Proceedings of the World Congress on Engineering and Computer Science 2008
WCECS 2008, October 22 - 24, 2008, San Francisco, USA

Passivity-based Controller Design for PWM DC/DC Buck Current Regulator

Xiuhong Guo, Quanyuan Feng, *Senior Member, IEEE*

***Abstract*—The passivity based control method is presented and applied in the design of a static and a dynamic controller for the PWM buck dc-dc current regulators on the premise that they are passive Euler-Lagrange (EL) systems. Simulations were performed for both the static and dynamic controllers in the regulation of a typical buck current regulator and the systems' start-up waveforms, line and load transient responses were analyzed. Simulation results indicate that both the static and dynamic controller achieve to regulate the output current of the regulator to the desired equilibrium value and present high robustness while sudden line and load transients occur and that the dynamic controller applied case has better overall performance with soft-start scheme to alleviate the startup overshoot problem.**

***Index Terms*—DC/DC buck current regulator, passivity based control, static and dynamic controllers, Euler-Lagrange system**

I. Introduction

Switch-Mode current regulators, as a class of switched mode DC to DC converters, are mainly used as constant current sources for LED, LED flashlights, industry lighting, ect. As newer generations, high-current (high-brightness) flash LEDs in mobile phones, for example, raising new driving capability request for these regulators, new control methods are needed to improve their performance. So far, various control techniques, either linear or nonlinear, to regulate the DC/DC converters have been proposed, such as linear design [1], [2], sliding mode control [3]–[5], current-mode-control [6], neural network control [7], adaptive control [8] and passivity-based control (PBC) [11]. Since DC to DC converters are absolutely non-linear systems, for better performance, adopting non linear control methods could be a good solution. The PBC method, an essentially nonlinear control technique, widely researched ([9]-[10]) and successfully applied in many areas has many merits (sufficiently simple in algorithm yet quite robust) in comparison with other nonlinear control methods.

The objective of this paper is to introduce the average model of PWM buck DC-DC converters obtained through EL approach and in succession to present the passivity-based feedback controller design, both static and dynamic, for the PWM buck current regulators.

Manuscript received June 27, 2008.

Xiuhong Guo is with the Institute of Microelectronics, Southwest Jiao Tong University, Chengdu, China. From June, 2004 to August, 2006 she was with Ecole Centrale de Nantes, Nantes, France, where she won the national Eiffel scholarship of France. (Phone: +86-15882148164; e-mail: xguo@ hotmail.fr).

Quanyuan Feng (M'02-SM'07), was with the Southwest Research Institute of Magnetism, Mianyang, China, where he was awarded "the third class award of scientific and technologic progress of Electronic Industry Ministry" and the "National Mao Yisheng scientific and technologic award of Chinese Scientific and Technologic development foundation". Since 2002, he has been with the School of Information Science and Technology of Southwest Jiaotong University, where he won "the first class award of scientific and technologic progress of Sichuan Province". Up to the present, he has more than 100 papers published on "IEEE Transactions on Magnetics" ,"Acta Physica Sinica" , "Chinese Journal of Semiconductors", "Research & Progress of Solid State Electronics" etc, among which more than 50 were registered by SCI and EI. (email: fengquanyuan@swjtu.edu.cn).

II. BUCK CONVERTER PRESENTATION AND MODELING

Figure 1 shows the framework of PWM buck DC-DC converter circuit [1].

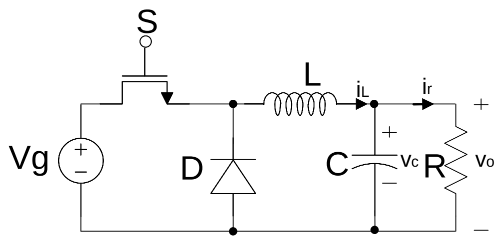


Figure 1: the framework of buck converter circuit

The derivation of passivity based control law of the buck converters is evolved on the premise that they are a class of passive EL systems. EL systems are those that can be described by the following EL equations [9]:

$$\frac{d}{dt}\left(\frac{\partial \boldsymbol{L}}{\partial \dot{\boldsymbol{q}}}(\boldsymbol{q},\dot{\boldsymbol{q}})\right)-\frac{\partial \boldsymbol{L}}{\partial \boldsymbol{q}}(\boldsymbol{q},\dot{\boldsymbol{q}})=\boldsymbol{Q} \quad (\boldsymbol{q},\boldsymbol{Q}\in \boldsymbol{R}^n) \tag{2.1}$$

where, $\boldsymbol{q}$ are generalized coordinates, then $\dot{\boldsymbol{q}}$ could be the generalized velocity, $\boldsymbol{L}(\boldsymbol{q},\dot{\boldsymbol{q}})=\boldsymbol{T}(\boldsymbol{q},\dot{\boldsymbol{q}})-\boldsymbol{V}(\boldsymbol{q})$ is the lagrangian function in which $\boldsymbol{T}(\boldsymbol{q},\dot{\boldsymbol{q}})$ is the kinetic energy function and $\boldsymbol{V}(\boldsymbol{q})$ is the potential energy function, $\boldsymbol{Q}$ are external forces that can present in three types: control input forces, dissipation forces, and disturbance forces.

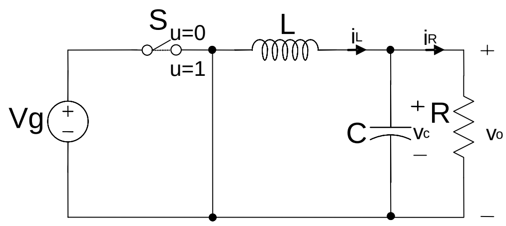


Figure 2: buck converter model

Considering the buck converter model shown in Figure 2, just as for the boost and buck-boost converters presented in [11], the electrical charges on the inductor (q_L) and on the capacitor (q_C) could be corresponded to the generalized coordinates in EL equations, consequently $\dot{q}_L$ is inductance current and $\frac{q_C}{C}$ is capacitor voltage. Under continuous conduction mode (CCM), the EL parameters associated with each one of the two possible positions of the regulating switch established, the following average system description in denoting $z_1 = \dot{q}_L$ and $z_2 = q_C / C$ can be obtained in using the classical EL equations (2.1),

$$\begin{cases} \dot{z}_1 = -\dfrac{1}{L} z_2 + \dfrac{\mu V_g}{L} \\ \dot{z}_2 = \dfrac{1}{C} z_1 - \dfrac{1}{RC} z_2 \end{cases} \tag{2.2}$$

where μ is the duty ratio function definitely lying in the closed interval [0, 1] of the real line.

In matrix notation, it is as follows：

$$\boldsymbol{D}\dot{\boldsymbol{z}} + (\boldsymbol{J} + \boldsymbol{R})\boldsymbol{z} = \mu\boldsymbol{\varepsilon} \tag{2.3}$$

where,

$$\boldsymbol{D} = \begin{bmatrix} L & 0 \\ 0 & C \end{bmatrix}; \quad \boldsymbol{J} = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}; \quad \boldsymbol{R} = \begin{bmatrix} 0 & 0 \\ 0 & 1/R \end{bmatrix}; \quad \boldsymbol{\varepsilon} = \begin{bmatrix} V_g \\ 0 \end{bmatrix} \tag{2.4}$$

III. PASSIVITY-BASE CONTROLLER DESINGN FOR PWM BUCK CURRENT REGULATOR

In this section, the design of the passivity-based feedback controllers, both static and dynamic, for the PWM buck current regulators are presented due to the minimum phase character of the buck type converters. The design process involves two steps: energy shaping and damping injection [9]. With energy shaping the potential energy function is modified in such way that a new point of equilibrium is obtained at a desired location. The damping injection modifies the Rayleigh dissipation function so that the new point of equilibrium will be globally asymptotically stable (GAS).

