International Journal of Technical Research and Applications e-ISSN: 2320-8163,
www.ijtra.com Volume 3, Issue 1 (Jan-Feb 2015), PP. 97-103

ANALYSIS AND SIMULATION OF BUCK SWITCH MODE DC TO DC POWER REGULATOR

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Abstract-This project envisages a Buck dc – dc converter mathematical analysis and simulation. This power regulator is made up of some vital circuit elements such as inductor, freewheeling diode, filter capacitor and electronics power switch. The circuit is analysed based on two modes of operation namely: continuous current conduction mode and discontinuous current mode. Ansoft Simplorer software is used to carry out the circuit simulation under the two modes of operation which aided in verifying the calculated results. Both calculated and simulated waveforms are displayed. The results obtained are very similar.

***Keywords-* Buck converter, Continuous current conduction mode, Discontinuous current conduction mode Pulse Width Modulation, Power regulator.**

I. INTRODUCTION

DC to DC power converters are applied in a variety of applications, including power supplies for personal computers, office equipment, spacecraft power systems, laptop computers, and telecommunication equipment, trolley cars, track motor control, as well as dc motor drives. The converter input is usually an unregulated dc voltage / current sources derived from any of such sources like electromechanical dc generator, a dc battery, a rectified ac source, a solar photovoltaic panel, hydrogen based fuel cell etc as shown in fig. 1.

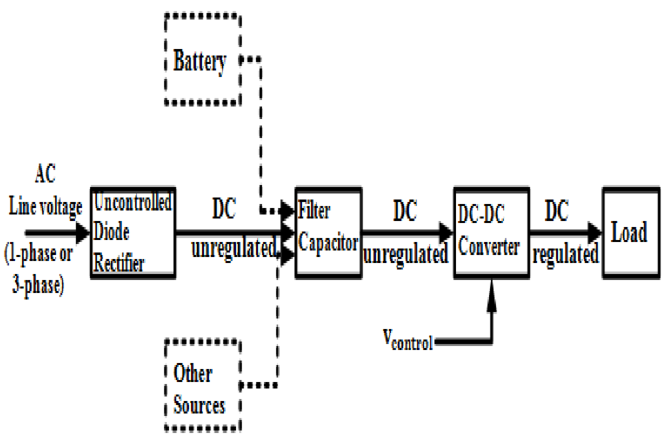

Fig.1. A Block Diagram of dc-dc Converter System

When the converter load is a dc motor or an electromechanical process load (such as a battery on charge), the load is usually generalized as a series combination of a resistance, an inductance and a load electromotive force (emf). On the other hand, especially for the most applications with regulated dc output, the converter load is usually a resistance in parallel with a filter capacitance. The converter produces a regulated output voltage, having a magnitude (and possibly polarity) that differs from the input [1]. The regulation is normally achieved by pulse width modulation at a fixed frequency. The converter switch can be implemented by using a (1) power bipolar junction transistor (BJT), (2) metal oxide semiconductor field effect transistor (MOSFET), (3) gate turn off thyristor or (4) insulated gate bipolar transistor (IGBT) [2].

In the main, there are six types of the basic dc to dc with each type having performance characteristics suitable for a particular application. These basic types are the step down or Buck converter, the step up or Boost converter, the convectional Buck-Boost converter, the Cuk's converter, the sepic converter, and the Zeta converter. The performance of buck converter has been analysed in many papers amongst them are [3][4]. In this paper a detailed analysis of Buck dc to dc converter will be analysed.

II. THE GENERALIZED BASIC HARD-SWITCHED DC TO DC CONVERTER

The basic hard-switched dc to dc converter has one main unidirectional active semiconductor switch, one main diode and one main inductance of which performs the dual function of a filter and a current limiter. In the hard switching of the active switch, both the switch current and voltage vary during the switch transition interval from the ON state to the OFF state and vice versa. If the converter inductor current is represented as a current $\mathbf{I_L}$, the basic hard-switched converter can be generally be represented by Fig. 2 as having three major nodes (node 1, 2 and 3). $\mathbf{S_m}$ is the converter main unidirectional active switch, $\mathbf{D_m}$ is the main converter diode or freewheeling diode, while $\mathbf{V_{12}}$ is the dc voltage between nodes 1 and 2.

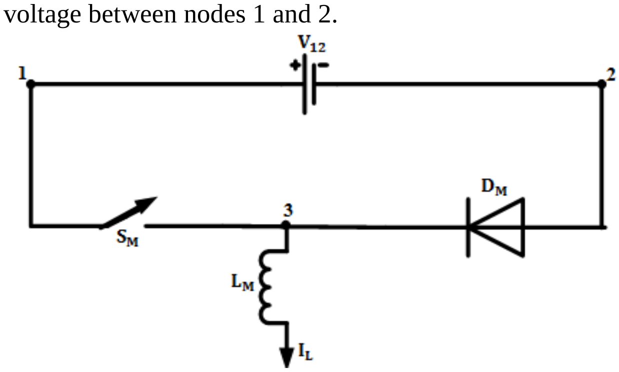

Fig. 2 The generalized equivalent circuit of the basic dc to dc converter.

