Modeling and Transient Performance Analysis of Dc-Dc Buck Converter

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Abstract:-**This paper presents new model of switch mode dc-dc buck converter. The dc-dc converter (buck) will step down the input dc voltage of 24V to 12V. The switching frequency of the dc-dc converter (buck) is set to 100 kHz for faster switching operation. The switching frequency of the converter must for fast transient operation.**

In this paper our aim is to study the effect of variation of input voltage & switching frequency in open loop & close loop control mode, so steps can be taken to nullify the effect on performance of converter. For the same we have derived a Simulink model of buck converter in MATLAB environment.

Keywords: - Open loop & Close loop Buck Converter, PID Controller, Switching Frequency, MATLAB Simulink - Modeling

I. OVERVIEW

Direct current to direct current (DC-DC) converters are power electronic circuits, that converts direct current (DC) voltage input from one level to another. DC-DC converters are also called as switching converters, switching power supplies or switches. DC-DC converters are important in portable device such as cellular phones and laptops. Main target in power electronics is to convert electrical energy from one form to another. To make electrical energy to reach the load with highest efficiency is the target to be achieved. Power electronics also targets to reduce the size of the device to convert these energy which aims to reduce cost, smaller in size and high availability. The dc-dc converter for this paper is buck converter. Buck is use to convert unregulated dc input to a controlled dc output with a desired voltage level. The buck will step down the input voltage 12 Vdc to 5Vdc with the switching frequency 100 kHz and 400 kHz. Together with buck is PID controller that uses to control the behaviours of the system in linear. This system is a close loop system with feedback. The software is use to do simulation is MATLAB SIMULINK.

II. BUCK CONVERTER

A. Operation of Buck Converter

Figure 1 shows a simplified schematic of the buck power stage with a drive circuit block included. The power switch Q1 is an n-channel MOSFET. The diode CR1 is usually called the catch diode or freewheeling diode. The inductor (L) and capacitor (C) make up the output filter. The capacitor, ESR, R_C (equivalent series resistance) and the inductor DC resistance R_L are included in the analysis. The resistor R represents the load seen by the power stage output.

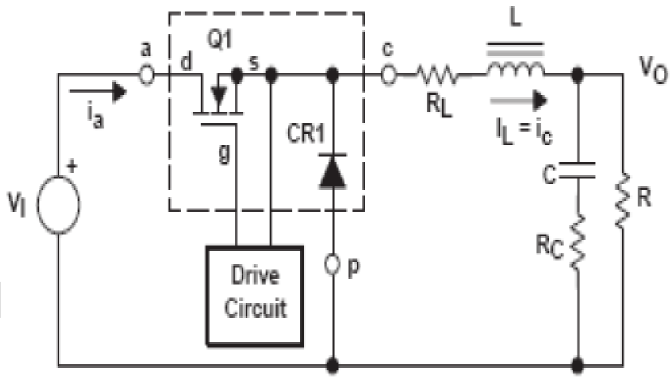

Figure 1: Buck Power Stage Schematic

During normal operation of the buck power stage, Q1 is repeatedly switched on and off with the on and off times governed by the control circuit. This switching action causes a train of pulses at the junction of Q1, CR1 and L which is filtered by the L / C output filter to produce a dc output voltage, V_o. A more detailed quantitative analysis is given in the following sections.

B. Buck Steady-State Continuous Conduction Mode Analysis

The following is a description of steady-state operation in continuous conduction mode. Steady state implies that the input voltage, output voltage, output load current and duty - cycle is fixed and not varying.

