Effect of Load Variations in DC-DC Converter

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***Abstract*—The effect of load variations on the stability of the open-loop DC-DC boost converter is investigated in this paper. Mathematical model of boost converter is derived using state-space averaging technique and perturbation technique presented in this paper to linearize the small AC components. The calculations have been done to ensure the converter is operates in continuous conduction mode (CCM). The open-loop system of boost converter is developed using MATLAB/Simulink software along with the simulation results. The changing of load parameter has been studied so that the stable design of boost converter can be carried out by following a systematic procedure. From the simulation results, it can be shown that load variation gives significant effect on the transient response of the converter.**

Keywords-DC-DC boost converter; state-space averaging technique; perturbation technique; continuous conduction mode (CCM); MATLAB/Simulink

I. INTRODUCTION

DC-DC converters are widely used in many power electronic appliances and also application circuits, such as power generating solar device, battery powering circuit, uninterruptible power supply (UPS), and etc. There are many discussion have been made already regarding such in [1], [2] are commonly applied in many electronic applications due to their smaller size and high efficiency [3], [4], [5]. Boost converter is the one of six topologies of DC-DC converters. It provide an output voltage higher than the input voltage which is have high demand as front-end converters for battery sources, fuel cells, and photovoltaic solar system [6], [7].

The main function of a boost converter is to maintain the output voltage as close as possible to a desired reference voltage. In the open loop mode, it exhibits unsatisfactory dynamic response, and poor voltage regulation, thus, in order to deal with the output voltage regulation, boost converter is generally provided with closed loop control. The mode of operation of the converter is simply varied from ON to OFF state of the switch. Small signal linearization techniques have been utilized for controller design. However, due to the presence of a right-half-plane zero, boost converter is known as a nonminimum which causes slow dynamic response [8]. Recently, there are several methods of controller design based on a small-signal linearized model and by implementing basic circuit of boost converter into closed-loop control have been studied in [9], [10].

This paper proposes a basic circuit of DC-DC boost converter which is simulated with different load resistance value so that the effect of load variations at the output can be analyzed. The nonlinear components that lied between 0 and 1 of duty cycle and small-signal linear components will be derived using state-space averaging technique, while Kirchhoff's law is employed to obtain the differential equation of each state of the converter. The technique of averaging is the best choice to solve the mathematical model in this paper. By taking a linearly weighted average of the separate equations for each switched configuration of the converter, a single equation can be figured out to describe the converter approximately over a number of switching cycles. The most common averaging technique, state space averaging [11], [2] is used to model the switching DC-DC boost converter.

II. MODELING OF DC-DC BOOST CONVERTER

The proposed model of open-loop boost converter using a MOSFET as a switching element is shown in Fig. 1. The specifications of the converter's parameters are shown in Table 1.

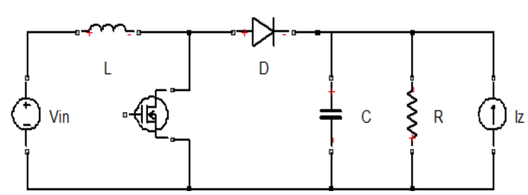

Figure 1. Boost converter circuit.

The mode of operation of boost converter is based on two states; ON state and OFF state. It is also known as charging mode instead of ON state, and discharging mode instead of OFF state. During the charging mode; when the switch is closed, the diode is in reversed-biased condition. When the switch is open that is discharging mode, the inductor current cannot change instantaneously, thus the diode becomes forward-biased in order to provide a path for inductor current. A current generator I_Z is added in parallel with the load resistor to facilitate in examining the response of the converter to the load changes.

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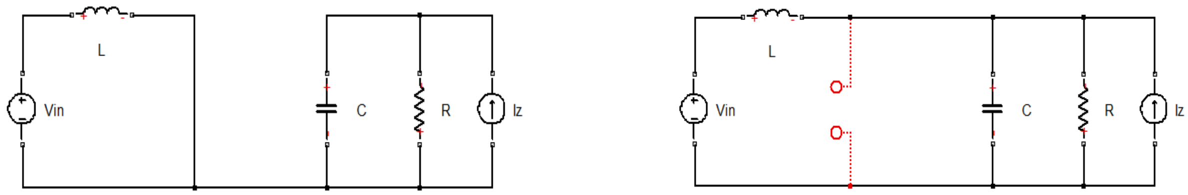


(a) (b)

Figure 2. Boost converter circuit (a) ON state (b) OFF state.

III. Mathematical Model of DC-DC Boost Converter

The boost converter with ideal switching devices will be considered in this paper which is operating with the switching period and duty cycle, D. The converter is considered to operate in continuous conduction mode (CCM). Hence, the state equations can be easily obtained by applying Kirchhoff's voltage law on the loop containing the inductor meanwhile Kirchhoff's current law on the loop which is containing the capacitor branch.