The following nodes are noted;
Node 1: Located at the anode (input) of the active switch, $\mathbf{S_m}$.
Node 2: Located at the anode of the freewheeling diode $\mathbf{D_m}$,
Node 3: Point of outflow of the inductor current $\mathbf{I_L}$ from the common point conectiong the cathodes of $\mathbf{S_m}$ and $\mathbf{D_m}$ [5].

At time t = 0, $\mathbf{S_m}$ is closed. In the ON state of $\mathbf{S_m}$, $\mathbf{D_m}$ is reverse biased by $\mathbf{V_{12}}$ and therefore is OFF, thus forcing the current $\mathbf{I_{Lm}}$ to flow through $\mathbf{S_m}$. For an interval (1-D) $\mathbf{T_s}$ seconds in a switching cycle, the switch $\mathbf{S_m}$ is open thus causing the current $\mathbf{I_{Lm}}$ to flow through $\mathbf{D_m}$ as long as $\mathbf{I_{Lm} > 0}$. Based on the generalized basic converter of fig. 2, the Buck dc to dc hard-switched converter topology is presented and analyzed in this work.

III. MODE OF CIRCUIT OPERATION

The step down or Buck dc to dc converter shown in fig. 3 converters the unregulated dc input voltage $\mathbf{V_S}$ to a regulated dc output voltage $\mathbf{V_0}$ which can be varied from zero to maximum dc voltage equal to the input dc voltage $\mathbf{V_S}$. It is assumed that the input and the output filter capacitors $\mathbf{C_1}$ and $\mathbf{C_0}$ are large enough to make the input voltage and current ($\mathbf{V_0}$, $\mathbf{I_0}$) ripple content negligible. The principal nodes (1, 2, 3) in fig. 3 identify the generalized form of the basic converter as depicted in fig. 2.

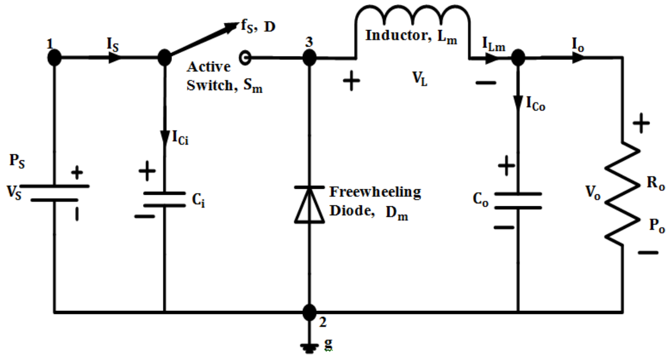

Fig. 3 The basic buck dc to dc converter circuit configuration

Suppose the active switch $\mathbf{S_m}$ is turned ON as shown in fig. 4, for a time interval DT seconds (0 < D < 1), the freewheeling diode, $\mathbf{D_m}$ becomes reverse biased and the input provides energy to the load as well as to the inductor.

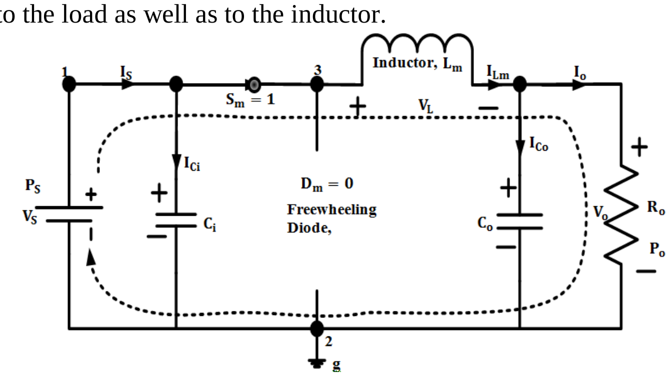

Fig. 4 Buck Converter Operation when $\mathbf{S_m}$ is ON

Furthermore, if the active switch $\mathbf{S_m}$ is turned OFF as shown in fig. 5, for the remaining interval of (1-D)*T seconds in a cycle of period T seconds. During this interval, the inductor current flows through the freewheeling diode, $\mathbf{D_m}$ transferring some of its stored energy to the load.

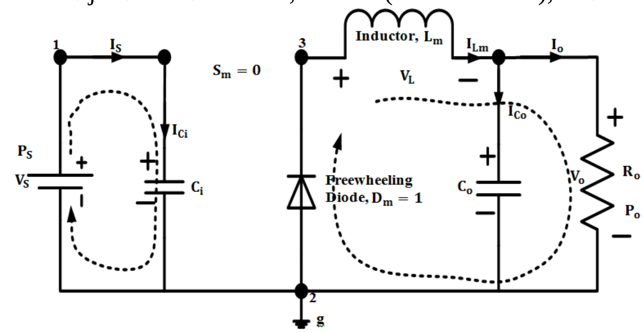

Fig. 5 Buck Converter Operation when $\mathbf{S_m}$ is OFF

Under this operation condition the converter current conduction can be continuous or discontinuous. Continuous current conduction is the case if the freewheeling diode $\mathbf{D_m}$ is on conducting the inductor current $\mathbf{I_{Lm}}$ for the entire interval (1-D)*T seconds in a switching cycle operation. Discontinuous current conduction is the case if the freewheeling diode $\mathbf{D_m}$ is on conducting the inductor current $\mathbf{I_{Lm}}$ for an interval $(\mathbf{t_x - DT})$ seconds where $\mathbf{t_x}$ is less than T, implying that the diode current $(\mathbf{I_{Dm} = I_{Lm}})$ decayed to zero thus turning $\mathbf{D_m}$ OFF (T-$\mathbf{t_x}$)seconds in a switching cycle.