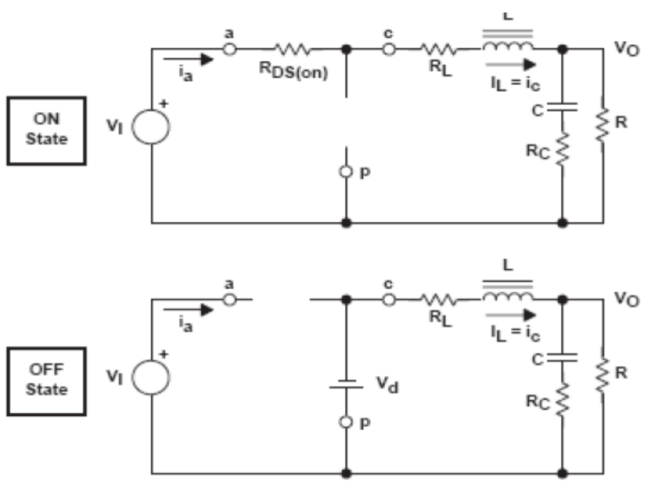

Figure 2: Buck Power Stage States

In continuous conduction mode, the Buck power stage assumes two states per switching cycle. The ON state is when Q1 is ON and CR1 is OFF. The OFF state is when Q1 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 circuits during each state. The circuit diagram for each of the two states is shown in Figure 2.

C. State space averaged model of buck converter

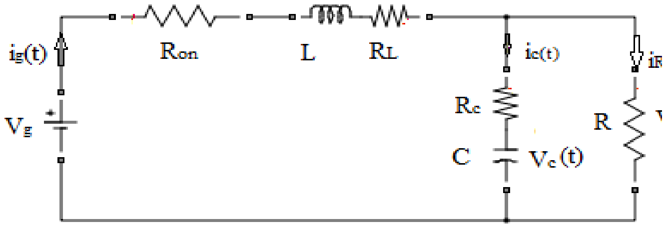

Figure 3: Buck converter ON state

The differential equations related to state variables are:

$$V_g(t) = R_{on} i_L(t) + L\frac{di_L(t)}{dt} + R_L i_L(t) + v_o(t)$$

$$\therefore L\frac{di_L(t)}{dt} = v_g(t) - R_{on} i_L(t) - R_L i_L(t) - v_o(t)$$

$$\text{Also, } C\frac{dv_c(t)}{dt} = \frac{R}{R+R_C} i_L(t) - \frac{1}{R+R_C} v_C(t)$$

$$\text{And, } v_o(t) = i_R R$$

Using Kirchhoff's voltage and current laws to obtain state equation:

$$L\frac{di_L(t)}{dt} = v_g(t) - [R_{on} + R_L + (R/R_C)] i_L(t) - \frac{R}{R+R_C} v_C(t)$$

$$C\frac{dv_c(t)}{dt} = \frac{R}{R+R_C} i_L(t) - \frac{1}{R+R_C} v_C(t)$$

$$i_g(t) = i_L(t)$$

$$v_o(t) = \left(R/R_c\right) i_L(t) + \frac{R}{R+R_c} v_c(t)$$

Therefore,

$$A1 = \begin{bmatrix} -(R_{on} + R_L + \left(R/R_c\right)) & -\frac{R}{R+R_C} \\ \frac{R}{R+R_c} & -\frac{1}{R+R_C} \end{bmatrix}$$

$$B1 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$$

$$C1 = \begin{bmatrix} \left(R/R_c\right) & \frac{R}{R+R_C} \\ 1 & 0 \end{bmatrix}$$

$$E1 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Similarly the equivalent circuit when switch Q1 is OFF and Q2 is ON:

State equation for above circuit is given by

$$\therefore L\frac{di_L(t)}{dt} = -\langle R_{on} + R_L + \left(R/R_C\right)\rangle i_L(t) - \frac{R}{R+R_C} v_C(t)$$