The equations of the inductor current i_L and the capacitor voltage V_C describing the converter behavior during the ON state from the corresponding sub-circuit as shows in Fig. 2(a) is

$$\frac{d_{iL}}{dt}=\frac{1}{L}(V_{in}) \tag{1}$$

$$\frac{d_v}{dt}=\frac{1}{C}(i_Z-\frac{V}{R}) \tag{2}$$

and the equations obtained during the OFF state as shows in Fig. 2(b) are presented by,

$$\frac{d_{iL}}{dt}=\frac{1}{L}(V_{in}-V) \tag{3}$$

$$\frac{d_v}{dt}=\frac{1}{C}(i_L-i_Z-\frac{V}{R}) \tag{4}$$

where i_L represents the inductor current and the output voltage is represent by V.

TABLE I. Specification of DC-DC Boost Converter

Parameter	Value
V_{in}	12V
V_0	24V
Inductor, L	335µH
Capacitor, C	10µF
Resistor, R_L	11Ω, 27Ω, 33Ω
Duty cycle, D	0.5

IV. Averaging Small-Signal Modeling

The switching circuit of boost converter is divided into two continuous conduction modes (CCM) different structures consistently the technique of state-space averaging can be employed. Each structure is defined based on circuit theory so that the derivatives of inductor currents and capacitor voltages can be obtained. The inductor current i_L and the capacitor voltage V can be defined $x(t)=[i_L(t).V(t)]^T$ as the state vector, thus the system is described by the following set of continuous-time state-space

$$\dot{x}=A_x+B_u \tag{5}$$

where

$$A=dA_{on}+(1-d)A_{off}$$
$$B=dB_{on}+(1-d)B_{off} \tag{6}$$

Let x_1=i and x_2=v, the state equations of (1) and (2) become,

$$x_1=\frac{1}{L}(V_{in}) \tag{7}$$

$$x_2=\frac{1}{C}(i_Z-\frac{x_2}{R}) \tag{8}$$

In state space representation;

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\underbrace{\begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}}_{A_{on}}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\underbrace{\begin{bmatrix} \frac{1}{L} & 0 \\ \frac{1}{C} & 0 \end{bmatrix}}_{B_{on}}\begin{bmatrix} V_{in} \\ I_Z \end{bmatrix} \tag{9}$$

The state equation for (3) and (4) will become,

$$x_1=\frac{1}{L}(V_{in}-x_2) \tag{10}$$

$$x_2=\frac{1}{C}(i_L-i_Z-\frac{x_2}{R}) \tag{11}$$

In state space representation;

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}}_{A_{off}} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \underbrace{\begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{C} \end{bmatrix}}_{B_{off}} \begin{bmatrix} V_{in} \\ I_Z \end{bmatrix} \quad (12)$$

By considering the average of the two linear equations from (6), a set of nonlinear continuous equations can be obtained (13). By using (13), the matrices of A and B can be obtained through the equations.

$$\dot{x}(t) = [d(t)A_{on} + (1-d(t))A_{off}]x(t) + [d(t)B_{on} + (1-d(t))B_{off}]u(t) \quad (13)$$

The time varying system as described in (13) can be linearized using perturbation technique in abreast to study the behavior of the small signal. Small ac components are introduced in the dc steady state components. The ac components which are perturbation signal is represented by ~.

$$x(t) = X + \tilde{x}(t)$$

$$v_0(t) = V_0 + \tilde{v}_0(t) \quad (14)$$

$$d(t) = D + \tilde{d}(t)$$

The expression in (14) then substituted into (5) and the small ac quantities are neglected, thus a linear equation of the system is obtained as shown in (15). The matrix of C can be obtained by considering the output voltage $V_0 = Cx_2$. Therefore, the E matrix of DC-DC boost converter is generated by (16).

$$\dot{\tilde{x}} = A_{\tilde{x}} + B_{\tilde{u}} + E_{\tilde{d}} \quad (15)$$

$$E = (A_{on} - A_{off})x + (B_{on} - B_{off})u \quad (16)$$

$$E = \begin{bmatrix} 0 & \frac{1}{L} \\ 0 & \frac{1}{C} \end{bmatrix}$$

V. Simulation of Open-Loop of Boost Converter

The proposed model of DC-DC boost converter is then implemented in Matlab/Simulink by utilized all the expressions that obtained from state space modeling. The value of load resistor has been varying in this simulation so that the output from this simulation can be analyzed to ensure whether the variation of load can be effected the output or not.

The analysis of the system is focused at the percentage of overshoot (OS), the rise time (t_r), and also the settling time (t_{sett}) before the system reaches the steady state. Fig. 3 shows the model of boost converter using the parameters given in Table 1.

