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Digital Voltage Control of DC-DC Boost Converter

T. M. Swathy*, Arun Kumar Wadhwani**
*Research Scholar, Department of Electrical Engineering, MITS, Gwalior
** Professor, Department of Electrical Engineering, MITS, Gwalior

ABSTRACT
The need for digital control for faster communication between power stage module & system controllers is increased with requirement of load complexity. The requirements also include stability of power module with the parametric variation. This paper presents a digital control of a dc-dc boost converter under nominal parameter conditions. The system controller has been verified in both frequency response as well as MATLAB-Simulink under nominal & parametric varying condition. The modeling of converter has been illustrated using state-space averaging technique. Direct digital design method is equipped to design the controller in frequency response to yield constant load voltage. The characteristic of load voltage before & after parametric variation is shown.
Keywords – DC-DC Converter, Small-Signal modeling, Digital Direct Design approach

I. INTRODUCTION

With the necessity of higher efficiencies, smaller output ripple and smaller converter size for modern power electronic systems conventional voltage regulator could be replaced by Switch Mode Power Supplies. Based on the requirement of the design, SMPS have reduced component, smaller size, lower cost, higher efficiency, higher reliability lower switching stress, wide conversion range, power factor correction, output voltage regulation and better performance. Due to these features the trend of SMPS has proliferated in various areas. Some of these areas that employ SMPS are personal computers, battery chargers, space stations, critical medical equipments etc. The SMPS employ high switching frequency dc-dc converter and the improvement in these circuit are nowadays in progress for the following reasons: 1) to improve performance; 2) to attain better reliability and 3) to increase the power density [1]-[3]. These developments are made in such a manner that they meet the requirements of fast dynamic response and low EMI.

Conventionally power electronic converters have been controlled using analog controller technology. Analog controlling techniques were prevalent due to their ease of implementation and lower cost. In spite of this, they are sensitive to external influences such as noise, temperature and aging [4]. Besides, execution of advanced control in analog circuit is problematic. Earlier the price and performance aspects of analog controllers were popular, but this ratio for digital signal processors has descended and digital controlling technique turned out more popular. Certain limitations of analog controller seized by digital controller and it offers some advantages such as faster design process, offers facility to integrate with other digital system, consume low power than analog controller, low sensitive to external influence, get better performance, less effective to environmental variations, better noise immunity, improves system reliability and has flexibility to make the modifications so as to reach the desired needs [5]-[6]. As in current years, the enhancement in microprocessor or in digital signal processors the application of digital controller for high frequency converters are developing interest.

As the area of application of SMPS requires constant regulation of load voltage even for the variation of load and source voltage and this is now a complicated task for power supply design engineers.

In past years, the power stage of the converter has been modeled using conventional and developed modeling methods. The controller has to be developed in order to attain desired performance characteristics. But due to parametric variation the system become unstable for some operating conditions. Hence there appear the requirements of the controller that will control the switching of the converter due to which it regulate the constant load voltage even for any change in load, source or other parametric variations.

II. MATHEMATICAL MODEL FORMULATION OF BOOST CONVERTER

The circuit diagram of a dc-dc boost converter is shown in Fig.1. Here it is assumed that the converter is operating in CCM and in one switching cycle it exhibits two modes of operation which depends on the switch 'ON' and 'OFF' time. In mode I the switch is ON the inductor current rises and the diode becomes reverse biased at o<t<DTs. In mode II the switch is turned OFF and the diode becomes forward biased at DTs<t<Ts, where 'D' is the duty ratio of the switch. For the performance analysis of the converter it requires steady-state and small-signal models. By using time domain analysis steady-state