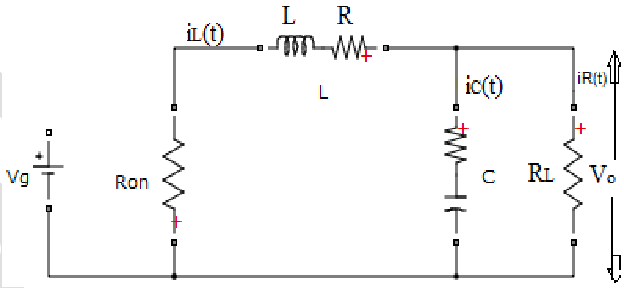

Figure 4: - Buck converter OFF state

$$C\frac{dv_c(t)}{dt} = \frac{R}{R+R_C} i_L(t) - \frac{1}{R+R_C} v_C(t)$$

$$i_g(t) = 0$$

$$v_o(t) = \left(R/R_c\right) i_L(t) + \frac{R}{R+R_C} v_c(t)$$

Therefore,

$$A2 = \begin{bmatrix} -(R_{on} + R_L + \left(R/R_c\right)) & -\frac{R}{R+R_C} \\ \frac{R}{R+R_c} & \frac{-1}{R+R_C} \end{bmatrix}$$

$$C2 = \begin{bmatrix} \left(R/R_c \right) & \dfrac{R}{R+R_C} \\ 0 & 0 \end{bmatrix}$$

$$E2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

Now, a state space averaged model that describes the converter in equilibrium is

0= AX + BU and Y = CX + EU

Where the averaged matrices are

$A = DA_1 + D'A_2$

$B = DB_1 + D'B_2$

$C = DC_1 + D'C_2$

$E = DE_1 + D'E_2$

Applying state-space averaging, the following equations are obtained

$$A = \begin{bmatrix} -\dfrac{R_L R_C}{(R_L+R_C)L} & -\dfrac{R_L}{(R_L+R_C)L} \\ \dfrac{R_L}{(R_L+R_C)C} & -\dfrac{1}{(R_L+R_C)C} \end{bmatrix}$$

$$B = \begin{bmatrix} D\dfrac{1}{L} & \dfrac{R_L R_L}{(R_L+R_C)L} \\ 0 & -\dfrac{R_L}{(R_L+R_C)C} \end{bmatrix}$$

$$C = \begin{bmatrix} \dfrac{R_L R_C}{R_L+R_C} & \dfrac{R_L}{R_L+R_C} \end{bmatrix}$$

$$E = \begin{bmatrix} 0 & -\dfrac{R_L}{R_L+R_C} \end{bmatrix}$$

D. Simulink Model of Buck Converter

Figure 5 shows the matlab based electrical model of Buck converter. In the shown model capacitor is shown with ESR, we have considered inductor as non-ideal and has series resistance. To facilitate subsequent simulation, and feedback controller design and verification, the inputs to buck converter sub-block are input voltage Vi and duty ratio D. The outputs are inductor current, capacitor voltage and output voltage. The non-idealities of transistor ON resistance and inductor series resistance are appropriately included.

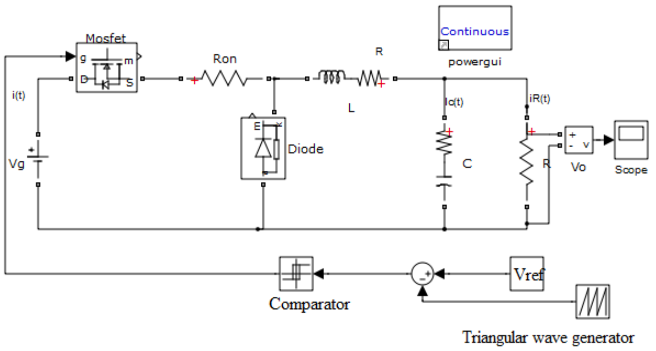

Figure 5: - Simulink model of buck converter

E. Open Loop Response of Buck Converter

Using the above described model and with calculated parameters, we find the effect of variation of input voltage and switching frequency on transient and steady state performance of buck converter.

F. Effect of Variation of Input Voltage

To observe the effect of variation input voltage, we analyze the output waveforms of converter at one higher input voltage.

1). Simulation Result without Disturbance at Vi = 24 Volts:- The below graph Figure 6 is the output of the model in open loop at rated input voltage.

