

Design and Modeling of DC/ DC Boost Converter for Mobile Device Applications

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ABSTRACT

This paper presents the design and modeling of DC/DC boost (step-up) converter for Advanced Intelligent Systems using Matlab/Simulink. The steady-state and average-value models for the proposed converter are developed and simulated. This work offers modeling and simulation techniques to analyze and design for an overall efficiency optimization of standard synchronous and asynchronous boost converter topologies including variable switching frequency and load resistance. Loss equations are developed, modeled, and simulated along with common power electronic components using Matlab/Simulink.

Keywords: *Switching converters; Matlab/Simulink; system modeling Efficiency; Boost converters; loss Modeling.*

1. INTRODUCTION

The demand for high efficiency DC/DC converters is increasing dramatically, especially for use in battery-operated devices such as cellular phones and laptop computers. In these devices, it is intrinsic to extend battery life [1][2]. By employing DC-DC converter power saving techniques, power efficiency can be significantly increased, thereby extending battery life. The boost is a popular non-isolated power stage topology, sometimes called a step-up power stage. Power supply designers choose the boost power stage because the required output voltage is always higher than the input voltage, is the same polarity, and is not isolated from the input. The input current for a boost power stage is continuous, or non-pulsating, because the input current is the same as the inductor current. The output current for a boost power stage is discontinuous, or pulsating, because the output diode conducts only during a portion of the switching cycle. The output capacitor supplies the entire load current for the rest of the switching cycle.

This application report describes steady-state operation and gives ideal waveforms for the boost converter in continuous and discontinuous modes in section II. Section III introduces boost converter circuits loss models. Section IV outlines simulation methodology and study cases. Simulation results are presented in Section V, and conclusion in section VI.

Fig.1 and Fig.2 show Asynchronous and Synchronous simplified schematic of the boost power stage respectively [3][4], with a drive circuit block included. Power switches M1 and M2 are n-channel MOSFET. The output diode is CR1. Inductor L and capacitor C make up the effective output filter. The capacitor equivalent series resistance

(ESR), Resr, and the inductor dc resistance, RL, are included in the analysis. Resistor Rload represents the load seen by the power supply output.

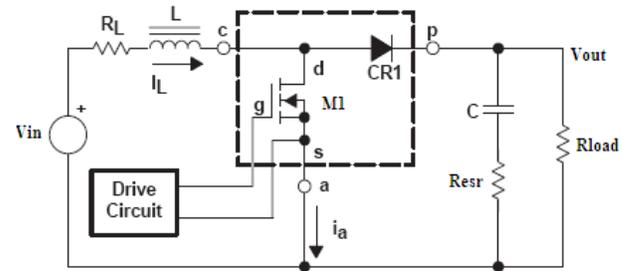


Fig. 1. Asynchronous Boost Power Stage Schematic

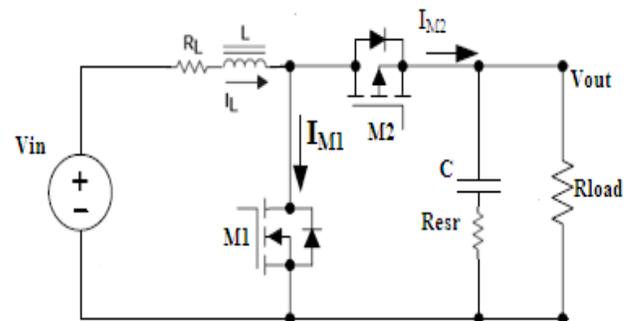


Fig. 2. Synchronous Boost Power Stage Schematic

2. BOOST POWER STAGE STEADY-STATE ANALYSIS

A power stage can operate in continuous or discontinuous inductor current mode. In continuous inductor current mode, current flows continuously in the inductor during the entire switching cycle in steady-state operation. In

discontinuous inductor current mode, inductor current is zero for a portion of the switching cycle. It starts at zero, reaches a peak value, and returns to zero during each switching cycle [4].

2.1 Boost Steady-State Continuous Conduction Mode Analysis

The following is a description of steady-state operation in continuous conduction mode. The main result of this section is a derivation of the voltage conversion relationship for the continuous conduction mode boost power stage. This result is important because it shows how the output voltage depends on duty cycle and input voltage, or how, conversely, the duty cycle can be calculated based on input and output voltages. Steady state implies that the input voltage, output voltage, output load current, and duty-cycle are fixed and not varying. Capital letters are generally given to variable names to indicate a steady-state quantity.

