Adaptive Passivity-Based Control of Extended-Period Quasi-Resonant Converters

H. F. Ho and K. W. E. Cheng

***Abstract*-- An adaptive passivity based control scheme is proposed for the stabilization of average model of extended-period quasi-resonant (EPQRC) power converter. The output load of the converter is assumed constant but unknown. A generalized state space average model of a buck-type series-mode extended-period quasi-resonant converter (SM-EPQRC) is derived. The adaptive controller is designed based on the derived model and the passivity–based control (PBC) technique. Simulation results are presented to illustrate the features of the proposed controller.**

***Index Terms*-- DC-DC power converter, modeling, adaptive control**

I. Introduction

Quasi-resonant power converters are derived from pulse-width modulation (PWM) dc-dc converters by replacing the switching device with a resonant switch [1]. The resonant switch which is a combination of inductor and capacitor to shape the switching device's current and/or voltage wave-shapes quasi-sinusoidal. Zero-current or zero-voltage conditions are created for the switching device operate at very low switching losses. Despite of the success to reduce switching losses, the control scheme of quasi-resonant converters (QRC) suffered from a complicated frequency-control by varying the switching frequency in order to achieve voltage regulation. Therefore, quasi-resonant converters (QRC) operating at constant switching frequency have been proposed [2-6]. By adding an extended period switch, soft-switching and duty-cycle control are proposed in [4-6]. The extended period circuit is added in a quasi-resonant converter, either in a series configuration with the resonant switch, or in a parallel configuration with the resonant switch. These soft-switching converters are especially useful in the application of high efficiency and high frequency power converter systems.

Recently, the feedback control of the buck and boost type QRC have been studied [7-9], [11]. The controller design are based on the average model of the QRC derived from generalized state space averaging (GSSA) technique [10]. Based on the derived model, a passivity-based control scheme is proposed to the stabilization of the buck and boost QRC. In this paper, the development of an adaptive passivity-based control for the stabilization of the SM-EPQRC is presented. In this work, the output load resistance of the converter is assumed constant but unknown. The controller design is carried out using the derived generalized state space average model of the SM-EPQRC and follows the ideas of passivity-based approach reported in [8-9],[12]. The average model is derived using the classical Euler–Lagrange (EL) equations together with the generalized state space averaging (GSSA) technique. The EL parameters and the corresponding differential equations for each of the six operation stages of the buck-type SM-EPQRC in a switching cycle are first found. The GSSA technique is then applied to the six sets of differential equations to obtain the GSSA equation of the buck-type SM-EPQRC. It is proved that the closed-loop system is stable in the sense of Lyapunov approach and the converter voltage output can track the desired reference value with unknown load.

This paper is organized as follows. Formulation of a buck-type SM-EPQRC average model is presented in Section 2. The designed in passivity-based adaptive control is included in Section 3. Simulation results for the proposed control scheme are included in Section 4. Finally, the paper is concluded in Section 5.

II. Average Modeling Of Buck Type SM-EPQRC

In this section, the derivation of the mathematical model of the buck-type SM-EPQRC using the GSSA technique and the EL modeling approach is presented.

A. *Generalized State-Space Averaging Technique [10]*

Consider a periodically switched network with m different switched modes in each switching cycle. The state equation in each operation mode is described by

$$\dot{x}(t) = A_i x(t) + B_i(t), \qquad i = 1,2,\cdots,m \qquad (1)$$

where $x \in R^p$ is the state vector of the system, $A_i \in R^{p\times p}$ is the state matrix, $B_i \in R^q$ is the input control variable functions. The ith equation of (1) is defined on the time interv $\varsigma_i = [t_{i-1}, t_i]$, where $t_{i-1} = t_0 + \sum_{j=1}^{i-1} \tau_j$ and $t_i = t_{i-1} + \tau_i$. It is assumed that $\tau_j > 0$ and $j = 1,2,\cdots,k$ are fixed. The initial time $t_0 \geq 0$ is a given time, $T = \sum_{j=1}^{m} \tau_j$ denotes the switching period, and $f_s = 1/T$ is the switching frequency.