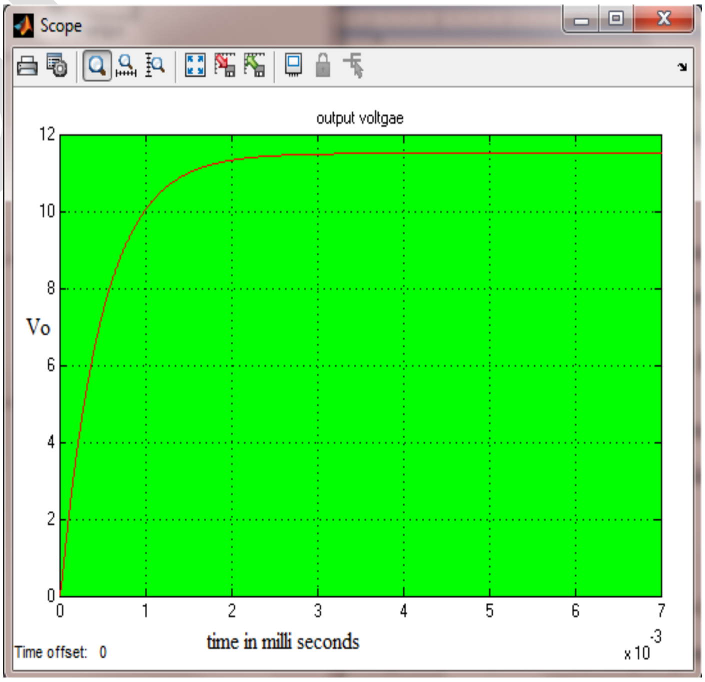

Figure 6: - Simulation Response open loop Buck converter without disturbance.

We can observe from the graph shown in fig.6 that rise time is around 2ms, steady state error of 4.5% in voltage.

2). Simulation Result with Higher Input Voltage at Vi = 28 Volts:- The below graph fig.7 is the output of the model in open loop at below the rated input voltage.

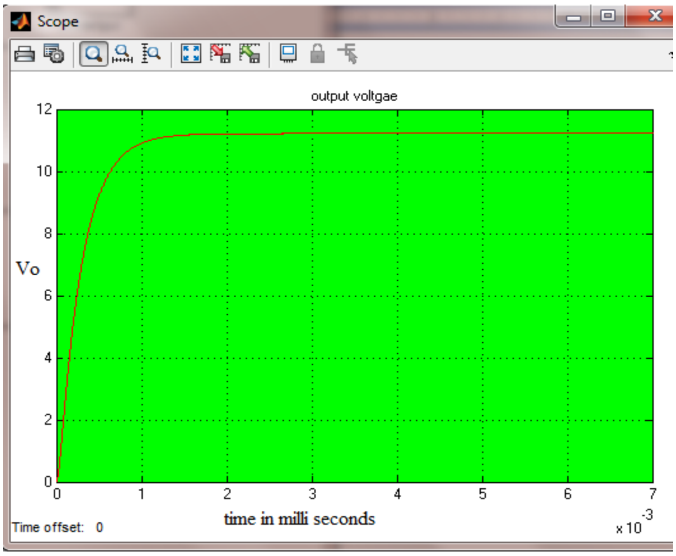

Figure 7: - Simulation Response open loop Buck converter with higher input voltage

We can observe from the graph shown in fig.7 that rise time is 1ms, steady state error of 5% in voltage.

G. Effect of Variation of Switching Frequency: -

To observe the effect of variation switching frequency we analyze the output waveforms of converter at one higher switching frequency.