In continuous conduction mode Fig.1, the boost power stage assumes two states per switching cycle. In the ON state, M1 is ON and CR1 is OFF. In the OFF state, M1 is OFF and CR1 is ON. A simple linear circuit can represent each of the two states where the switches in the circuit are replaced by their equivalent circuit during each state. Fig.3 shows the linear circuit diagram for each of the two states.

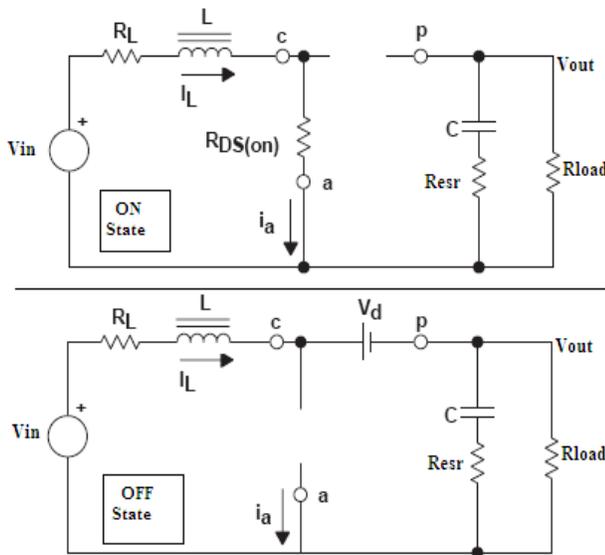


Fig. 3. Boost Power Stage States

The duration of the on state is $D \times T_s = T_{ON}$, where D is the duty cycle set by the control circuit, expressed as a ratio of the switch ON time to the time of one complete switching cycle, T_s . The duration of the OFF state is T_{OFF} . Since there are only two states per switching cycle for continuous conduction mode, T_{OFF} is equal to $(1 - D) \times T_s$. The quantity $(1 - D)$ is sometimes called D' . These times are shown along with the waveforms in Fig.4.

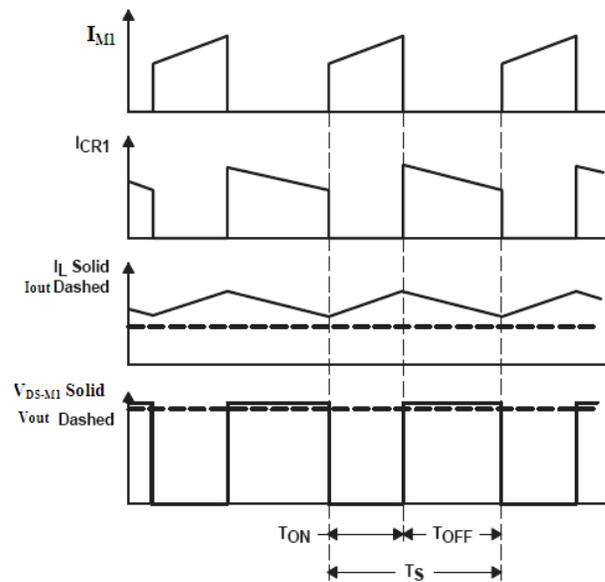


Fig. 4. Continuous Mode Boost Power Stage Waveforms

Refer to Fig.1, Fig.3 and [4], During the ON state. The inductor-current increase can be calculated by using a version of the familiar relationship:

$$V_L = L \times \frac{di_L}{dt} \Rightarrow \Delta I_L = \frac{V_L}{L} \times \Delta T \quad (1)$$

The inductor current increase during the on state is given by:

$$\Delta I_L(+)= \frac{V_{in}-(R_{DS}+I_L \times R_L)}{L} \times T_{ON} \quad (2)$$

The quantity $\Delta I_L(+)$ is the inductor ripple current. During this period, all of the output load current is supplied by output capacitor C .

During the OFF state, the inductor current decrease during the off state is given by:

$$\Delta I_L(-)= \frac{(V_{out}+V_d+I_L \times R_L)-V_{in}}{L} \times T_{OFF} \quad (3)$$

The quantity $\Delta I_L(-)$ is also the inductor ripple current.

