Design and simulation DC-DC Power Converters Buck and Boost for Mobile Applications using Matlab/Simulink

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Abstract—**Nowadays, The demand for portable devices players has grown significantly and mobile applications become increasingly complex and multi-function. Research aims to increase the autonomy of portable devices by acting on several factors, one of the most discussed areas is to increase the efficiency of voltage converters in order to reduce consumption. In this context, DC / DC converters are used in portables to generate multiple DC levels for powering the circuits in a device, They are also used to reduce ripples ie, they carry out two main functions: modify the voltage level (step-up or step- down) , regulate voltage.**

This paper first reviews the commonly used DC-DC converters in portable power device, and then presents the design and modeling of DC/DC Buck and Boost converter using Matlab/Simulink.

Keywords-DC/DCconverters,mobile applications,Matlab/Simulink, buck converters, Boost converters.

I. INTRODUCTION

The emergence of integrated circuit around 1964 due to transistor's miniaturization facilitated a great revolution of electronics which allowed the emergence of various portable applications. Consequently, mobile equipment industry has known strong growth and mobiles integrate more and more functionalities in smaller volumes. In other words, battery-powered mobile equipment has become an important pillar of the electronic consumer market .However, all these mobile equipment have the same major weakness: their battery provides a limited operating time, which can only be increased in two ways. First, the energy density of the battery can be increased by developing new battery chemistries. Second, the battery energy can be used more efficiently by improving energy management. We will focus on the latter, and especially on voltage conversion, which is used in mobile equipment. A way used to optimize the battery run-time consists in inserting a DC-DC converter between the battery and supplied load. In recent years , these converters have received an increasing deal of interest in many areas of applications due to maintain the voltage supplied to the load constant from no load to full load with high conversion efficiency [1]. Consequently, they are employed in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunications equipment, as well as dc motor drives. The input to a DC-DC converter is an unregulated DC voltage. The converter produces a regulated output voltage having a magnitude (and possibly polarity) that differs from the input voltage [2]. In other words, it regulates the voltage provided by the battery to a constant value, fixed by the design. High efficiency is invariably required, since cooling of inefficient power converters is difficult and expensive. The ideal DC-DC converter exhibits 100% efficiency. In practice, efficiencies of 70% to 95% are typically obtained. This is achieved using switched-mode, or chopper, circuits whose elements dissipate negligible power [2]. Buck and boost converters are ones of the basic DC-DC converters. They have a broad applicable background because of the simple circuit structure and good control effort. In general, they have two basic mode of work operation, i.e., continuous inductor current mode (CCM) and discontinuous inductor current mode (DCM) [3]. CCM is that the inductor current is always greater than zero without interruption of current in a switch period; however, DCM is that the inductor current is zero during the switch-off some time [4]. This paper presents DC-DC converters, describes steady state operation and gives waveforms of buck and boost converters in CCM and DCM, then presents modelling of buck and boost converters using Matlab/Simulink .

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II. DC-DC VOLTAGE CONVERTERS ROLE

At present, mobiles are composed of several integrated circuits. Fig.1 illustrates their distribution. Namely, circuits used to transmit and receive data through the antenna, circuit manages digital parts like memories, microcontroller and processor, circuits incorporate analog/digital circuits and battery management functions. Since the constraints are very different for each of these circuits, they are realized in a technology adapted to their functions.

