A Controller Design for SEPIC in a Fuel Cell System

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ABSTRACT

The single-ended primary-inductance converter (SEPIC) is a DC/DC converter that is capable of both step-down and step-up conversions. In order for the converter to work, a feedback controller is necessary that modulates the duty cycle of the switch in response to the change in the input voltage. In this paper, we present a controller design for a SEPIC converter to be used with a direct methanol fuel cell (DMFC). The output of the fuel cell is from 8 V to 24 V. The output of the converter must be 12 V with less than 2% variations at least in the frequency range from DC to 40 Hz. The size of the converter is 24 W.

A linearized mathematical model of SEPIC is derived using the state-space averaging technique. This model is cast into a standard disturbance rejection control problem. A controller is designed to satisfy the requirement. Simulations and experimental observations validate the efficacy of the controller.

Keywords: dc/dc converter, single-ended primary-inductance converter (SEPIC), disturbance rejection

1 INTRODUCTION

The single-ended primary-inductance converter (SEPIC) is a DC/DC converter that can maintain a constant output with a wide range of input voltages. In fact, the input voltage can be either lower or higher than the output voltage. This feature is particularly useful for a fuel cell, as the output of the fuel cell can vary drastically depending on the operating parameters.

In order for SEPIC to work, a feedback controller is necessary that modulates the switch in response to the change in the input volage. A downside of using a SEPIC is that the dynamic model is of fourth order, and it is rather difficult to design a feedback control. The control design in the literature is either without the details [1] or heuristic [2]. On the other hand, the control design must be based on the requirements of the converter. For example, the converter must maintain a constant output within the specified ripple with the specified input voltage range in the given frequency range.

In this paper, we present a controller design for a SEPIC converter to be used with a direct methanol fuel cell (DMFC). The output of the fuel cell (thus, the input to the converter) is from 8 V to 24 V. The output of the converter must be 12 V with less than 2% variations at least in the frequency range from DC to 40 Hz. The size of the converter is 24 W.

In order to design a controller for the converter, a linearized mathematical model of SEPIC is derived using the state-space averaging technique. This model is cast into a standard disturbance rejection control problem. A controller is designed to satisfy the requirement. A prototype converter is built. Simulations and expeirmental observations validate the effectiveness of the controller.

2 SEPIC MODEL

Fig. 1 shows the basic structure of the SEPIC. The switching of the MOSFET Q1 modulates the output voltage. The input-output characteristics of the SEPIC is inherently nonlinear because of the switching. However, if the switching occurs much faster than the dynamics of the input, an averaging technique can be used to obtain a linear model that can describe the converter with a reasonable accuracy in the low frequency region [3,4].

In a nutshell, the circuit operation is separately considered when the MOSFET Q1 is on and off. As shown in Fig. 2(a), the output voltage v_{out} is supplied by the output capacitor C_2, when Q1 is on. If Q1 is off, the output voltage is determined by the secondary inductor L_2 and the coupling capacitor C_1, as illustrated in Fig. 2(b). The duty ratio d is defined as the time ratio during which Q1 is on with respect to the switching period. Thus, if the switching

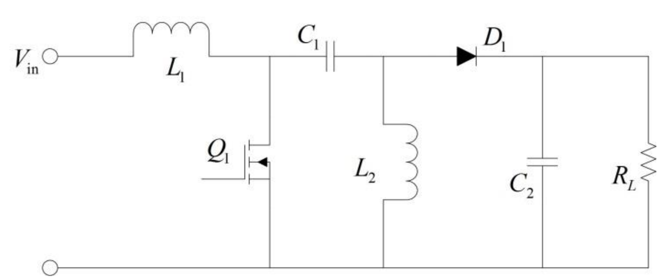

Figure 1: Single-ended primary-inductance converter (SEPIC)

