Australian Journal of Basic and Applied Sciences, 9(21) Special 2015, Pages: 196-201

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Dynamic Performance Analysis of DC-DC Boost Regulator Operating in CCM

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ARTICLE INFO

Article history:
Received 12 January 2015
Accepted 1 May 2015
Available online 8 May 2015

Keywords:
Boost converter, CCM, Dynamic modeling, Matlab/ Simulink, State Space Equations.

ABSTRACT

The switching regulators are modeled with a view to obtain high performance control. In this paper, the dynamic modeling is obtained in the form of state space equations of the Pulse Width Modulated (PWM) open loop boost converter operating in continuous conduction mode (CCM).Both turn on and turn off modes are considered with unknown load current and non-ideal nature of inductor, capacitor, diode and active switch with voltage drop in conduction condition. The digital simulation is carried out in Matlab/ Simulink environment for the boost converter model by considering no load and load conditions. From the simulation results it is shown that the output voltage is found to be almost twice the input voltage.

To Cite This Article: B. Janaranjani and D. Murali., Dynamic Performance Analysis of DC-DC Boost Regulator Operating in CCM. ***Aust. J. Basic & Appl. Sci.**, 9(21): 196-201, 2015*

INTRODUCTION

Due to the non ideal nature of switches and their conduction mode resistance, there is some power loss in DC-DC power converters. Because of the switching properties of power elements, the converters are non linear and time variant. The small signal analysis and linear controller design for DC-DC converters are carried outin frequency domain. Since the control input of the boost converter (duty cycle of the triggering pulse) is presented in both voltage and current equations, the state equation's solution and controlling this regulator is more difficult.

In 1970, cuke and Middlebrook started working on state space average model of boost converter without including any uncertainities (Mohan, N., 2003). Alonge, Tomescue and Towati considered the boost regulator with inductance resistance, capacitance resistance and output current (Erickson, R.,; Towati, A., 2008). Benyakov designs a robust controller considering output current and capacitance resistance (Naim, R., 1997).

A linear model for Pulse Width Modulator (PWM) switch with an ideal diode and switch in both continuous and discontinuous current mode is presented in (Vorperian, V., 1990; Ivan, C.M., 2006) and the effect of turn on resistance of diode and switch is considered in this model. Also, an average model to the PWM switch is presented by considering the diode and switch resistance and their voltage drop in discontinuous current mode without presenting the state space averaged model of regulator (Mohammad Reza Modabbernia, 2013).

In this paper, on the basis of state space average method, the state space equations of a Boost regulator in turn on and turn off modes is obtained by considering all the system parameters such as an inductor with resistance, a capacitor with resistance, a diode and switch on mode resistance and voltage drop, a load resistance and unidentified load current. Then the state equations are linearized around circuit operation point (input DC voltage and current versus output DC voltage). The coefficients of state space equations will therefore be dependent on the DC operating point in addition to the circuit parameters. At the end the duty cycle parameter "d" (control input) is extracted from the coefficients and introduced as an input. Then the boost converter Benchmark circuit is simulated in MATLAB / SIMULINK (SOLVER- ODE45)environment.

II. Development of Dynamic Model of Boost Regulator During Turn on and Off Modes:

In state space model, the state variables which principally are the elements that store the energy of circuit or system (capacitance voltage and inductor

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Australian Journal of Basic and Applied Sciences, 9(21) Special 2015, Pages: 196-201

current) have significant importance. In an electronic circuit, the first step in modeling is converting the complicated circuit, into basic circuit in which the circuit laws can be established.

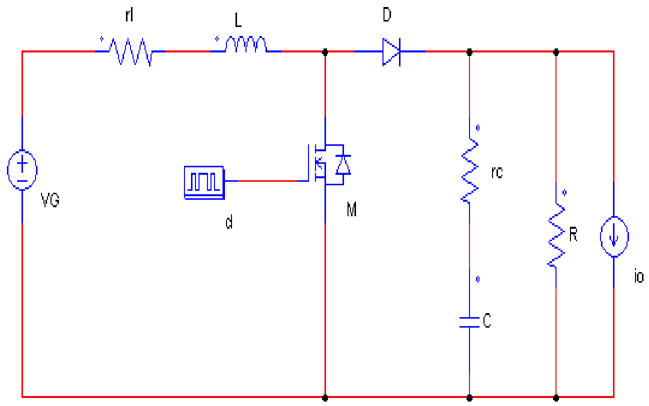

Fig. 1: Boost regulator circuit.