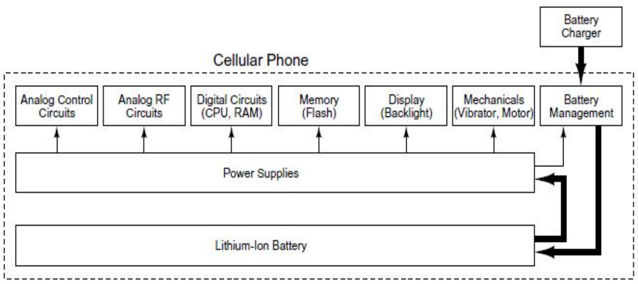


Fig.1. Integrated circuits of a mobile phone

Every integrated circuit needs a constant supply voltage. However, the only way to store electrical energy in portable equipment is in DC energy reservoirs (e.g., batteries, accumulators and capacitors), which all suffer from the same drawback:their voltage decreases when they discharge [5]. The voltage delivered must be regulated and adapted to voltage requested by integrated circuits in mobile devices [6]. This makes the integration of DC-DC converters for mobile systems essential. In brief, the role of DC-DC voltage regulators will be to generate several regulated voltages, stable and constant in time,from the single,variable and distorted voltage that delivers the rechargeable battery to power integrated circuits. ie, DC-DC converter must provide a regulated dc output voltage even subjected to load and input voltage variation[7].

Current needs are cost reduction and miniaturization which manifest in the development of new integrated DC-DC voltage regulators structures purely CMOS.

III. DC-DC CONVERTERS OPERATING PRINCIPLE

In the following approaches, converters are supposed to operate in steady-state with a constant input voltage and a constant output voltage. Further, the components are taken ideal and no parasitics are considered (e.g, the power transistors are assimilated to ideal switches having an infinite resistance when turned off, and no resistance when turned on).In general , a large number of dc-dc converter circuits are known that can increase or decrease the magnitude of the dc voltage and/or invert its polarity [8].The conversion ratio $M(D)$ of a converter is the ratio of the dc output voltage to the dc input voltage under steady-state conditions which D is the duty cycle that is the fraction of time when the power MOSFET switch is ON here are several commonly used dc-dc converter circuits,namely buck converter, which reduces the dc voltage and has conversion ratio $M(D)=D$. Then boost converter which produces an output voltage that is greater in magnitude than the input voltage. Its conversion ratio is $M(D)=1/(1-D)$. Buck-boost converter inverts the polarity of the voltage, and can either increase or decrease voltage magnitude. The conversion ratio is $M(D)=-1/(1-D)$. The Cuk converter contains inductors in series with the converter input and output ports. Its conversion ratio $M(D)$ is identical to that of the buck-boost converter. The single-ended primary inductance converter (SEPIC) can also either increase or decrease the voltage magnitude. However, it does not invert the polarity. The conversion ratio is $M(D)=1/(1-D)$ [2].

A. Buck converter

Buck converter is one of the simplest but most useful power converters. It is a step-down converter that converts an unregulated dc input voltage to a regulated dc output at a lower voltage [9]. Fig.2 depicts the basic circuit configuration used in the buck converter. As can be seen, it consists of a power MOSFET switch Q, diode D, inductor L, output capacitor C, and load resistance R. The inductor L acts as energy storage element that keeps the current flowing while the diode facilitates inductor current wheeling during the OFF time of the MOSFET. Filter made of capacitor (C) is normally added to the output of the converter to reduce output voltage ripple [10].

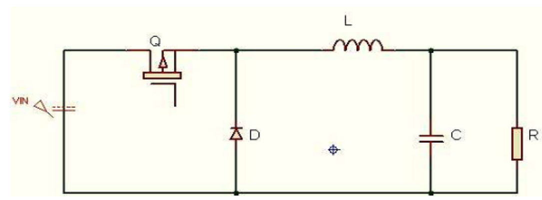


Fig2. Buck converter

Usually P-channel MOSFET (PMOS) is preferred to be used as switch instead of NMOS, because if the NMOS is employed as a MOSFET switch since both the gate and the source are connected to the voltage supply then it would be hard to drive it [11]. In order to improve power efficiency, the diode is usually replaced by an n-channel MOSFET (NMOS) because voltage drop in conducted MOSFET is very low comparison to conducted diode. In this case, it is referred to a synchronous buck converter. The operation of a buck converter can be divided into two time according to the state of MOSFET switch. During ON state, the current through the inductance increases linearly. The voltage across the diode is negative, no current passes through it.The off-state begins when MOSFET switch Q is blocked. The diode becomes conductive. It ensures continuity of the current in the inductor. The current through the inductor decreases.

