AN IMPLEMENTATION OF FULL-STATE OBSERVER AND CONTROLLER FOR DYNAMIC STATE-SPACE MODEL OF ZETA CONVERTER

Hafez Sarkawi[1], Mohd Hafiz Jali[2]

[1]Faculty of Electronics and Computer Engineering (FKEKK),

University Technical Malaysia Melaka (UTeM), Melaka

[2]Faculty of Electrical Engineering (FKE),

University Technical Malaysia Melaka (UTeM), Melaka

[1]hafez@utem.edu.my(+606-5552025) and [2]mohd.hafiz@utem.edu.my(+606-5552331)

Abstract

Zeta converter is a fourth order dc-dc converter that can increases (step-up) or decreases (step-down) the input voltage. The converter needs feedback control to regulate its output voltage. A full-state observer can be used to estimate the states of the system in condition the output must be observable. The estimated states can be fed to full-state feedback controller to control the plant. This paper presents the dynamic model of zeta converter. The converter is modeled using state-space averaging (SSA) technique. Full-state observer and controller are implemented on the converter to regulate the output voltage. The simulation results are presented to verify the accuracy of the modeling and the steady-state performance subjected to input and load disturbances.

Keyword: Modeling, zeta converter, SSA technique, full-state feedback controller, full-state observer

Abstrak

Penukar Zeta adalah penukar dc-dc empat peringkat yang boleh menaik atau menurunkan voltan masukan. Sesuatu penukar memerlukan pengawal suap-balik untuk mengatur voltan keluarannya. Pemantau keadaan-penuh boleh digunakan untuk menganggarkan keadaan dalam sesuatu sistem tetapi dengan syarat keluaran system tersebut boleh dipantau. Keadaan yang telah dianggarkan tersebut boleh di suap ke perngawal suap-balik keadan penuh untuk mengawal sesuatu loji. Kertas ini mempersembahkan model dinamik untuk penukar zeta. Penukar tersebut dimodelkan menggunakan teknik purata ruang-keadaan (PRK). Pemantau dan pengawal keadaan-penuh diletakkan pada penukar tersebut untuk mengatur voltan keluaran. Hasil simulasi akan dipersembahkan untuk mengesahkan ketepatan model penukar tersebut dan sambutan keadaan mantapnya apabila dimasukkan hingar pada masukan dan beban.

Kata kunci: Pemodelan, penukar zeta, teknik PRK, pengawal suap-balik keadaan penuh, pemantau keadaan penuh

1. Introduction

Zeta converter is fourth order dc-dc converter that can step-up or step-down the input voltage. The converter is made up of two inductors and two capacitors. Modeling plays an important role to provide an inside view of the converter's behavior. Besides that, it provides information for the design of the compensator. The most common modeling method for the converter is state-space averaging technique (SSA). Open-loop system has some disadvantages where the output cannot be compensated or controlled if there is variation or disturbance at the input. For the case of zeta converter, the changes in the input voltage and/or the load current will cause the converter's output voltage to deviate from desired value. This is a disadvantage because when the converter is used as power supply in electronic system, problem could be happened in such that it could harm other sensitive electronic parts that consume the power supply. To overcome this problem, a closed-loop system is required. Full-state feedback controller is one of the compensator used in closed-loop system. Compared to other compensator such as PID, full-state feedback controller is time-domain approach which makes the controller design is less complicated than PID approach which is based on frequency-domain approach. This is due to the modeling process is based on state-space matrices technique. It is sometimes impossible to measure certain variables except input and output. Full-state observer can overcome this issue because it can estimate the states of the system by using input and output measurement only.

2. Modeling of Zeta Converter

2.1 Overview of SSA Technique

State-space averaging (SSA) is a well-known method used in modeling switching converters [1]. To develop the state space averaged model, the equations for the rate of inductor current change along with the equations for the rate of capacitor voltage change that are used.

A state variable description of a system is written as follow:

$$x' = Ax + Bu \tag{1}$$

$$v_O = Cx + Eu \tag{2}$$

where *A* is *n x n* matrix, *B* is *n x m* matrix, *C* is *m x n* matrix and *E* is *m x m* matrix. Take note that capital letter *E* is used instead of commonly used capital letter *D*. This is because *D* is reserved to represent duty cycle ratio (commonly used in power electronics).