1). Simulation Result without Disturbance at Frequency = 100 KHz:- The below graph Fig. 8 is the output of the model in open loop at rated input voltage

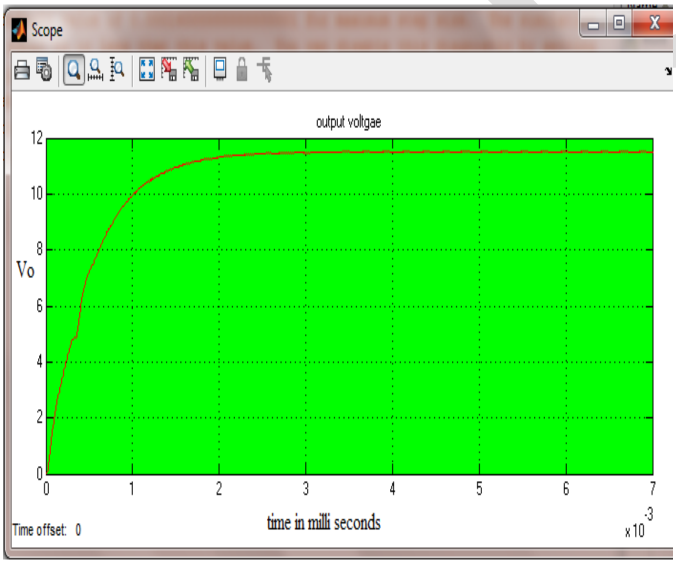

Figure 8: - Simulation Response open loop Buck converter with standard rated switching frequency

2). Simulation Result without Disturbance at Frequency = 200 KHz:- The below graph Fig. 9 is the output of the model in open loop at rated input voltage

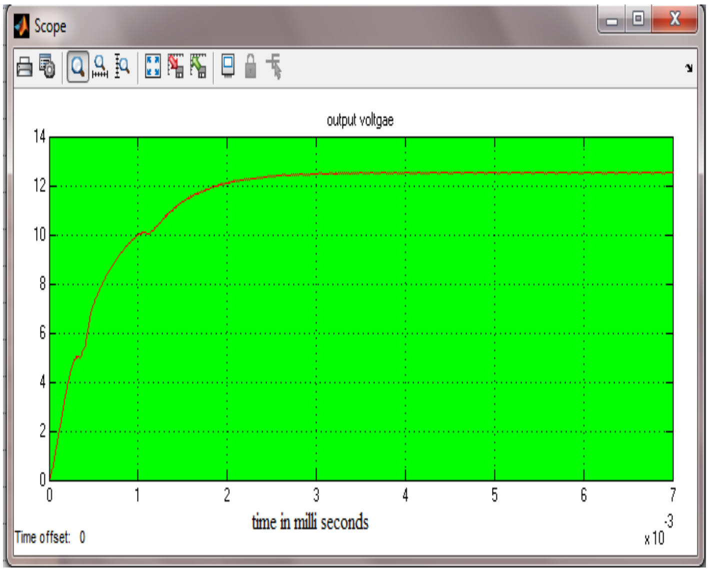

Figure 9: - Simulation Response open loop Buck converter with higher switching frequency

H. Effect of Variation of Load: -

To observe the effect of variation of input voltage we analyze the output waveforms of converter at one higher and a lower input voltage.

I. Close Loop Model of Buck Converter: -

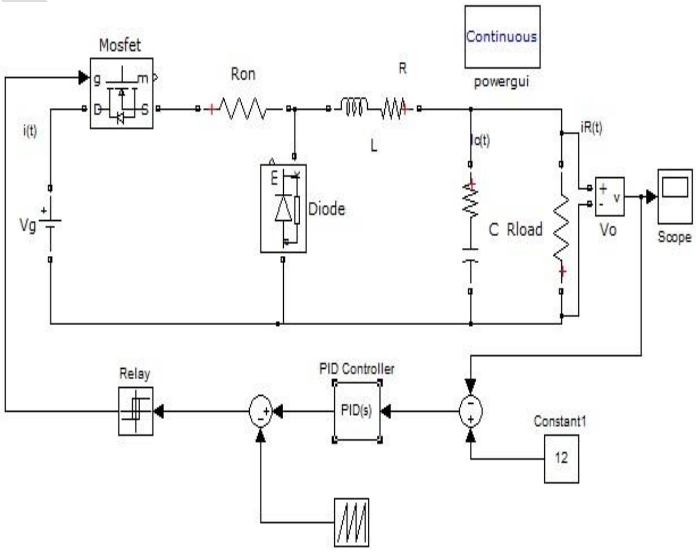

Figure 10:- Close Loop Model Buck Converter

J. Effect of Variation of Input Voltage: -

We analyze the output waveforms of converter at one higher input voltage. In close loop mode to find the performance of converter under variable voltage and switching frequency.

