THE STUDY OF EFFECT OF EQUIVALENT SERIES RESISTANCE FOR BUCK-BOOST CONVERTER

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ABSTRACT
This paper presents the study of effect of equivalent series resistance in buck-boost converter using system identification technique with a consideration of dynamic condition. By varying the input signal of the system, the output dynamic response can be achieved. The output is then analyzed and compared by using both software simulation and hardware experiment. Finally, the analyzed result is then used for identifying the transfer function of the converter. Furthermore, the effects of variation of equivalent series resistance (ESR) in capacitors to the performance of converter are studied. As seen in the results, the increase of equivalent series resistance will decrease the percentage of overshoot and rise time of entire response.

KEY WORDS
Equivalent series resistance (ESR), buck-boost converter, system identification

1. Introduction

In the design of power electronic circuit, especially with energy storage devices like capacitors, the consideration of the hidden resistance is usually neglected. However, in practical work, this value of resistance will have several effects on the performance of the circuit. This resistance is defined as “Equivalent Series Resistance: ESR”. There are several researches study about the effects of ESR on power electronic circuit. For example, the study of the stable range of equivalent series resistance of a low drop out regulator by building a model and using the principles of control system to determine performances of the circuit were presented in [1]. It is concluded that ESR in a capacitor affects the stability of regulator and it is necessary to maintain the ESR value in a stable range. In [2], the ripple factor due to the ESR on a frequency response of a dc-to-dc converter were studied. It is found that ESR has effects on frequency responses and stability of boost converter and also has similar results in buck-boost converter.

In this paper, the model of a Buck-Boost converter can be determined by using the system identification technique. By varying the duty cycle of the system, it will cause a dynamic output voltage signal which can be used to analyze the performance of circuit and can be applied to the system identification theory [3] to determine the transfer function of converter. Furthermore, the effects of ESR values on the converter were studied and compared by varying capacitors which have the same capacitance but differ in ESR values. The results will be compared in three ways: Mathematic model, simulation model, and experiment.

2. Equivalent Series Resistance

Normally, in the design of dc-to-dc converter, an electrolytic capacitor is used. Figure 1 shows the equivalent circuit of an electrolytic capacitor.

Figure 1. Simplified equivalent circuit of an electrolytic capacitor [4]

As seen in Figure 1, the impedance of an electrolytic capacitor can be expressed as:

$$Z_C = ESR + j\omega ESL - \frac{j}{\omega C}$$  (1)

Figure 2. the evolution of ESR (R), capacitive reactance (X_C) and inductive reactance (X_L) with frequency, for an electrolytic capacitor

Figure 2 shows the values of ESR (R), capacitive reactance (X_C) and inductive reactance (X_L) with frequency, for an electrolytic capacitor [4].
3. Buck-Boost Converter, its Model and System Identification

Buck-Boost converter is one type of DC-to-DC converters which can control an output voltage \( V_o \) to be lesser or greater than input voltage \( V_i \). The model of a Buck-Boost converter is composed of a switching device, inductor, diode, and capacitor as shown in Figure 3.

In the design of Buck-Boost converter with continuous mode, the parameters of converter can be determined as followings:

A minimum inductance:
\[
L_{min} = \frac{(1-D)^2 R}{2f} \tag{2}
\]

A capacitance:
\[
C = \frac{D}{RF} \tag{3}
\]

Where, \( r \) = ripple factor; In this paper, \( r \) is set to 1%. 
\( f \) = switching frequency (where \( f = \frac{1}{T} \))
\( D \) = duty cycle

The state space model is used to analyze the dynamic system by considering two main equations:

State equation:
\[
\dot{x} = Ax + Bu \tag{4}
\]

Output equation:
\[
y = Cx + Du \tag{5}
\]

By considering a switching device in both off and on conditions, let \( u \) is switching conditions, where
\[
u = \begin{cases} 
1, & 0 \leq t \leq t_{on} \\
0, & t_{on} \leq t \leq T 
\end{cases} \tag{6}
\]

The state space model of a Buck-Boost converter can be written as:
\[
\frac{d}{dt} \begin{bmatrix} l \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} l \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} (V_o + V_s) \\ -\frac{1}{C} \end{bmatrix} u \tag{7}
\]

