Journal of Engineering and Development, Vol. 17, No.6, December 2013 , ISSN 1813- 7822

The Effect Of Resistive Load Variations On The Open-Loop Control Of Dc-Dc Buck Converter

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Abstract :

An open-loop control scheme of high level to low level DC-DC voltage signal buck converter is implemented in this paper. The parameters of the buck have been selected and the mathematical calculations have been done to ensure the converter operates in continuous conduction mode. The employed buck converter was represented by its states space averaging technique and it was simulated by Matlab/ Simulink software package. The pure resistive load is illustrated and the resistance value has been changed to check the performance of the open-loop model of the converter. The simulation is carried out and the analysis of the simulation results showed that variation of load resistance gives significant effect on the behavior of the converter model and affect the stability of the system.

Keywords; DC-DC buck converter; state-space averaging technique; Matlab/Simulink.

تأثير التغييرات على حمل المقاومة الكهربائية في دائرة السيطرة الالكترونية المفتوحة لمحول الفولتية المستمرة من نوع باك (Buck)

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الخلاصة:

في هذا العمل استخدمت دائرة سيطرة الكترونية من النوع المفتوح للتحكم بعمل محول الفولتية المستمرة (Buck Converter) . من المستوى العالي إلى الواطئ . تم اختيار عناصر المحول واستخدام المعادلات الرياضية المناسبة لغرض الحصول على حالة التوصيل المستمر للتيار الكهربائي وتطبيق النموذج الرياضي للمحول من خلال تقنية ال(State Space) ..

تم اختيار حمل كهربائي من نوع مقاومة كهربائية متغيرة وإجراء التغيير في قيم هذه المقاومة لغرض ملاحظة التأثير على أداء المحول مع تنفيذ المحاكاة لهذا النموذج في الحاسوب عن طريق برنامج (Matlab/Simulink) وقد بينت نتائج المحاكاة وجود تأثير واضح لهذا التغيير على أداء واستقرارية منظومة السيطرة للمحول

1. Introduction

The DC-DC converters are electrical circuits that used to transfer the electrical energy from a DC voltage source to a load and regulate the output voltage. These converters have been widely employed in the power supply equipment for most electronic systems to regulate the output voltage against the changes of the input voltage and load current [1]. The most commonly used converter is the buck, which is used to convert a DC input voltage to a lower DC output voltage with the same polarity. The name “Buck” or step-down voltage regulator presumably provides non-isolated, switch-mode DC-DC conversion with the advantages of simplicity and low cost [2].

One of the step-down regulator topology, the buck converter employs a square-wave pulse width modulation (PWM) control signal, and Power transistor (MOSFET) as controllable switch to achieve voltage regulation. The output voltage is regulated by varying the duty cycle of the power MOSFET driving signal. The mode of operation of the converter is simply varied from switch (ON) to (OFF) state and the Kirchhoff’s law is applied to obtain the differential equation of each state of the converter [3]. The state space averaging technique is used to model the DC-DC converter in each switched configuration mode with the help of Matlab/Simulink as a tool for simulation.Conceptually, the simulation programs developed for the study of converters in open loop control were sufficient to establish the general behavior of the system and make the design of the circuit possible [4].

To obtain high performance control of buck converter, the load is often the most variable part of the converter model. If the load current and the output voltage are measured, then there are possibilities to obtain a good model of the converter [5].The main objective of this work is to utilize the open loop scheme of DC-DC ideal buck converter in continuous conduction mode with using different values of the resistive load so that the effect of load variations at the outputs of the converter can be analyzed.

This paper is organized as follows; the proposed and Mathematical modeling of DC-DC buck converter is given in sections 2 and 3 respectively. Section 4 describes the implementation of MATLAB /Simulink environment including the simulation results and the concluding remarks are given in section 5.

2. The Buck Converter Model

The proposed buck converter with ideal switching devices is considered. it is essentially consists of a power MOSFET , a freewheeling diode, an inductor (L), a filter capacitor(C) and resistive load as shown in **Figure (1).** The switching network composed of the transistor and the diode ‘chops’ the dc input voltage (Vin) and therefore the converter is often called a ‘chopper’, which produces a reduced average voltage [3].

