LOAD RESISTANCE AND OUTPUT VOLTAGE ESTIMATION OF DC-DC BUCK CONVERTERS USING A CONSTANT GAIN OBSERVER

ƯỚC LƯỢNG ĐIỆN TRỞ TẢI VÀ ĐIỆN ÁP ĐẦU RA CỦA BỘ BIẾN ĐỔI GIẢM ÁP MỘT CHIỀU SỬ DỤNG BỘ QUAN SÁT HỆ SỐ HẰNG

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ABSTRACT

This paper proposes an estimation method of the load resistance and output voltage for DC-DC buck converters. The state-space model of the converter is structured into the form of a locally uniformly observable system with the states of the inductor current, output voltage, and load resistance. Additionally, by using the Diode voltage of the converter as an input, a nonlinear observer is formulated with a constant matrix gain to estimate the resistance and output voltage. The observer is based on the output of the available inductor current, which has been the feedback of the double-loop control system of the converter. The observer is simple and robust with a single output and a constant gain. Simulation results confirm the performance of the proposed observer that the resistance and voltage can be sufficiently used for the feedback of voltage regulator and power management system.

Keywords: *Constant gain observer, DC-DC buck converter, locally uniformly observable system, parameter estimation, state estimation.*

TÓM TẮT

Bài báo đề xuất phương pháp ước lượng điện trở tải và điện áp đầu ra của bộ biến đổi giảm áp một chiều. Trước hết, mô hình không gian trạng thái của bộ biến đổi được đưa về cấu trúc của hệ thống quan sát được đều cục bộ với các biến trạng thái là dòng điện qua cuộn cảm, điện áp đầu ra và điện trở tải. Sau đó, với đầu vào là điện áp trên Đi-ốt của bộ biến đổi, bộ quan sát phi tuyến được thiết kế với ma trận hệ số hằng để ước lượng điện trở tải và điện áp đầu ra. Bộ quan sát dựa trên một đầu ra là dòng điện qua cuộn cảm có sẵn, đã được sử dụng làm phản hồi cho hệ thống điều khiển vòng kép của bộ biến đổi. Bộ quan sát với hệ số hằng và một biến đầu ra nên có cấu trúc đơn giản và đáp ứng nhanh. Kết quả mô phỏng xác nhận tính hợp lệ của của bộ quan sát đã đề xuất và kết quả quan sát được có thể sử dụng làm phản hồi cho bộ điều khiển và đầu vào cho hệ thống quản lý năng lượng.

Từ khóa: *Bộ quan sát hệ số hằng, bộ biến đổi giảm áp một chiều, hệ quan sát được đều cục bộ, ước lượng thông số, ước lượng trạng thái.*

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1. INTRODUCTION

Buck converter is popularly selected in industrial and commercial applications to step down the output voltage to an appropriate level in order to supply DC loads. It has been known as a low-cost and robust topology of the DC-DC converter (see Figure 1), which is typically utilized in renewable energy systems, smart grids, and electric vehicles [1, 2].

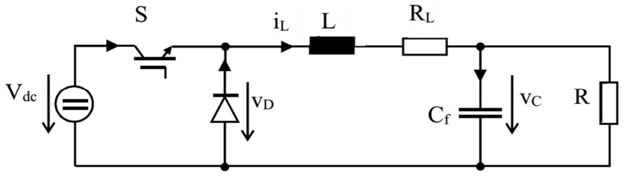

Figure 1. Topology of the buck converter

During the operation, the information of currents and voltages in the converter circuit is required for monitoring, controlling, and other technical purposes [3, 4]. For the controllers, inductor current and output voltage or capacitor voltage are usually measured by using dedicated sensors. Furthermore, regarding the power management of renewable energy systems or smart grids, it is necessary to have information about the load such as the power consumption, which can be calculated based on two among three values of the output voltage, load current, and load resistance. Therefore when the load resistance and the output voltage are known the load power can be simply computed. It must be underlined that the management of load power consumption is essential to DC microgrids for various purposes such as demand-side management [5] or real-time load management [6].