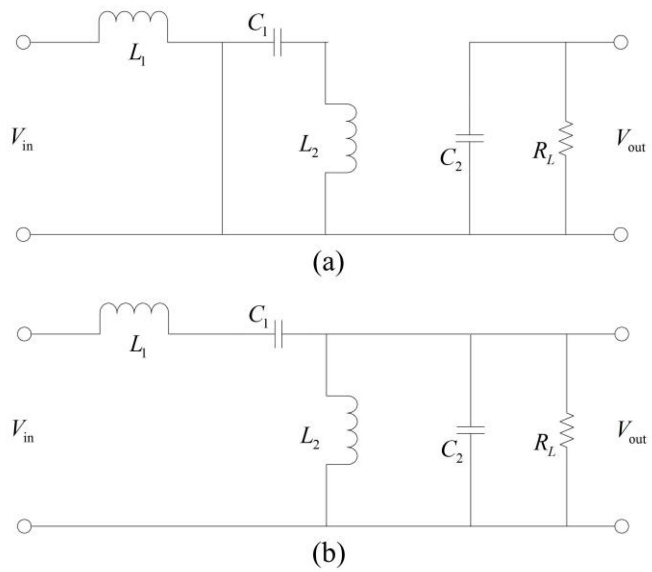

Figure 2: (a) SEPIC circuit when Q1 is on, and (b) SEPIC when Q1 is off

period is T_s, Q1 is on during $0 \le t \le dT_s$. For the circuit of Fig. 2(a), the circuit equations can be set up and arranged into a state-space form [3]

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}_1\mathbf{x} + \mathbf{B}_1 v_{\text{in}} \\ v_{\text{out}} &= \mathbf{Q}_1\mathbf{x} \end{aligned} \tag{1}$$

where the state vector $\mathbf{x}$ is defined as $\begin{bmatrix} i_1 & v_1 & i_2 & v_2 \end{bmatrix}^t$. Here, i_1 and i_2 are the currents through the inductors L_1 and L_2, respectively. Also, v_1 and v_2 are the voltages across the capacitors C_1 and C_2, respectively. For the time period of $dT_s \le t \le T_s$, a similar state-space equation can be obtained

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}_2\mathbf{x} + \mathbf{B}_2 v_{\text{in}} \\ v_{\text{out}} &= \mathbf{Q}_2\mathbf{x} \end{aligned} \tag{2}$$

The state-space averaging technique assumes that the two state-space models of (1) and (2) can be time-averaged. For example, the overall system matrix can be obtained from

$$\mathbf{A} = \mathbf{A}_1 d + \mathbf{A}_2 d' \tag{3}$$

where the complimentary duty ratio d' is defined as $1-d$. Furthermore, it is assumed that the variables are the sums of steady-state values and small pertubations

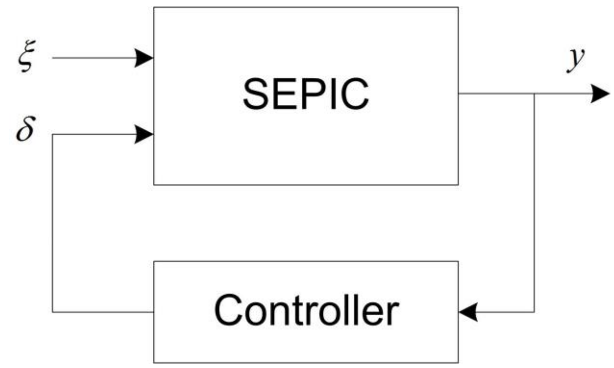

Figure 3: Block diagram of the SEPIC model

$$\begin{aligned} v_{\text{in}} &= V_{\text{IN}} + \xi \\ v_{\text{out}} &= V_{\text{OUT}} + y \\ d &= D + \delta \end{aligned} \tag{4}$$

Plugging (4) into the averaged model and eliminating the higher order terms, we get a linearized model

$$\begin{aligned} \dot{\mathbf{x}} &= \mathbf{A}\mathbf{x} + \mathbf{B}_\delta \delta + \mathbf{B}_\xi \xi \\ y &= \mathbf{Q}\mathbf{x} \end{aligned} \tag{5}$$

The matrices of (5) are as follows.