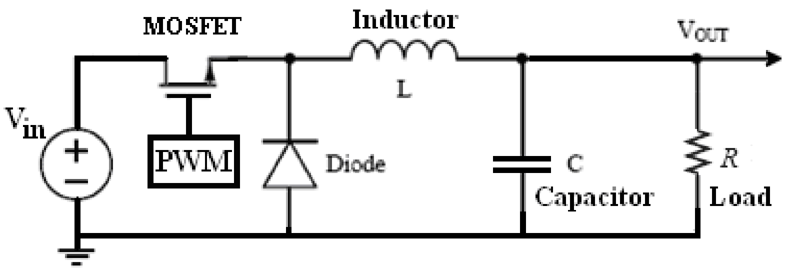
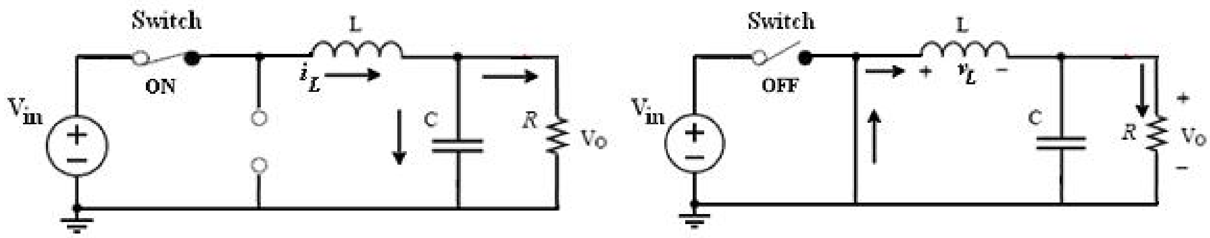


Fig. (1) the Schematic Diagram of the Proposed DC-DC Buck Converter.

The buck converter uses a MOSFET as a switch by applying a pulse width modulating signal to its gate and varying its (*ON*) and (*OFF*) times. The ratio of (*ON*) time to switching period is the duty cycle (*D*). The buck converter can operate in two mode namely as a continuous conduction mode (CCM) and a discontinuous conduction mode (DCM), depending on the waveform of the inductor current. In (CCM) the inductor current flows continuously during the entire cycle, whereas in DCM the inductor current flows only during part of the cycle and it falls to zero [3]. According to the switching signal operation there is two equivalents circuit states per switching cycle, The first sub-circuit state is when the switch is turned on, diode is reverse biased and inductor current flows through the switch as shown in **Figure (2a).** The second sub-circuit state is when the switch is turned off and current freewheels through the diode as shown in **Figure (2b)** [5].



(a) ***(b)***

Fig. (2) the Buck Converter Sub-Circuits a-(ON) State. b-(OFF) State.

Applying Kirchoff's current law (KCL) and Kirchoff's voltage law (KVL) in the circuits of **Figure (2)** [4] [5].

The output equations for the (*ON*) period are

$$L\frac{di_L}{dt}+V_C=V_{in} \quad \text{------------------------------}(1)$$

$$i_L+\frac{V_C}{R}+C\frac{dV_C}{dt}=0 \quad \text{------------------------------}(2)$$

$$V_O=V_C \quad \text{------------------------------}(3)$$

By dividing both sides of equation (1) by (L) and equation (2) by (C), then

$$\frac{di_L}{dt} = \frac{1}{L}(V_{in} - V_C) \quad \text{------------------------------} (4)$$

$$\frac{dV_C}{dt} = \frac{1}{C}(i_L - \frac{V_C}{R}) \quad \text{------------------------------} (5)$$

The output equations for the (*OFF*) period are

$$\frac{di_L}{dt} = -\frac{V_C}{L} \quad \text{------------------------------} (6)$$

$$\frac{dV_C}{dt} = \frac{1}{C}(i_L - \frac{V_C}{R}) \quad \text{------------------------------} (7)$$

Where

i_L is current through the inductor.
V_C is voltage across the capacitor.
V_{in} is DC input voltage

3. Mathematical Model of DC-DC Buck Converter

For mathematical modelling, the buck converter in the continuous conduction mode operation acts as a time-invariant system when the MOSFET is (*ON*), while it acts as another time-invariant system when the device is (*OFF*). .It is deemed as a variable structure system and the circuit topology changes in accordance with the switching action of the semiconductor device .Consequently, the converter can be modeled as a time-variant system and the state-space averaging technique is one method to approximate this time-variant system with a linear continuous-time invariant system [6].