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Let f_o denote the highest natural frequency of state matrix A_i. If the input control variable functions B_i are bounded and $f_s >> f_o$, then by defining $\tau_i = d_i T$, the periodically switched network of (1) can be characterized by the following GSSA equation:

$$\dot{x} = \left(\sum_{i=1}^{m} d_i A_i \right) x + \frac{1}{T} \sum_{i=1}^{m} \int_{t_{i-1}}^{t} B_i(\lambda) d\lambda \qquad (2)$$

Next, the Lagrangian dynamics formulations of the circuits associate with the six operation of the buck-type SM-EPQRC are presented.

B. Euler-Lagrange Equations

The EL dynamics of an electrical circuit without any magnetic couplings between its different branches is given by the following set of nonlinear differential equations [12]:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}} \right) - \frac{\partial L}{\partial q} = -\frac{\partial D}{\partial \dot{q}} + F_q \qquad (3)$$

where $q \in R^n$ is the vector of electric charges and $\dot{q} \in R^n$ represents the vector of flowing currents. The vector of electric charges and flowing currents constitutes the generalized coordinates describing the circuit. D is the Rayleigh dissipation cofunction of the system and F_q represents the components of the set of the generalized forcing functions, or voltage sources, associated with the generalized coordinates. The Lagrangian L of the system is defined as

$$L(\dot{q}, q) = T(\dot{q}, q) - V(q) \qquad (4)$$

where $T(\dot{q}, q)$ is the magnetic co-energy and $V(q)$ is the electric field energy of the circuit.

C. A Lagrangian Approach to Modeling the SM-EPQRC Buck Converter

Consider the buck-type SM-EPQRC in Fig.1, two different kinds of energy storage elements are presents. The two energy storage states are the resonant tank state and the filter state. The filter states will be considered as state variables while the variable associated with the resonant tank are considered as input control variables. This is because the state variable in resonant tank can be determined in each operation mode when the state variables associated with the low-pass filter are found.

For this converter, a complete switching cycle can be divided into six stages. It is assumed that SW_1 and SW_2 are identical switches. The six operation modes are shown in Fig. 2 [4], [6], with the following assumptions:

Assumption 1. $L_o >> L_r, C_o >> C_r$;
Assumption 2. switching frequency f_s is much higher than the natural frequency of the low-pass filter L_oC_o, thus capacitor voltage v_{Co} and inductor current i_{Lo} can be treated as constant in each switching cycle;
Assumption 3. all elements are ideal.

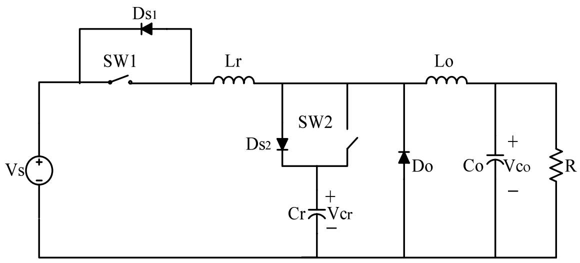


Fig. 1. The buck-type SM-EPQRC circuit.

