for the switch closed D and then for the switch open (1-D) as shown in figure 3. For steady state operation, the total change in inductor current over one period is equal to zero as follow:

$$\Delta i_{L,ON} + \Delta i_{L,OFF} = 0$$

Now, we study what the inductor current equal to during both cases. Considering the on-resistance $R_{DS(on)}$ of the MOSFET, the diode voltage drop V_f , and inductor winding resistance R_L, the required duty cycle is larger to compensate for the voltage drop across the switch, diode, and inductor in order to regulate output voltage. When the switch is closed, the voltage across the inductor v_l can be modeled during DT as:

$$v_L = L\frac{\Delta i_{L,ON}}{dt} = V_s - I_o R_{DS} - I_o r_L - V_o$$

When the switch is opened, the voltage across the inductor v_l can be modeled during (1-D)T as

$$v_L = L\frac{\Delta i_{L,OFF}}{dt} = -V_o - V_f - I_o r_L$$

Therefore,

$$(V_s - I_o R_{DS} - I_o r_L - V_o)DT$$
$$= (V_o + V_f + I_o r_L)(1-D)T$$

Then we get

$$D = \frac{V_o + V_f + I_o r_L}{V_s + I_o r_L - I_o R_{DS}}$$

The values of the components in equation above can be obtained and found in the component selection in the next sections. The on-resistance of the MOSFET RDS(on) = 0.3 Ω for IRFP350. the diode forward voltage drop Vf = 1.8V for BYT12P and the inductor winding resistance r_L= 5mΩ. Since the input voltages are two Values, the duty ratio must be calculated for each one independently. the duty ratios will be as follow:

$$D_{350} = \frac{48 + 1.8 + 8.33 * 0.005}{350 + 8.33 * 0.005 - 8.33 * 0.3}$$

2.2.3. Inductor (L)

The inductor, L is selected in such a way that the inductor ripple current Δi_L is chosen to be a practical 30% of the load current[4].AS well as, it needs to satisfy the minimum inductance requirements L_{min}.

$$L_{min} = \frac{(1-D)\times R}{2\times f} = \frac{(1-0.143)\times 5.76}{2\times 300\times 1000} = 8.227\ \mu H$$

and,

$\Delta iL = 30\% * Io = 0.3* 8.33 \approx 2.5$ A

The inductor value as a function of inductor ripple current that guarantee the Continues current mode CCM can be obtained as follow:

$$L = \frac{(V_s - I_o R_{DS} - I_o r_L - V_o)\times D}{\Delta i_L \times f_s}$$

The average inductor current for buck converter must be equal to the output current because the average capacitor current is equal to zero for steady-state operation[1]. Then, we can find the maximum and minimum inductor currents as follow:

$$I_{L(max)} = I_L + \frac{\Delta i_L}{2} = 8.33 + \frac{2.5}{2} = 9.58\ A$$

$$I_{L(min)} = I_L - \frac{\Delta i_L}{2} = 8.33 - \frac{2.5}{2} = 7.08\ A$$

2.2.4. Capacitor (C)

The voltage ripple across capacitor is equal to the sum of voltage ripple caused by the Effective Series resistance (ESR), the voltage sag caused by the load current which is generated by the capacitor as the inductor is discharged, and the voltage ripple caused by the capacitors Effect Series Inductance ESL[5]. The ESL specification is usually not specified by the capacitor vendor. ESL value is assumed to be zero. Nevertheless, as switching frequencies are increased, the ESL specification becomes more significant [6]. The capacitance of buck converter can be calculated as:

$$C = \frac{(V_o + V_f + I_o r_L)(1-D)}{8\,L\times(\frac{\Delta V_o}{V_o})\times f^2}$$

by adjusting the ripple voltage to be 1% of output voltage $\Delta Vo = 0.01*48 = 0.48V$. then the capacitance become as follow:

$$C = \frac{(48+1.8+8.33*0.005)(1-0.143)}{8*\ 57*10^{-6}\times(\frac{0.48}{48})\times(300\times 1000)^2}$$

For the capacitor 100 µF the ESR = 0.154. The voltage ripple due to effective series resistance (ESR), $\Delta V_{ESR} = \Delta i_{LESR}$ = 2.5 * 0.154 = 0.385V

The resultant output voltage ripple will be as :

$$\frac{\Delta V_{0,total}}{V_0} = \frac{\Delta V_0 + \Delta VESR}{V_0} = \frac{0.48+0.385}{48} = 0.01802$$

2.3. Components Selection

The components of the designed system are selected based on different criteria. The general criteria are the cost, the ratings, and availability of the chosen components. Some devices have a special properties to be chosen based on i.e MOSFET, and diodes. The following analysis is to model the system with proper components.