models can easily be formulated, whereas small-signal models can be determined using state-space methods [7].
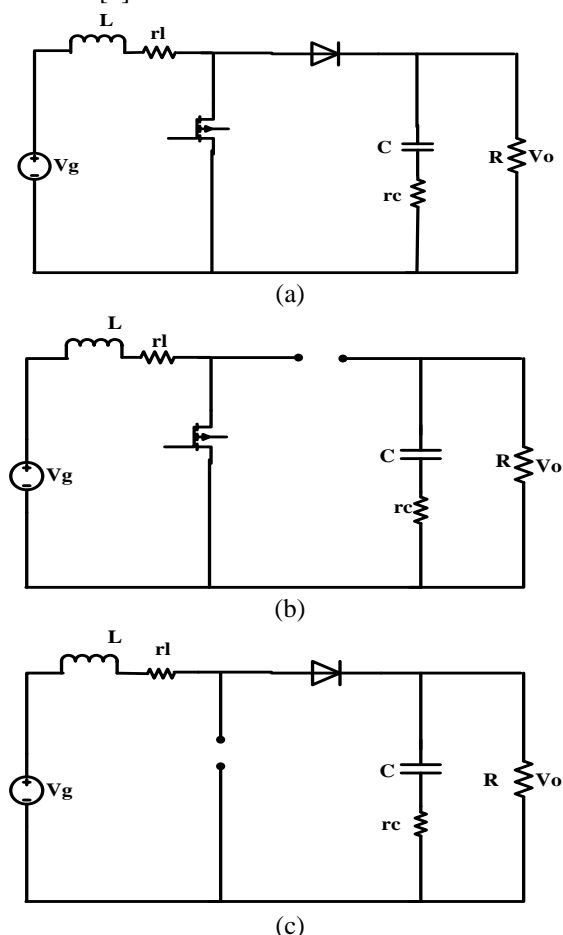

(a)

(b)

(c)

Fig.1. Boost converter and its operating modes. (a) Boost converter circuit diagram. (b) Mode-I operation. (c) Mode-II operation.

2.1 Steady- State Analysis

In this section, the following assumptions are considered to determine the steady-state analysis of the converter: an ideal switch, a constant instantaneous input voltage Vg, and a purely resistive load. By making the use of Kirchoff's voltage and current laws, steady-state relationships among different voltages and currents can be obtained. The voltage gain of the converter obtained:

$$\frac{V_o}{V_g} = \frac{1}{1-D} \qquad (1)$$

2.2 State-space Modeling

State-space modeling is well created in the switch-mode power conversion systems. The following analysis is done to obtain a small-signal transfer function. In a continuous-conduction mode, there are two states: one state relates to when the switch is on and the other when the switch is off. During each circuit state, the state equations are given by:

$$[\dot{x}] = [A][x] + [B][u] \qquad (2)$$
$$[y] = [E][x] \qquad (3)$$

Where [A]-state matrix,[B] -input matrix,[E] -output matrix and,[x] -state vector,[y] -output vector,[u] -excitation vector.

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

$$A_2 = \begin{bmatrix} -(r_L/L)-Rr_c/L(r_c+R) & -R/L(r_c+R) \\ R/C(r_c+R) & -1/C(r_c+R) \end{bmatrix}$$

$$B_1 = \begin{bmatrix} 1/L & 0 \end{bmatrix}^T \quad B_2 = \begin{bmatrix} 1/L & 0 \end{bmatrix}^T$$