The circuit of the buck converter is redrawn as in Figure (3) for obtaining the state equations with the control input (u) of the converter. The control input u, representing the switch position function, taking values in the set {0, 1}.The capacitor voltage (V_c) and the inductor current (i_L) and can be defined as the state vector x_1, x_2 respectively. The duration of the *(ON)* state is [$T_{ON} = DT_S$], while the duration of the *(OFF)* state is [$T_{OFF} = (1–D)\ T_S$] where (D) is the duty cycle expressed as a ratio of the switch *(ON)* time to the time of one complete switching cycle *(Ts)*[6] [7].

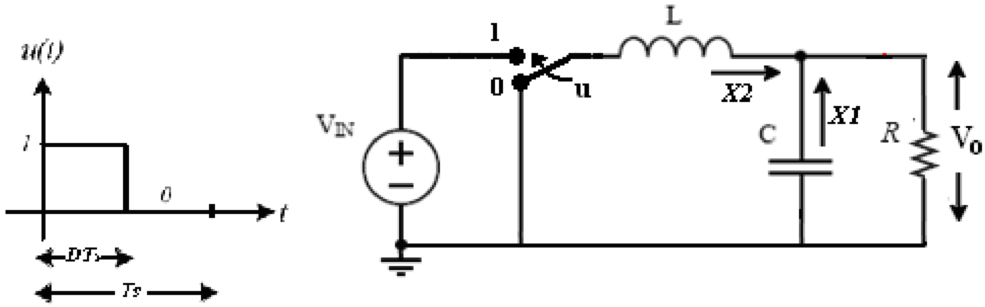


Fig. (3) The Ideal Switch Representation of the Open-Loop DC-DC Buck Converter.

Hence, the buck converter can be represented by two piecewise-linear vector differential equations.

$$During(T_{ON}) \quad \dot{x} = A_1 x + B_1 \quad ----------(9)$$

$$During(T_{OFF}) \quad \dot{x} = A_2 x + B_2 \quad ----------(10)$$

Where

$x = [x_1\ x_2]^T = [V_c\ i_L]^T$ is the state vector

A representation of the buck converter through a single equivalent dynamic equation can be obtained via combining equations (9) and (10) as given below [5]

$$\dot{x} = (A_1 x + B_1)u + (A_2 x + B_2)(1-u) \quad ----------(11)$$

$$\dot{x} = A_2 x + B_2 + (A_1 - A_2)xu + (B_1 - B_2)u \quad ----------(12)$$

Since (u = 1) during T_{ON} and (u = 0) during T_{OFF}, *(A)* and *(B)* are the system matrices and

$$A_1 = A_2 = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \quad , B_1 = \begin{bmatrix} \frac{V_{in}}{L} \\ 0 \end{bmatrix} \quad , B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Then expression **(**12**)** becomes

$$\dot{x} = A_1 x + B_1 u \quad ----------(13)$$

Assuming constant frequency operation, the discrete variable (u) is substituted by a continuous variable *d (t)* which can take all the values between 0 and 1. Therefore, equation (13) becomes

$$\dot{x} = A_1 x + B_1 d(t) \quad ----------(14)$$

Therefore the equations from (4) to (7) can be written in the following state space form to represent the ideal buck converter:

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & \frac{-1}{L} \\ \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{V_{in} d(t)}{L} \\ 0 \end{bmatrix} \quad ----------(15)$$

4. Simulation

The ideal buck converter has been simulated and modelled using its state space dynamic equations to create an open loop MATLAB/Simulink model. The input voltage (V_{in}), duty cycle (D) and various values of load resistor (R) have been employed as an input to the buck model. Whereas, the outputs of the model are the voltage across the load (V_{out}), inductor current (i_L) and load current (I_{out}) as shown in **Figure (4)** [8].