2.3.1. Selection of the power MOSFET

The suitable power MOSFET any application considers the reduction the losses. The losses depend on the current, duty cycle, switching frequency and the switching rise and fall times. The MOSFET selection typically takes into account the rating of that device and its capability to handle the systems power. In this system, The considered intrinsic parameters of MOSFET are the high breakdown voltage VDSS, current carrying capability ID, and resistance RDS(on) [7].
The maximum stress on the switch during off state can be calculated as follow:

$V_{sw(max)} = V_{in} = 350V$

The maximum current that flow through switch can be calculated as follow:

$I_{sw(max)} = I_o = 8.33A$

From above analysis the required high breakdown voltage V_{DSS} should be ≥ 350V and the drain current I_D should be ≤ 8.33 A.

Based on above switch stress analysis, The power MOSFET type IRFP350 with low RDS(on) = 0.3Ω is selected for the switch [8].

2.3.2. Selection of the Diode

Diode selection criteria depends on reverse breakdown voltage, V_{rr}, forward voltage drop, V_f and forward current, in high frequency application, the OFF time of the Diode plays an important role in term of efficiency. A fast recovery diode is required to avoid overlapping of voltage and current

across the diode that increases power losses. AS well as a high reverse breakdown voltage V_{rr} of above 350V (The stress on diode during the switch closed) is required. A reduced forward voltage drop V_f as well as forward current If are also needed [9]. The diode type BYT12P is chosen since the ratings are sufficient enough to withstand the systems ratings [10].

2.3.3. Selection of the Passive components

The passive components include the inductor and the capacitor. For this system, the inductor must sustain a peak current of 9.58A without saturating. It is important that the inductor maintains its inductance at the high operating temperature based on board temperature and inductor loss. A saturating inductor will lead to extreme current in the MOSFET, reduces applications reliability, and may lead to electrical overstress which can damage the MOSFET. The inductor of current rating above 9.58 A will be perfection. The inductors winding resistance are given in the specification as r_L = 5 mΩ . the commercial value of inductor found to be 57μH. The selected inductor for this circuit is (14 104 54) Bobbin inductor [11].

The realistic capacitor Includes both ESL and ESR. The equivalent series inductance, ESL is regularly neglected and become significant at high frequencies [12]. The voltage rating of the capacitor is need to be higher than the output voltage $V_{C(rated)} \geq 48V$. the Commercial value of capacitor found to be 100 μF which have an equivalent series resistance ESR = 0.154 Ω.The capacitor chosen for this system is 120 ATC [13].

2.4. Power Losses

The power efficiency of the system depends on the power losses in the components that modeled the buck converter. The switching frequency plays an important role of increasing the power losses. The relationship between the switching frequency and power losses in MOSFET are proportional. On the other hand, the increasing of switching frequency will dramatically decrease the passive component size, which in turn decrease the power dissipated in them. In this system, the power losses considered are losses in MOSFET, diode, inductor, and capacitor.

2.4.1. Power losses in MOSFET

The main power losses in MOSFET are the conduction losses and switching losses [14]. The Switching losses value is very small , so it is neglected in this study .The conduction losses during ON state of MOSFET depend on the value of RDS(on) and the current flows in the switch. Equation below shows the conduction power dissipated in MOSFET.

$$P_{conduction} = I_o^2 \times D \times R_{DS} = 8.33 \times 0.143 \times 0.3 = 0.357 \text{ Watt}$$

The Switching losses are the losses produced by the high switching frequency, which is proportionate to switching frequency. Equation below shows the derived equation for switching power losses in MOSFET.

$$P_{switching} = \left(\frac{I_o V}{2}\right)(t_r + t_f) f + (C_{oss}\, f\, V^2)$$

Where

$$V = (Vs - I_o R_{DS(on)} - I_o r_L - V_o)$$

$$= (350 - 8.33 \times 0.3 - 8.33 \times 0.005 - 48) = 299.459 \text{ V.}$$

t_r is the rise time of the MOSFET which is equal to 1ns in this study.

t_f is the fall time of the MOSFET which is equal to 1ns in this study

C_{oss} is the output capacitance of MOSFET. If V_{DS} = 350 V, the output capacitance C_{oss}= 40 pf [15].