$$E_1 = \begin{bmatrix} 0 & R/(R+r_c) \end{bmatrix}$$

$$E_2 = \begin{bmatrix} r_c/(1+r_cR) & R/(r_c+R) \end{bmatrix}$$

$$[u] = v_g \qquad [x] = \begin{bmatrix} i_L & v_c \end{bmatrix}^T$$

III. ATTRIBUTES FOR COMPENSATOR DESIGN

After the power stage transfer function are developed, then the digital controller can easily be to attain a desired characteristics. Two approaches can be used in the design of digital compensator. One is digital redesign approach and second one is digital direct design approach. In direct redesign method the compensator is first designed in s-domain then the continuous domain compensator is converted into discrete-time compensator by proper conversion technique. In digital direct design approach the compensator is designed directly in discrete-time domain by including time delay. This method has the advantage that pole-zero of the compensator are placed directly which results in better phase margin and bandwidth of the converter. In this paper the digital direct design approach has been implemented to develop a compensator for the converter. In digitally controlled converter system the loop gain is expressed by L(z)=Gc(z)Gvd(z), where Gc(z) is a digital controller. The closed loop of the converter is shown in Fig. 2. The foremost steps that are effective at the design stage are as follows: 1) to achieve better speed response higher the bandwidths, however the loop gain lies in the range of fs/10<fc<fs/5; 2) to achieve higher low-frequency gain pole needs to be placed at origin; 3) the phase margin of open loop transfer function must be in the range of 45°-75°. 4) Gain margin of open loop transfer function should be at least 6dB [7]. These guidelines have to use while controller design to attain desired characteristics. Depending on the nature of the transfer function of converter fine tuning of compensator is needed. The loop-gain of the closed loop system, including compensator is in the form is shown in equation (4) and (5) respectively.

$$L = \frac{a_3 z^3 + a_2 z^2 + a_1 z + a_0}{b_3 z^3 + b_2 z^2 + b_1 z + b_0} \quad (4)$$

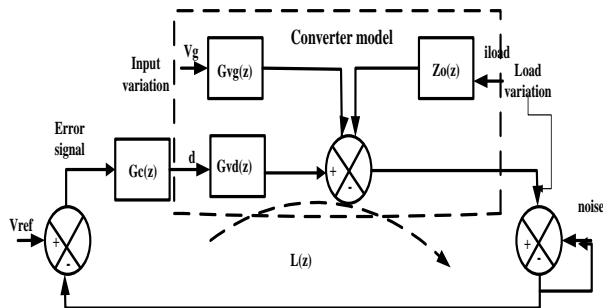$$G_C(z) = \frac{k(z-a)}{(z-1)} \quad (5)$$

Fig.2. Block diagram of closed loop of the converter

IV. RESULTS AND DISCUSSION

A dc-dc boost converter with 50 kHz switching frequency is considered. The converter has been developed in MATLAB- Simulink platform to endorse the digital control of the converter at 28V, 30W load. The components values of the converter are listed in Table I. The modeling and steady state analysis are discussed in section II. Fig.3 shows the frequency response bode plot of small-signal transfer function of the converter, loop gain and compensator. It has been observed from the plot that the compensator which has been developed yield high gain at low frequency for open loop transfer function. Hence this will reduce the steady state error in the power supply output. The frequency response bode plot of small signal transfer function of converter and loop gain under parametric variation is shown in Fig.4.

TABLE I
CONVERTER PARAMETERS

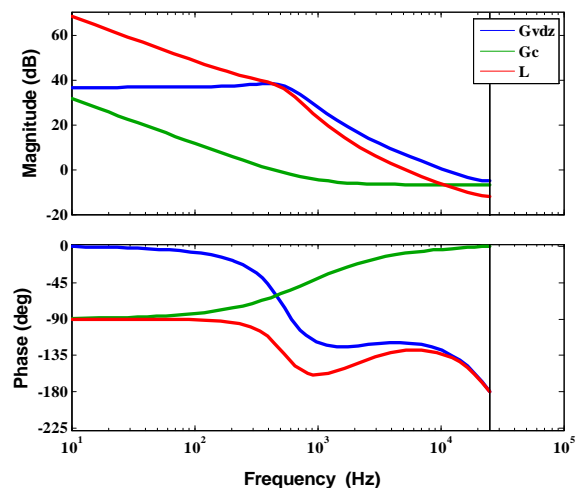| Parameters	Value
V_g	12V
V_o	28V
R	26Ω±50%
L, r_L	63.72µH,0.08Ω
C, r_C	250µF,0.03Ω
f_s	50kHz

Fig.3. Frequency response bode plot of Gvd(z),controller and loop gain transfer function of the system