For a system that has a two switch topologies, the state equations can be describe as [2]:

Switch closed

$$x' = A_1 x + B_1 u$$

$$v_O = C_1 x + E_1 u$$

Switch open

$$x' = A_2 x + B_2 u$$

$$v_O = C_2 x + E_2 u$$

For switch closed at time *d*T and open for (1-*d*)T, the weighted average of the equations are:

$$x' = [A_1 d + A_2(1-d)]x + [B_1 d + B_2(1-d)]u \quad (3)$$

$$v_O = [C_1 d + C_2(1-d)]x + [E_1 d + E_2(1-d)]u \quad (4)$$

By assuming that the variables are changed around steady-state operating point (linear signal), the variables can now be written as:

$$\begin{aligned} x &= X + \tilde{x} \\ d &= D + \tilde{d} \\ u &= U + \tilde{u} \\ v_O &= V_O + \tilde{v}_O \end{aligned} \quad (5)$$

where *X*, *D*, and *U* represent steady-state values, and $\tilde{x}$, $\tilde{d}$, and $\tilde{u}$ represent small signal values. During steady-state, the derivatives (*x'*) and the small signal values are zeros. Equation (1) now becomes:

$$0 = AX + BU \quad (6)$$

$$X = -A^{-1}BU \quad (7)$$

while Equation (2) can be written as:

$$V_O = -CA^{-1}BU + EU$$

The matrices are weighted averages as:

$$\begin{aligned} A &= A_1 D + A_2(1-D) \\ B &= B_1 D + B_2(1-D) \\ C &= C_1 D + C_2(1-D) \end{aligned} \quad (8)$$

For the small signal analysis, the derivatives of the steady-state component are zero:

$$x' = X' + \tilde{x}' = 0 + \tilde{x}' = \tilde{x}'$$

Substituting steady-state and small signal quantities in Equation (5) into Equation (3), the equation can be written as:

$$\tilde{x}' = \left[A_1\left(D+\tilde{d}\right)+A_2\left(1-\left(D+\tilde{d}\right)\right)\right]\left(X+\tilde{x}\right)+\left[B_1\left(D+\tilde{d}\right)+B_2\left(1-\left(D+\tilde{d}\right)\right)\right]\left(U+\tilde{u}\right)$$

If the products of small signal terms $\tilde{x}\tilde{d}$ can be neglected, the equation can be written as:

$$\tilde{x}' = \left[A_1 D+A_2(1-D)\right]\tilde{x}+\left[B_1 D+B_2(1-D)\right]\tilde{u}+\left[(A_1-A_2)X+(B_1-B_2)U\right]\tilde{d}$$

or in simplified form,

$$\tilde{x}' = A\tilde{x}+B\tilde{u}+\left[(A_1-A_2)X+(B_1-B_2)U\right]\tilde{d} \tag{9}$$

Similarly, the output from Equation (4) can be written as:

$$\tilde{v}_O = \left[C_1 d+C_2(1-d)\right]\tilde{x}+\left[E_1 d+E_2(1-d)\right]\tilde{u}+\left[(C_1-C_2)X+(E_1-E_2)U\right]\tilde{d}$$

or in simplified form,

$$\tilde{v}_O = C\tilde{x}+E\tilde{u}+\left[(C_1-C_2)X+(E_1-E_2)U\right]\tilde{d} \tag{10}$$

2.2 Modeling of Zeta Converter By SSA Technique

The schematic of zeta converter is presented in Fig. 1. Basically the converter are operated in two-states; ON-state (*Q* turns on) and OFF-state (*Q* turns off). When *Q* is turning on (ON-state), the diode is off as shown in Fig. 2. During this state, inductor L_1 and L_2 are in charging phase. When *Q* is turning off (OFF-state), the diode is on as presented in Fig. 3. At this state, inductor L_1 and L_2 are in discharge phase. Energy in L_1 and L_2 are discharged to capacitor C_1 and output part, respectively. To ensure the inductor current i_{L1} and i_{L2} increases and decreases linearly on respective state, the converter must operate in Continuous Conduction Mode (CCM). CCM means the current flows in inductors remains positive for the entire ON-and-OFF states. Fig. 4 shows the waveform of i_{L1} and i_{L2} in CCM mode. To achieve this, the inductor L_1 and L_2 must be selected appropriately. According to [3], the formula for selection the inductor values are:

$$L_1 > \frac{(1-D)^2 R}{2Df}\left(1+\frac{r_{L2}}{R}+\frac{r_{C1}D}{R(1-D)}\right)$$