As mentioned previously, it can operate in continuous conduction mode (CCM) or in discontinuous conduction mode (DCM), depending on the waveform of inductor current [11].

In continuous conduction mode, the Buck power stage assumes two states per switching cycle [12]. During the ON state the transistor operates in its linear region between the drain and the source from which it is equivalent to a low-resistance R_{DS} and the diode is off. The d.d.p between R_{DS} terminals is therefore:

$$V_{DS} = R_{DS}\, i_{IN} = R_{SD}\, i_L$$

The d.d.p between inductor terminals is therefore:

$$V_L = V_{IN} - V_{DS} - V_{OUT} \text{ where } i_L = i_{IN} \qquad (1)$$

Using equation (1) and taken into accunt the variations of V_L, we obtained :

$$\Delta i_L^+ = T_{ON} \frac{V_{IN} - V_{OUT} - R_{DS} i_L}{L} \qquad (2)$$

where the quantity Δi_L^+ is called inductor ripple current.

During off state, MOSFET is off. The inductor, the load and the diode are in series. The current will decrease linearly $i_L = i_D$ and $V_L = -(V_D + V_{OUT})$. The variation of i_L during OFF state is then:

$$\Delta i_L^- = T_{OFF} \frac{(V_{OUT} + V_D)}{L} \qquad (3)$$

Under the conditions of stationary state, increase of inductor current Δi_L^+ during the ON state and its decrease during the OFF state Δi_L^- must be equal:

$$V_{OUT} = (V_{IN} - V_{DS}) \frac{T_{ON}}{T_{ON} + T_{OFF}} - V_D \frac{T_{OFF}}{T_{ON} + T_{OFF}} \qquad (6)$$

The developpement of the equation (6) taking into accunt the value of duty cycle $D = T_{ON} / (T_{ON} + T_{OFF})$ is given by:

$$V_{OUT} = (V_{IN} - V_{DS}) D - V_D (1 - D) \qquad (7)$$

If we assume V_{DS} and V_D are small enough:

$$V_{OUT} = V_{IN} D \qquad (8)$$

In Fig.3. are shown the variations of MOSFET current i_Q diode current i_D, inductor current i_L and the PWM control voltage.

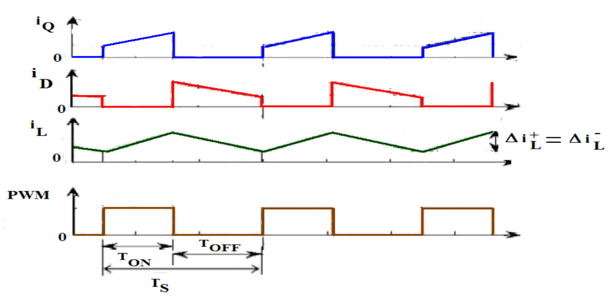


Fig.3. Waveforms of Current and voltage in continuous conduction

In discontinuous conduction mode, the amount of energy required by the load is sufficiently low; it can be transferred in a shorter time than a switching period. During this period the MOSFET and the diode are both off [13]; the current through the inductor is zero $(i_L = 0)$. The difference between this mode of conduction and continuous conduction is to add a third time (idle state) in the period. T_S .In this case, T_{OFF} is different from $(1 - D) T_S$.

Fig.4. illustrates the variation of MOSFET current, diode current, inductor current and the PWM control voltage of buck converter in discontinuous conduction mode

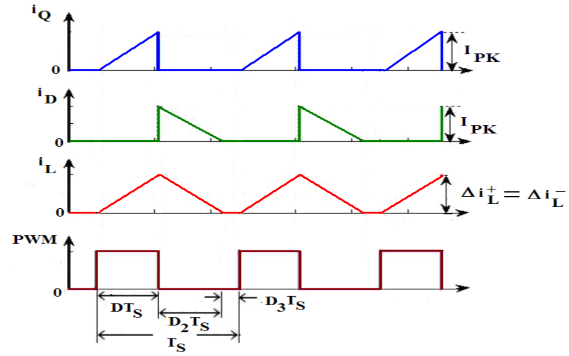


Fig.4.Waveforms of current and voltage in DCM.