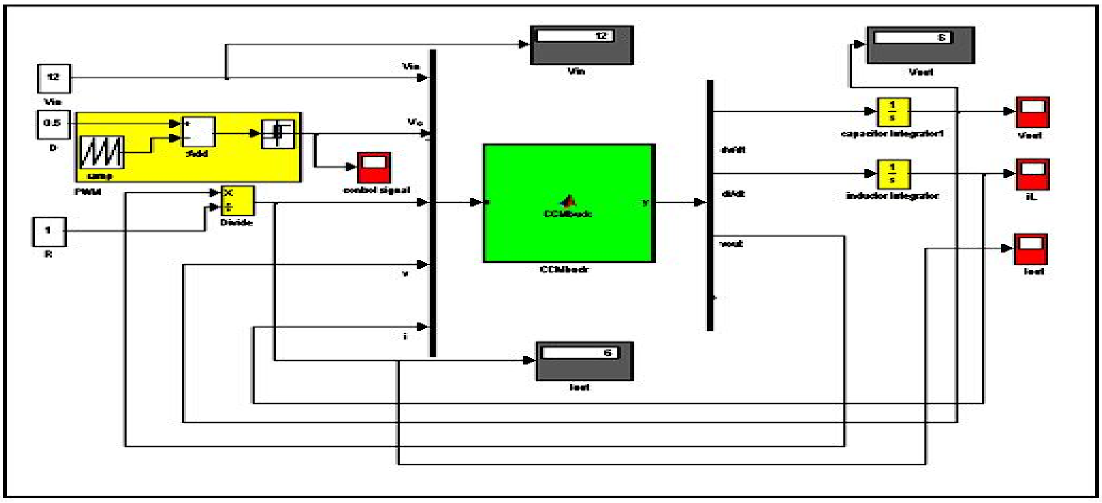


Fig. (4) the Proposed Open-Loop Simulink Model of Ideal Buck Converter [8]

The simulation of the proposed simulink model of the buck is carried out under fixed duty ratio where the inductor and capacitor are modeled as ideal elements. To ensure reliable operation in continuous conduction mode, a minimum value of inductor is calculated, the value of resistive load is varied and the switching frequency (*fs*) is set to 100 kHz, the parameters of the buck are listed in **table (1).**

Table (1) The Parameters of the Buck Converters

step	*Vin*	*L*	*C*	*R*	f_s	*D*
1	12V	100 µH	200 µF	1.5 W	100kHz	0.5
2	12V	100 µH	200 µF	1 W	100kHz	0.5
3	12V	100 µH	200 µF	0.5 W	100kHz	0.5

In this model the duty cycle is used to calculate the desired value of signal level control and the pulse width modulating signal is generated by comparing a signal level control with a repetitive waveform at constant frequency as shown in **Figure (5).**Running the open loop simulink model of the buck converter, the simulation results of the output voltage, output current and inductor current for different values of load resistance are displayed in **Figures (6), (7) & (8**) respectively. In the steady state regime, the mean value results are listed in **Table (2).**

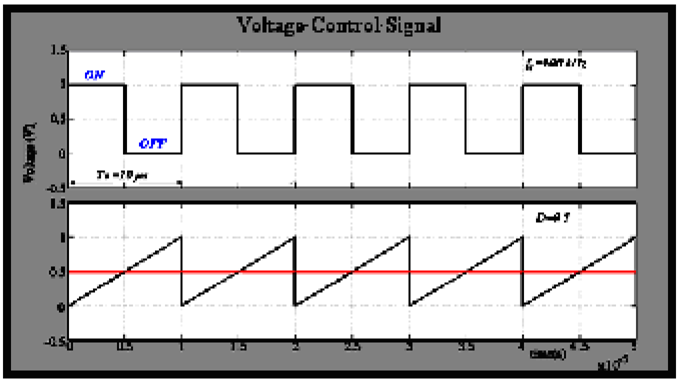


Fig. (5) the Voltage Control Signal of The Buck Converter.

Running the open loop simulink model of the buck converter , the simulation results of the output voltage, output current and inductor current for different values of load resistance are displayed in **Figures (6),(7)& (8)** respectively .In the steady state regime, the mean value results are listed in **Table (2).**