$$L_2 > \frac{(1-D)R}{2f}\left(1+\frac{r_{L2}}{R}\right)$$

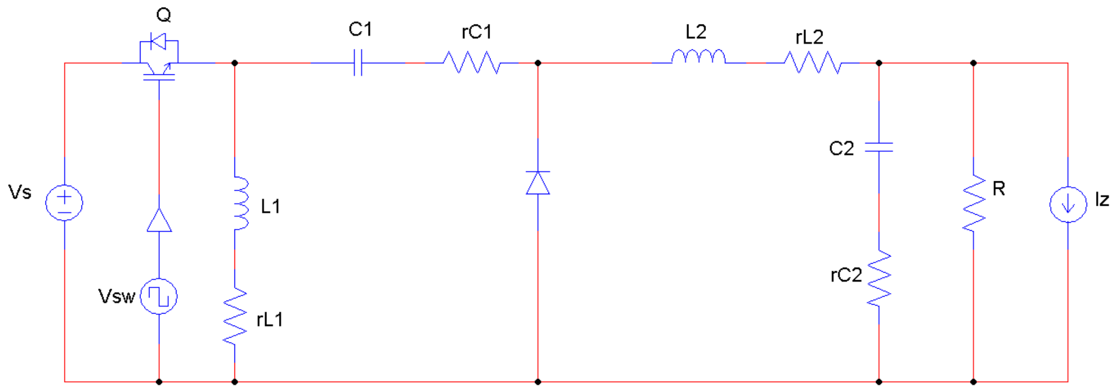

Fig. 1. Dynamic model of zeta converter

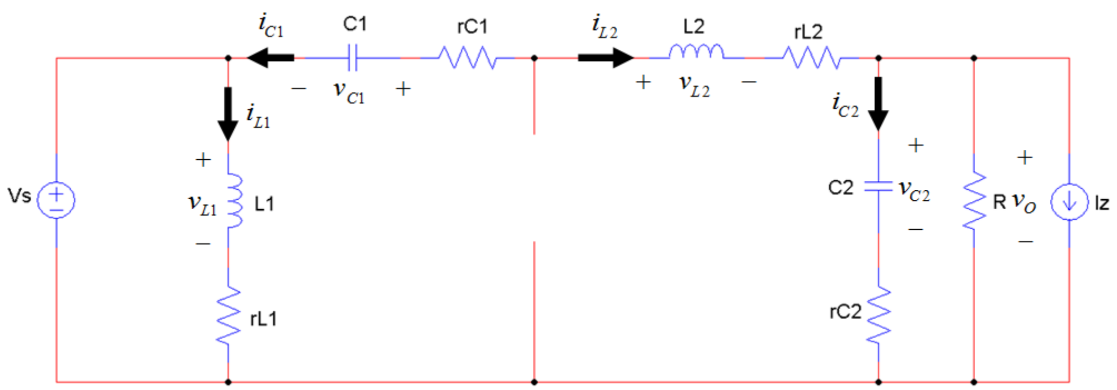

Fig. 2. Equivalent zeta converter circuit when Q turns on

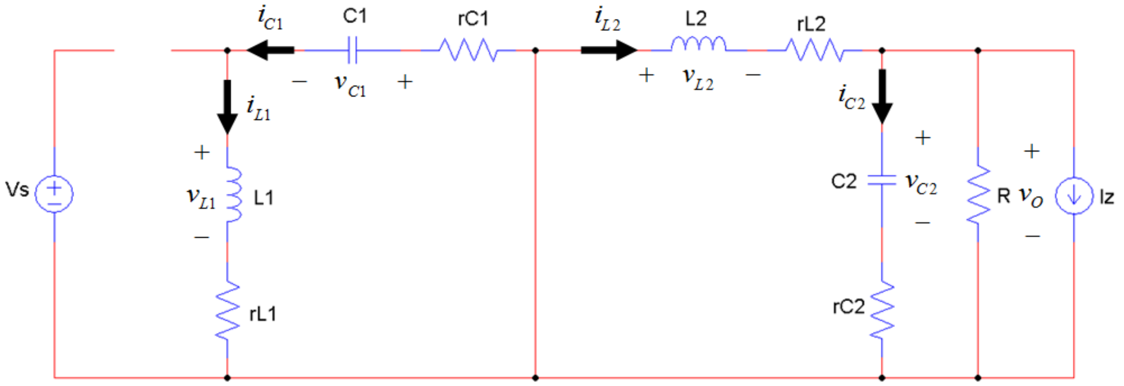

Fig. 3. Equivalent zeta converter circuit when *Q* turns off

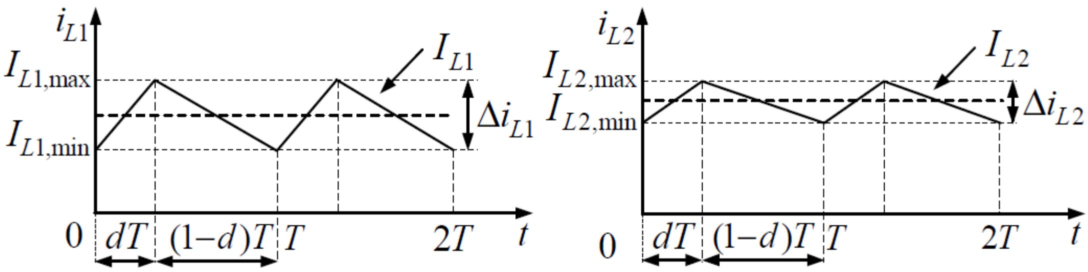

Fig. 4. i_{L1} (left) and i_{L2} (right) waveform in CCM [3]