It should be noted that the utilization of more sensors increases the complexity and cost of the system. To overcome this drawback, the state estimation can be applied to the converter system, so that the information about states and parameters can be achieved with minimal use of sensors. Moreover, state estimation is also seen as an efficient way to manage the condition of the converter [1, 2].

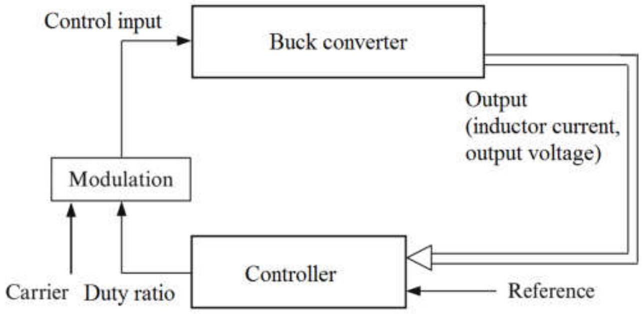

Figure 2. The buck converter with the controller

A typical buck converter system with the controller is shown in Figure 2. In this structure, it is required to measure the output voltage and inductor current to feedback the controller. Moreover, in many applications using the buck converters for stepping down voltage levels to supply the load, it is also needed to have the knowledge of the load power consumption.

The main contribution of this study is to design an observer with a constant gain, which estimates the output voltage based on the measurement of the available inductor current. The estimated voltage can be used to feedback the voltage controller that allows neglecting the utilization of voltage sensor for output voltage. Besides, the load resistance is also estimated and utilized as a useful input for the power management of the load.

The remainder of this article is organized as follows: The buck converter model and control system are described in section 2; It is then formulated in an appropriate form to calculate the gain observer in section 3; Simulation results are used to validate the performance of the observer in section 4; The article ends with some conclusions.

2. MODEL OF BUCK CONVERTER AND CONTROL SYSTEM

2.1. DC-DC buck converter model

In this study, the load is presented by using a resistor, which can be calculated from the output voltage and load current. When the Diode voltage, also called leg midpoint voltage, is used as an input, a state-space model can be obtained without requiring to measure the input voltage or the driving signal of the power electronic switch [1].

Applying the Kirchhoff's voltage and current laws to the circuit given in Figure 1, the state-space model of the buck converter can be written as:

$$\begin{cases} L\dfrac{di_L}{dt} = R_L i_L + v_D - v_C \\ C_f\dfrac{dv_C}{dt} = i_L - \dfrac{v_C}{R} \end{cases} \tag{1}$$

where R_L, L are the resistance and inductance of the inductor respectively; C_f is the capacitance of the capacitor; R is the load resistance; i_L is the inductor current; v_C is the output voltage, which is also the capacitor voltage; and v_D is the leg midpoint voltage.

2.2. Control system of the buck converter

Various control methods of buck converter can be found in the literature, such as linear control, sliding mode control, adaptive control, and fuzzy logic-based control. More details and comparisons can be found in [7] and the references cited in. Control structures of buck converters are mainly divided into the single-loop and double-loop types. The single-loop structure is simple in practice implementation thanks to the utilization of only a voltage regulation loop, while the double-loop structure uses both current and voltage regulation loops. However, the double-loop structure provides better dynamic performance and anti-interference ability [8]. In this study, the control application of the buck converter system with the double-loop structure, shown in Figure 2, will be considered. A typical double-loop control diagram is depicted in Figure 3.

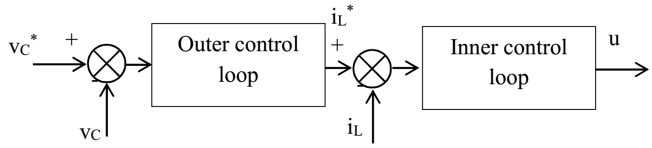

Figure 3. Control diagram of the buck converter

The control system of the buck converter is designed with:

- An outer loop of inductor current, which is a traditional proportional-integral regulator;

- An inner loop of output voltage which uses a sliding mode regulator. The control form is given by [9]:

$u = 0{,}5[1 + \mathrm{sign}(i_L - i_L^*)]$.