A. Continuous Current conduction operation

Under continuous current conduction mode, the inductor current $\mathbf{I_{Lm}}$ is greater than zero at all times in a cycle except at the instant of turn ON of the active switch $\mathbf{S_m}$ when $\mathbf{I_{Lm}}$ can be greater than or equal to zero. A more generalized definition of continuous current operation is that the freewheeling diode $\mathbf{D_m}$ remains ON conducting current in the interval$\mathbf{DT \leq t \leq T}$. Fig. 6 shows the converter steady state circuit current and voltage waveforms for converter operation at continuous current conduction mode. For the interval $\mathbf{0 \leq t \leq DT}$, the switch $\mathbf{S_m}$ is ON and $\mathbf{D_m}$ is reverse biased by $\mathbf{V_{12}} = \mathbf{V_S}$ and therefore OFF. In this interval therefore the inductor voltage and current are given by

$$\mathbf{V_L} = \mathbf{L_M}\frac{\mathbf{dI_{LM}}}{\mathbf{dt}} = \mathbf{V_S} - \mathbf{V_o} \qquad (1)$$

From Equation (1) inductor current can be determined as

$$\mathbf{I_{LM}} = \frac{\mathbf{1}}{\mathbf{L_M}}\,(\mathbf{V_S} - \mathbf{V_o})*t + K \qquad (2)$$

The integration constant K can be determined by evaluating equation (2) at the value of t = 0 and the corresponding value of the inductor current ie $\mathbf{I_{LM} = I_{min}}$, which implies that the value of K is $\mathbf{I_{min}}$. Thus equation (2) can be modified as

$$\mathbf{I_{LM}} = \frac{\mathbf{1}}{\mathbf{L_M}}\,(\mathbf{V_S} - \mathbf{V_o})*t + \mathbf{I_{min}} \qquad (3)$$

From equation (3) when t = DT, $\mathbf{I_{LM}}$ becomes $\mathbf{I_{max}}$, hence the change in inductor current can be determined as

$$\mathbf{\Delta I_L = I_{max} - I_{min}} = \frac{(\mathbf{V_S - V_o})\mathbf{DT}}{\mathbf{L_M}} = \frac{(\mathbf{V_S - V_o})\mathbf{D}}{\mathbf{fL_M}} \qquad (4)$$

For the interval DT < t < T, $\mathbf{S_m}$ is turned off and $\mathbf{D_m}$ conducts the inductor current as show in fig. 5 giving $\mathbf{V_L}$ and $\mathbf{I_{LM}}$ as

$$\mathbf{V_L} = \mathbf{L_M}\frac{\mathbf{dI_{LM}}}{\mathbf{dt}} = -\mathbf{V_o} \qquad (5)$$

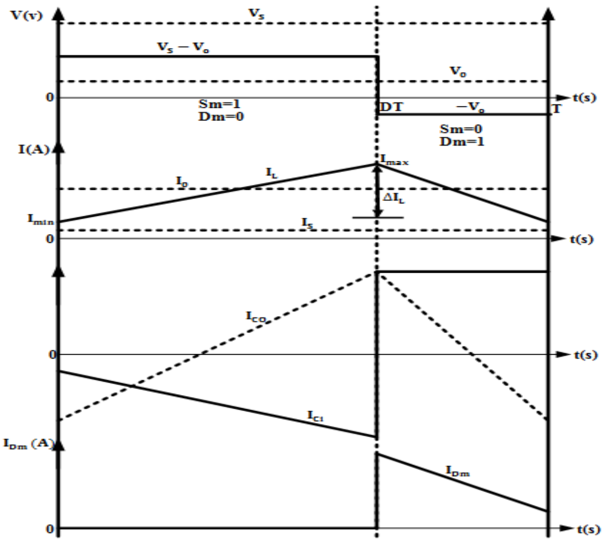

Fig. 6 Circuits waveforms of the basic buck converter under continuous current conduction operation.

From Equation (5) inductor current can be determined as

$$I_{LM} = \frac{1}{L_M}(-V_o)*(t-DT) + M \quad (6)$$

The integration constant M can be determined by evaluating equation (6) at the value of t=DT and the corresponding value of the inductor current i.e. $I_{LM} = I_{max}$, which implies that the value of M is I_{max}. Thus equation (6) can be modified as

$$I_{LM} = -\frac{V_o}{L_M}*(t-DT) + I_{max} \quad (7)$$

At t = T, I_{LM} becomes I_{min} again and the cycle is repeated. Hence the change in inductor current is expressed by

$$\Delta I_L = I_{max} - I_{min} = \frac{V_o(1-D)T}{L_M} = \frac{V_o(1-D)}{fL_M} \quad (8)$$