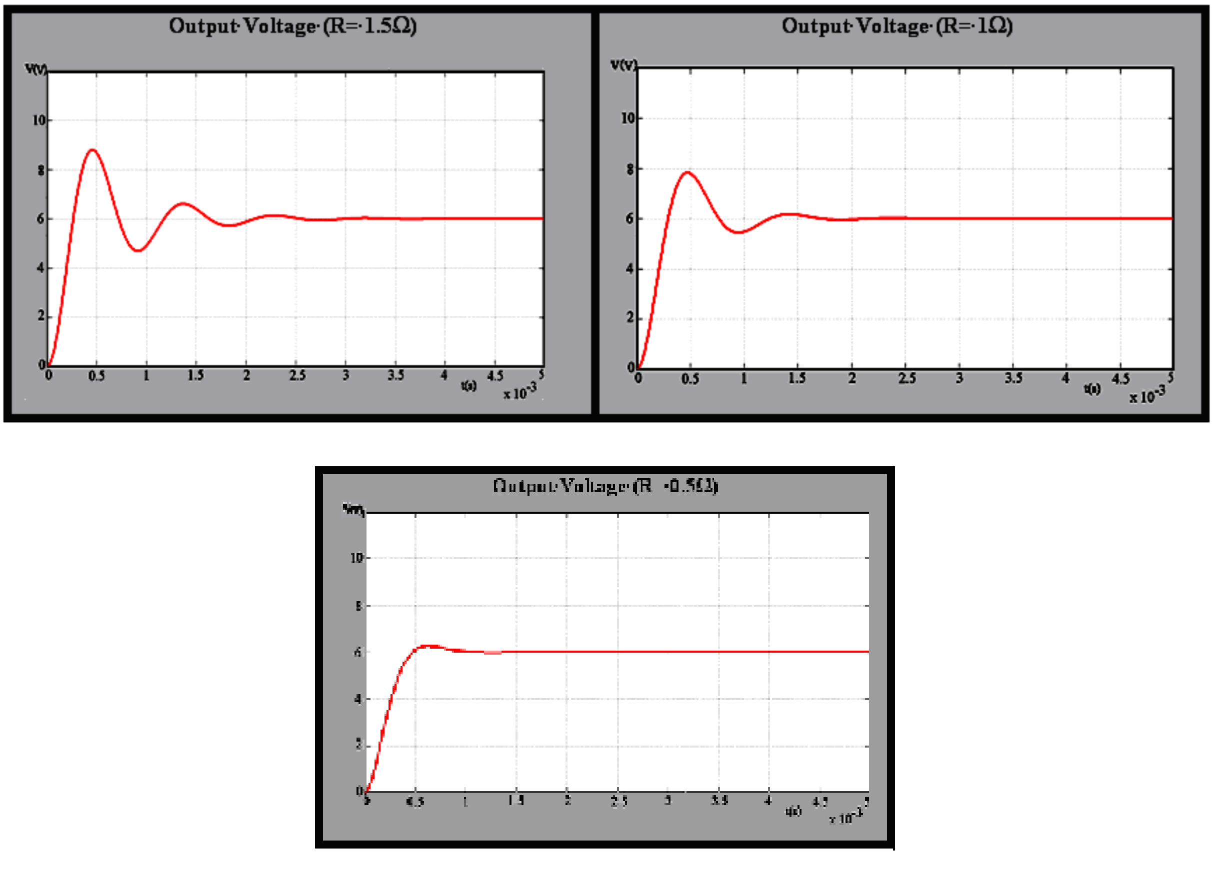


Fig. (6) the Waveforms of Output Voltages.