In steady-state conditions, the current increase, $\Delta I_L(+)$, during the on time and the current decrease, $\Delta I_L(-)$, during the off time are equal. Otherwise the inductor current would have a net increase or decrease from cycle to cycle which would not be a steady state condition. Therefore, these two equations (2) and (3) can be equated and solved for V_{out} to obtain the continuous conduction mode boost voltage conversion relationship:

The steady-state equation for V_{out} is:

$$V_{out} = (V_{in} - I_L \times R_L) \times \left(1 + \frac{T_{ON}}{T_{OFF}}\right) - V_d - V_{DS} \times \left(\frac{T_{ON}}{T_{OFF}}\right) \quad (4)$$

And, using T_s for $T_{ON} + T_{OFF}$ and using $D = \frac{T_{ON}}{T_s}$ and $(1 - D) = \frac{T_{OFF}}{T_s}$ the steady-state equation for V_{out} is:

$$V_{out} = \frac{V_{in} - I_L \times R_L}{1 - D} - V_d - V_{DS} \times \frac{D}{1 - D} \quad (5)$$

A common simplification is to assume V_{DS} , V_d , and R_L are small enough to ignore. Setting V_{DS} , V_d , and R_L to zero, the above equation (5) simplifies considerably to:

$$V_{out} = \frac{V_{in}}{1 - D} \quad (6)$$

2.2 Boost Steady-State Discontinuous Conduction Mode Analysis

To begin the derivation of the discontinuous current mode boost power stage voltage conversion ratio Fig.1, recall that there are three unique states that the power stage assumes during discontinuous current mode operation. The on state is when M1 is on and CR1 is off. The off state is when M1 is off and CR1 is on. The idle state is when both M1 and CR1 are off. The first two states are identical to the continuous mode case, and the circuits of Fig.3 are applicable except that $T_{OFF} \neq (1 - D) \times T_s$. The remainder of the switching cycle is the idle state. In addition, the dc resistance of the output inductor, the output diode forward voltage drop, and the power MOSFET on-state voltage drop are all assumed to be small enough to omit. The duration of the on state is $T_{ON} = D \times T_s$, where D is the duty cycle set by the control circuit, expressed as a ratio of the switch on time to the time of one complete switching cycle, T_s . The duration of the off state is $T_{OFF} = D_2 \times T_s$. The idle time is the remainder of the switching cycle and is given as $T_s - T_{ON} - T_{OFF} = D_3 \times T_s$. These times are shown with the waveforms in Fig.5.

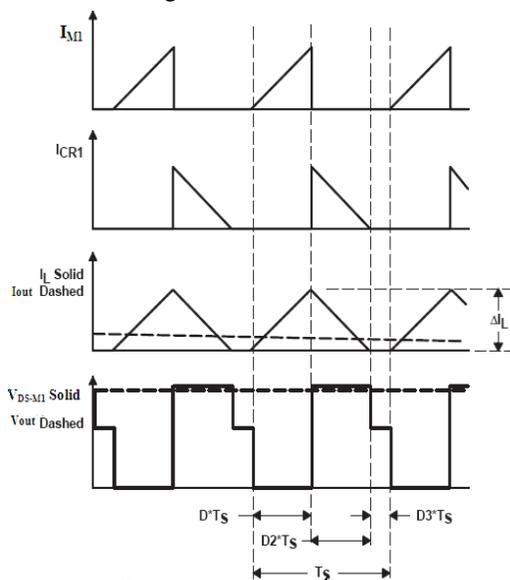


Fig. 5. Discontinuous Mode Boost Power Stage Waveforms

Without going through the detailed explanation as before, the equations for the inductor current increase and decrease are given below.

The inductor current increase during the on state is given by:

$$\Delta I_L(+)=\frac{V_{in}}{L} \times T_{ON}=\frac{V_{in}}{L} \times D \times T_s=I_{PK} \quad (7)$$

The ripple current magnitude, $\Delta I_L(+)$, is also the peak inductor current, I_{PK} because in discontinuous mode, the current starts at zero each cycle.

The inductor current decrease during the off state is given by:

$$\Delta I_L(-)=\frac{V_{out}-V_{in}}{L} \times T_{OFF}=\frac{V_{out}-V_{in}}{L} \times D_2 \times T_s \quad (8)$$

As in the continuous conduction mode case, the current increase, $\Delta I_L(+)$, during the on time and the current decrease during the off time, $\Delta I_L(-)$, are equal. Therefore, these two equations (7) and (8) can be equated and solved for V_{out} to obtain the first of two equations to be used to solve for the voltage conversion ratio:

$$V_{out}=V_{in} \times \frac{T_{ON}+T_{OFF}}{T_{OFF}}=V_{in} \times \frac{D+D_2}{D_2} \quad (9)$$

Now calculate the output current (the output voltage V_{out} divided by the output load R_{load}). It is the average over the complete switching cycle of the inductor current during the D_2 interval.

$$I_{out}=\frac{V_{out}}{R_{load}}=\frac{1}{T_s} \times \left[\frac{1}{2} \times I_{PK} \times D_2 \times T_s \right] \quad (10)$$