Suppose the desired regulator output capacitor voltage and inductor current vector is $\boldsymbol{z}_d = [z_{1d}(t), z_{2d}(t)]^T$, where $z_{1d}(t)$ and $z_{2d}(t)$ satisfy the corresponding relationships described by (2.3). Denote the average error vector $\boldsymbol{z} - \boldsymbol{z_d}$ by $\boldsymbol{e}(t)$, the average error dynamic of the buck converter described by (2.3) is,

$$\boldsymbol{D}\dot{\boldsymbol{e}}(t) + (\boldsymbol{J} + \boldsymbol{R})\boldsymbol{e}(t) = \mu\boldsymbol{\varepsilon} - [\boldsymbol{D}\dot{\boldsymbol{z}}_d(t) + (\boldsymbol{J} + \boldsymbol{R})\boldsymbol{z}_d(t)] \tag{3.1}$$

This represents the energy shaping stage of the process. The damping injection stage, as presented in [11] and [12], involves insert a term $\boldsymbol{R}_i\boldsymbol{e}(t)$ on both sides of (3.1), $\boldsymbol{R}_i$ is a matrix that assures the desired dissipation term.

$$\boldsymbol{R}_i = \begin{bmatrix} R_i & 0 \\ 0 & 0 \end{bmatrix}; \quad R_i > 0 \tag{3.2}$$

And then an average error system is obtained. Considering the average error system to be unforced, an energy storage function H_d can be defined in the coordinate $\boldsymbol{e}(t)$ for the unforced average error system, to ensure the stabilization error behavior be asymptotically stable to zero independent of the value of μ, it is demanded that

$$\mu\boldsymbol{\varepsilon} = [\boldsymbol{D}\dot{\boldsymbol{z}}_d(t) + (\boldsymbol{J} + \boldsymbol{R})\boldsymbol{z}_d(t)] - \boldsymbol{R}_i\boldsymbol{e}(t) \tag{3.3}$$

Explicitly we have:

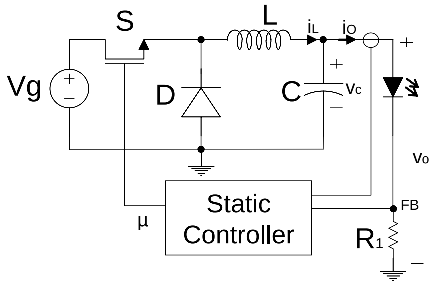
$$\begin{cases} \mu V_g = L\dot{z}_{1d} + z_{2d} - R_i(z_1 - z_{1d}) \\ 0 = C\dot{z}_{2d} - z_{1d} + \dfrac{z_{2d}}{R} \end{cases} \tag{3.4}$$

A. The Static Controller Design

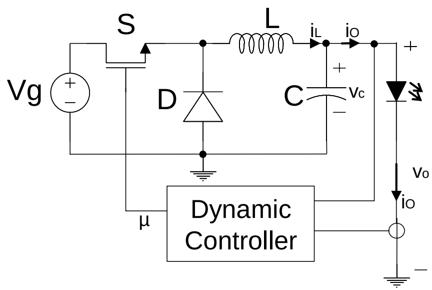
As is shown in Figure 3(a) where R_1 is a constant resistance, it concerns to regulating the output capacitor voltage at a desired equilibrium value and then transferring it into the obtaining of a desired equilibrium value V_{FBd} of the feedback voltage. Then the desired output current is determined by V_{FBd}/R_1.

Suppose the desired output capacitor voltage is $z_{2d} = V_d$, it derives from (3.4) that

$$\mu = \frac{V_d}{V_g} - \frac{R_i}{V_g}\left(z_1 - \frac{V_d}{R}\right) \tag{3.5}$$



(a)



(b)

Figure 3: the frameworks of buck current regulator circuit controlled by the static controller (a) and controlled by the dynamic controller (b)

Also,

$$\frac{z_2}{R} = \frac{v_{FB}}{R_1} \tag{3.6}$$

With the desired feedback voltage being V_{FBd}, it can be derived from (3.5) and (3.6) that

$$\mu = \frac{V_{FBd}R}{R_1 V_g} - \frac{R_i}{V_g}\left(z_1 - \frac{V_{FBd}}{R_1}\right) \tag{3.7}$$

Here the duty ratio function synthesizer is a static feedback controller.