Therefore,

$$P_{switching} = \left(\frac{8.33 \times 299.459}{2}\right)(1 \times 10^{-9} + 1 \times 10^{-9}) \times 300 \times 1000 + (40 \times 10^{-12} \times 300 \times 1000 \times 299.459^2)$$

$$= 1.076 \text{ Watt}$$

Total power in MOSFET = $P_{conduction} + P_{switching}$

$$= 0.357 + 1.076 = 1.433 \text{ Watt}$$

2.4.2. Power losses in diode.

The diode only conducts in OFF state of MOSFET. Thus, the conduction losses of diode only appear in (1-D) state. Equation 10 shows the conduction power losses in diode.

$$P_{losses\text{-}dioide} = V_f \times (1 - D) \times I_o$$

$$= 1.8 * (1 - 0.143) * 8.33 = 12.849 \text{ Watt.}$$

2.4.3. Power losses In Inductor.

The power dissipated in inductor is mostly due to inductor winding resistance r_L and it can be shown in Equation below.

$$P_{Iosses\text{-}Inducter} = Io^2\, r_L = (8.33)^2 * 0.005 = 0.346 \text{ Watt}$$

2.4.4. Power losses In Capacitor.

The power dissipation in capacitor is due to equivalent series resistance ESR and Equation below shows the estimated power losses.

$$P_{losses\text{-}capacitor} = \Delta i_L * ESR = 2.5 * 0.154 = 0.385 \text{ Watt}$$

$$\text{Total losses} = 1.433 + 12.84 + 0.346 + 0.385$$

$$= 15.013 \text{ Watt.}$$

2.5. Circuit Diagram of The Buck converter.

The circuit diagram of proposed design is shown in fig. 3 with all parameterized variables discussed above.

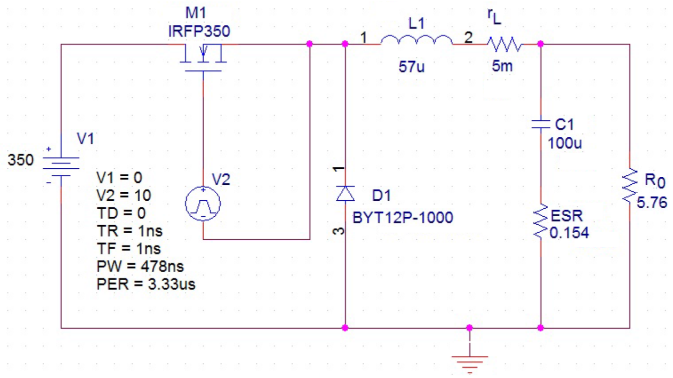

Fig. 3. The circuit diagram of proposed buck converter.

3. SIMULATION RESULTS AND DISCUSSION

The simulation and results are characterized based on each input voltage independently in order to show their corresponding output parameters and performance analysis. The parameters and performance analysis consider the non-idealities of buck converter. The data representation includes the parameters of the system such as the voltages and currents in MOSFET, inductor and diode as well as, ripple voltage and ripple current, and the output current, voltage and power waveforms .

A study was performed on effects of duty ratio on power losses, and effects of ESR on ripple voltage.

As shown in fig. 4, The MOSFET is operated in peak voltage of V_{DS} equal to 348.682V during saturation. It turns on for a short period due to duty ratio requirements. The current conducts for a short period having a current of 9.506 A which is the same current in the inductor. During ON state an excessive current flows through MOSFET for a very little time.

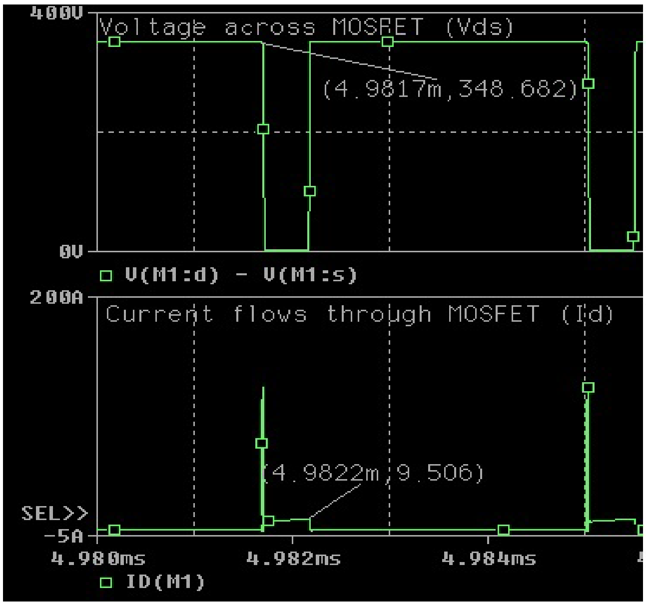

Fig. 4. Voltage and current in MOSFET.