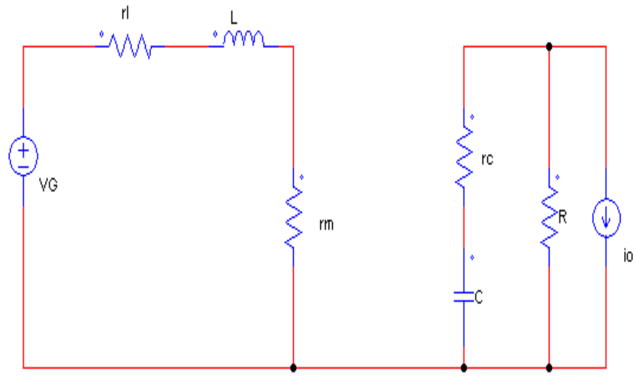

Fig. 2: Circuit modelof Boost regulator in on times.

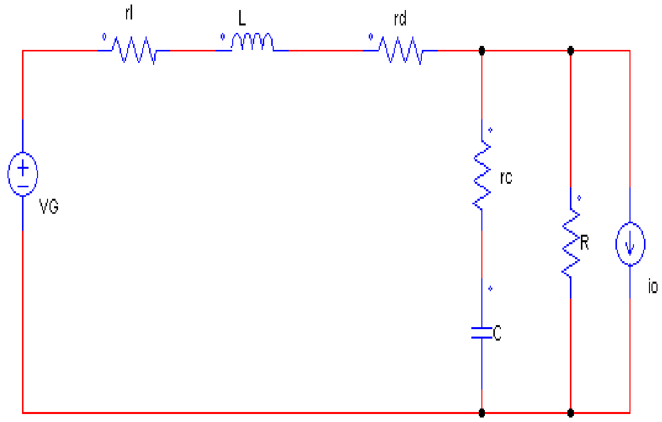

Fig. 3: Circuit modelof Boost regulator in off times.

In switching regulators there are two regions; the on region and off region. The on time denoted by dT, and the off time is denoted by d'T=(1-d)T, in which T is the period of steady state output voltage. Fig. 1.shows a boost switching regulator. The switch is turned on(off) by a pulse with a period of T and its duty cycle is d. The equivalent circuit of the system in on and off modes with dT and d'T seconds is represented by Fig. 2. and Fig. 3. respectively.

Considering i_L and v_C as our state variables ($x=[i_L \quad v_C]'$) and of writing the KVL for the loops of Fig. 2.the results will be

$$\dot{x}= A_1x+ B_1u$$

$$y= C_1x+ D_1u$$

$$A_1=\begin{bmatrix} \frac{-(r_L+r_m)}{L} & 0 \\ 0 & \frac{-1}{(R+r_C)C} \end{bmatrix}$$

$B_1=\begin{bmatrix}\frac{1}{L} & 0 & \frac{-1}{L} & 0\\ 0 & \frac{-R}{(R+r_c)C} & 0 & 0\end{bmatrix}$, $C_1=\begin{bmatrix}0 & \frac{R}{(R+r_c)}\end{bmatrix}$,

$D_1=\begin{bmatrix}0 & \frac{-Rr_c}{(R+r_c)} & 0 & 0\end{bmatrix}$ (1)

Also for off time or d'T seconds the KVL equations from Fig.3. are given by (2).

$\dot{x}= A_2x+ B_2u$

$y= C_2x+ D_2u$

$x=\begin{bmatrix}i_L\\ v_C\end{bmatrix}$, $u=\begin{bmatrix}v_G\\ i_O\\ v_M\\ v_D\end{bmatrix}$, $y=\begin{bmatrix}v_o\\ i_{Out}\\ i_L\end{bmatrix}$

$A_2=\begin{bmatrix}\frac{-(Rr_c+Rr_L+r_cr_L+Rr_d+r_dr_c)}{(R+r_c)L} & \frac{-R}{(R+r_c)L}\\ \frac{R}{(R+r_c)C} & \frac{-1}{(R+r_c)C}\end{bmatrix}$

$B_2=\begin{bmatrix}\frac{1}{L} & \frac{Rr_c}{(R+r_c)L} & 0 & \frac{-1}{L}\\ 0 & \frac{-R}{(R+r_c)C} & 0 & 0\end{bmatrix}$,

$C_2=\begin{bmatrix}\frac{Rr_c}{(R+r_c)} & \frac{R}{(R+r_c)}\end{bmatrix}$,

$D_2=\begin{bmatrix}0 & \frac{-Rr_c}{(R+r_c)} & 0 & 0\end{bmatrix}$ (2)

The above set of state equations shows the state of boost regulator in the on and off time of switch.