From the equations (4) and (5), the ratio of the converter output to input voltage is obtained as

$$\frac{V_o}{V_s} = D \quad (9)$$

The input and output capacitor currents I_{CI} and I_{CO} and active switch current I_{SM} in the interval $0 \le t \le DT$ are given (see fig. 4) as

$$I_{CI} = I_S - I_{LM} \quad (10)$$

$$I_{CO} = I_{LM} - I_0 \quad (11)$$

$$I_{SM} = I_{LM} \quad (12)$$

Where I_S and $I_0$are the average converter input and output currents respectively. From the converter waveforms of fig. 6, I_S and I_0 are seen to be the average values of the main switch current I_{SM} and the inductor current I_{LM},

$$I_S = \frac{1}{T}\int_0^{DT} I_{LM}\,dt = \frac{1}{2}(I_{max} + I_{min})D \quad (13)$$

$$I_0 = \frac{1}{T}\int_0^{T} I_{LM}\,dt = \frac{1}{2}(I_{max} + I_{min}) \quad (14)$$

From equations (13) and (14), the ratio of the converter output current I_0 to the input current I_S can be shown to be inverse of the ratio of the output voltage V_0 to the input voltage V_S. This is the common characteristic of all dc to dc converters assuming lossless circuit components.

$$\frac{I_o}{I_s} = \frac{V_S}{V_O} = \frac{1}{D} \quad (15)$$

Alternatively, the voltage ratio, $\frac{V_o}{V_s}$, can be determined by equating the average voltage across the filter inductor L_M to zero since, in a practical and stable switching converter circuit, an inductor has no dc or average voltage across it. This is same as equating the area under the inductor voltage waveform over a cycle to zero. From fig. 6, the inductor average voltage equated to zero is

$$\int_0^T V_L\,dt = (V_S - V_o)DT - V_o(1-D)T = 0 \quad (16)$$

On simplifying equation (16) yields the same result as given in equation (9).

Similarly, $\frac{I_o}{I_s}$ can alternatively be determined by equating the average current through each of the filter capacitors (C_1 and C_0) to zero. This is equivalent the average current through each capacitor current (I_{CI} and I_{CO}) to zero. From the waveforms of (I_{CI} and I_{CO}) in fig. 6 give the same result as obtained in equation (15).

The filter inductor peak to peak ripple current ΔI_L is given in equations (4) and (8) as

$$\Delta I_L = I_{max} - I_{min} = \frac{V_o(1-D)}{fL_M} = \frac{V_S(1-D)D}{fL_M} \quad (17)$$

From equation (17) the maximum value of ΔI_L occurs at $D=\frac{1}{2}$ and is given by

$$\Delta I_{Lmax} = \Delta I_L\left(D = \frac{1}{2}\right) = \frac{V_o}{2fL_M} = \frac{V_s}{4fL_M} \quad (18)$$

The ripple factor $Rf_{I_{Lm}}$ of the inductor current is the ratio of the inductor peak ripple current $\frac{\Delta I_L}{2}$ to the inductor average current, I_{Lo}

$$Rf_{I_{Lm}} = \frac{V_o(1-D)}{2fL_M I_o} = \frac{V_S(1-D)D}{2fL_M I_o} \quad (19)$$

The minimum and the maximum instantaneous inductor current I_{min} and I_{max} are obtained by the simultaneous solution of equations (14) and (17)

$$I_{min} = I_0 - \frac{\Delta I_L}{2} \quad (20)$$

$$I_{max} = I_0 + \frac{\Delta I_L}{2} \quad (21)$$

The condition for maximum current conduction mode is that the minimum inductor current must be greater than or equal to zero. Therefore the condition for continuous current conduction is

$$I_{min} \ge 0 \quad (22)$$

This implies (from equations (17), (20) and (22)) that

$$1 \ge \frac{V_o(1-D)}{2fL_M I_o} = \frac{R_o(1-D)}{2fL_M} \quad (23)$$

Where the output load resistance, $R_0 = \frac{V_o}{I_o}$

From equation (23), the minimum filter inductance L_{Mmin} that just makes the inductor current I_{LM} continuous for a given duty cycle, specified load and operating frequency is

$$L_{Mmin} = \frac{R_o(1-D)}{2f} \quad (24)$$

The peak to peak input filter capacitor voltage ripple ΔV_{CI} is the change in the capacitor voltage during the interval that the capacitor current I_{CI} is either positive or negative. Assuming an operating condition in which $I_S \le I_{Lmin}$, I_{CI} is positive during the interval (1-D)T seconds when S_M is off thus giving ΔV_{CI} as,

$$\Delta V_{CI} = \frac{I_S(1-D)T}{C_I} = \frac{I_o(1-D)D}{fC_I} \qquad (25)$$

It can be easily deduced from equation (25), that the maximum value of ΔV_{CI} occurs at D = $\frac{1}{2}$ and that this maximum value is expressed as

$$\Delta V_{CImax} = \Delta V_{CI}\left(D = \frac{1}{2}\right) = \frac{I_o}{4fC_I} \qquad (26)$$

The ripple factor $Rf_{V_{CI}}$ of the converter input voltage (V_S) is defined as the ratio of the capacitor C_I peak ripple voltage to the input voltage.

$$Rf_{V_{CI}} = \frac{\frac{\Delta V_{CI}}{2}}{V_S} = \frac{D(1-D)I_o}{2V_S fC_I} = \frac{D^2(1-D)}{2R_o fC_I} \qquad (27)$$

Note that $Rf_{V_{CI}}$ has its maximum value at D = $\frac{1}{2}$.