2.2.1 State-space Description of Zeta Converter

ON-state (Q turns on)

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{r_{L1}}{L_1} & 0 & 0 & 0 \\ 0 & -\frac{1}{L_2}\left(r_{L2}+r_{C1}+\frac{r_{C2}R}{r_{C2}+R}\right) & \frac{1}{L_2} & -\frac{R}{L_2(r_{C2}+R)} \\ 0 & -\frac{1}{C_1} & 0 & 0 \\ 0 & \frac{R}{C_2(r_{C2}+R)} & 0 & -\frac{1}{C_2(r_{C2}+R)} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & 0 \\ \frac{1}{L_2} & \frac{r_{C2}R}{L_2(r_{C2}+R)} \\ 0 & 0 \\ 0 & -\frac{R}{C_2(r_{C2}+R)} \end{bmatrix} \begin{bmatrix} v_S \\ i_Z \end{bmatrix}$$

OFF-state (Q turns off)

$$\begin{bmatrix} \frac{di_{L1}}{dt} \\ \frac{di_{L2}}{dt} \\ \frac{dv_{C1}}{dt} \\ \frac{dv_{C2}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{1}{L_1}(r_{C1}+r_{L1}) & 0 & -\frac{1}{L_1} & 0 \\ 0 & -\frac{1}{L_2}\left(r_{L2}+\frac{r_{C2}R}{r_{C2}+R}\right) & 0 & -\frac{R}{L_2(r_{C2}+R)} \\ \frac{1}{C_1} & 0 & 0 & 0 \\ 0 & \frac{R}{C_2(r_{C2}+R)} & 0 & -\frac{1}{C_2(r_{C2}+R)} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & 0 \\ \frac{1}{L_2} & \frac{r_{C2}R}{L_2(r_{C2}+R)} \\ 0 & 0 \\ 0 & -\frac{R}{C_2(r_{C2}+R)} \end{bmatrix} \begin{bmatrix} v_S \\ i_Z \end{bmatrix}$$

Output voltage equation for both states:

$$v_O = \begin{bmatrix} 0 & \frac{r_{C2}R}{r_{C2}+R} & 0 & \frac{R}{r_{C2}+R} \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} 0 & -\frac{r_{C2}R}{r_{C2}+R} \end{bmatrix} \begin{bmatrix} v_S \\ i_Z \end{bmatrix}$$

The weighted average matrices for ON-state and OFF-state are:

$$A = \begin{bmatrix} -\frac{r_{C1}(1-D)+r_{L1}}{L_1} & 0 & -\frac{1-D}{L_1} & 0 \\ 0 & -\frac{(r_{C2}+R)(r_{L2}+Dr_{C1})+r_{C2}R}{L_2(r_{C2}+R)} & \frac{D}{L_2} & -\frac{R}{L_2(r_{C2}+R)} \\ \frac{1-D}{C_1} & -\frac{D}{C_1} & 0 & 0 \\ 0 & \frac{R}{C_2(r_{C2}+R)} & 0 & -\frac{1}{C_2(r_{C2}+R)} \end{bmatrix}$$

$$B = \begin{bmatrix} \frac{D}{L_1} & 0 \\ \frac{D}{L_2} & \frac{r_{C2}R}{L_2(r_{C2}+R)} \\ 0 & 0 \\ 0 & -\frac{R}{C_2(r_{C2}+R)} \end{bmatrix} \qquad C = \begin{bmatrix} 0 & \frac{r_{C2}R}{r_{C2}+R} & 0 & \frac{R}{r_{C2}+R} \end{bmatrix} \quad E = \begin{bmatrix} 0 & -\frac{r_{C2}R}{r_{C2}+R} \end{bmatrix}$$

2.2.2 Zeta Converter Steady-state

U is consisted of two input variables which are V_S and I_Z. However, for the steady-state output equation, the goal is to find the relationship between output and input voltage. Thus only variable V_S is used for the derivation. However for I_Z multiplication, matrices B and E are included. For this reason, B and E matrices need to be separated into two matrices; B_S, E_S (for input variable V_S) and B_Z, E_Z (for input variable I_Z) which are presented as follow:

$$B = \begin{bmatrix} B_S & B_Z \end{bmatrix} = \begin{bmatrix} \frac{D}{L_1} & 0 \\ \frac{D}{L_2} & \frac{r_{C2}R}{L_2(r_{C2}+R)} \\ 0 & 0 \\ 0 & -\frac{R}{C_2(r_{C2}+R)} \end{bmatrix}$$

$$E = \begin{bmatrix} E_S & E_Z \end{bmatrix} = \begin{bmatrix} 0 & -\frac{r_{C2}R}{r_{C2}+R} \end{bmatrix}$$