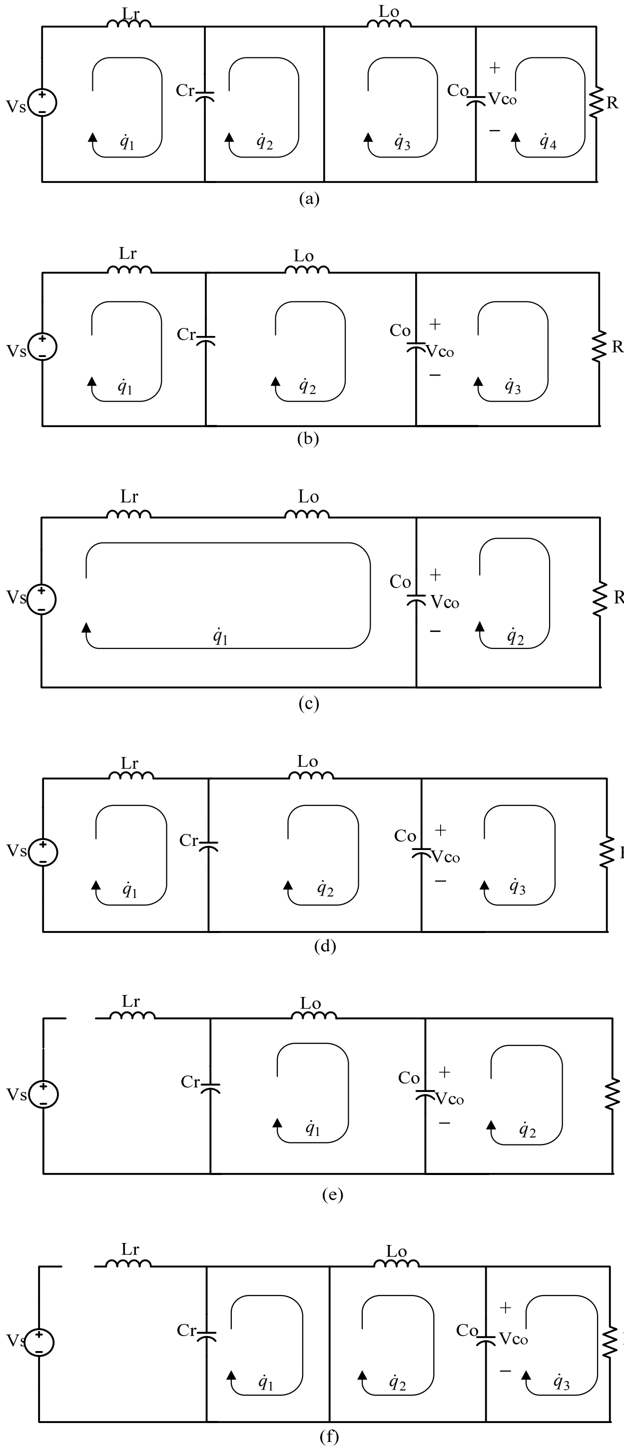


Fig. 2. Equivalent circuit of the SM-EPQRC in sex operation states.

In order to use the standard notation for EL dynamics of a electric circuit, the inductor current i_{L_o}, the resonant inductor current i_{Lr},the resonant capacitor voltage v_{Cr} and the output voltage v_{Co} are rewritten as $\dot{q}_L, \dot{q}_{Lr}, q_{Cr}/C_r$ and q_{Co}/C_o, respectively. The Lagrangian dynamics formulations of the six circuits are treated separately. In each stage, The EL parameters and the corresponding differential equations obtained using the EL equation (1) are given. Define T_i, V_i and D_i as the magnetic co-energy, the electric field energy and Rayleigh dissipation cofunction of the circuit corresponding to the i th state, respectively. Also define, F_{iq_j} as the j th loop voltage source in a circuit and $\dot{q}_j$ as the j th loop current. The formulations are as follows.

1) Linear Stage [Fig.2(a)]: The EL parameters for this stage are formed by

$$T_1 = \frac{1}{2}L_r\dot{q}_1^2 + \frac{1}{2}L_o\dot{q}_3^2$$

$$V_1 = \frac{1}{2C_r}(q_1 - q_2)^2 + \frac{1}{2C_o}(q_3 - q_4)^2 \quad (5)$$

$$D_1 = \frac{1}{2}R\dot{q}_4^2,\ F_{1q1} = V_s\ \ F_{1q_2} = F_{1q_3} = F_{1q_4} = 0$$

Define $\dot{q}_{Lr} = \dot{q}_1$, $\dot{q}_{Lo} = \dot{q}_3$, $\dot{q}_4 = \dot{q}_{Lo} - \dot{q}_{Co}$ and according to (3), (4), the dynamics for this stage are given by the corresponding differential equations

$$\ddot{q}_{Lr} = \frac{V_s}{L_r} - \frac{q_{Cr}}{L_rC_r}, \ddot{q}_{Lo} = -\frac{q_{Co}}{L_oC_o},$$

$$\dot{q}_{Co} = -\frac{q_{Co}}{RC_o} + \dot{q}_{Lo} \quad (6)$$

and the duration is given by

$$T_{1d} = \frac{L_r\dot{q}_{Lo}}{V_s} \quad (7)$$

2) Resonant State A [Fig.2(b)]: The EL parameters for this stage are formed by

$$T_2 = \frac{1}{2}L_r\dot{q}_1^2 + \frac{1}{2}L_o\dot{q}_2^2$$

$$V_2 = \frac{1}{2C_r}(q_1 - q_2)^2 + \frac{1}{2C_o}(q_2 - q_3)^2 \quad (8)$$

$$D_2 = \frac{1}{2}R\dot{q}_3^2,\ F_{2q1} = V_s,\ F_{2q_2} = F_{2q_3} = 0$$

Define $\dot{q}_{Lr} = \dot{q}_1$, $\dot{q}_{Lo} = \dot{q}_2$, $\dot{q}_3 = \dot{q}_{Lo} - \dot{q}_{Co}$ and according to (3), (4), the dynamics for this stage are given by the corresponding differential equations