1). Simulation Result at Rated Input Voltage V_i = 24 Volts:- We can observe from the graph shown in fig.11 that rise time is around 0.35 ms, steady state error of 0.33% only.

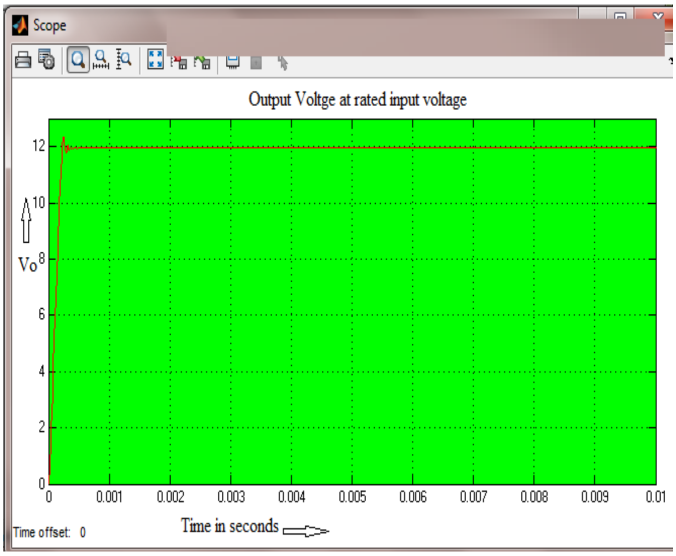

Figure 11:- Simulation Response close loop Buck converter without disturbance.

2). Simulation Result with Higher Input Voltage at Vi = 28 Volts

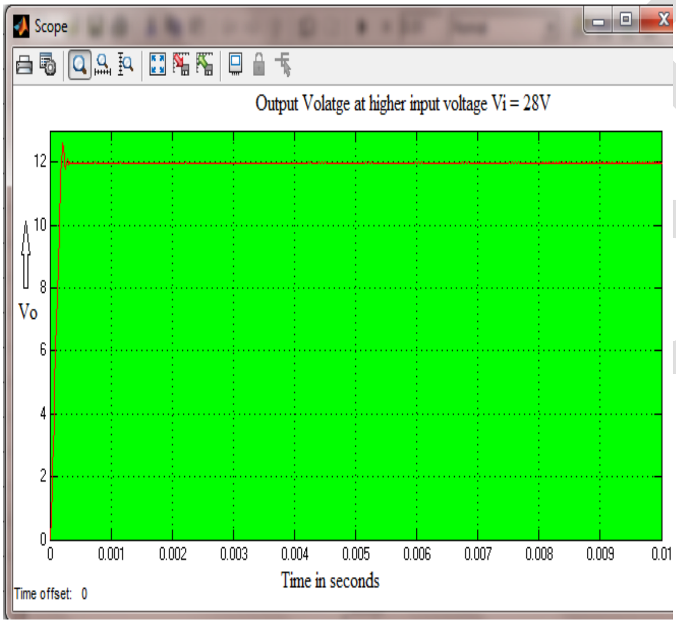

Figure 12:- Simulation Response close loop Buck converter with higher input voltage

We can observe from the graph shown in fig.12 that rise time is 0.3 ms, steady state error of 0.25 % in output voltage.

H. Effect of Variation of Switching Frequency:-

To observe the effect of variation switching frequency, we analyze the output waveforms of converter at one higher switching frequency.