$$\mathbf{A} = \begin{bmatrix} 0 & -\dfrac{D'}{L_1} & 0 & -\dfrac{D'}{L_1} \\ \dfrac{D'}{C_1} & 0 & -\dfrac{D}{C_1} & 0 \\ 0 & \dfrac{D}{L_2} & 0 & -\dfrac{D'}{L_2} \\ \dfrac{D'}{C_2} & 0 & \dfrac{D'}{C_2} & -\dfrac{1}{R_L C_2} \end{bmatrix} \tag{6}$$

$$\mathbf{B}_\delta = \begin{bmatrix} \dfrac{1}{L_1}(V_{\text{IN}} + V_{\text{OUT}}) \\ -\dfrac{1}{C_1}(I_{\text{IN}} + I_{\text{OUT}}) \\ \dfrac{1}{L_2}(V_{\text{IN}} + V_{\text{OUT}}) \\ -\dfrac{1}{C_2}(I_{\text{IN}} + I_{\text{OUT}}) \end{bmatrix}, \quad \mathbf{B}_\xi = \begin{bmatrix} \dfrac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{7}$$

$$\mathbf{Q} = \begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

In (6), D' is defined as $1-D$.

The system model of (5) can be thought as the system with the control input δ and the disturbance ξ (the variations in the input voltage). The job of the controller is

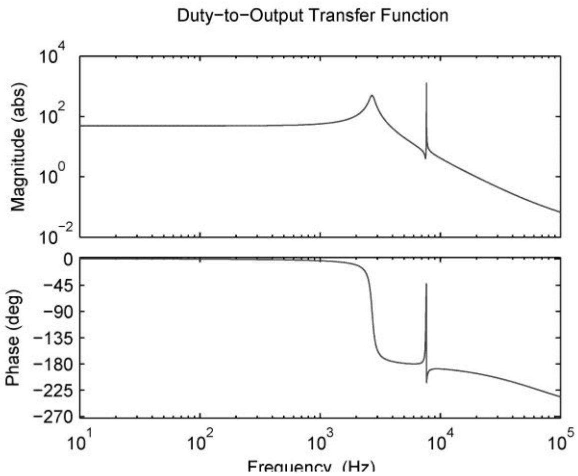

Figure 4: Duty-to-output open-loop transfer function

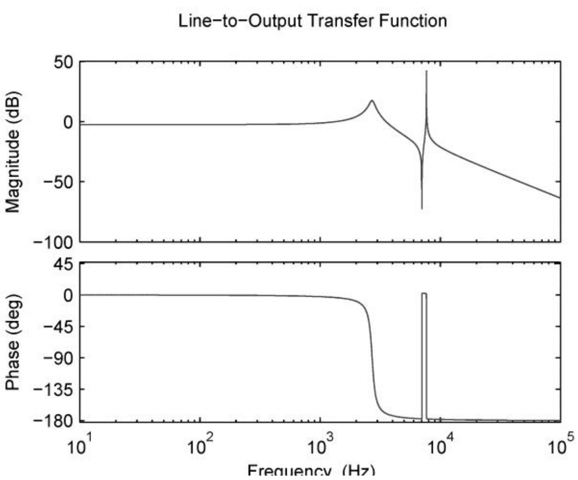

Figure 5: Line-to-output open-loop transfer function

then to control the duty cycle in order to maintain constant output voltage in spite of the fluctuations in the input voltage. The block diagram in Fig. 3 illustrates the structure of the SEPIC model.

Fig. 4 and 5 display the open-loop transfer functions of SEPIC. The duty-to-output transfer function in Fig. 4 is the transfer function $T_{\delta y}$ from δ to y and obtained from

$$T_{\delta y} = \mathbf{Q}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}_{\delta} \tag{9}$$

The line-to-output transfer function in Fig. 5 is $T_{\xi y}$.

$$T_{\xi y} = \mathbf{Q}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}_{\xi} \tag{10}$$

These transfer functions are consistent with the experimental measurements in [5].

3 CONTROLLER DESIGN

The DC-DC converter that is described in this paper is to be used in a 24-W direct methanol fuel cell (DMFC) system. The output of the fuel cell varies between 8 and 24 volts. The converter needs to maintain 12 volts while capable of supplying 2 amps of total current to output devices. A SEPIC converter is designed for this purpose. The parameters of the converter is summarized in Table 1.