To get an equation that relates the output and input voltage, the above equation (7) needs to be modified by replacing U=V_S, B=B_S and E=E_S=0:

$$V_O = -CA^{-1}B_S V_S$$

or in circuit parameters form [1]:

$$V_O = V_S\left(\frac{D}{1-D}\right)\left(\frac{1}{1+\frac{r_{L2}}{R}+\frac{r_{C1}}{R}\left(\frac{D}{1-D}\right)+\frac{r_{L1}}{R}\left(\frac{D}{1-D}\right)^2}\right)$$

2.2.3 Zeta Converter Small-signal

Equation (6) is substituted into (9), thus the small signal state-space equation can be written as:

$$\tilde{x}' = A\tilde{x} + B\tilde{u} + \left[-(A_1 - A_2)A^{-1}BU + (B_1 - B_2)U\right]\tilde{d}$$

or

$$\tilde{x}' = A\tilde{x} + B\tilde{u} + B_d\tilde{d}$$

where,

$$B_d = -(A_1 - A_2)A^{-1}BU + (B_1 - B_2)U$$

in circuit parameters form [4]:

$$B_d = \frac{1}{R(1-D)^2\left[1 + \frac{r_{L2}}{R} + \frac{r_{C1}}{R}\left(\frac{D}{1-D}\right) + \frac{r_{L1}}{R}\left(\frac{D}{1-D}\right)^2\right]}\begin{bmatrix} \frac{1}{L_1}\left[((1-D)(R+r_{L2}) + Dr_{C1})V_S - Dr_{L1}RI_Z\right] \\ \frac{1}{L_1}\left[(1-D)(R+r_{L2})V_S - (r_{C1}(1-D) + Dr_{L1})RI_Z\right] \\ -\frac{1}{C_1}\left[DV_S + R(1-D)I_Z\right] \\ 0 \end{bmatrix}$$

Equation (10) is recalled, the small signal output equation is written as

$$\tilde{v}_O = C\tilde{x} + E\tilde{u} + \left[(C_1 - C_2)X + (E_1 - E_2)U\right]\tilde{d}$$

Since $C_1 = C_2$ and $E_1 = E_2$, the equation above is simplified as:

$$\tilde{v}_O = C\tilde{x} + E\tilde{u}$$

3. Control of Zeta Converter Using Full-state Feedback Controller (FSFBC) and Observer (FSO)

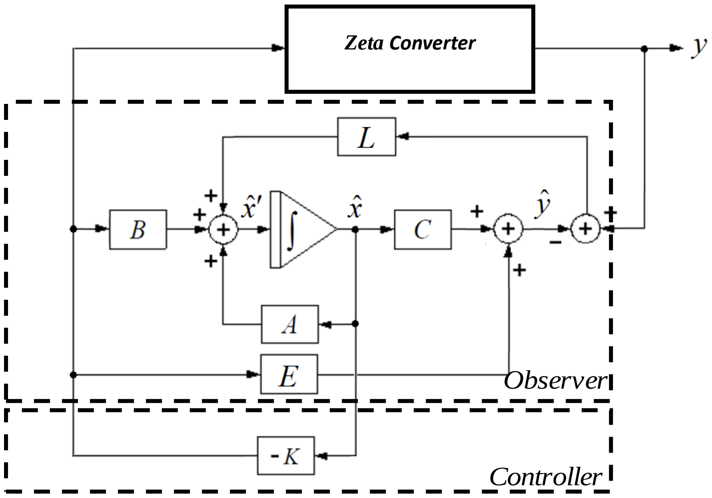

Fig. 5. An estimated full-state feedback controller

3.1 FSFBC Based on Pole Placement Technique

Desired poles must be placed further to the left handside (on s-plane) of the system's dominant poles location to improve the system steady-state error response. A good rule of thumb is that the desired poles are placed five to ten times further than the system's dominant poles location [5]. For the full-state feedback controller, the closed-loop characteristic equation can be determined by:

$$\left|\lambda I-(A-BK)\right|=0$$

3.2 FSFBC Based on Optimal Control Technique

To optimally control the control effort within performance specifications, a compensator is sought to provide a control effort for input that minimizes a cost function:

$$J = \int_0^\infty \left(x^T Q x + u^T R u\right) dt$$

This is known as the linear quadratic regulator (LQR) problem. The weight matrix Q is an n x n positive semi-definite matrix (for a system with n states) that penalizes variation of the state from the desired state. The weight matrix R is an m x m positive definite matrix that penalizes control effort [3].