Now, substitute the relationship for I_{PK} ($\Delta I_L(+)$) into the above equation to obtain:

$$I_{out}=\frac{V_{out}}{R_{load}}=\frac{1}{T_s} \times \left[\frac{1}{2} \times \left(\frac{V_{in}}{L} \times D \times T_s \right) \times D_2 \times T_s \right] \quad (11)$$

$$I_{out}=\frac{V_{out}}{R_{load}}=\frac{V_{in} \times D \times D_2 \times T_s}{2 \times L} \quad (12)$$

We now have two equations, one for the output current just derived, and one for the output voltage, both in terms of V_{in} , D , and D_2 . Now solve each equation for D_2 and set the two equations equal to each other. The resulting equation can be used to derive an expression for the output voltage, V_{out} .

The discontinuous conduction mode boost voltage conversion relationship is given by:

$$V_{out}=V_{in} \times \frac{1+\sqrt{1+\frac{4 \times D^2}{K}}}{2} \quad (13)$$

Where K is defined as:

$$K = \frac{2 \times L}{R_{load} \times T_s}$$

The above relationship shows one of the major differences between the two conduction modes. For discontinuous conduction mode, the voltage conversion relationship is a function of the input voltage, duty cycle, power stage inductance, switching frequency, and output load resistance, for continuous conduction mode, the voltage conversion relationship is only dependent on the input voltage and duty cycle.

3. CONVERTER LOSS MODELING

Listings of DC/DC converter losses may be found in [5] and [6][10]. Boost converter losses considered in this work are given in Table 1, as itemized and developed analytically in the following subsections.

Table 1. Boost Converter Losses Considered

Synchronous	Asynchronous
M1:NMOS conductions	M1:NMOS conductions
M1:NMOS Switching	M1:NMOS Switching
M1:NMOS Gate Drive	M1:NMOS Gate Drive
M1:NMOS Body diode	Diode conduction
M2:NMOS conductions	Diode leakage
M2:NMOS Switching	Diode junction Capacitance
M2:NMOS Gate Drive	
M2:NMOS Body diode	
Dead Time	

3.1 NMOS Source Switch Conduction Loss

$$M1SL = \frac{1}{2} I_{M1S} \times V_{M1S} \times f_s \left(\frac{Q_{G(SW)}}{V_G + \frac{I_{M1S}}{G_m}} + \frac{Q_{G(SW)}}{V_{DD} - (V_G + \frac{I_{M1S}}{G_m})} \right) \quad (16)$$

3.3 NMOS Source Switch Gate Drive Loss

Gate drive loss accounts for the energy dissipated by the MOSFET to drive the gate for the switching operation. The loss equation is given in eqn. (17). NMOS gate drive loss is associated with both converters.

$$NMOS \text{ Gate drive Loss} \triangleq M1GDL = Q_{G(SW)} \times V_G \times f_s \quad (17)$$

3.4 NMOS Switch Body Diode Loss

NMOS body diode loss is associated with only the synchronous converter.

$$NMOS \text{ body diode Loss} \triangleq M1BDL = i_{leakage} \times V_{M1} \times (1 - D) \quad (18)$$

When the NMOS transistor is in forward conduction there is a resistive loss in accordance with eqn.(14),[8],[7]. NMOS conduction loss is associated with both asynchronous and synchronous converters.

$$NMOS \text{ conduction Loss} \triangleq M1CL = I_{M1}^2 \times R_{DS} \times D \quad (14)$$

Where I_{M1} =NMOS current (Amp) R_{DS} =NMOS forward conduction ON Resistance (Ohm), D =duty ratio [7],[8]

3.2 NMOS Source Switch Switching Loss

During the transition of voltage rising or falling between the maximum and minimum steady-state value across either switch, and similarly the rise or fall transition of current through the same switch, losses occur. Much work has been performed in an effort to correctly model this behavior [5][9], without a highly accurate model still as yet developed [9]. A combination of the work of [8] and [9] are presented here to develop the switch model beginning with eqn.(15), NMOS switching loss is associated with both converters.

$$M1SL = \frac{1}{2} I_{M1S} \times V_{M1S} \times f_s (t_{s(off)} + t_{s(on)}) \quad (15)$$

where $M1SL$ =MOSFET switching loss power (Watt), I_{M1S} =current through MOSFET (Amp), V_{M1S} =drain to source voltage across MOSFET (Volt), f_s =switching frequency (Hertz), $t_{s(off)}$ =MOSFET switching time transitioning off (second), $t_{s(on)}$ =MOSFET switching time transitioning on (second) [8],[9]

All parameters of eqn.(15) are readily measurable in a physical circuit except the switching time terms t_{off} and t_{on} which are developed in [10].