Similarly the peak to peak ripple voltage ΔV_{Co} of the output filter capacitor C_o is the change in the capacitor voltage in the interval, in a cycle of operation, during which C_o is either charge or discharge. From fig (6), C_o is charge by I_{CO} in the interval $\frac{DT}{2} \leq t \leq \frac{(1+D)T}{2}$. Therefore, ΔV_{Co} is the area under I_{Co} waveform in this interval divided by the capacitance C_O.

$$\Delta V_{Co} = \frac{\Delta I_{Lm}T}{8C_O} = \frac{(1-D)V_o}{2f^2L_mC_o} = \frac{V_S D(1-D)}{8L_M f^2 C_o} \qquad (28)$$

It is seen from equation (28) that the maximum value of ΔV_{Co} occurs at D = $\frac{1}{2}$ and this maximum value

$$\Delta V_{Comax} = \Delta V_{Co}\left(D = \frac{1}{2}\right) = \frac{V_o}{16f^2L_MC_o}$$

(29)

The ripple factor $Rf_{V_{Co}}$ of the converter output voltage is defined as the ratio of its ripple voltage to its average voltage.

$$Rf_{V_{Co}} = \frac{\frac{\Delta V_{Co}}{2}}{V_o} = \frac{(1-D)}{16f^2L_MC_o} \qquad (30)$$

Note again that $Rf_{V_{Co}}$ has its maximum value at D = $\frac{1}{2}$.

Considering the boundary condition between continuous and discontinuous conduction, the boundary average inductor current I_{LB} is given by

$$I_{LB} = \frac{I_{Lmax}}{2} = \frac{(V_S - V_o)D}{2fL_M} = I_{OB} \qquad (30a)$$

In fig. 7, I_{LB} is plotted against the duty cycle, D. From the plot it is observed that the maximum boundary inductor current occurs $I_{LB,Max}$ at D = $\frac{1}{2}$. Therefore during operating condition, if the average output current becomes less than I_{LB}, then I_L will become discontinuous [6].

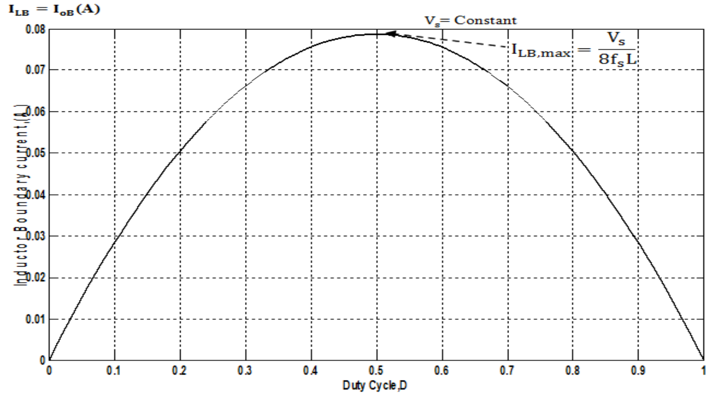

Fig. 7 Current at boundary of continuous-discontinuous conduction

B. Discontinuous Current Conduction Operation

In discontinuous current conduction operation, the steady state inductor current decreases from its maximum value to zero at t = t_x where DT < t_x < T thus causing Dm to be OFF for the rest of the cycle. In other words, the minimum inductor current I_{LM} at instant of turn on of the active switch S_m at t = 0 is zero and the inductor current becomes zero again at t = t_x. The general condition for discontinuous current condition operation is fulfilled if equation (24) is untrue. Therefore for discontinuous current conduction operation, the following equation applies

$$1 \leq \frac{V_o(1-D)}{2fL_M I_o} = \frac{R_o(1-D)}{2fL_M} \qquad (31)$$

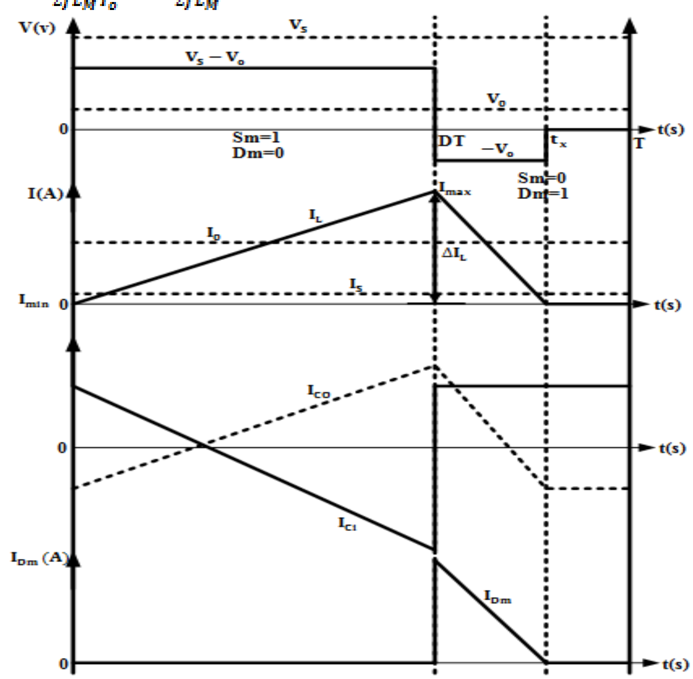

Fig. 8 Circuits waveforms of the basic buck converter under discontinuous current conduction operation.