To solve the optimization problem over a finite time interval, the algebraic Ricatti equation is the most commonly used:

$$PA + A^T P - PBR^{-1} B^T P + Q = 0$$

$$K = R^{-1} B^T P$$

where P is symmetric, positive definite matrix and K is the optimal gain matrix that is used in full-state feedback controller. Since the weight matrices Q and R are both included in the summation term within the cost function, it is really the relative size of the weights within each quadratic form which are important [6].

3.3 FSO State Estimation

The output of the estimator $\hat{y}$ can be compared to the output of the system, and any difference between them can be multiplied with an observer gain matrix L and fed back to the state estimator dynamics. Basically, the full-state observer has the form [7]:

$$\hat{x}' = A\hat{x} + Bu + Lz$$

where z is the difference between output and estimated output.

4. Simulation Model

Table I shows the parameters that are used for the zeta converter circuit. By substituting all the parameters in the state equations derived previously, the state matrices can be gathered as presented.

Table I: Zeta Converter Circuit Parameters

Circuit parameters	Values	Circuit parameters	Values
V_S	9V	Vo	24V
C_1	100uF	C_2	220uF
r_{C1}	0.8Ω	r_{C2}	0.35Ω
L_1	100uH	L_2	68uH
r_{L1}	0.034Ω	r_{L2}	0.029Ω
R	28Ω	f	100kHz

$$A = \begin{bmatrix} -2.38x10^3 & 0 & -2.55x10^3 & 0 \\ 0 & -1.43x10^4 & 1.10x10^4 & -1.45x10^4 \\ 2.55x10^3 & -7.45x10^3 & 0 & 0 \\ 0 & 4.49x10^3 & 0 & -1.60x10^2 \end{bmatrix} \quad [B_S \quad B_Z] = \begin{bmatrix} 7.45x10^3 & 0 \\ 1.2x10^4 & 5.08x10^3 \\ 0 & 0 \\ 0 & -4.49x10^3 \end{bmatrix}$$

$$C = [0 \quad 3.46x10^{-1} \quad 0 \quad 9.88x10^{-1}] \quad [E_S \quad E_Z] = [0 \quad -3.46x10^{-1}]$$

$$B_d = \begin{bmatrix} 3.50x10^5 \\ 4.75x10^5 \\ -3.36x10^4 \\ 0 \end{bmatrix}$$

$$p_{1,2} = (-7.00 \pm j9.91)x10^3 \qquad p_{3,4} = (-1.42 \pm j1.09)x10^3$$

Table II: FSFBC Gain for Various Pole Placement (Top) and Cost Function Weight (Bottom)

Pole placement	FSFBC gain, *K*			
	k_1	k_2	k_3	k_4
Poles 3x	0.42	-0.18	-0.14	3.66
Poles 5x	1.37	-0.76	-0.25	27.88
Poles 7x	1.81	-1.08	-1.82	108.67

Cost function weight	FSFBC gain, *K*			
	k_1	k_2	k_3	k_4
i_{L2}^2, v_{C2}^2	$1.14x10^{-3}$	$3.42x10^{-1}$	$2.24x10^{-2}$	$9.57x10^{-1}$
i_{L2}^2, $100v_{C2}^2$	$1.49x10^{-4}$	$5.23x10^{-1}$	$2.31x10^{-2}$	9.83
$100i_{L2}^2$, v_{C2}^2	$7.70x10^{-5}$	3.43	$2.24x10^{-2}$	$8.54x10^{-1}$

Table III: FSO Gain for Various Poles Placement

FSO gain, *L*	Poles placement		
	Poles 3x	*Poles 5x*	*Poles 7x*
l_1	$1.17x10^6$	$1.11x10^7$	$4.68x10^7$
l_2	$1.75x10^5$	$8.45x10^5$	$4.15x10^6$
l_3	$3.83x10^5$	$1.22x10^6$	$1.77x10^6$
l_4	$6.74x10^3$	$-1.71x10^5$	$-1.27x10^6$