The duration of the ON state is $T_{ON} = DT_S$,the OFF state is $T_{OFF} = D_2 T_S$ and idle time is given by: $D_3 T_S = T_S - (T_{ON} + T_{OFF})$

The increase of inductor current during ON state is given by

$$\Delta i_L^+ = T_{ON} \frac{V_{IN} - V_{OUT}}{L} = \frac{V_{IN} - V_{OUT}}{L} DT_S = I_{PK} \qquad (9)$$

where I_{PK} is the peak of input current

Ripple current of the inductor Δi_L^+ is also its peak current because in discontinuous conduction mode current begins at zero every cycle.

During OFF state, inductor current decreases by:

$$\Delta i_L^- = T_{OFF} (V_{OUT} / L) \qquad (10)$$

Since $\Delta i_L^+ = \Delta i_L^-$

$$V_{OUT} = V_{IN} \frac{T_{ON}}{T_{ON} + T_{OFF}} = V_{IN} \frac{D}{D + D_2} \qquad (11)$$

The output current is the average inductor current

$$i_{OUT} = \frac{V_{OUT}}{R} = \frac{I_{PK}}{2} \frac{DT_S + D_2 T_S}{T_S} \qquad (12)$$

Subssting (9) into (12) gives:

$$V_{OUT} = 2V_{IN} \left(1 + \left(1 + \frac{4K}{D^2}\right)^{0.5}\right)^{-1} \text{ with } K = 2L / RT_S \qquad (13)$$

For discontinuous conduction mode, the voltage conversion ratio depends on the input voltage V_{IN}, the duty cycle D, the inductor L, the switching frequency fs and the load R. But for continuous conduction mode, the voltage conversion ratio depends only on the input voltage V_{IN} and the duty cycle D

B. Boost converter

It has a topology similar to buck converter except that the positions of MOSFET switch and inductor are interchanged As shown in Fig.5 It provides an output voltage greater than the input voltage.

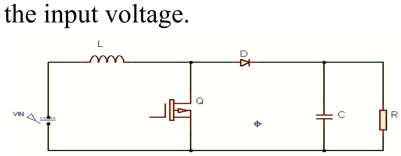


Fig.5.Boost converter

In continuous conduction mode, current flows continuously in the inductor during the entire switching cycle. As a consequence, the boost power stage assumes two states per switching cycle. The ON state where the MOSFET switch Q is on and diode D is blocked. During this sequence, the current through the inductor L increase linearly and energy is stored in the inductor. The capacitor C supplies energy to the load R. The OFF state starts when the MOSFET switch is off and the diode becomes conductive. During this sequence, the energy stored in the inductor L is returned to the capacitor and the load R. In this state, the fact that the inductance L is in series with the input voltage source constitutes an elevator circuit.

The duration of on state is $T_{ON} = DT_S$ .Since there are two states, T_{OFF} is equal to. $(1-D)T_S$.

During ON state (by applying the PWM control on the transistor gate), MOSFET switch operates in its linear region The d.d.p between its terminals is:

$$V_{DS} = R_{DS}.i_L \qquad (14)$$

The D.d.p between the terminals of the inductor is therefore:

$$V_L = V_{IN} - R_{DS}.i_L \qquad (15)$$

Taking on account the expression of V_L , inductor ripple curent is given by :

$$\Delta i_L^+ = T_{ON}\frac{V_{IN} - R_L.i_L}{L} \qquad (16)$$

During OFF state, MOSFET switch is off, inductor, diode and load are in series with the power supply V_{IN} .The current i_L will decrease linearly.