With consideration of ESR in capacitor \( (R_C) \), the new state space model can be expressed from the state and output equations as following:
\[
\frac{d}{dt} \begin{bmatrix} l \\ V_o \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} l \\ V_o \end{bmatrix} + \begin{bmatrix} \frac{1}{L} (V_o + V_s) \\ -\frac{1}{C} \end{bmatrix} u \tag{8}
\]

Based on above mentioned equations, state-space matrices can be written as:
\[
A = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, \quad B = \begin{bmatrix} \frac{1}{L} (V_o + V_s) \\ -\frac{1}{C} \end{bmatrix} \tag{9}
\]

The transfer function of Buck-Boost converter can be derived by using the following equation:
\[
G(s) = D + CS(s - A)^{-1}B \tag{10}
\]

Thus,
\[
G(s) = \frac{V_o(s)}{V_i(s)} = \frac{(V_o + V_s) + (R_C(C + V_o + V_s) - L) s}{LCs^2 + (R_C C + \frac{1}{R} + 1)} \tag{11}
\]

The system identification technique relies on two parameters of a considering system: input and output signals. In this paper, the Output Error (OE) model is selected and least square regression is adopted to find the converter parameters. To apply the system identification technique, firstly, the input and output signals are required. Then, the Output Error model needs to enter three parameters of the system, which are: number of poles \( (n_p) \), number of zeroes plus one \( (n_z + 1) \), and number of delays \( (n_d) \). As seen in (12), there are some parameters, \( f_1, f_2, ..., f_{nf} \) and \( b_1, b_2, ..., b_{nb} \) of the transfer function needed to be determined.

The Output Error model is given as
\[
G(s) = \frac{b_{ns} s^{(nb-1)} + b_{ns-1} s^{(nb-2)} + ... + b_1}{s^{nf} + s^{nf-1} + ... + s} \tag{12}
\]

4. Simulation and Experimental Results

In this research work, the designed hardware of the buck-boost converter is composed of two parts, which are PWM generator and DC-to-DC converter. PWM is generated by using the microcontroller PIC 18F4520. The output PWM voltage level is +5V and it is then boosted to +15V by MOSFET gate driver circuit using IR2110. After that, +15V PWM is then used to drive a MOSFET which operates as a switching device at 50 kHz frequency. In this paper, there are 9 types of 100 uF capacitors with different ESR values. By measuring, 9 different ESR values, which are: 0.0607, 0.0818, 0.1488, 0.1624, 0.23, 0.313, 0.42, 0.713 and 1.077 Ω, can be obtained. For DC-to-DC converter, an inductor 380 uH and load 30 Ω load were adopted in the circuit. +12V lead acid battery was used as an input voltage source.
The model using for simulation is shown in Figure 4. As seen in this figure, four values of duty cycle of a buck-boost converter are set to 25% and 45% in the buck mode operation and 55% and 75% in the boost mode operation.

As seen in Figure 4, the resistor connected in series with capacitor represents as the ESR. This resistance value is subjected to change to nine different values as previously measured. By properly specified signals in MATLAB simulink, the input signals shown in Figure 5 are obtained. Based on the model in (12), substituting $L = 380 \mu H$, $C = 100 \mu F$, $R = 30 \Omega$, and $R_c$ is an ESR which are one of the values $0.0607$, $0.230$, $0.713$, and $1.077 \Omega$. By applying the system identification toolbox on MATLAB, the models of DC-DC converter with various ESR can be determined. Poles, slope, and overshoot percentage can be concluded as in Table 1.

As seen in Table 1, overshoot is decreased when the ESR is increased. The percentage of best fit is also decreased when increasing the ESR. To verify the above mentioned results, the time domain responses of the converter with 9 different ESRs are investigated. Figure 6 shows the example of pole plots of the converter with various ESRs.

DC-DC converter was designed and implemented on real circuit. Table 2 illustrates the poles, slope, and overshoot percentage of the step response on buck-boost circuit.

5. Conclusion

According to simulation and experimental results, we can conclude that an increase in ESR value leads to a decrease in overshoot voltage and a decrease in slope magnitude of pole plot in complex plane. In addition, increasing in ESR value has an effect on system identification result, since the best fit percentage is decreased. However, ESR causes loss in form of heat, which affects the efficiency of the buck-boost converter.
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References