B. The Dynamic Controller Design

As is shown in Figure 3(b), the dynamic controller attempts to directly regulate the output inductor current to the desired equilibrium value $z_{1d} = I_d$, substituting it into the first equation of (3.4), we obtain

$$z_{2d}(t) = \mu(t)V_g + R_i(z_1 - I_d) \tag{3.8}$$

Put (3.8) into the second equation of (3.4), the expression of the dynamic feedback duty ratio synthesizer turns out to be of the form,

$$\dot{\mu} = \frac{1}{RCV_g}\left[\left(I_d R - \mu V_g\right) - R_i\left(z_1 - I_d\right)\right] + \frac{R_i}{LV_g}\left(z_2 - \mu V_g\right) \quad (3.9)$$

IV. SIMULATION RESULTS

For a typical PWM buck current regulator circuit with the following circuit parameters: *V_g=12V, L=10μH, C=40μF, R=3Ω* and a switching frequency of *1.6MH,* simulations to analyze the startup characters, the line transient responses *(V_g=12V for t ∈[10us,3ms], V_g= 15V for t ∈[3.001ms, 5ms], V_g=10V for t ∈[5.001ms, 10ms])* and the load transient responses *(R=3Ω for t ∈[0, 7ms], R=1Ω for t ∈[7.001ms, 9ms], R=3Ω for t ∈[9.001ms, 10ms])* of the regulator were performed for both the static and dynamic passivity-based controller applied cases with the damping injection parameter *R_i=0.5, 2, 5.* To ensure the computed duty ratio function values not exceed the physical bounds interval [0, 1], a hard limiter was added. The desired output current was set to be *I_d=3A*. The constant resistance in the static controller was set to be *R_1=0.1Ω*. Figure 4 shows the startup characters of the regulator controlled by the static controller (dotted curves) and by the dynamic controller (solid curves). As it can be seen, when the dynamic controller applied, much higher overshoots present which may destroy the load. The startup overshoot problem, fortunately, can be alleviated in using soft-start scheme (letting the output current increase gradually to its desired equilibrium in an appropriate period, which was set to be *100μs* in the simulation), as is shown in Figure 5. Figures 6 and 7 show respectively the line transient responses and the load transient responses of the regulator in Static controller Controlled Case (SCC), Figures 8 and 9 display respectively those of the regulator in Dynamic controller Controlled Case (DCC). It can be concluded from Figures 6 to 9 that the regulator in DCC has smaller load transient overshoots but higher line transient overshoots than in SCC, however the line transient overshoots in DCC are smaller than the load transient overshoots in SCC, moreover, in DCC, the regulator responds faster to sudden line or load transients. Therefore, the performance of the regulator in DCC is better than that in SCC with soft-start scheme used to alleviate the startup overshoot problem.