The d.d.p of the inductor terminals is therefore:

$$V_L = V_{IN} - (V_{OUT} + V_D) \qquad (17)$$

Similarly to the current increase i_L :

$$\Delta i_L^- = T_{OFF}\frac{(V_{OUT} + V_D) - V_{IN}}{L} \qquad (18)$$

Since $\Delta i_L^+ = \Delta i_L^-$ and $D = T_{ON} / (T_{ON} + T_{OFF})$.

$$V_{OUT} = \frac{V_{IN}}{1-D} - V_D - V_{DS}\frac{D}{1-D} \qquad (19)$$

If we assume V_{DS} , V_D are small enough:

$$V_{OUT} = V_{IN} / (1-D) \qquad (20)$$

Fig.6. shows variations of MOSFET current i_Q , diode current i_D , inductor current i_L and the PWM control voltage.

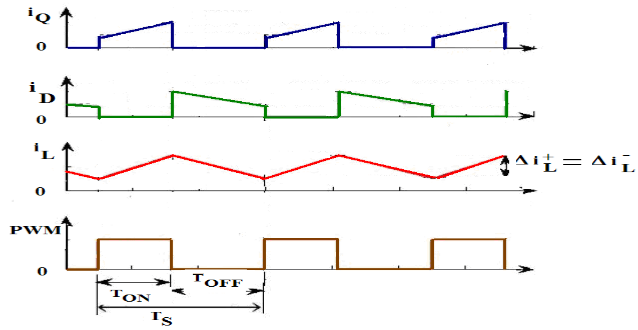


Fig.6. Waveforms of curent and voltage in CCM

In discontinuous conduction mode, the quantity of energy required by the load is low enough to be transferred in a shorter time than a switching period. During this period, the MOSFET switch and the diode are blocked. The current through the inductor is equal to zero and this time period is given by:

$$D_3T_S = T_S - T_{ON} - T_{OFF}$$

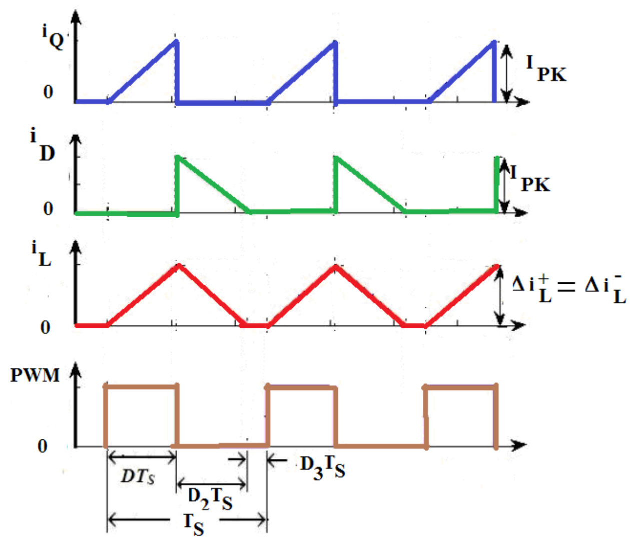


Fig.7. Waveforms of current and voltage in discontinuous conduction mode

T_{OFF} is different from $(1-D)T_S$. Fig.7. shows variations of transistor current i_Q, diode current i_D, inductor current i_L and the PWM control voltage.

If R_{DS} ,V_D are small enough, The increase of inductor current during the ON state is given by:

$$\Delta i_L^+ = T_{ON}\frac{V_{IN}}{L} = \frac{V_{IN}}{L}DT_S = I_{PK} \qquad (21)$$

where I_{PK} is the peak inductor current .

The ripple current magnitude, Δi_L^+ , is also the peak inductor current I_{PK} , because in discontinuous mode, the current starts at zero each cycle.