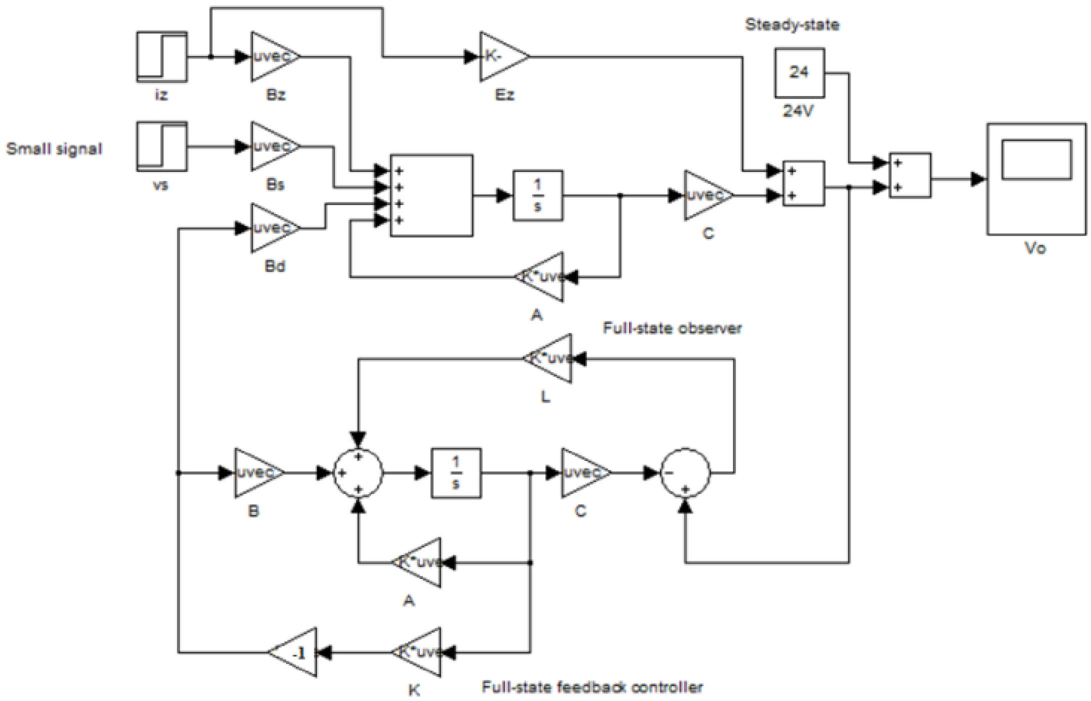

Fig. 9. Closed-loop zeta converter with full-state observer model

The eigenvalues for the zeta converter system can be calculated. *Poles 3x*, *Poles 5x* and *Poles 7x* refer to the pole location at 3 times, 5 times and 7 times further than the most dominant eigenvalues that is at $-7x10^3$ (real s-plane). FSFBC gain, *K* for various pole location and cost function weight are calculated for the closed-loop compensation and are shown in Table II. Table III on the other hand shows the FSO gain, *L* for the full-state observer. As for the Simulink model, the zeta converter open-loop with the implementation of full-state observer and controller is shown in Fig. 6.

5. Results

For the open-loop, when subjected to input voltage disturbance of $\tilde{v}_S=1V$, the output increased significantly to approximately 27V while for load current disturbance of $\tilde{i}_Z=1A$, the output decreased to about 21.6V (Fig. 10). This response to disturbance is very undesirable. To reduce the effect of the disturbances, full-state feedback controller is used. The controller is designed based on pole placement and optimal control technique. When subjected to input disturbance of $\tilde{v}_S=1V$, the response is shown in Fig. 11. In the figure, the pole location that yield the best compensation is *Poles 7x* with output voltage of 24.006V. while cost function weight i_{L2}^2, $100v_{C2}^2$ produced the best compensator with the output voltage of 24.002V for optimal control technique. On the other hand, when subjected to load current disturbance of $\tilde{i}_Z=1A$, again *Poles 7x* (23.95V) and i_{L2}^2, $100v_{C2}^2$ (23.95V) produced the best results as shown in Fig. 12. Table IV shows the summary of the voltage regulation when subjected to input voltage disturbance and/or load current disturbance for FSFSC based on pole placement and optimal control technique. It is required that the VR is $\leq \pm$ 1%. For pole placement technique, only pole location at *Poles 7x* can achieve this requirement while for optimal control technique, i_{L2}^2, $100v_{C2}^2$ can be used for the output voltage regulation requirement. Since both pole placement and optimal control technique can achieve required voltage regulation requirement, it is up to individual to choose their preference technique.

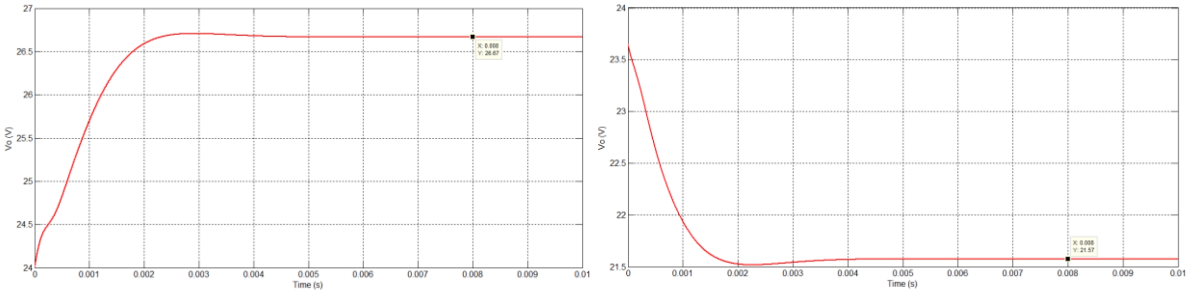

Fig. 10. Open-loop output voltage, V_O response to disturbance $\tilde{v}_S$=*1V* (left) and $\tilde{i}_Z$=*1A* (right)