Where $i_{leakage}$ =reverse bias leakage current (Amp)

3.5 NMOS Load Switch Conduction Loss

Load switch conduction loss is similar to that of the source switch shown in eqn. (14), differing by the (1-D) factor as this loss occurs during the latter portion of the switching period. This loss is represented in eqn. (19). NMOS conduction loss is associated with only the synchronous converter.

$$NMOS \text{ Conduction Loss} \triangleq M2CL = I_{M2}^2 \times R_{DS} \times (1 - D) \quad (19)$$

where I_{M2} =load switch drain to source voltage(Volt)

3.6 NMOS Load Switch Switching Loss

The load switch MOSFET switching loss is calculated with the same model as the source switch shown in (16). NMOS switching loss is associated with only the synchronous converter.

3.7 NMOS Load Switch Gate Drive Loss

NMOS gate drive loss is accounted for by simply doubling the gate drive loss equation (17) for the synchronous case. NMOS gate drive loss is associated with only the synchronous converter.

3.8 NMOS Load Switch Body Diode Loss

The load switch body diode loss occurs only in the load switch due to the reverse bias during the d portion of the period [6]. The reverse-bias voltage and leakage current dissipate power according to the equation shown in eqn. (20). NMOS body diode loss is associated with only the synchronous converter.

$$NMOS \text{ body diode Loss} \triangleq M2BDL = i_{leakage} \times V_{M2} \times D \quad (20)$$

where $i_{leakage}$ =reverse bias leakage current (Amp), V_{M2} =load switch drain to source voltage (Volt).

3.9 Synchronous Switching Dead-Time Loss

Dead-time loss occurs through the load switch when neither transistor is on as the load switch is in forward conduction [8]. A period of dead-time must exist to prevent current “shoot-through” whereby current flows through both switches simultaneously to the load. The value of t_{dead} is assumed to be 60ns as is typical for DC/DC converter controllers [6]. The dead-time loss representation is shown in eqn.(21). Synchronous switching dead-time loss is associated with only the synchronous converter.

$$Dead - Time Loss \triangleq deadL = I_{load} \times V_{M2} \times f_s \times t_{dead} \quad (21)$$

Where I_{load} =load current (Amp), t_{dead} =time where both switches are off (Second)

3.10 Diode Conduction Loss

Diode forward conduction losses are found with the equation shown in (22). Diode conduction loss is associated with only the asynchronous converter.

$$Diode \text{ conduction Loss} \triangleq DcL = I_D \times V_f \times (1 - D) \quad (22)$$

Where I_D =current through diode (Amp), V_f =diode forward voltage (Vol)

3.11 Diode Reverse Bias Loss

During the portion of the period d, the diode has a reverse bias across it. There is a certain amount of leakage current under this condition that is listed by the manufacturer on the data sheet. This value is used to calculate diode reverse bias leakage loss in eqn. (23). Diode reverse bias loss is associated with only the asynchronous converter.

$$Diode \text{ Reverse Bias Loss} \triangleq DrbL = V_D \times i_{leakage} \times D \quad (23)$$

Where V_D =voltage across diode (Volt)

3.12 Diode Junction Capacitance Loss

Diodes have a certain capacitance associated with changing voltages across them [8]. The charging and discharging of this capacitance creates a power loss as modeled by equation (24). Diode junction capacitance loss is associated with only the asynchronous converter.

$$Diode \text{ Capacitance Loss} \triangleq DcapL = \frac{C \times V_D^2 \times f_s}{2} \quad (24)$$

Where C=capacitance (Farad)

4. PERFORMANCE SIMULATION OF SYNCHRONOUS AND ASYNCHRONOUS DC/DC BOOST CONVERTER

The boost converter asynchronous and synchronous circuits shown in Fig.1 & Fig.2 and using references [10][11][12] are modeled in Matlab/Simulink as shown in Fig.6 & Fig.7. The analytic loss equations developed in Section 3 are modeled as shown in Fig.8 (redundant models are not shown). Fig.9 shows the simulator loss summation and efficiency calculation for the synchronous case.