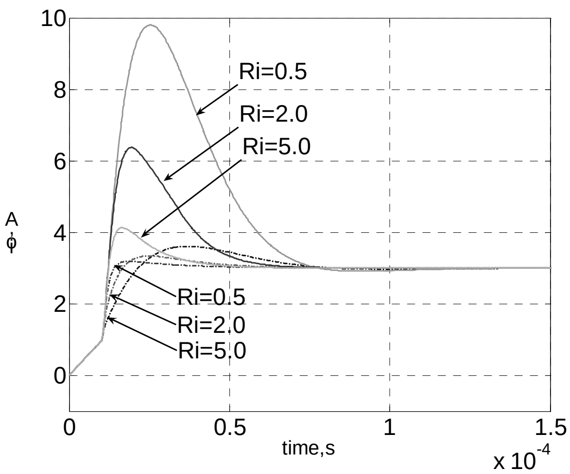


Figure 4: Startup test waveform of the regulator without soft-start

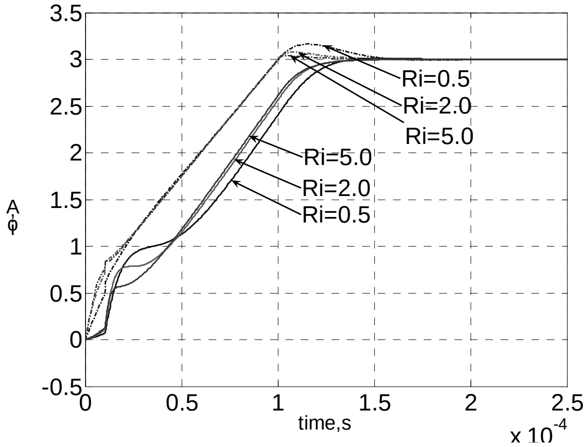


Figure 5: Startup test waveform of the regulator with soft-start

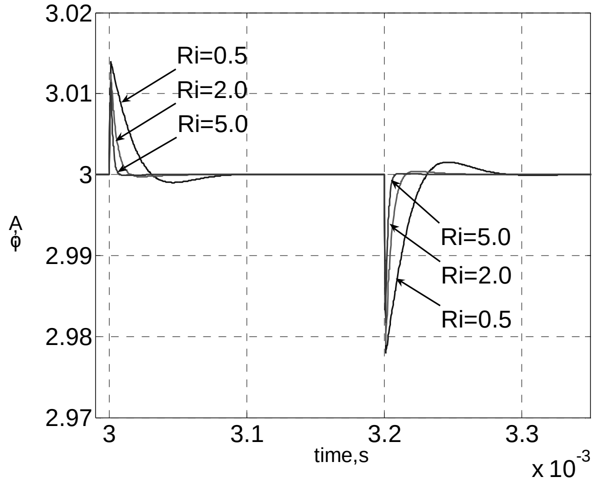


Figure 6: Line transient response of the regulator with static controller

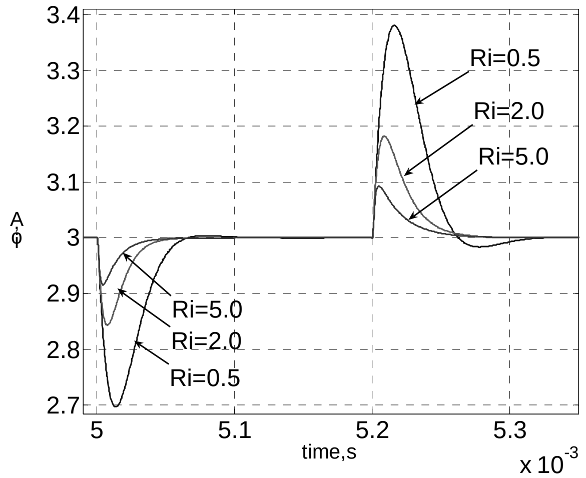


Figure 7: Load transient response of the regulator with static controller

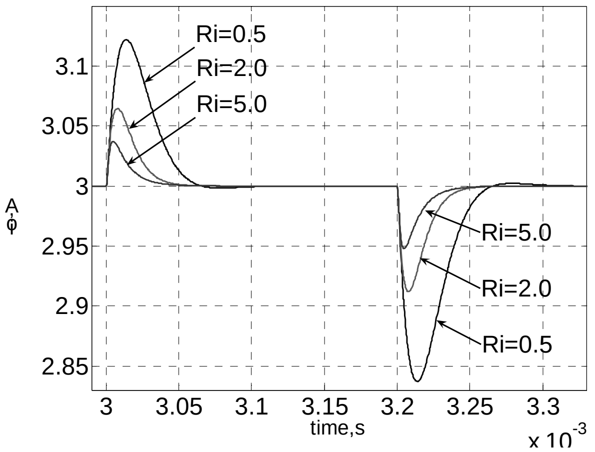


Figure 8: Line transient response of the regulator with dynamic controller

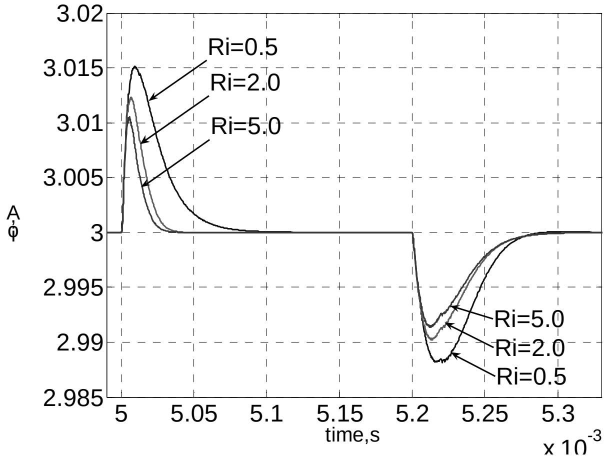


Figure 9: Load transient response of the regulator with dynamic controller

Furthermore, all the above simulation results indicate that both the static and dynamic controllers designed achieve the regulation of the output current of the power converter around the desired equilibrium value while exhibiting a high degree of robustness with respect to sudden line or load transients. The damping injection ratio affects greatly the controllers' regulation abilities, a smaller damping injection ratio results in slower line/load transient responses and higher transient overshoots of the regulator, thus appropriate damping injection should be chosen to optimize the controllers' regulation capabilities.