These two set of equations can be combined as follows.

$\dot{x}= A_px+ B_pu$

$y= C_px+ D_pu$

$A_p=A_1d+A_2(1\text{-}d)$

$B_p=B_1d+B_2(1\text{-}d)$

$C_p=C_1d+C_2(1\text{-}d)$

$D_p=D_1d+D_2(1\text{-}d)$ (3)

By substituting equations "(1)" to "(2)"the coefficients of $A_p$to D_p can be obtained.

A. Linearisation Of State Equations Around Operating Point:

When the circuit time constant is much larger than the period of switching, the results presented are acceptable. If the duty cycle is a constant value(d=D), the state equations in (3) will become linear. For regulating the voltage on a desired value, the value of D has to be changed by a controller. In general, the state equations of (3) are nonlinear and have to be linearisedaround an operating point(input DC voltage and current versus output DC voltage). When the system is in equilibrium and the duty cycle is on its nominal value, then we can obtain the system state values in equilibrium points ($x=[i_L \quad v_C]'$) and the DC output voltage.

$$\dot{x}= A_px+ B_pu=0; \qquad X= -A_p^{-1}B_p\begin{bmatrix}V_G\\ I_O\\ V_M\\ V_D\end{bmatrix}=\begin{bmatrix}I_L\\ V_C\end{bmatrix} \tag{4}$$

$$X=\begin{bmatrix}\frac{(R+r_c)V_G}{\Delta}+\frac{(Rr_cD'-R^2D')I_o}{\Delta}-\frac{(R+r_c)(1-D')V_M}{\Delta}-\frac{(R+r_c)D'V_D}{\Delta}\\ \frac{-RD'(R+r_c)V_G}{\Delta}+\frac{R(R^2D'^2-RD'^2r_c-\Delta)I_o}{\Delta}+\frac{RD'(1-D')(R+r_c)V_M}{\Delta}+\frac{RD'^2(R+r_c)V_D}{\Delta}\end{bmatrix} \tag{5}$$

Where,

$$\Delta=(R+r_c)(r_L+r_m)+(Rr_c+Rr_d+r_cr_d+Rr_L+r_cr_L)D'+R^2D'^2 \tag{6}$$

and

$V_0=C_pX+D_pU$

$$V_0=\frac{-RD'(R+r_c)V_G}{\Delta}+\frac{R(R^2D'^2-RD'^2r_c-\Delta)I_o}{\Delta}+\frac{RD'(1-D')(R+r_c)V_M}{\Delta}-\frac{RD'^2(R+r_c)V_D}{\Delta} \tag{7}$$

Finally for linearization of the system, on basis of classic method, the variables are divided into two parts. The first part is static part (a fixed DC level), and the second part is a small amplitude that modulates the DC level. On this basis, the variables in the state equations can be defined as follows:

$x(t) =X+\hat{x}$, $u(t) = U+\hat{u}$

$d(t) =D+\hat{d}$, $v_0(t) = V_0+\hat{v_o}$ (8)

in which V_O, $x=[i_L \quad v_C]'$ and $U=[V_G \quad I_G \quad V_M \quad V_D]'$ are the nominal values of theDC output voltage, state variables and no controllable inputs respectively. Each of them has small variations (denoted with ∧) around nominal values. By substituting equations (8) in (3) and assumed that the duty cycle d has also variation $\hat{d}(d(t) = D + \hat{d})$,

$$\dot{X} + \dot{\hat{x}} = A_P\hat{x} + B_P\hat{u} + [(A_1-A_2)X + (B_1-B_2)U]\hat{d} + \dot{X}$$

$$V_0 + \hat{v_0} = C_P\hat{x} + D_P\hat{u} + [(C_1-C_2)X+(D_1-D_2)U]\hat{d} + V_0 \quad (9)$$

$$\dot{\hat{x}} = A_P\hat{x} + B_P\hat{u} + E\hat{d} \quad E= (A_1-A_2)X + (B_1-B_2)U$$

$$\hat{v_0} = C_P\hat{x} + D_P\hat{u} + F\hat{d} \quad F= (C_1-C_2)X \quad (10)$$

$$E=\begin{bmatrix} \frac{(K-R^2D')V_G}{\Delta L} + \frac{[K(Rr_cD'-R^2D')+R^2(R^2D'^2-Rr_cD'^2-\Delta)]I_0}{\Delta L(R+r_c)} \\ -\frac{(1-D')(K-R^2D')V_M}{\Delta L} - \frac{(KD'+R^2D'^2)V_D}{\Delta L} \\ \frac{-RV_G}{\Delta C} + \frac{(-R^2r_cD'^2+R^3D')I_0}{\Delta(R+r_c)C} + \frac{R(1-D')V_M}{\Delta C} + \frac{RD'V_D}{\Delta C} \end{bmatrix}$$