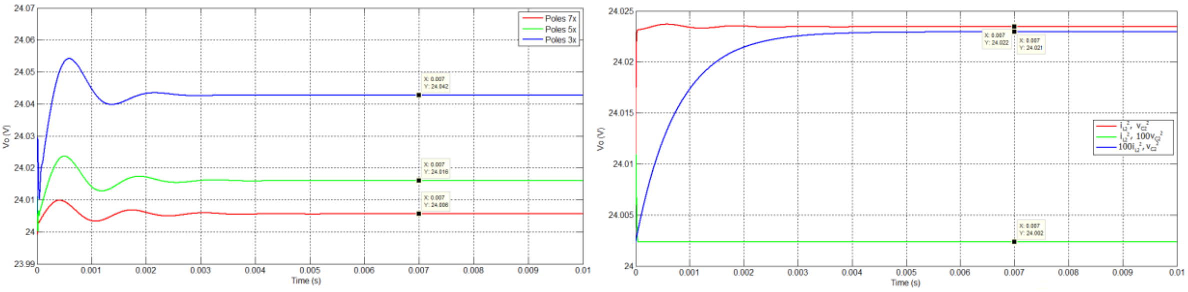

Fig. 11. Compensated output voltage, V_O response to disturbance $\tilde{v}_S$=*1V* using FSFBC based on: pole placement (left) and optimal control technique (right)

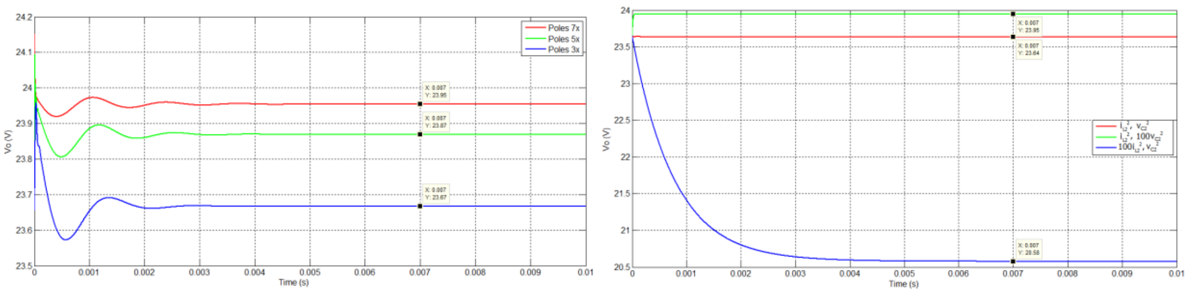

Fig. 12. Compensated output voltage, V_O response to disturbance $\tilde{i}_Z$=*1A* using FSFBC based on: pole placement technique (left) and optimal control technique (right)

Table IV: Output Voltage Regulation Using FSFBC Based On Pole Placement and Optimal Control Technique Comparison

	Pole Placement			Optimal Control		
	Poles 3x	*Poles 5x*	*Poles 7x*	i_{L2}^2, v_{C2}^2	$i_{L2}^2, 100v_{C2}^2$	$100i_{L2}^2, v_{C2}^2$
V_S = 9V ± 25%, I_Z = 0A	±0.40%	±0.15%	±0.05%	±0.22%	±0.02%	±0.22%
V_S = 9V, I_Z = 4A	-5.55%	-2.18%	-0.76%	-6.06%	-0.92%	-57.05%
V_S = 9V + 25%, I_Z = 4A	-5.15%	-2.03%	-0.71%	-5.84%	-0.89%	-56.83%
V_S = 9V - 25%, I_Z = 4A	-5.95%	-2.33%	-0.81%	-6.28%	-0.94%	-57.26%

6. Conclusions

In this paper, modeling and control of a zeta converter operating in Continuous Conduction Mode (CCM) has been presented. The state-space averaging (SSA) technique was applied to find the steady-state equations and small-signal linear dynamic model of the converter. To ensure the output voltage maintain at the desired voltage regulation requirement, full-state observer and controller are used as the controller. To compensate the output voltage from the input voltage and load current disturbances, feedback controller gain for *Poles 7x* and (i_{L2}^2, $100v_{C2}^2$) is proven to produce the best compensated output voltage for FSFBC based on pole placement and optimal control technique, respectively.

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