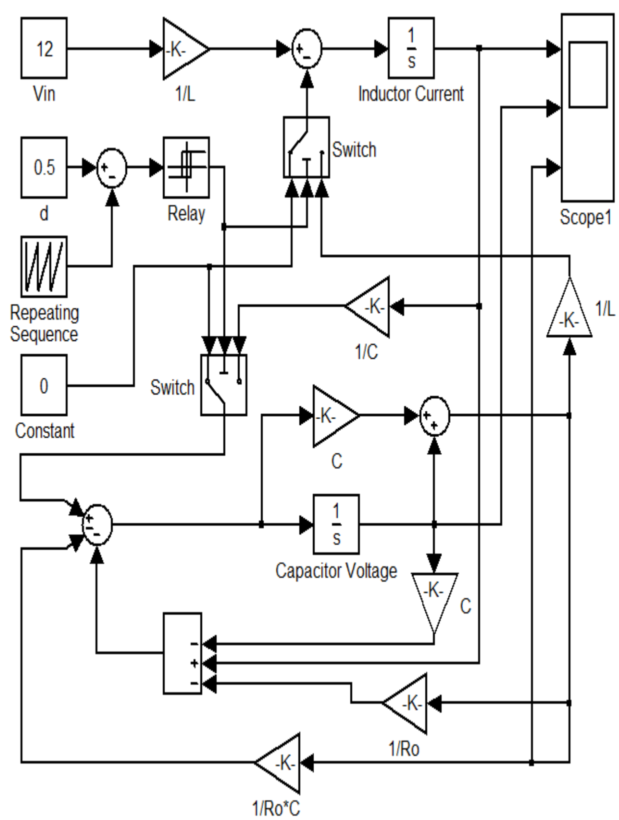
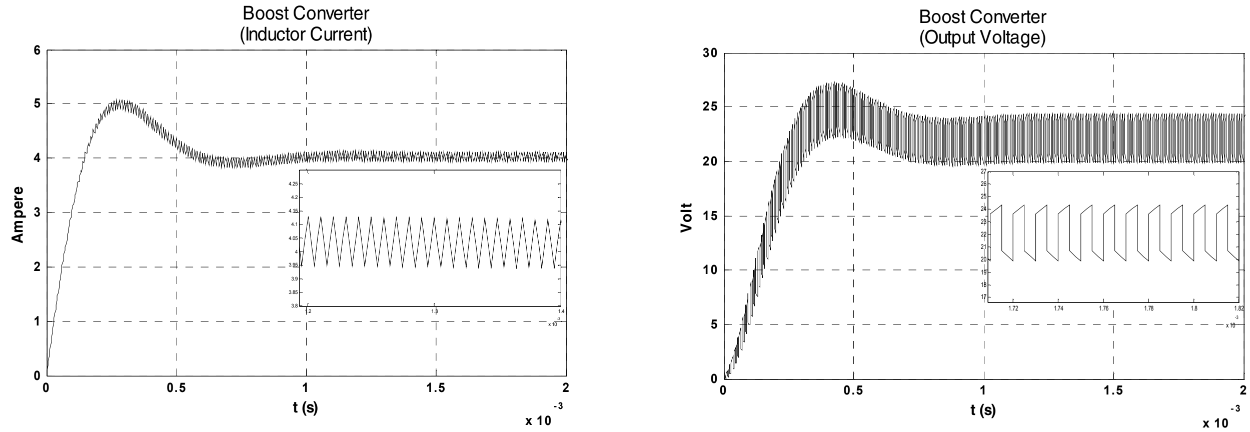
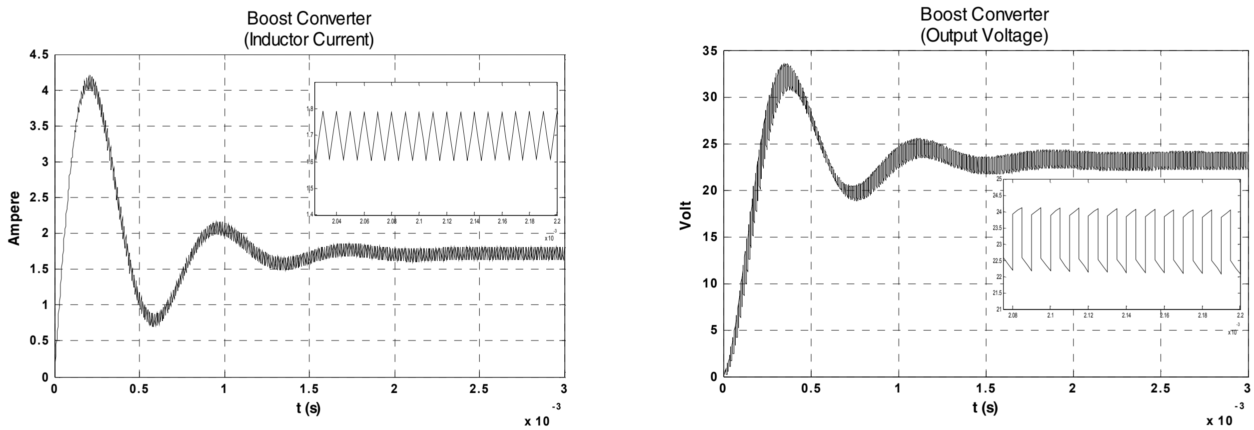


Figure 3. Open-loop modeling of boost converter.