$$\ddot{q}_{Lr} = -\frac{q_{Cr}}{L_rC_r} + \frac{V_s}{L_r}, \ddot{q}_{Lo} = \frac{q_{Cr}}{L_oC_r} - \frac{q_{Co}}{L_oC_o},$$

$$\dot{q}_{Co} = -\frac{q_{Co}}{RC_o} + \dot{q}_{Lo} \quad (9)$$

where

$$V_{Cr} = V_s(1 - \cos\omega_n t),\ \omega_n = \frac{1}{\sqrt{L_rC_r}},\ Z_n = \sqrt{\frac{L_r}{C_r}} \quad (10)$$

and the duration is given by

$$T_{2d} = \frac{\pi}{\omega_n} \quad (11)$$

3) Extended Period State [Fig.2(c)]: The EL parameters for this stage are formed by

$$T_3 = \frac{1}{2}L_r\dot{q}_1^2 + \frac{1}{2}L_o\dot{q}_1^2$$

$$V_3 = \frac{1}{2C_o}(q_1 - q_2)^2 \quad (12)$$

$$D_3 = \frac{1}{2}R\dot{q}_2^2, F_{3q1} = V_s,\ F_{3q2} = 0$$

Define $\dot{q}_{Lr} = \dot{q}_{Lo} = \dot{q}_1$, $\dot{q}_2 = \dot{q}_{Lo} - \dot{q}_{Co}$ and from assumption $L_o >> L_r$ so that $L_o + L_r \approx L_o$,according to (3), (4), the dynamics for this stage are given by the corresponding differential equations

$$\ddot{q}_{Lo} = \frac{V_s}{L_o} - \frac{q_{Co}}{L_oC_o}, \dot{q}_{Co} = -\frac{q_{Co}}{RC_o} + \dot{q}_{Lo} \quad (13)$$

and the duration is given by

$$T_{3d} = \mu T \quad (14)$$

where T_{3d} is the extended period, μ is the duty ratio and $T = 1/f_s$ is the switching period.

4) Resonant State B [Fig.2(d)]: The EL parameters for this stage are formed by

$$T_4 = \frac{1}{2}L_r\dot{q}_1^2 + \frac{1}{2}L_o\dot{q}_2^2$$

$$V_4 = \frac{1}{2C_r}(q_1 - q_2)^2 + \frac{1}{2C_o}(q_2 - q_3)^2 \quad (15)$$

$$D_4 = \frac{1}{2}R\dot{q}_3^2,\ F_{4q1} = V_s,\ F_{4q_2} = F_{4q_3} = 0$$

Define $\dot{q}_{Lr} = \dot{q}_1$, $\dot{q}_{Lo} = \dot{q}_2$, $\dot{q}_3 = \dot{q}_{Lo} - \dot{q}_{Co}$ and according to (3), (4), the dynamics for this stage are given by the corresponding differential equations

$$\ddot{q}_{Lr} = -\frac{q_{Cr}}{L_rC_r} + \frac{V_s}{L_r}, \ddot{q}_{Lo} = \frac{q_{Cr}}{L_oC_r} - \frac{q_{Co}}{L_oC_o},$$

$$\dot{q}_{Co} = -\frac{q_{Co}}{RC_o} + \dot{q}_{Lo} \quad (16)$$

where

$$V_{Cr} = V_s(1 + \cos\omega_n t) \quad (17)$$

and the duration is given by

$$T_{4d} = \frac{\alpha}{\omega_n} - \frac{\pi}{\omega_n} \quad (18)$$

where

$$\alpha = 2\pi - \sin^{-1}(Z_n\dot{q}_{Lo}/V_s) \quad (19)$$

5) Recovering State [Fig.2(e)]: The EL parameters for this stage are formed by

$$T_5 = \frac{1}{2}L_o\dot{q}_1^2$$

$$V_5 = \frac{1}{2C_r}q_1^2 + \frac{1}{2C_o}(q_1 - q_2)^2 \quad (20)$$

$$D_5 = \frac{1}{2}R\dot{q}_2^2,\ F_{5q_1} = F_{5q_2} = 0$$

Define $\dot{q}_{Lo} = \dot{q}_1$, $\dot{q}_2 = \dot{q}_{Lo} - \dot{q}_{Co}$ and according to (3), (4), the dynamics for this stage are given by the corresponding differential equations