1). Simulation Result without Disturbance at Frequency = 100 KHz (rated)

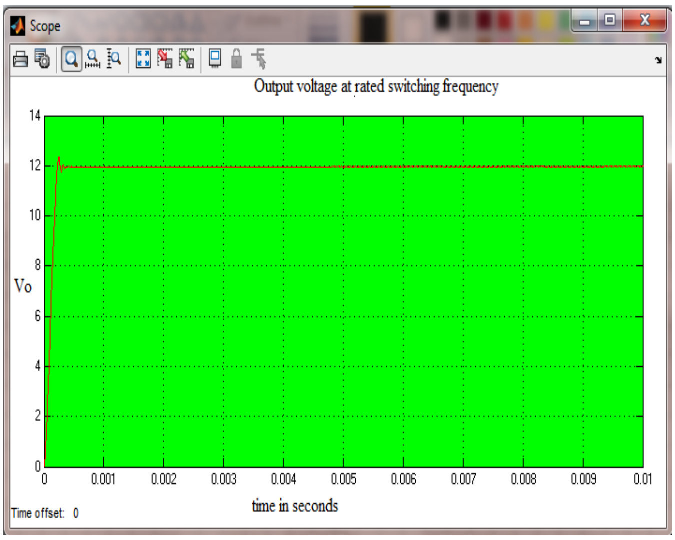

Figure 13:- Simulation Response close loop Buck converter with standard rated switching frequency

2). Simulation Result without Disturbance at Frequency = 200 KHz

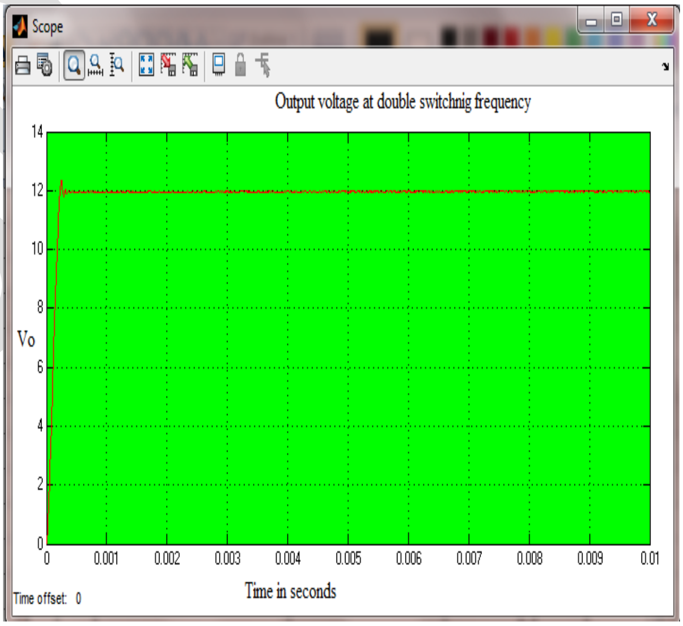

Figure 14:- Simulation Response close loop Buck converter with higher switching frequency

CONCLUSIONS

In this presented work we have derived a mathematical model of the Buck converter. For deriving the model we have used state space averaging and linearising technique. We designed a buck converter for a rated input voltage of 24 volts and output voltage 12 volts and specification like maximum ripple voltage and current. The following are the main points of our study:-

A. In Open Loop Buck Converter System:-

- With change in input voltage the output voltage is affected such that with higher input voltage output voltage is also more than rated value, system transient response become fast.
- Operation with more than specified switching frequency leads to higher output voltage i.e. output average voltage increases with increase in switching frequency,

B. In Close Loop Controlled Buck Converter System:-

- With close loop voltage control at the load lower than the rated load response of the system is fast, transient time is small, but the steady state error is large, in our particular case we find it is 15% approx, and our specification is only 1%. Output voltage is higher than the specified rated voltage.
- With variable switching frequencies maximum overshoot increases with increase in switching frequencies, but the circuit steady state performance is not affected by change of switching frequency. A buck converter under light load as well as at overload takes more time to achieve steady state.

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