V. CONCLUSIONS

Passivity-based control method, an essentially non-linear control method based on the system's energy balancing properties, was applied to the buck current regulators' controller design. Both a static and a dynamic controller were obtained and simulation results for evaluating their regulation capabilities were given and analyzed in detail. And the following conclusions are drawn from the simulation results: the controllers obtained, both static and dynamic, achieve to regulate the current regulator's output current to the desired equilibrium value and the steady-state error can infinitely tends to zero, which is a merit that conventional linear control methods can't achieve; although the dynamic controller applied case present rather higher startup overshoots, this problem can be alleviated with soft-start scheme; the regulator in DCC responds faster and has smaller load transient overshoots but larger line transient overshoots than in SCC; however the line transient overshoots in DCC is smaller than the load transient overshoot in SCC; thus the regulator has better overall transient responses in DCC than in SCC with soft-start scheme used to alleviate the startup overshoot problem; appropriate damping injection should be applied to optimize the controllers' regulation capabilities and the regulator's performance because too small damping injection ratio results in slower line/load transient responses and higher transient overshoots.

ACKNOWLEDGMENT

The authors would like to express their gratitude to Xiang Qianyin and other group members of the Institute of microelectronics, Southwest Jiaotong University.

REFERENCES

[1] R.P. Severn and G.E. Bloom, "Modern DC to DC Switch Mode Power Converter Circuits", Van Nostrand-Reinhold, New York, 1982.
[2] J.G. Kassakii, M. Schlecht and G.C. Verghese, "Principles of Power Electronics", Addison-Wesley, Reading, Massachusetts, 1991.
[3] R. Venkataramanan, A. Sabanovic, S. Cuk, "Sliding Mode Control of DC-to-DC Converters," IECON Conf. Proc., 1985, pp. 251-258.
[4] H. Sira-Ramirez, "Sliding motions in bilinear switched networks", IEEE Trans. Circuits Syst., vol. CS-34, no. 8, Aug. 1987, pp. 919–933.
[5] G. Spiazzi, P. Mattavelli, L. Rossetto, L. Malesani, "Application of Sliding Mode Control to Switch-Mode Power Supplies," Journal of Circuits, Systems and Computers (JCSC), Vol. 5, No. 3, September 1995, pp.337-354.
[6] J. Alvarez-Ramirez and G. E. Perez, "Stability of current-mode control for dc–dc power converters," Syst. Contr. Lett., vol. 45, 2002, pp. 113–119.
[7] Hau-Chuen Chan, K. T. Chau, and C. C. Chan, "A neural network controller for switching power converters", IEEE PESC Rec 1993, pp. 887-892.
[8] Y. Haroen, H Hindersyah et al., "The adaptive inverse model controller for new system of DC-DC convener for Rolling Stock auxiliary power Supply". IEEE Trans. Power Electronics. 1999, l6(4):784-788
[9] U. Ortega, R Kelly, et al. On passivity-based output feedback global stabilization of Euler -Lagrange systems. Proc. Of the 33" IEEE conference on decision and control, 1994, vol.1, pp.381-386
[10] S. L Shishkin, "Output feedback globally stable tracking of nonstationary Euler-Lagrange systems with large unknown disturbances". Proc. Of the 35th IEEE conference on decision and control, 1996, pp. 3026-3031.
[11] Sira-Ramirez H., R. Perez-Moreno, R. Ortega, and M. Garcia-Esteban, "Passivity-based controllers for the stabilization of DC-to-DC power converters", Automatica, 1997.
[12] A. Kwasinski and P. T. Krein, "Passivity-Based Control of Buck Converters with Constant-Power Loads", Power Electronics Specialists Conference, 2007, PESC 2007, IEEE, pp.259-265.