$$\ddot{q}_{Lo} = \frac{q_1}{L_oC_r} - \frac{q_{Co}}{L_oC_o},\ \dot{q}_{Co} = -\frac{q_{Co}}{RC_o} + \dot{q}_{Lo} \quad (21)$$

where

$$V_{Cr} = -\frac{\dot{q}_{Lo}}{C_r}t + V_s(1-\cos\alpha) \quad (22)$$

and the duration is given by

$$T_{5d} = \frac{V_s}{\omega_n Z_n \dot{q}_{Lo}}(1-\cos\alpha) \quad (23)$$

6) Free-Wheeling State [Fig.2(f)]: The EL parameters for this stage are formed by

$$T_6 = \frac{1}{2}L_o\dot{q}_2^2$$

$$V_6 = \frac{1}{2C_r}q_1^2 + \frac{1}{2C_o}(q_2 - q_3)^2 \quad (24)$$

$$D_6 = \frac{1}{2}R\dot{q}_3^2,\ F_{6q_1} = F_{6q_2} = F_{6q_3} = 0$$

Define $\dot{q}_{Lo} = \dot{q}_2$, $\dot{q}_3 = \dot{q}_{Lo} - \dot{q}_{Co}$ and according to (3), (4), the dynamics for this stage are given by the corresponding differential equations

$$\ddot{q}_{Lo} = -\frac{q_{Co}}{L_oC_o},\ \dot{q}_{Co} = -\frac{q_{Co}}{RC_o} + \dot{q}_{Lo} \quad (25)$$

The duration of this state is given by

$$T_{6d} = T_s - T_{1d} - T_{2d} - T_{3d} - T_{4d} - T_{5d} \quad (26)$$

The differential equations of the six operation modes given by (6), (9), (13), (16), (21) and (25) can be written in the following form:

$$\dot{x}(t) = A_i x(t) + B_i(t), \qquad i = 1,2\cdots,6 \quad (27)$$

where

$$x = [\dot{q}_{Lo} \quad q_{Co}]^T,\ \dot{x} = [\ddot{q}_{Lo} \quad \dot{q}_{Co}]^T$$

$$A_1 = A_2 = A_3 = A_4 = A_5 = A_6 = \begin{bmatrix} 0 & -1/L_oC_o \\ 1 & -1/RC_o \end{bmatrix}$$

$$B_1 = B_6 = \begin{bmatrix} 0 \\ 0 \end{bmatrix},$$

$$B_3 = \begin{bmatrix} v_s/L_o \\ 0 \end{bmatrix}, B_2 = B_4 = B_5 = \begin{bmatrix} v_{Cr}/L_o \\ 0 \end{bmatrix} \quad (28)$$

The GSSA equation of the buck-type EP-ZCQRC can be obtained using (2). Define $z_1 = \dot{q}_{Lo}$, $z_2 = q_{Co}/C_o$ where z_1 and z_2 are the average inductor current and average output voltage, respectively. Hence, the GSSA equation of the buck-type SM-EPQRC is given by

$$\dot{z}_1 = -\frac{z_2}{L_o} + \frac{V_s}{L_o}\left[\mu(t) + \frac{k}{2\pi}\Psi(V_s, z_1)\right]$$
$$\dot{z}_2 = -\frac{z_2}{RC_o} + \frac{z_1}{C_o} \quad (29)$$

where

$$k = f_s / f_n,\ \Psi(V_s, z_1) = \alpha + \frac{Z_n z_1}{2V_s} + \frac{V_s(1-\cos\alpha)}{Z_n z_1} \quad (30)$$

From the GSSA equation (29), we can get its GSSA equivalent circuit model as show in Fig. 3 with

$$V_g = V_s \cdot \Theta(\mu, z_1) \quad (31)$$

It is noted that the voltage conversion ratio of (29) which is the same as that given in [4], [6] and the constant equilibrium values z_1 and z_2 for a constant duty ratio $\mu = U$ are given by

$$z_1 = I_d = \frac{V_d}{R}, z_2 = V_d = V_s(U + \frac{k}{2\pi}\Psi(V_s, z_1)) \quad (32)$$

where V_d and I_d are the desired constant values of the output voltage V_{Co} and the output current i_{Lo}, respectively. For the buck-type SM-EPQRC under consideration, it is assumed that the resistive load is unknown but constant. The control objective is to find an adaptive feedback controller for stabilization the output voltage towards the desired value V_d.