In fig. 8 is shown the circuit waveforms of the buck converter under discontinuous current conduction operation.

For the interval $0 \leq t \leq DT$

$$I_{LM} = \frac{1}{L_M}(V_S - V_o)*t + K \qquad (32)$$

The integration constant K can be determined by evaluating equation (32) at the value of t = 0 and the corresponding value of the inductor current i.e. $I_{LM} = I_{Min} = 0$, which implies that the value of K is 0. Thus equation (32) can be modified as

$$I_{LM} = \frac{1}{L_M}(V_S - V_o)*t \quad (33)$$

At t = DT, $I_{LM} = I_{Max}$

$$I_{Max} = \frac{1}{L_M}(V_S - V_o)*DT \quad (34)$$

Similarly, for the interval DT $\leq t \leq T$ (see equation (8), where $I_{mim} = 0, t = t_x$)

$$I_{max} = \frac{V_o(t_x - DT)}{L_M} \quad (35)$$

Comparing equations (34) and (35) yields the voltage gain $\frac{V_O}{V_S}$ under discontinuous current conduction mode which is given as

$$\frac{V_O}{V_S} = \frac{D}{t_x/T} \quad (36)$$

Since t_x/T is less than unity, the voltage gain under discontinuous current conduction operation is higher than the voltage gain at continuous current conduction operation for the same duty cycle D.

From the waveforms of the inductor current I_L and the main switch current I_{sm}, the average output current I_o and the input current I_S can be determined as

$$I_O = \frac{1}{T}\int_0^{t_x} I_L\,dt = \frac{I_{max}\,t_x}{2T} \quad (37)$$

Average input current can be computed as

$$I_S = \frac{1}{T}\int_0^{DT} I_L\,dt = \frac{I_{max}\,DT}{2T} \quad (38)$$

The current gain $\frac{I_O}{I_S}$ is calculated from equations (37) and (38) which is given by

$$\frac{V_O}{V_S} = \frac{t_x/T}{D} \quad (39)$$

Putting equations (4), (with $I_{Lmin} = 0$) and (36) into equation (37) yields

$$V_O^{\,2} + \frac{D^2 V_S R_O V_O}{2fL_m} - \frac{D^2 V_S^{\,2} R_O}{2fL_m} = 0. \quad (40)$$

Solving equation (40) using quadratic formula gives the converter output voltage as

$$V_O = \frac{D^2 V_S R_O}{4fL_m}\left[-1 + \sqrt{\left(1 + \frac{8fL_m}{D^2 R_O}\right)}\right] \quad (41)$$

Equation (41) can be modified as

$$\frac{V_O}{V_S} = \frac{2D^3 I_{LBmax}}{I_O}\left[-1 + \sqrt{\left(1 + \frac{I_O}{D^3 I_{LBmax}}\right)}\right] \quad (42)$$

Where, $\frac{I_O}{I_{LBmax}} = \frac{8fL_M I_O}{V_S}$.

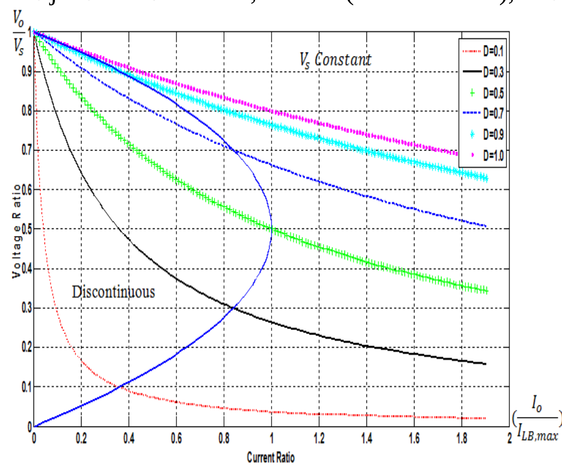

Fig. 9 Buck Converter Characteristics keeping V_s constant

Fig. 9 shows the step-down converter characteristic in both modes of operation for a constant source voltage, V_S. The voltage ratio ($\frac{V_O}{V_S}$) is plotted as a function of $\frac{I_O}{I_{LBmax}}$ for various values of duty cycle using equations (9) and (42). The boundary between the continuous and the discontinuous mode, shown by the curved line is established by equations (9) and (30a).

C. Control of Buck DC to DC Converter

In dc – dc converter, the average dc output voltage must be controlled to equal a desired level, though the input voltage and the output load may fluctuate. Switch-mode buck dc – dc converter utilizes one or more switches to transform dc from one level to another. In a dc – dc converter with a given input voltage, the average output voltage is controlled by controlling the switch on and off duration. (t_{on} and t_{off}).

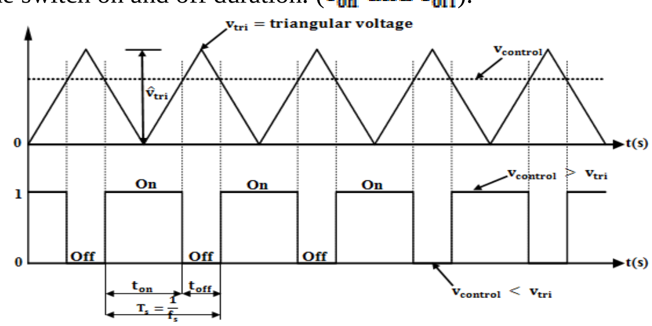

Fig. 10 Pulse-width modulator with comparator signals.