(11)

Where $k= Rr_c + Rr_d + r_d r_c - r_m r_c - Rr_m$ (12)

$F= (C_1-C_2)X$

$$F= \frac{-Rr_c}{\Delta}V_G - \frac{-Rr_c(-R^2D'+Rr_cD')}{\Delta(R+r_c)}I_0 + \frac{Rr_c(1-D')}{\Delta}V_M + \frac{Rr_cD'}{\Delta}V_D \quad (13)$$

Δ is givenby equation(6).

III. State Space Average Model:

An important point in the set of equations is that A_P and C_P are related to d' =(1-d). Since $d = D + \hat{d}$ then A_P and C_P are related to d' . With good approximation this dependence is negligible. By substitution A_P, B_P, C_P and D_P by their equivalents in terms of d, A_1,B_1,C_1 and D_1, the result will be as

$$\dot{\hat{x}}= [A_1 d + A_2(1-d)]\hat{x}+ [B_1 d + B_2(1-d)]\hat{u}+ E\hat{d}$$

$$\hat{y}= [C_1 d + C_2(1-d)]\hat{x}+ [D_1 d + D_2(1-d)]\hat{u}+ F\hat{d} \quad (14)$$

D= $D + \hat{d}$, the above equation can be modified as,

$$\dot{\hat{x}}= [A_1 D + A_2(1-D)]\hat{x}+ [B_1 D + B_2(1-D)]\hat{u}+ E\hat{d}+(A_1-A_2)\hat{d}\hat{x}+ (B_1-B_2)\hat{d}\hat{u} \quad (15)$$

Since $\hat{d}$, $\hat{u}$ and $\hat{x}$ denotes small variation of the duty cycle, input and state of system respectively, their product is very small and we can neglect terms such as $\hat{d}\hat{x}$ and $\hat{d}\hat{u}$.

$$\dot{\hat{x}} = A_P\hat{x} + B_P\hat{u} + E\hat{d} \quad (16)$$

In the same manner, the effect of $\hat{d}\hat{x}$ and $\hat{d}\hat{u}$ in equation (14) is negligible. Therefore the boost regulator state equations can be represented as follows:

$$\dot{\hat{x}} = A_P\hat{x} + B_P\hat{u} + E\hat{d}$$

$$\hat{y}= C_P\hat{x} + D_P\hat{u} + F\hat{d}$$

$$x=\begin{bmatrix} i_L \\ v_C \end{bmatrix}, \quad u=\begin{bmatrix} v_G \\ i_O \\ v_M \\ v_D \end{bmatrix}, \quad y=\begin{bmatrix} v_o \\ i_{Out} \\ i_L \end{bmatrix} \quad (17)$$

$$A=\begin{bmatrix} \frac{-[(Rr_L+r_cr_L+Rr_m+r_mr_c)+(Rr_c+Rr_L+r_cr_L+Rr_d+r_dr_c)D']}{(R+r_c)L} & \frac{-RD'}{(R+r_c)L} \\ \frac{RD'}{(R+r_c)C} & \frac{-1}{(R+r_c)C} \end{bmatrix}$$

$$B=\begin{bmatrix} \frac{1}{L} & \frac{Rr_cD'}{(R+r_c)L} & \frac{(D'-1)}{L} & \frac{-D'}{L} \\ 0 & \frac{-R}{(R+r_c)C} & 0 & 0 \end{bmatrix},$$

$$C= \begin{bmatrix} \frac{Rr_cD'}{(R+r_c)} & \frac{R}{(R+r_c)} \end{bmatrix}, D= \begin{bmatrix} 0 & \frac{-Rr_c}{(R+r_c)} & 0 & 0 \end{bmatrix} \quad (18)$$

Simulation Results and Discussion:

The simulations are performed under the following conditions: L = 200µH,C =220µ F ,R = 44ΩandV_G= 24V. The switching frequency is 240 kHz and various cases of simulation have been considered. The conducting voltage drop of diode and mosfet are assumed to be 0.71V and 0.07 V. The Circuit diagram of Boost Regulator in MATLAB/ SIMULINK is shown in Fig. 4.[8].

