Modeling of DC-DC Converter for Solar Energy System Applications

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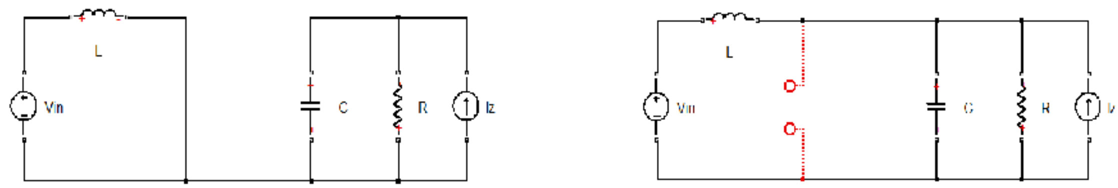
Abstract— **This paper presents the design and simulation of a DC-DC boost converter which uses solar system as input source. In general, solar is one of renewable energy sources which is sustainable and free if compared to other alternative energy. The voltage of solar system can produce a maximum voltage up to 16V during daylight and it is compatible enough with DC-DC boost converter system to charge batteries at any time due to behavior of DC-DC boost converter. The operation principle of boost converter working in continuous conduction mode (CCM) has been introduced. The continuous part of the converter is modeled by differential equations and state space models, while the switching actions are recently more accurately modeled by state charts. Circuit model for open loop system may be conveniently implemented using the MATLAB's Simulink toolbox environment. Simulation was performed with different load resistors to study the effect of load variations thus the results obtained can be analyzed to ensure that the variations of load impacting on the stability of the converter. This paper attempts to model the continuous part of the converters using state space averaging technique so that it can be proceeded to design a controller to improve the converter's performance of less overshoot and faster settling time.**

Keywords- DC-DC boost converter; solar system; renewable energy; continuous conduction mode (CCM); Matlab/Simulink; state space averaging technique

I. INTRODUCTION

Nowadays, many renewable energy sources such as solar photovoltaic (PV) and wind energy are well developed and have been put in the limelight as the alternative energy as part of effort in limiting the dependency on the conventional energy sources like fossil fuels, coal, and natural gas. These energy sources have attracted many researches [1, 2] due to the fact that both of this energy is free and sustainable besides environmental friendly. From previous research [3], it has been indicated that these energy sources especially PV is simply easy to integrate with existing topology of switched mode DC-DC power converters. Normally a solar panel will only produce approximately 16V in full, nearly normal sunlight and it will limit the maximum power production to only few hours charging batteries at 12V [4]. A DC-DC boost converter controlled by PWM control technique is placed between the solar panel and the batteries, in order to boost up the voltage of solar panel to charge the batteries at any time even when the panel voltage is less than battery charging voltage. Since solar cells are costly, DC-DC boost converter takes a role in solving this situation [5]. Boost converter is one of the four basic topologies in switched mode DC-DC converters [7] which produce different outputs according to the different topologies. This paper proposes a basic circuit of DC-DC boost converter which is simulated with different values of load resistor so that the effect of load variations at the output in terms of overshoot, rise time, and settling time can be analyzed. Comparing with previous research [11] on applying basic circuit of boost converter, the proposed circuit in this paper is stimulated with a current generator. The nonlinear components that lie 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. The most common averaging technique, state space averaging [6], [7] is used to model the switching DC-DC boost converter. Generally, boost converter operates in two basic modes of work operation, i.e., continuous conduction mode (CCM) and discontinuous conduction mode (DCM). The state of the converter in which the inductor current is never zero for any period of time is called (CCM) meanwhile, in the (DCM); the inductor current is zero during a portion of the switching period [8]. The state space average model obtained then implemented in MATLAB/SIMULINK to simulate power converters. This research only aims at development of the basic model of boost converters in open loop response; which is a technique that avoids using the measured output to adjust the control input and sometimes referred to as feed forward control, simulated with different load resistor values so that the effect of load variations at the output can be analyzed. Unlike closed-loop response, open-loop response cannot compensate for disturbance or noise. In contrast, closed-loop response can provide such compensation besides this system do not require an accurate system model, something that is difficult to obtain in practice [9]. So that this model in open loop system can be proceed to any close loop scheme besides providing a controller so that the converter can perform more satisfactory performance.



(a) (b)

Figure 1. Boost converter circuit (a) ON state (b) OFF state

II. PHYSICAL MODEL OF BOOST CONVERTER

The proposed scheme is applied to a boost converter, as shown in Fig. 2. The parameters of the proposed scheme are represented by: a solar cell as DC input voltage source V_{in}, controllable switch, filter inductor L, filter capacitor C, load resistor R, and a PWM block that controlled duty cycle represented by d.