In fig. 5, the diode voltage and current can be shown. The diode conducts as soon as the MOSFET turns OFF. The voltage across the diode is equal to 348.177V and the current conducts 9.536A.

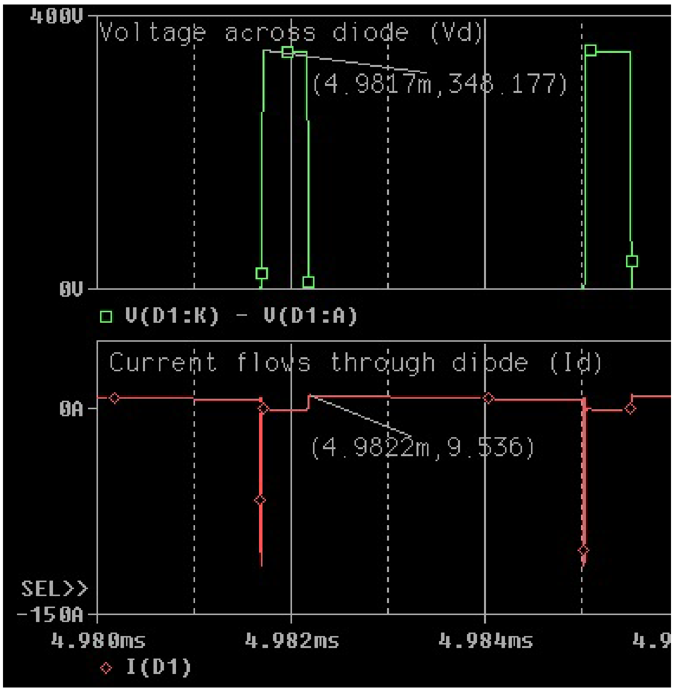

Fig. 5. Voltage and current in the diode.

The voltage and current in inductor can be shown in fig. 6. As calculated in section III, the voltage across inductor during D is equal to 299.597V and during(1−D) is equal to −49.445V. The maximum current is equal to 9.563A and the minimum current is equal to 7.1454A because of the assumption that we considered which is the ripple current should be 30% of load current.

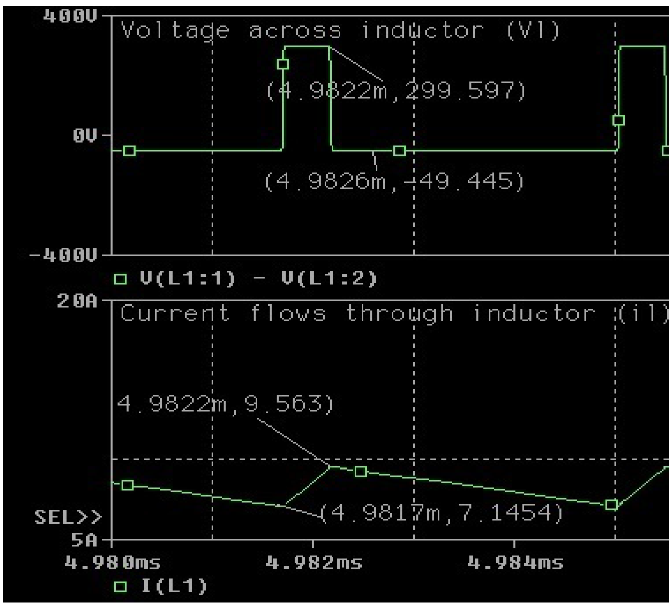

Fig. 6. Voltage and current in the inductor.

Fig. 7 shows the output voltage and voltage ripple waveforms. The output voltage of the system is slightly less than required output voltage (48V). This is due to the voltages drop of the circuit components. The ripple factor is successfully less than 5%.