In pulse-width modulation (PWM) switching at a constant frequency, the switch control signal, which controls the state (on and off) of the switch, is generated by comparing a signal-level control voltage $V_{control}$ with a repetitive waveform as shown in fig. 10. The frequency of the repetitive waveform with a constant peak, which is shown to be triangular waveform, $V_{triangle}$, establishes the switching frequency. This frequency is kept constant in a PWM control and is chosen to be in few kilohertz to a few hundred kilohertz range [6]. A comparator device can be used to compare the two signals to generate firing pulses, for the power switch which is characterized by on and off behavior.

IV. CALCULATION AND SIMULATION RESULTS

In the calculation and the simulation of Buck dc – dc converter the following parameters will be assumed.

Table 1 Parameters of buck dc-dc converter model

Parameters	Circuit Values
Input Voltage, V_S	12.6V
Switching frequency, f	20kHz
Duty Cycle, D	0.397
Output Current, I_O	200mA
Load Resistance, R_O	25Ω
Inductance, L_M	1mH
Input Capacitor, C_i	470uF
Output Capacitor, C_O	470uF

Table 2 Parameters for Buck dc – dc converter model

Parameters	Continuous Values Calculated	Discontinuous values Calculated	Continuous Values Simulated	Discontinuous values Simulated
Output Voltage, V_O	5.0V	5.44V	4.8V	5.40V
Minimum inductor current, I_{Lmin}	0.1245A	0A	0.110A	0A
Maximum inductor current, I_{Lmax}	0.2755A	0.457A	0.268A	0.470A

1. *Calculation Results for continuous and discontinuous current conduction modes*

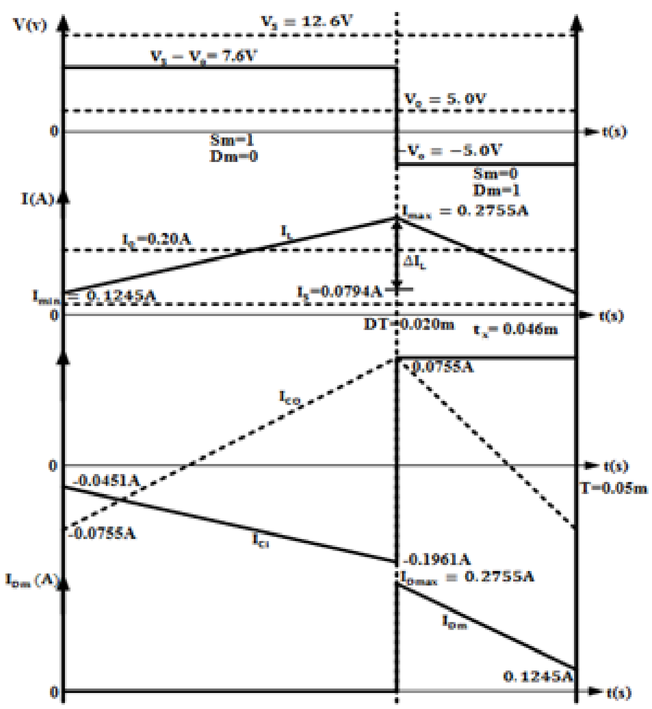

Fig. 11 Continuous current conduction mode

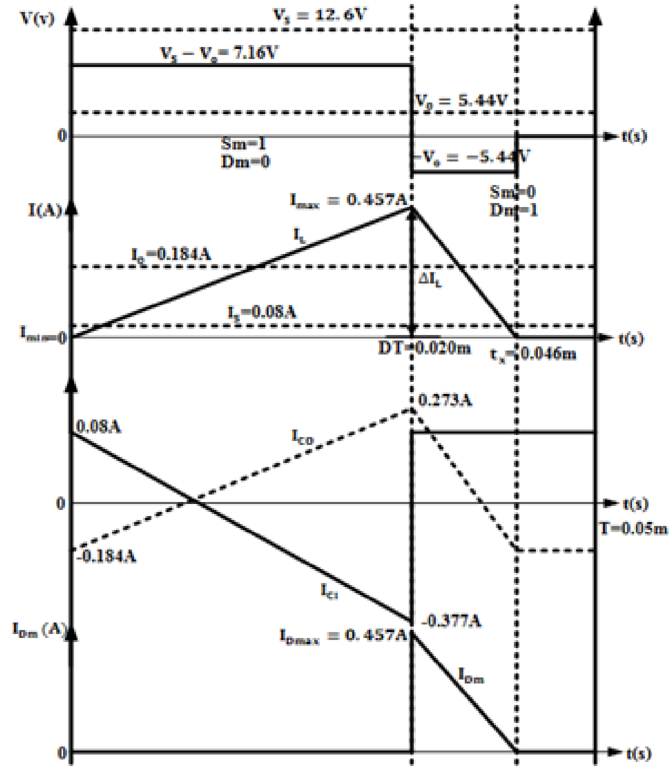

Fig. 12 Discontinuous Current Mode Waveforms

2. *Simulation Results for continuous and discontinuous current conduction modes*