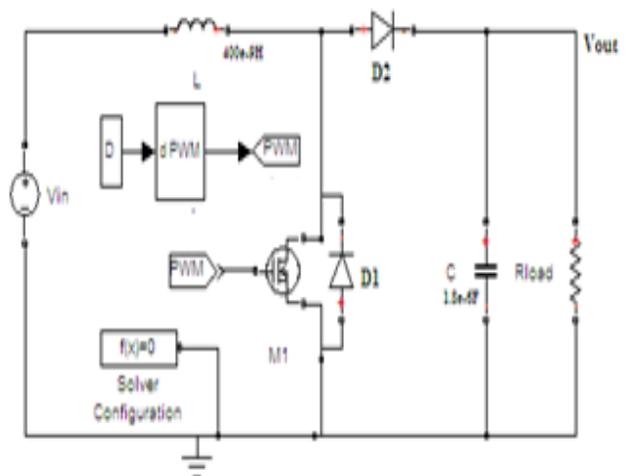


Fig. 6. Asynchronous Boost Converter Simulation

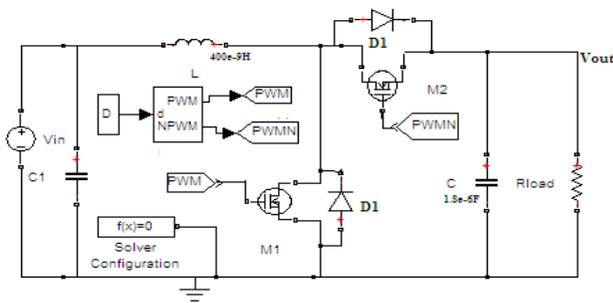


Fig. 7. Synchronous Boost Converter Simulation

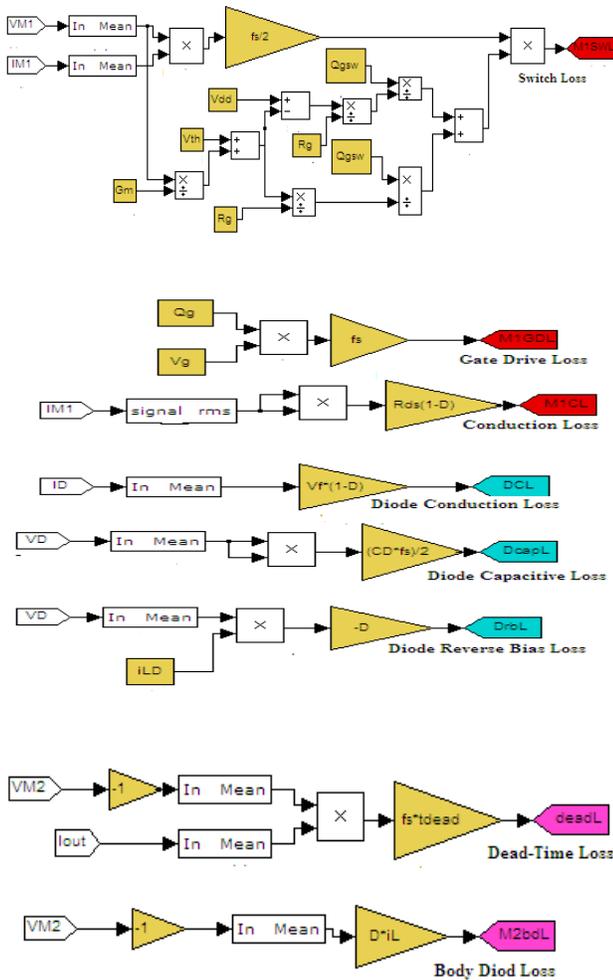


Fig. 8. Simulation Loss Models

5. SIMULATION RESULTS

The simulation model of Asynchronous and Synchronous DC/DC boost converter are build using above-mentioned steps is shown in Figures section 4. The DC/DC boost converter is previously designed and simulated using Matlab/Simulink package.

The supply voltage ranges from 2.6V to 4.2V .The experimental results show the different of boost converter Synchronous and asynchronous. Fig.10 and Fig.11 show

output current and voltage under time respectively. Fig.12 illustrates the efficiency under various load resistance for asynchronous and synchronous boost converter with switching frequency 50MHs. And Fig.13 illustrates the efficiency under various load resistance of Synchronous boost converter at 50MHz and 30MHz.