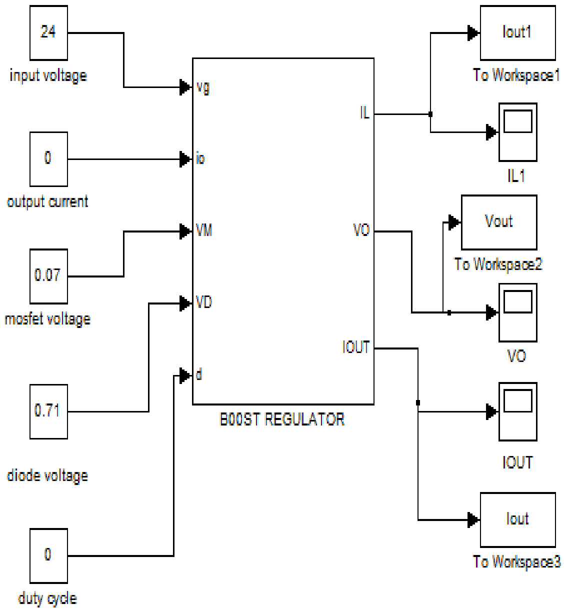

Fig. 4: Circuit diagram of Boost Regulator in MATLAB/ SIMULINK.

Case (i) when $i_0=0A$

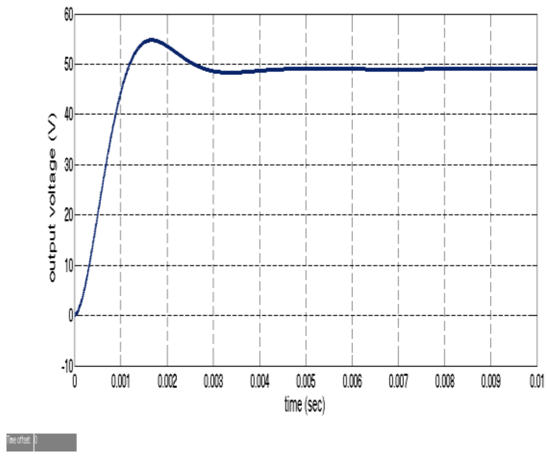

Fig. 5: Variation of output voltage with time fori_0= 0A

Case (ii) when $i_0=3A$

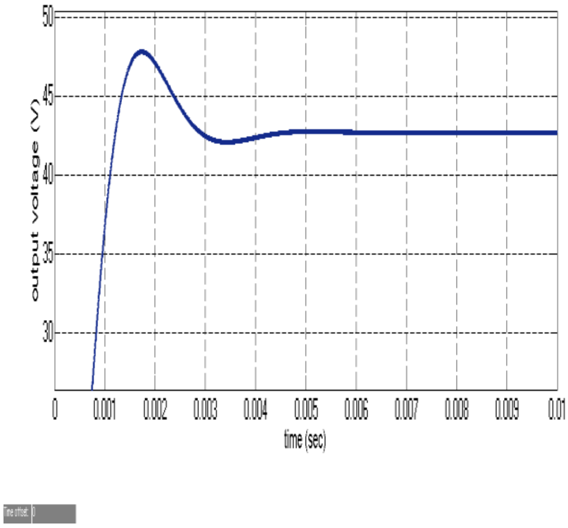

Fig. 6: Variation of output voltage with time for i_0= 3A.

The results of simulation with i_0=0A and i_0=3A are shown in Fig. 5. and Fig. 6. respectively.

Table I: Comparison Of Results.

Load current	Output Voltage	Overshoot	Settling Time
i_0= 0A	48.9V	55V	7.5 mS
i_0=3A	42.65V	48V	5.9mS

Conclusion:

In this paper, some of the most important uncertainties, such as uncontrollable input voltage, resistance of diode and active switch and their conductive voltage drop, capacitance and its resistance, inductance and its resistance, and load resistance and load current, of the DC-DC boost converter are considered. The effect of these uncertainities on the performance of the system is predominant when the magnitude of input voltage is low. However, the effect of these uncertainities is negligible in the higher level of input voltages. The dynamic model of the boost regulator has been simulated in MATLAB/ SIMULINK software platform to demonstrate the efficiency and effectiveness of the proposed approach. The operating conditions such as no-load and on- load are considered. Under load conditions, the output voltage is found to be boosted to nearly twice the input voltage. To satisfy the stability and performance conditions of the boost switching regulator, the dynamic model employed in this paper can be used to design a precise and robust controller.

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