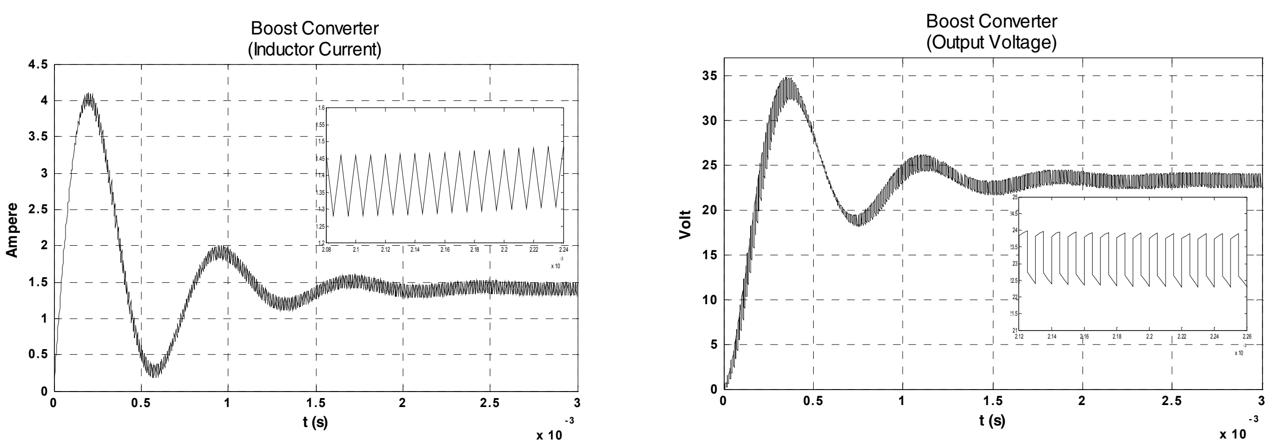
(a) (b)

Figure 4. Output of open-loop boost converter by using R_L=11Ω (a) Inductor current (b) Output voltage.



(a) (b)

Figure 5. Output of open-loop boost converter by using R_L=27Ω (a) Inductor current (b) Output voltage.



(a) (b)

Figure 6. Output of open-loop boost converter by using R_L=33Ω (a) Inductor current (b) Output voltage.

Fig. 4, 5 and 6 show the results of the open-loop DC-DC boost converter when simulated in Matlab/Simulink environment. The open loop response from the simulation shows the corresponding of the state of the converter to a second order system. Comparison has been made through the observation of the result to examine the variation of inductor current and output voltage by changing the value of resistance load, R_L. All datas that obtained in the simulation is simplified as in Table 2.

TABLE II. ANALYSIS OF OUTPUT VOLTAGE PERFORMANCE FOR DIFFERENT VALUES OF R_{LOAD}

R_{Load} (Ω)	% OS	t_r (ms)	t_{sett} (ms)
11	13.3	0.23	0.46
27	39.6	0.19	1.37
33	45	0.22	1.5

Results above show that the open-loop response of DC-DC boost converter considered in this paper is stable and at the end of the simulation the voltage reaches the expected value of 24V much higher than the input value of 12V with constant duty ratio of 0.5. During start up, there is a high overshoot in the output voltage and inductor current which increases as we increase the load resistance. It shows that the variation in the load resistance significantly effects the output voltage. The analysis in Table 2 indicates that the percentage of overshoot can raise up to a maximum of 45% by simulating with the highest value of the load resistance. Hence, an unsatisfactory response is contributed by incresing the value of load resistance due to its effect on overall damping of the converter system. A controller is needed due to large maximum overshoot and long settling time in order to achieve a satisfactory performance of less than 10% overshoot and faster settling time of less than 0.5ms.

VI. CONCLUSIONS

The analysis and simulation of nonlinear, state space model of open-loop DC-DC boost converter are presented in this paper. The analysis has led to a conclusion that changes in the load resistances contributes an effect to the inductor current and output voltage of the converter. The simulation environment Matlab/Simulink is the most convenient option to model the circuit and the dynamic behavior of the open-loop converter. The model of boost converter in this paper only considers the continuous part. The model of open-loop DC-DC boost converter presented in this paper may then be used to undertake controller design and later closed-loop performance can be examined for future work.

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