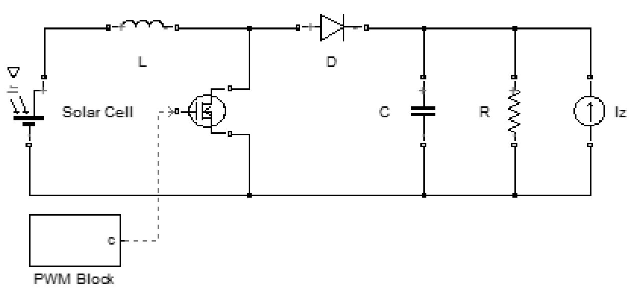


Figure 2. DC-DC boost converter.

A current generator represented by I_z is added in parallel with the load resistor so that the response of the converter to the load changes can be examined. The proposed scheme is considered to operate in continuous conduction mode (CCM). When the switch is ON, the diode is reversed biased, thus isolating the output stage and the input supplies energy to the inductor. Otherwise, the output voltage receives energy from the inductor as well as from the input, when the switch is OFF. The controllable switch is considered as being ideal, and the losses in the capacitance and inductive elements are neglected. The relation between input and output voltage of the boost converter is

$$\frac{V_0}{V_{in}}=\frac{1}{(1\text{-}d)} \tag{1}$$

III. MATHEMATICAL MODEL OF DC-DC BOOST CONVERTER

The ideal dynamics of the boost converter are derived by the state space averaging method. During a small-signal transient; when the duty ratio perturbation is sufficiently small, an equivalent linear system model is formed applying the method. During the ON time, the switch is closed, and the corresponding circuit as in Fig. 1(a). By applying Kirchhoff's voltage law on the loop containing the inductor:

$$\frac{d_{iL}}{dt}=\frac{1}{L}(V_{in}) \tag{2}$$

and Kirchhoff's current law on the node with the capacitor branch connected to it.

$$\frac{d_v}{dt}=\frac{1}{C}(i_z-\frac{V}{R}) \tag{3}$$

During OFF state, the switch is off and the diode is on. The corresponding sub-circuit is as shown in Fig.1(b). By applying the same procedures as in ON state, the equations of OFF state can be obtained. The inductor current represented by i_L meanwhile V is the output capacitor voltage.

$$\frac{d_{i_L}}{dt}=\frac{1}{L}(V_{in}\text{-}V) \tag{4}$$

$$\frac{d_v}{dt}=\frac{1}{C}(i_L\text{-}i_z\text{-}\frac{V}{R}) \tag{5}$$

IV. AVERAGING SMALL-SIGNAL MODELING

The state-space averaging method is a way to model DC-DC boost converter as time independent systems, defined by a unified set of differential equations that are capable of representing circuit waveforms [10]. Thus, it can be a convenient approach for designing controllers that will apply to boost converter by taking into account of the control transfer function. The switching circuit of boost converter is divided into two continuous conduction modes (CCM) different structures consistently such that 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

$$\dot{x}=A_x+B_u \tag{6}$$

where

$$A=dA_{on}+(1-d)A_{off}$$
$$B=dB_{on}+(1-d)B_{off} \tag{7}$$

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

$$x_1=\frac{1}{L}(V_{in}) \tag{8}$$

$$x_2=\frac{1}{C}(i_z-\frac{x_2}{R}) \tag{9}$$

In state space representation;

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\underbrace{\begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{RC} \end{bmatrix}}_{A_{on}}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\underbrace{\begin{bmatrix} \frac{1}{L} & 0 \\ \frac{1}{C} & 0 \end{bmatrix}}_{B_{on}}\begin{bmatrix} V_{in} \\ I_Z \end{bmatrix} \tag{10}$$

The state equation for (4) and (5) will become,

$$x_1=\frac{1}{L}(V_{in}-x_2) \tag{11}$$

$$x_2=\frac{1}{C}(i_L-i_Z-\frac{x_2}{R}) \tag{12}$$

In state space representation;

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}=\underbrace{\begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}}_{A_{off}}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\underbrace{\begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{C} \end{bmatrix}}_{B_{off}}\begin{bmatrix} V_{in} \\ I_Z \end{bmatrix} \tag{13}$$

The time varying system described in (5) can be linearized using perturbation technique in order to solve the small signal behavior. Small AC perturbations are introduced in the DC steady state quantities. The variables in this equation is written as the sum of a steady-state or DC component and a small-signal or AC component, which is represented by ~,

$$x(t)=X+\tilde{x}(t);\ v_0(t)=V_0+\tilde{v}_0(t);\ d(t)=D+\tilde{d}(t) \tag{14}$$