As can be seen from the open-loop line-to-output transfer function of Fig. 3(b), a feedback controller is needed to maintain constant output voltage. In the low frequency region, the magnitude of the line-to-output transfer function is around -2.5 dB, which means 0.75 V change in the output voltage with 1 V swing in the input voltage. It is required that the voltage ripple at the converter output is less than 2% within the frequency range from DC to 40 Hz. The open-loop characteristics falls well short of satisfying this requirement.

In most cases, a proportional-integral-derivative (PID) type (or lead-lag type) controller is used. However, it is very difficult to find suitable gains that satisfy the requirement because of the high frequency characteristics of the converter. In order to introduce some low-pass filtering action into the controller, we use a controller in the form of

$$G_c(s) = \frac{K(\tau_2^2 s^2 + 2\zeta\tau_2 s + 1)}{\tau_1^2 s^2 + 2\zeta\tau_1 s + 1} \tag{11}$$

The denominator time constant τ_1 determines the location of the poles, whereas the zero locations are related to τ_2. Since the converter needs to reject the disturbance up to 40 Hz, we select the pole location at 50 Hz, which translates into the time constant $\tau_1 = 1/(2\cdot\pi\cdot 50)$. The zero must be placed far from the poles, but not too far because of the high frequency characteristics. Through trial and error, $\tau_2 = \tau_1/80$ is selected. The damping factor ζ is selected to be 0.7, while the controller gain K is 1.

Parameter	**Symbol**	**Value**	**Unit**
Primary inductance	L_1	22	μH
Secondary inductance	L_2	22	μH
Coupling capacitance	C_1	10	μF
Output capacitance	C_2	100	μF
Load resistance	R_L	6	Ω
Nominal output voltage	V_{OUT}	12	V
Nominal output current	I_{OUT}	2	A
Input voltage	v_{in}	8~24	V

Table 1: Parameters of 24-W, 12-V SEPIC

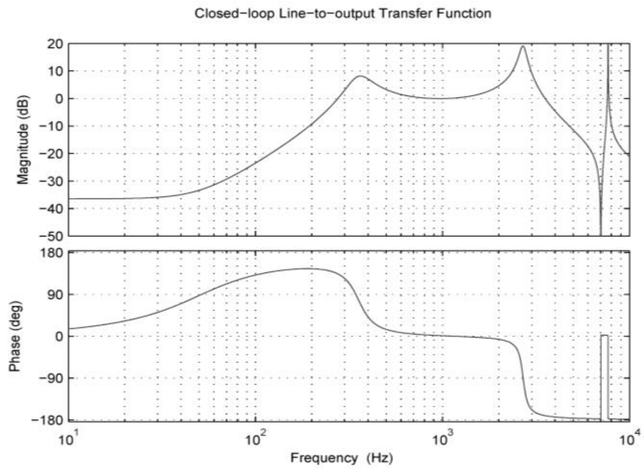

Figure 6: Closed-loop line-to-output transfer function

4 RESULTS

Since the fuel cell generates the voltage from 8 to 24 V, the average is 16 V with 8 V swing. The requirement of the converter is less than 2% change in the output. This means that the disturbance rejection must be

$$20\log_{10}\frac{12\times 0.02}{8} = -30.5\,\text{dB} \quad (10)$$

Fig. 6 shows the closed-loop line-to-output transfer function when the controller of (11) is applied. The rejection of input voltage variations up to 60 Hz is more than 30 dB, which satisfies the requirement. The high-frequency performance is poor. The disturbances above 300 Hz would result in output voltage variations greater than the change in the input. However, the dynamics of the DMFC fuel cell is very slow. Typically, it is lower than 10 Hz.

A prototype coverter circuit is built with the component values of Table 1. The controller is implemented on DS1104 (dSPACE, Germany). The output of the converter is measured while the input voltage is varied from 8 V to 16 V. The variation of the output voltage is less than 2% from the 12 V.

5 CONCLUSIONS

The single-ended primary-inductance converter (SEPIC) is ideal for a fuel cell, because it can either step-up or step-down the input. In this paper, we present a controller design that can satisfy the requirements of the converter. If the requirements become more stringent than those that was considered in this paper, it might be necessary to employ such control design techniques as the robust control strategy.

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