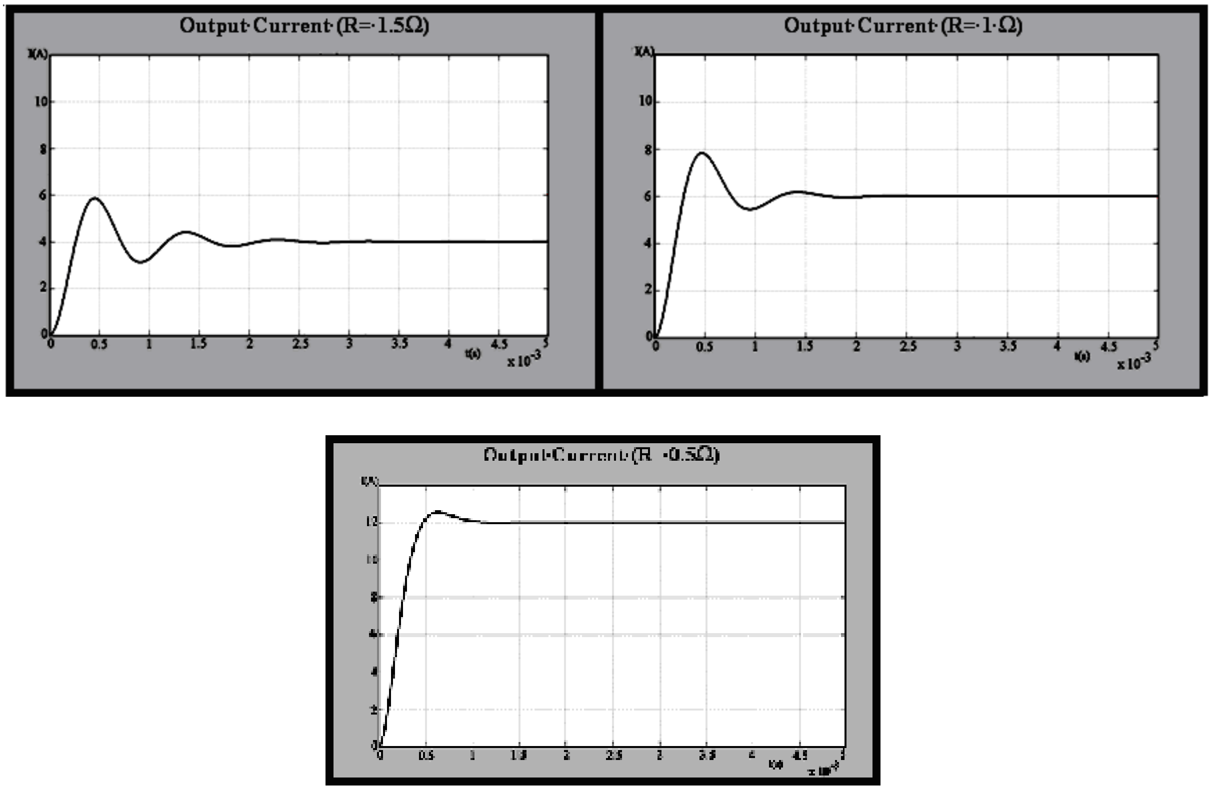


Fig. (7) the Waveforms of Output Currents.