The expressions in (13) substituted into (5), then the equation is multiplied out and the components of small-signal quantities are neglected. A linear equation is obtained and produces small changes in the variables as shown below:

$$\ddot{x}=A_{\tilde{x}}+B_{\tilde{u}}+E_{\tilde{d}} \tag{15}$$

By applying the expressions in (6), the A and B matrices can be obtained. The matrix of C is obtained by considering output voltage V_0= Cx_2. Thus, the E matrix of boost converter is given by:

$$E=(A_{on}-A_{off})x+(B_{on}-B_{off})u$$
$$E=\begin{bmatrix} 0 & \frac{1}{L} \\ 0 & \frac{1}{C} \end{bmatrix} \tag{16}$$

V. DESIGN AND SIMULATIONS

The proposed model of open loop DC-DC boost converter is then implemented in SIMULINK block diagrams as in Fig. 3 that governed by the state space averaging technique. The elements in the matrices are evaluated using the parameter values listed in Table 1.The value of load resistor has been varied in this simulation so that the output can be analyzed to ensure whether the variation of load affects the output in terms of overshoot voltage (OS), rise time (t_r), and settling time (t_{sett}).

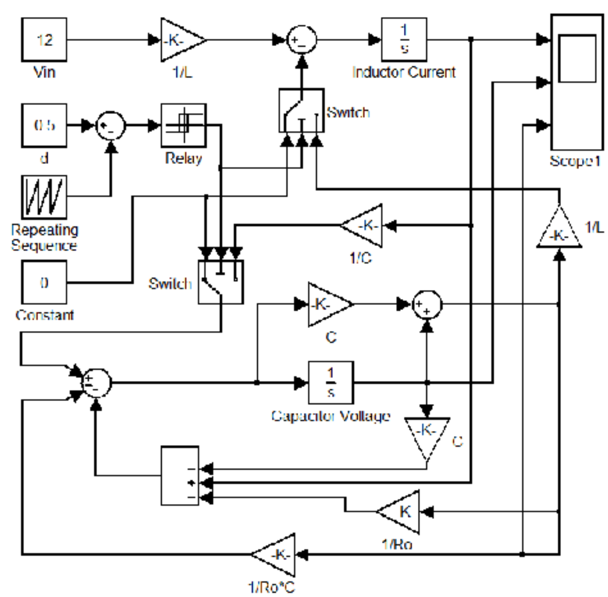
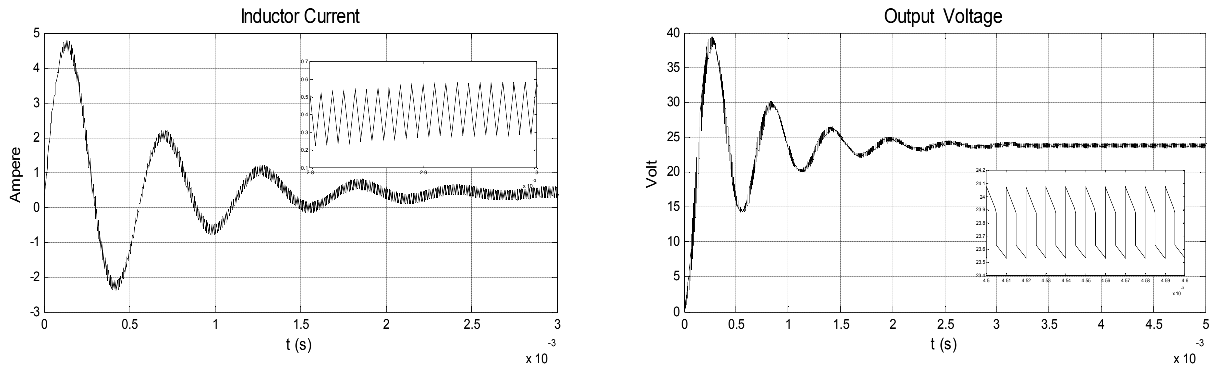


Figure 3. Open loop model of DC-DC boost converter.