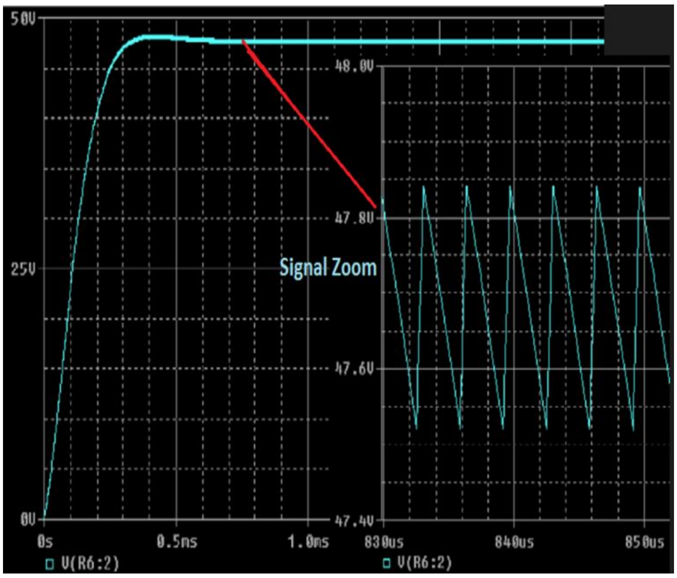

Fig. 7. Output voltage and voltage ripple waveforms.

The output current and inductor current ripple waveform is shown in fig. 8. The minimum and maximum currents obtained from the circuit are equal to 6.75 A and 9.8V respectively, therefore, the current ripple is within the acceptable range.

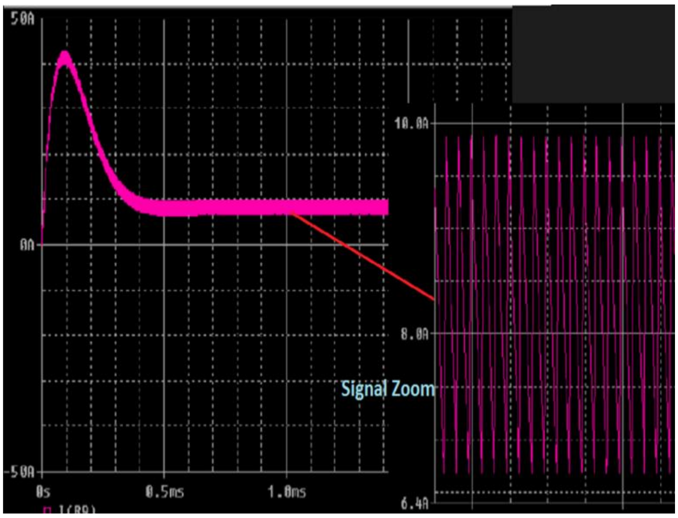

Fig. 8. output current and inductor current ripple waveform.

The output power can be shown in fig. 9. The output power is found to be 402.786 Watt which is very close to the required output power (400 Watt). The power efficiency is calculated as follow:

$$\text{Efficiency} = \frac{P_o}{P_{in}} = \frac{402.786}{772.376} \times 100\% = 52.14\%$$

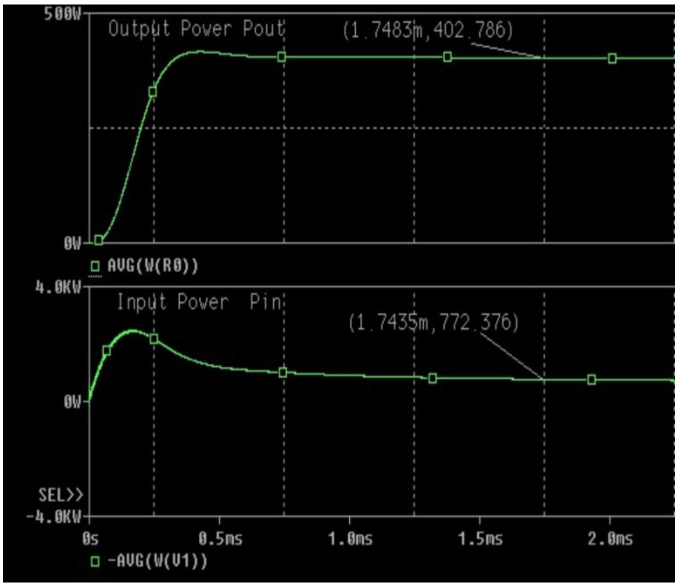

Fig. 9. Input and output power waveforms.

4. CONCLUSIONS

The buck converter designed in this project satisfies the required specification by a reasonable percentage. It designed based on real life situation where some parameters in ideal case that are neglected are considered in this design. The power MOSFET and diode realistic consideration plays an important role in term of power dissipated .So that, they may require a cooling system i.e. heat skin. The efficiency of the system is low because of the lower duty ratio and high switching frequency used. The duty ratio is low due to the requirement of stepping down the input voltage. While, the switching frequency is high in order to have a reasonable size of the passive components i.e. inductors and capacitors.

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