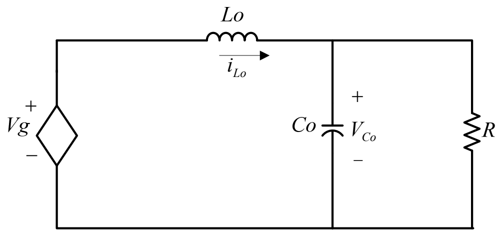


Fig. 3. GSSA equivalent circuit of the buck-type SM-EPQRC.

III. Passivity-Based Adaptive Controller For The Average Model Of SM-EPQRC

In this section, the design of the passivity-based adaptive controller for the SM-EPQRC is presented. It is assumed that the resistive load $R > 0$ is unknown but constant. The passivity-based adaptive scheme for achieving output regulation is described in the following proposition.

Proposition: Consider the GSSA model of the buck type SM-EPQRC (29), the adaptive feedback controller and the parameter adaptation law described by (33) and (34)

$$\mu = \frac{1}{V_g}\left[L_o\hat{\theta}V_d + V_d - R_1(z_1 - \hat{\theta}V_d) - \frac{V_s k}{2\pi}\Psi\right] \quad (33)$$

$$\dot{\hat{\theta}} = -\gamma(z_2 - V_d)V_d \quad (34)$$

where $\hat{\theta}$ denote the estimate of $1/R$ and the parameter R_1 and the adaptation gain γ are user-specified positive constants. The adaptive controller initial condition is chosen so that $\hat{\theta}(0) > 0$. Under these conditions, the closed-loop system (29) and (34) has an asymptotically stable equilibrium point given by

$$(z_1, z_2, \hat{\theta}) = (V_d / R, V_d, 1/R) \tag{35}$$

Proof: Define the resistive load parameter of the circuit as

$$\theta = 1/R \tag{36}$$

Define the state vector $z = [z_1\ z_2]^T$, (29) can be compactly written as:

$$\mathbf{D}\dot{z} + \mathbf{J}z + \mathbf{R}z = \Theta(\mu, z_1)\mathbf{E} \tag{37}$$

where

$$\mathbf{D} = \begin{bmatrix} L_o & 0 \\ 0 & C_o \end{bmatrix}, \mathbf{J} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \mathbf{R} = \begin{bmatrix} 0 & 0 \\ 0 & \theta \end{bmatrix},$$

$$\mathbf{E} = \begin{bmatrix} V_s \\ 0 \end{bmatrix} \tag{38}$$

$$\Theta(\mu, z_1) = \mu(t) + \frac{k}{2\pi}\Psi \tag{39}$$

In this output regulation scheme, the average output voltage z_2 is directly regulated to a desired constant voltage value $V_d > 0$. Since $1/R$ is unknown, define z_{1d} to be

$$z_{1d} = \hat{\theta}V_d \tag{40}$$

Thus

$$\dot{z}_{1d} = \dot{\hat{\theta}}V_d \tag{41}$$

and the output voltage is to be directly regulated to a desired constant value V_d

$$z_{2d} = V_d \tag{42}$$

Denote $e = z - z_d$ is a average state error vector and $z_d = [z_{1d}\ z_{2d}]^T$ is a desired value vector. (37) can be rewritten as

$$\mathbf{D}\dot{e} + \mathbf{J}e + \mathbf{R}e = \Theta\mathbf{E} - (\mathbf{D}\dot{z}_d + \mathbf{J}z_d + \mathbf{R}z_d) \tag{43}$$