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

$$\Delta i_L^- = T_{OFF}\frac{V_{OUT}-V_{IN}}{L} = \frac{V_{OUT}-V_{IN}}{L}D_2T_S \quad (22)$$

$\Delta i_L^+ = \Delta i_L^-$ implies:

$$V_{OUT} = (V_{IN})\frac{T_{ON}+T_{OFF}}{T_{OFF}} = V_{IN}\frac{D+D_2}{D_2} \quad (23)$$

Output current I_{OUT} represent the average values of the inductor current during the entire switching cycle which gives:

$$I_{OUT} = \frac{V_{OUT}}{R} = \frac{1}{T_S}\frac{I_{PK}}{2}D_2T_S \quad (24)$$

Substuting (21) into (24) gives:

$$V_{OUT} = \frac{1}{2}V_{IN}\left(1+\left(1+\frac{4D^2}{K}\right)^{0.5}\right) \text{ with } K = 2L/RT_S \quad (25)$$

For discontinuous conduction mode, output voltage is a function of the input voltage V_{IN}, duty cycle D, inductor L, switching frequency f_S and load R. However for continuous conduction mode output voltage only depends on input voltage and duty cycle.

IV. Modeling of DC-DC Converters

A. Buck converter modeling in CCM

Differential equations of inductor current i_L and capacitor voltage v_{out} as a variable respectively are established according to KVL and KCL theory [14]. During ON state, the dynamics of the inductor current and the capacitor voltage are given by:

$$\begin{cases} di_L/dt = (V_{IN}-v_{out})/L \\ dv_{out}/dt = (i_L - v_{out}/R)/C \end{cases}$$

and during OFF state :

$$\begin{cases} di_L/dt = -v_{out}/L \\ dv_{out}/dt = (i_L - v_{out}/R)/C \end{cases}$$

It is easy to set up Simulink model for buck converter based on the above equation as shown in Fig.8.[15]

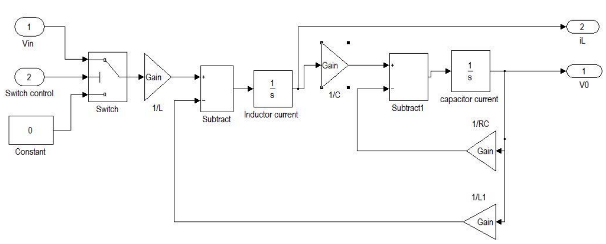


Fig.8.Model diagram of buck converter in CCM

B. Boost converter modeling in CCM

Assuming continuous conduction mode of operation, the state space equations during ON state are shown by :

$$\begin{cases} di_L/dt = (V_{IN}-v_{out})/L \\ dv_{out}/dt = -v_{out}/RC \end{cases}$$

And during OFF state

$$\begin{cases} di_L/dt = (V_{IN}-v_{out})/L \\ dv_{out}/dt = (i_L - v_{out}/R)/C \end{cases}$$

Simulink model for boost converter based on the above equation is shown in Fig.9

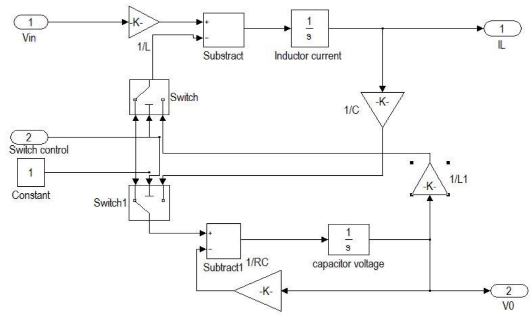
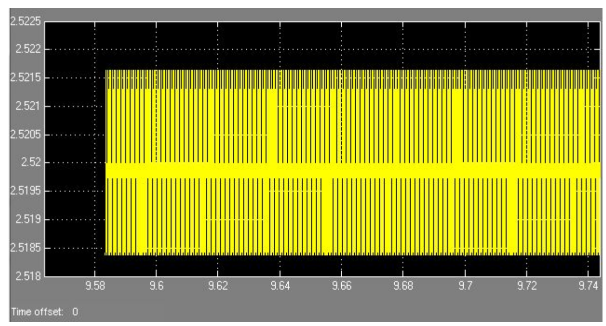