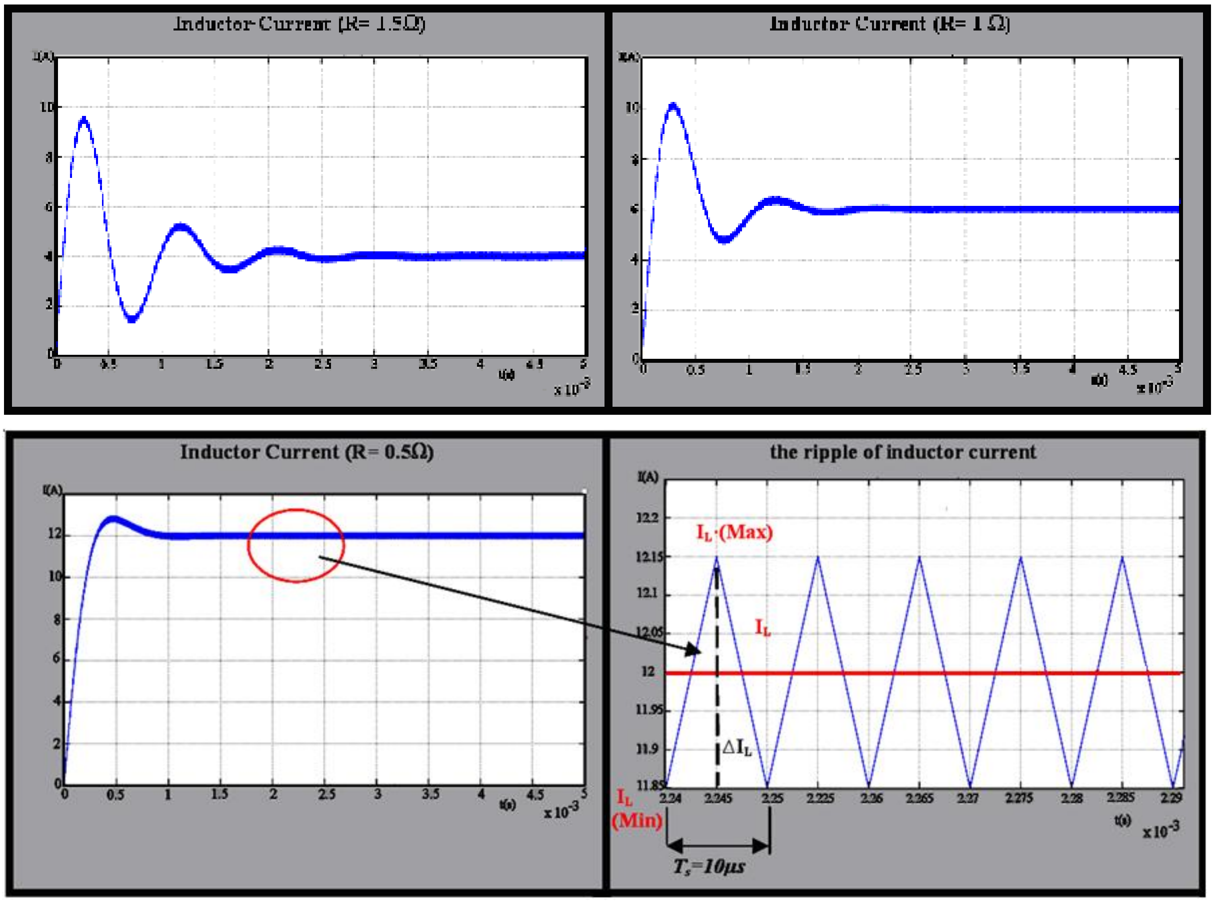


Fig. (8) the Waveforms of Inductor Currents.

Table (2) The Mean Value of the Output Voltage (V_{out}), Inductor Current (I_L), Output Current (I_{out}) and Input Voltage (V_{in}) of the employed Buck Converter.

Mean Value	Load resistance(R)		
	1.5Ω	1 Ω	0.5 Ω
V_{out} (V)	6	6	6
I_L(A)	4	6	12
I_{out}(A)	4	6	12
Vin(V)	12	12	12

Based on the inductor current waveforms shown in **Figure (8),** the following calculations can be made [1]:

$$\Delta i_L = \frac{1}{L}(V_{in} - V_o)DT = \frac{1}{100\times10^{-6}}(12-6)\times0.5\times10\times10^{-6} = 0.3A$$

$$I_{out} = \frac{V_o}{R} = \frac{6}{0.5} = 12A$$

The average value of the inductor current (I_L) is equal with the output current (I_{out}), then

$$i_L(\max) = I_L + \frac{\Delta i_L}{2} = 12 + \frac{0.3}{2} = 12.15A$$

$$i_L(\min) = I_L - \frac{\Delta i_L}{2} = 12 - \frac{0.3}{2} = 11.85A$$

Where

i_L (max) =the maximum values of inductor current.
i_L (min) =the minimum value of inductor current.
Δi_L= the ripple of inductor current.

It can be noticed from **Figure (6)** under test condition(R=0.5Ω),the output voltage response has settling time approximately (0.84 ms) with rise time (3.037) μs and it attends steady state value of 6 V which is expected output from this application. By changing the value of resistance load, it has been seen that as load resistance increase, the output overshoot is being too large and the settling time increase.In comparison, there is a difference of transient response is observed between steps 1, 2 and 3. It shows that the variation in the load resistance significantly affects the output voltage and inductor current response. The transient analysis leads to unsatisfactory response is obtained by increasing the value of load resistance. The step response performance parameters of the output voltage results after simulation are given in **Table (3)**

Table (3)
The Output Voltage Response Parameters of the Buck Converter

Load resistance (Ω)	Over shoot (%)	Settling time (ms)	Rise time (μs)
0.5	1.043	0.840	3.037
1	1.305	1.543	1.970
1.5	1.466	2.221	1.757

5. Conclusion

The open loop model of the DC/DC ideal buck converter was employed to step down the input voltage (12V) and to gain a regulated output voltage equal to (6V) at selected resistive load. The simulation has been done using Matlab tool at fixed switching frequency and constant duty cycle to predict the performance of this model. The simulation results show the voltage reaches the expected output value at the end of the simulation process and the load, inductor currents are varied by changing the resistance of the load. It can be observed the simulation result conform the calculation results and the variation of load resistance will affect the stability of the system. As concluding remark, a suitable controller is needed to improve the dynamic performance and to achieve a satisfactory output value.

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