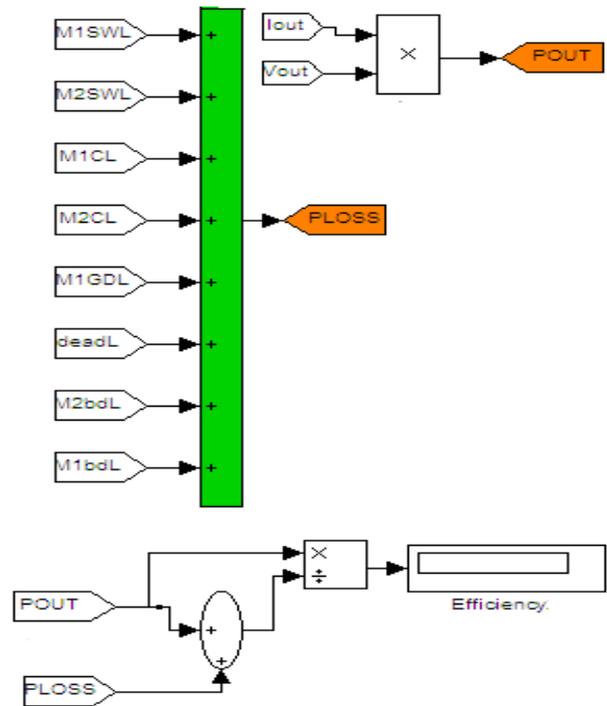


Fig. 9. Simulation Loss Summation with Efficiency Calculation (Synchronous)

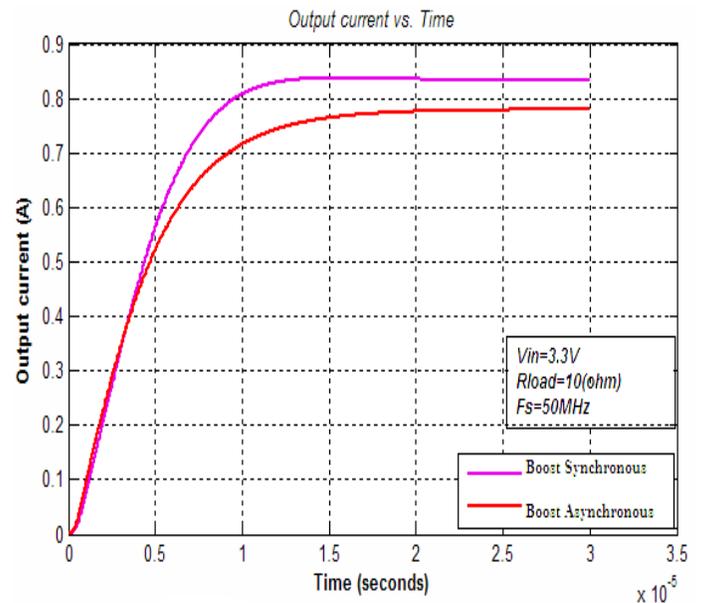


Fig. 10. Output Current under various Time and at different boost converter (Synchronous and asynchronous)

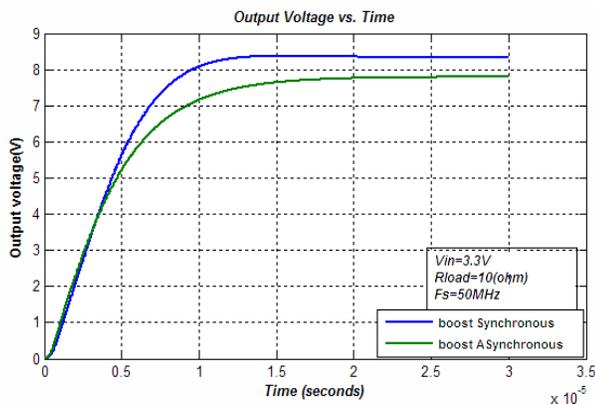


Fig. 11. Output Voltage under various Time and at different boost converter (Synchronous and asynchronous)

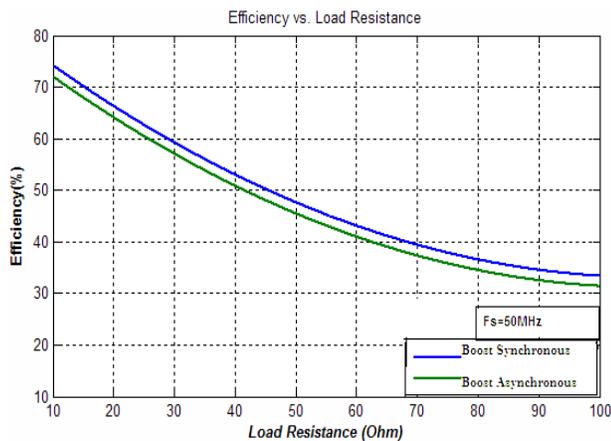


Fig. 12. Efficiency under various Load Resistance and at different boost converter (Synchronous and asynchronous)