To ensure asymptotic stability, a damping injection is performed on (43) by adding the desired error dissipation term

$$\mathbf{R_d}e = (\mathbf{R} + \mathbf{R_1})e \tag{44}$$

where

$$\mathbf{R_d} = \begin{bmatrix} R_1 & 0 \\ 0 & \theta \end{bmatrix}, \ \mathbf{R_1} = \begin{bmatrix} R_1 & 0 \\ 0 & 0 \end{bmatrix}, \ R_1 > 0 \tag{45}$$

Adding to both sides of (43), then rewrite (43) as

$$\mathbf{D}\dot{e} + \mathbf{J}e + \mathbf{R_d}e = \psi \tag{46}$$

where

$$\psi = \Theta\mathbf{E} - (\mathbf{D}\dot{z}_d + \mathbf{J}z_d + \mathbf{R}z_d - \mathbf{R_1}e) \tag{47}$$

Equation (47) can be written as

$$\begin{aligned} L_o\dot{z}_{1d} + z_{2d} - R_1(z_1 - z_{1d}) &= E(\mu(t) + \frac{k}{2\pi}\Psi) - \psi_1 \\ C_o\dot{z}_{2d} - z_{1d} + \theta z_{2d} &= -\psi_2 \end{aligned} \tag{48}$$

Using (33) and (40) and $\tilde{\theta} = \hat{\theta} - \theta$ yields

$$\psi_1 = 0, \psi_2 = \tilde{\theta}V_d \tag{49}$$

Now, consider a Lyapunov function the total energy of the stabilization error system plus the energy associated with the parameter estimation error

$$H_d(t) = \frac{1}{2}e^T\mathbf{D}e + \frac{1}{2\gamma}\tilde{\theta}^2 \tag{50}$$

The time derivative of H_d along the error trajectory (46) is

$$\dot{H}_d(t) = -e^T\mathbf{R_d}e + e_2\psi_2 + \frac{1}{\gamma}\tilde{\theta}\dot{\tilde{\theta}} \tag{51}$$

Using (34), (49) and the fact that $\dot{\tilde{\theta}} = \dot{\hat{\theta}}$, then we have

$$\dot{H}_d(t) = -e^T R_d e \le -\alpha\|e\|^2 \tag{52}$$

where $\alpha = \min(R_1, 1/R)$ .From (52), we known that e is bounded and every term in (46) and $\tilde{\theta}$ are bounded. Thus, the asymptotic convergence of the error is guaranteed by Barbalat's lemma [13].

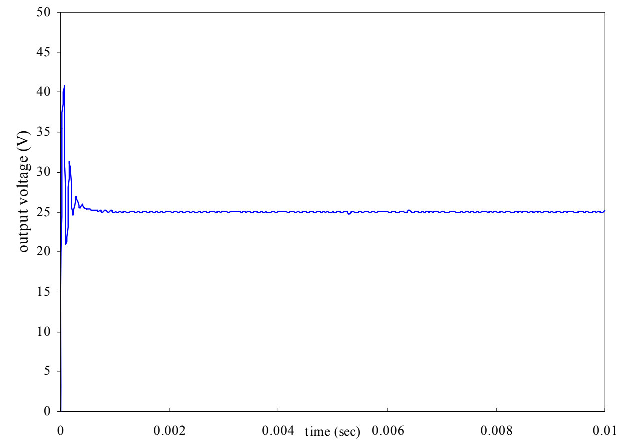
IV. Simulation Example

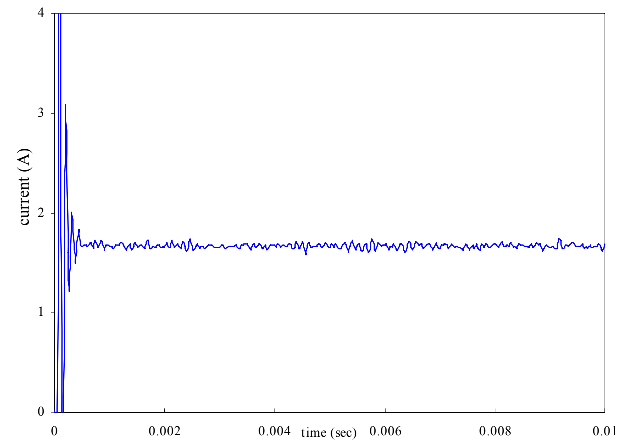
Simulation was performed on the perturbed version of the average buck-type SM-EPQRC (29), where η represents an external perturbation of the voltage source V_S. The magnitude of the perturbation was chosen to approximately $\pm 3\%$ of the value of V_s. The circuit parameter values were taken to be the following:
$L_o = 100\mu H$, $C_o = 3.3\mu F$, $R = 15\Omega$,
$C_r = 0.98\mu F$, $R_l = 0.15$, $L_r = 12.7\mu H$, $V_s = 50V$,
$k = 0.35$, $f_s = 30kHz$.