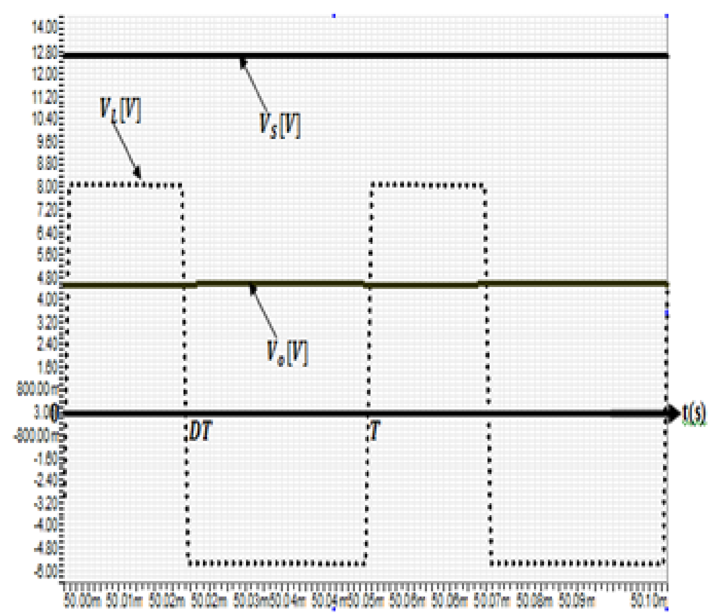

Fig. 13 Voltage Waveforms for Buck DC to DC Power Regulator in continuous current mode of Operation.

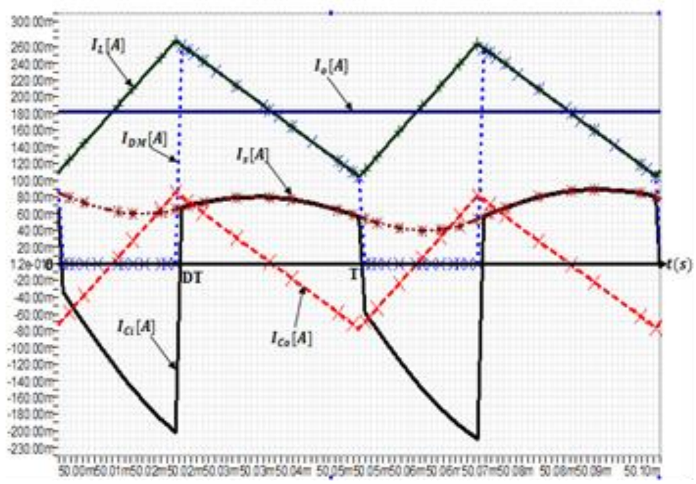

Fig. 14 Current Waveforms for Buck DC to DC power Regulator in Continuous Current Conduction mode.

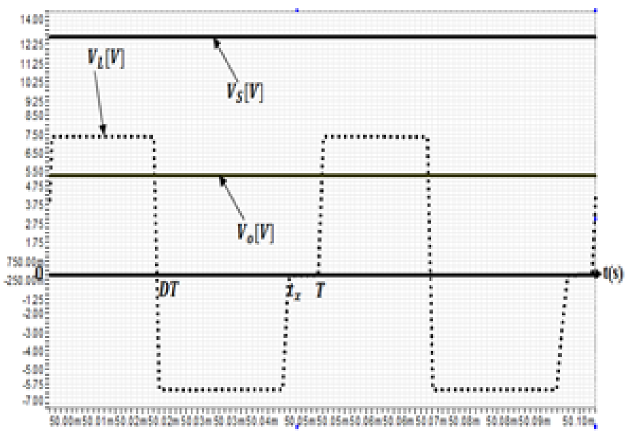

Fig. 15 Voltage Waveforms for Buck DC to DC Power Regulator in Discontinuous Current conduction Mode.

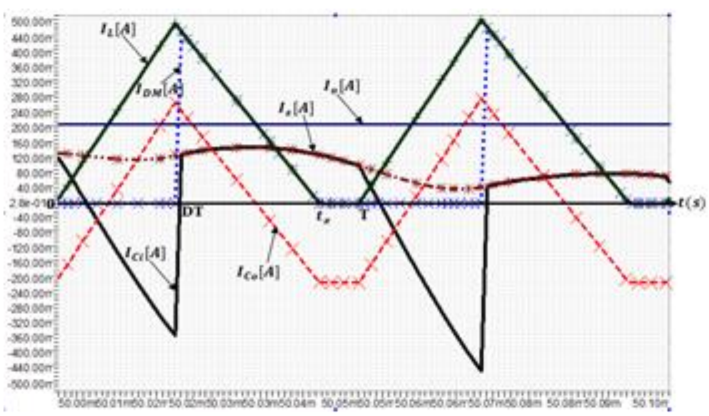

Fig. 16 Current Waveforms for Buck DC to DC Power Regulator in Discontinuous Current Conduction mode.

V. CONCLUSION

In this work an attempt has been made to analyse mathematically and simulate a buck dc-dc converter under a resistive load application. The circuit is analysed under two different modes of operation namely: Continuous and Discontinuous current conduction modes. The circuit is simulated using Ansoft Simplorer software. Now from all this, following conclusions can be drawn that the calculated results are approximately equal to the simulated results under both modes of operations. The waveforms obtained are closely related. This work successfully generated waveforms as desired and can be further verified by carrying out the prototype of the project.

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