The controller designed for the converter is:

$$G_C = K \frac{(z - z_1)}{(z - 1)} \quad (6)$$

The pole-zero placement of the controller depends on the required stability margins, the noise attenuation amount. The phase margin and gain margin attained for open loop transfer function are 51.6º and 12dB respectively. For practical consideration, source voltage and load variations have been considered. It is assumed that a constant source voltage is regulated but due to some faults fluctuations may be possible up to 30% around the nominal value (disturbance in source voltage Vg :9→12 V); similarly, the relative load variation is around 50% of the nominal value (disturbance of load resistance R : 26→52 Ω). The simulated result of the system under detailed parameter range:±30% source voltage variation and 50% load variation is shown in Fig.5 and Fig.6 respectively.
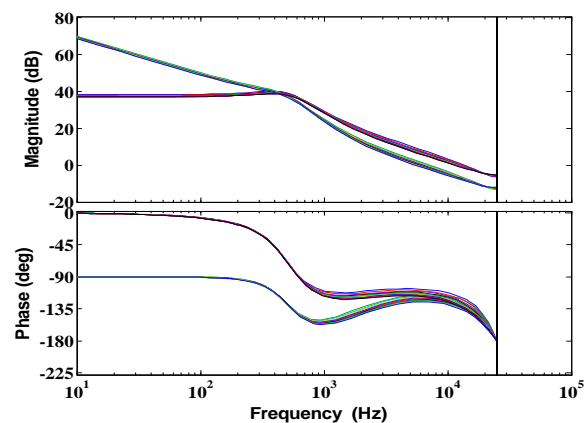

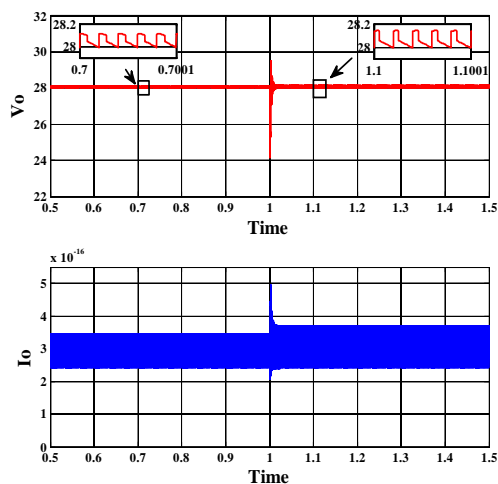Fig.4.Frequency response bode plot of loop gain transfer function of the system under parametric variation

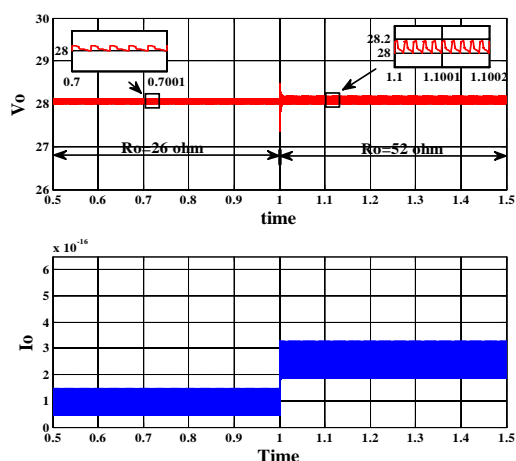Fig.5. Simulated result of the converter load voltage and current under source voltage variation from 12V-9V

Fig.6.Simulated result of converter load voltage and current under load variation from 26Ω-52Ω

V. CONCLUSION

A dc-dc second order boost converter has been digitally controlled to supply regulated 28V, 30W dc load. The power stage of the power supply is designed to operate in 50 KHz switching frequency. To analyze the frequency response of the converter a small-signal model is being formulated using state space averaging technique. In this paper he controller is developed using digital direct design approach with the help of frequency response of the power stage. The digital direct design approach has the advantage of direct placement of pole zero which results in better bandwidth and phase margin of the converter. The SMPS design is being simulated in MATLAB to show that it generates regulated desired output voltage with the ±30% in source voltage variation and ±50% load variation.

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