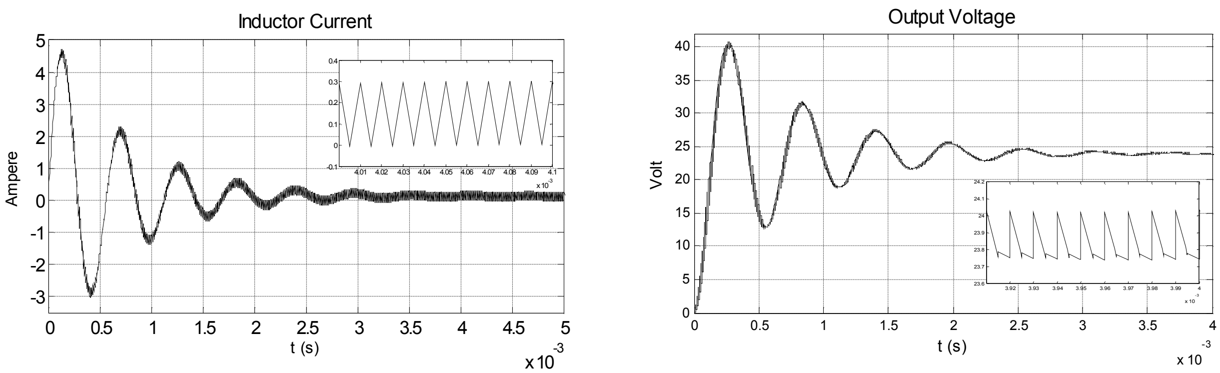
TABLE I. SPECIFICATION OF DC-DC BOOST CONVERTER

Parameter	Value
V_{in}	12V
V_0	24V
Inductor, L	200µH
Capacitor, C	10µF
Resistor, R_L	120Ω, 360Ω, 330kΩ
Duty cycle, D	0.5



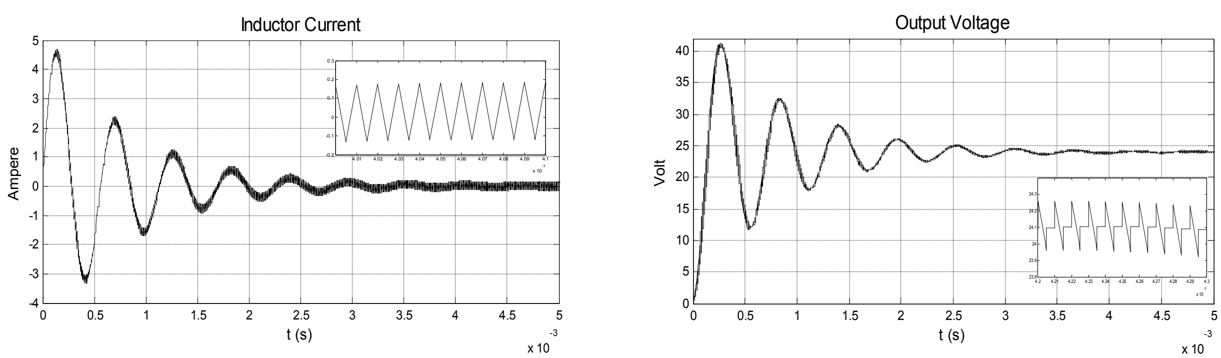
(a) (b)

Figure 4. Output of open-loop boost converter using R_L=120Ω (a) Inductor current (b) Output voltage.



(a) (b)

Figure 5. Output of open-loop boost converter using R_L=360Ω (a) Inductor current (b) Output voltage.



(a) (b)

Figure 6. Output of open-loop boost converter by using R_L=330kΩ (a) Inductor current (b) Output voltage.

Results of the open-loop DC-DC boost converter simulated in Matlab/Simulink environment is as shown in Fig. 4, 5 and 6. The open loop response from the simulation shows the corresponding of the state of the converter to a second order system. The results of the output voltage are considered in this work. Therefore, comparison has been made through the observation of the results to analyze the variation of the output voltage by changing the value of load resistor, R_L. All data that obtained in the simulation is simplified as in Table 2. Results show that the output voltage reaches the expected value of 24V higher than the input value of 12V with constant duty cycle of 0.5 at the end of the simulation and the open loop response of boost converter is considered stable in this work. At the beginning of simulation, high overshoot occurred in output voltage and inductor current and it is increases as the increases of load resistor. As in Fig. 4, the voltage is reaching up to the maximum of 39V at the beginning until it going down the steady state within 3ms. The circumstance of the output voltage is same as for Fig. 5 and Fig. 6 with increases of overshoot voltage as increases of load resistor. The analysis in Table 2 indicates that the percentage of overshoot can rise up to 72.9% by simulating with the higher value of load resistor. Hence, the voltage overshoot under load from the simulation of open-system can be unsatisfactory refers to the contribution of the increases in the value of load resistor due to its effect on overall damping of the converter system. A controller is needed due to large maximum overshoot and long settling time to achieve a satisfactory performance of less than 10% overshoot and faster settling time of less than 0.5ms.

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

R_{Load} (Ω)	% OS	t_r (ms)	t_{sett} (ms)
120	64.2	0.13	1.12
360	69.6	0.12	1.2
330k	72.9	0.1	2.0

VI. CONCLUSIONS

This paper describes the analysis and simulation of open-loop DC-DC boost converter. The analysis of nonlinear system and state-space model show validity against changes in the load resistance affected the output voltage and inductor current of the converter. The simulation environment MATLAB/SIMULINK is the most convenient option to model the circuit and the dynamic behaviour of converter structure in open-loop system. However, the model obtained considers only the continuous part in between the switching instants and therefore do not entirely represent the overall performance of the converter as a switching device. The open loop model of DC-DC boost converter may then be used to undertake controller design and later closed-loop performance can be examined for future work.

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