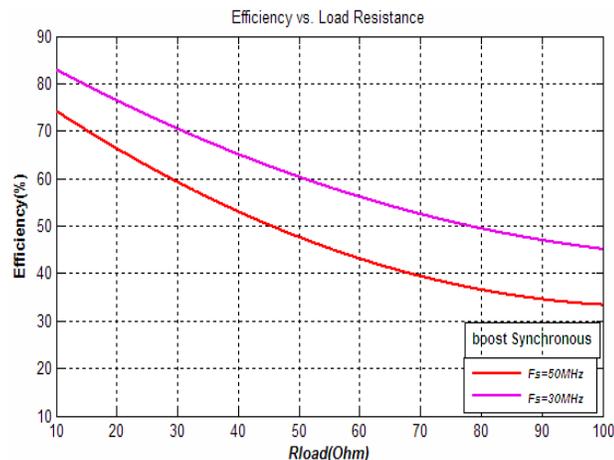


Fig. 13. Efficiency under various Load Resistance and at different Synchronous boost converter switching Frequency ($F_s=30\text{MHz}$ and $F_s=50\text{MHz}$)

6. CONCLUSION

Matlab/Simulink provides an effective environment for modeling and simulation of DC/DC converters. The boost converter is herein for optimized for efficiency

considering both synchronous and asynchronous topologies with variable switching frequency (30MHz and 50MHz) and load resistance from 10Ω To 100Ω .the optimal case offers performance at 85% in the load resistance 10Ω , switching frequency 30MHz and input voltage 3.3V . In general synchronous DC/DC boost converter with lower frequency and light load gives a higher efficiency.

REFERENCES

- [1] C. Simpson. (2003) Characteristics of Rechargeable Batteries. National.com.[Online].Available: <http://www.national.com/appinfo/power/files/fv.pdf>.
- [2] Lingyin Zhao, Jinrong Qian, "DC-DC Power Conversions and System Design Considerations for Battery Operated System", Texas Instruments.[Online]Available:<http://focus.ti.com/download/trng/docs/seminar/Topic%20%20-%20DC-DC%20Power%20Conversion%20and%20System%20Design%20Considerations%20for%20Battery%20Operated%20System.pdf>.
- [3] Vahid Yousefzadeh, Dragan Maksimovic "Sensorless Optimization of Dead Times in DC-DC Converters With Synchronous Rectifiers", IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 21, NO. 4, JULY 2006.
- [4] Texas Instruments. Understanding Boost Power Stage in Switchmode Power Supplies. Texas Instruments, Mar. 1999. PDF.
- [5] Siyuan Zhou, "Fully Integrated Power-Saving Solutions for DC-DC Converters Targeted for the Mobile, Battery- Powered Applications", Georgia Tech Analog Consortium Industry Research Review, 2003.
- [6] O. Djekic and M. Brkovic, "Synchronous Rectifiers vs. Schottky Diodes in a Buck Topology for Low Voltage Applications", Power Electronics Specialists Conference, Vol. 2, pp. 1974-1980, 1997.
- [7] M. Gildersleeve, H.P. Forghani-zadeh, and G.A. Rincon-Mora, "A Comprehensive Power Analysis and a Highly Efficient, Mode-Hopping DC-DC Converter", IEEE Asia- Pacific Conference on ASIC, 2002, pp. 153-156.
- [8] Jon Klein, "Synchronous buck MOSFET loss calculations with Excel Model", Fairchild Semiconductor Publication, 2006
- [9] Yali Xiong, Shan Sun, Hongwei Jia, Patrick Shea, Z. John Shen, "New Physical Insights on Power MOSFET Switching Losses", IEEE Transactions on Power Electronics, Vol. 24, No. 2, February 2009.

- [10]Sven E. Fagerstrom and Nagy N. Bengiamin "Buck/Boost Converter Modeling and Simulation for Performance Optimization"California State University at Fresno, Department of Electrical and Computer Engineering 5241 N. Maple Avenue, Fresno, CA 93740, U.S.A.
- [11]Fatima Zahra Amatoul, Moulay Tahar Lamchich, Abdelkader Outzourhit "Design and Simulation of DC/DC Buck Converter for Stand Alone Photovoltaic Energy System with Lead Acid Battery Storage" international journal of information sciences and Computer Engineering Volume 2, Number 2, 2011.
- [12]MOHAMED ASSAF, D. SESHACHALAM, D. CHANDRA, R. K. TRIPATHI " DC-DC CONVERTERS VIA MATLAB/SIMULINK" published in: proceeding ACMOS'05 Proceeding of the 7th WSEAS international conference on Automatic control ,modeling and simulation