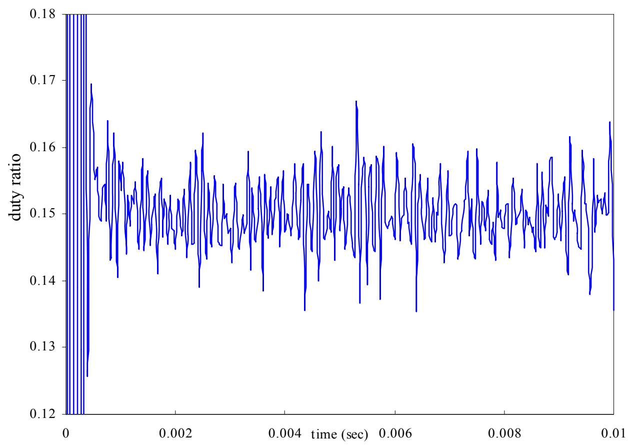
The initial value of parameter $\hat{\theta}$ was set by $\hat{\theta}(0) = 1.5$ and let the learning rate $\gamma = 60$. The desired average output voltage used was $V_d = 25V$ this corresponds to an ideal average input current $I_d = V_d / R = 1.67A$, with a steady-state duty ratio of $U = 0.149$ and the desired parameter value was $1/R = 0.067S$. Fig. 4 shows the closed-loop state trajectories of the average output voltage, the average output current, the duty ratio function, the estimate load resistance value and the magnitude of the perturbation noise. It can be seen that the passivity-based adaptive controller achieves the desired stabilization of the output voltage with unknown load and external perturbation.

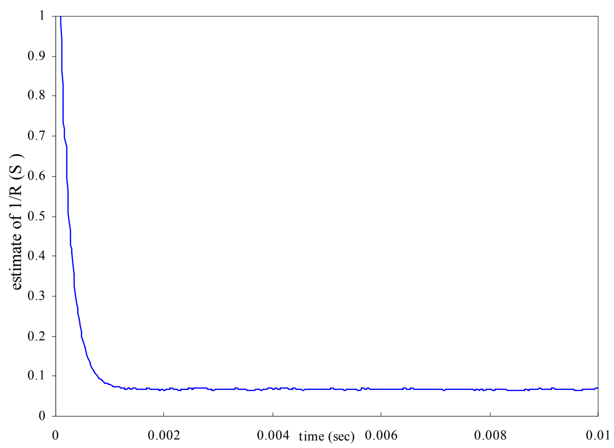
V. Conclusions

In this paper, the modeling and controller design have been proposed for the SM-EPQRC. A GSSA model based on EL system of the converter has been derived. A passivity-based adaptive voltage regulation scheme has been developed for the buck-type SM-EPQRC. Simulation has been proposed to illustrate the robust performance of the closed-loop system.









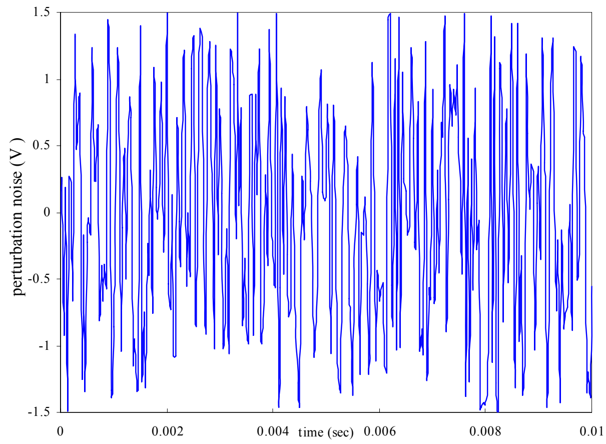


Fig. 4. Simulation results of the closed-loop performance in a buck-type SM-EPQRC.

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