Fig.9.Model diagram of boost converter in CCM

V.SIMULATION



A. Open loop control simulation

Fig.10 Buck converter output voltage

Based on the value of duty cycle, the switch is operated to get the required output voltage which is affected by external variations. Figure 10 and Figure 11 present the simulation result of buck converter for $V_{IN} = 12V$ and $D = 0.42$. For the boost converter, the result is shown in Figure 12 for $V_{IN} = 12V$ and $D = 0.6$

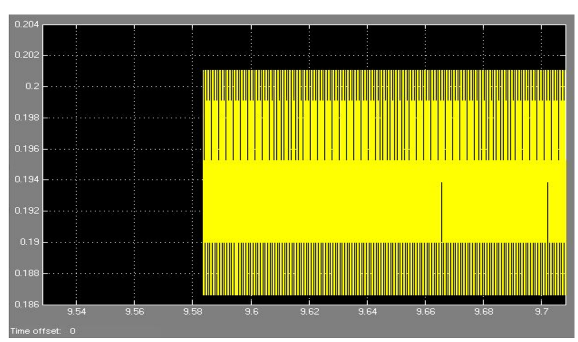


Fig.11. Buck converter output current

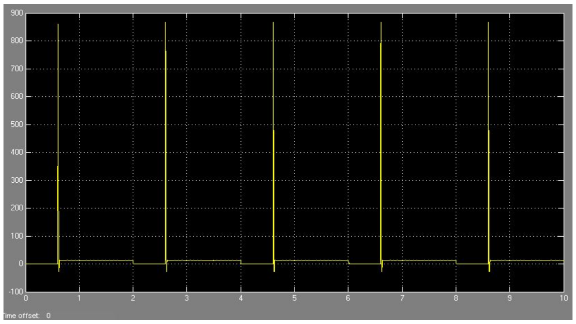


Fig.12. Boost converter output voltage

B. Sliding mode control

The sliding mode theory provides a method to design a controller for a system so that the controlled system is to be insensitive to parameter variations and external load disturbances [16]. Fig. 13 presents block diagram showing implementation of this control for DC-DC converters while Fig. 15 explains in detail the internal structure of the mode. used as a control for the DC-DC converter in Matlab/Simulink

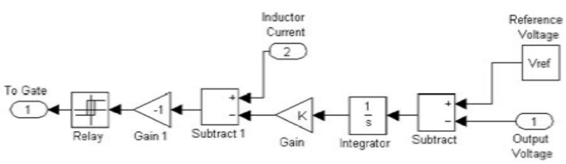


Fig.13.Sliding Mode Control (SMC) using Matlab .

The output response of buck converter using Sliding Mode Control is shown in Fig.14

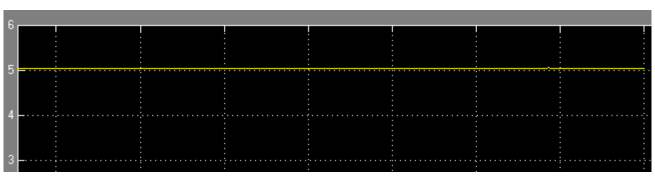


Fig.14. Output response of buck converter with (SMC)

In sliding mode a system's converter response remains insensitive to certain parameters variations and unknown disturbances i.e , (SMC) gives stable operation to DC-DC converters.

CONCLUSION

This article presents an overview on DC-DC converters . Firstly , a study of both buck and boost converters in CCM and DCM was established .Then modeling and simulation of buck and boost converters with open loop control and Sliding Mode Control which gives more stability to converter ie converter keep working in steady state even when it is affected variations was performed using Matlab/Simulink

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