3. DESIGN OF OBSERVER FOR OUTPUT VOLTAGE AND LOAD RESISTANCE

This section introduces the procedure of designing an observer to identify the output voltage and load resistance of the buck converter. Once the voltage and resistance are estimated, the system structure can be modified and shown in Figure 4. In this system, the sensor for measuring the output voltage can be neglected and replaced by the estimated voltage of the observer. In addition, the estimated voltage and resistance can also be used as inputs of the power management system.

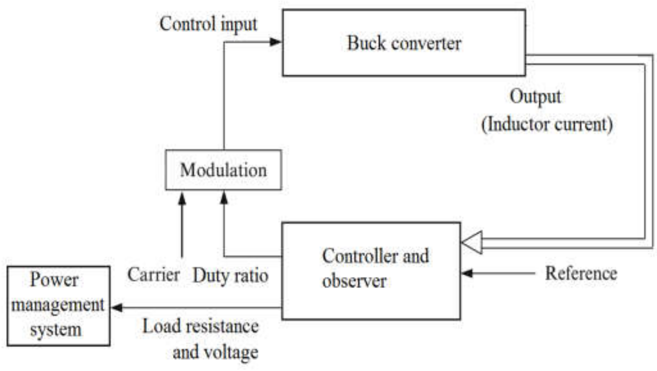

Figure 4. Control application of the buck converter with controller and observer

First, the state-space model described in equation (1) is rewritten as:

$$\begin{cases} \dot{x} = A(x).x + B(u) = f(u,x) \\ y = C.x = h(x) \end{cases} \qquad (2)$$

where x is the state, $x = [x_1\ x_2\ x_3]^T$, in which $x_1 = i_L$, $x_2 = v_C$ and $x_3 = 1/R$; y is the output, $y = x_1$;

$$A(x) = \begin{bmatrix} a_{11} & -a_{12} & 0 \\ a_{31} & 0 & -a_{31}x_2 \\ 0 & 0 & 0 \end{bmatrix} \text{ in which } a_{11} = \frac{R_L}{L},\ a_{12} = \frac{1}{L},$$

and $a_{21} = \frac{1}{C_f}$; $B(u) = [a_{12}u\ 0\ 0]^T$ where u is the input, $u = v_D$;

C is output matrix, $C = [1\ \ 0\ \ 0]$.

Consider the tangent map Tf_u: TM → T(TM) associated to f_u: M → TM, for every u∈U.

When $M = R^3$, TM can be identified with $R^3 \times R^3$, the lifted system associated to system (2) can be written of the form:

$$\begin{cases} \dot{z} = F(u,z) \\ y = Cz \end{cases} \qquad (3)$$

where $F(z) = [F_1(z)\ \ F_2(z)\ \ F_3(z)]^T$. It can be seen that $z_i = x_i$, i = 1, 2, 3.

Indeed, F(u,z) = A(z).z + B(z).u that u∈U, U = R, and f, h are clearly polynomial in u. In addition, $a_{12} = \frac{\partial F_1}{\partial z_2}(z) = -\frac{1}{L} \neq 0$ and $a_{23} = \frac{\partial F_2}{\partial z_3}(z) = -\frac{v_C}{C_f} \neq 0$ that satisfies the condition to design an observer which has the following form [10,11]:

$$\dot{\hat{z}} = F(u,\hat{z}) + \Delta_\alpha K\left(C\hat{z} - y\right) \qquad (4)$$

where $K = Q^{-1}C^T$; and Q is a positive defined matrix, ρ and η are positive constants such that for every (u, x), we have:

$$QA(u,x) + A(u,x)^TQ - \rho C^TC \leq \eta I \qquad (5)$$

where I is an identity matrix with appropriate size.

Δ_α a diagonal matrix given by:

$$\Delta_\alpha = \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \alpha^2 & 0 \\ 0 & 0 & \alpha^3 \end{pmatrix} \qquad (6)$$

After tuning procedure, we obtain the parameters of the observer as:

$K = [-8000\ 10000\ -27]^T$ and θ = 10;

Using this parameters, simulation will be developed to verify the performance of the observer in the next section.

4. SIMULATION RESULTS

4.1. Observation results of load resistance and voltage

The system and observer of the buck converter are simulated in the following conditions:

- The buck converter is simulated using the model given in equation (1) and parameters provided in the appendix. The initial states are given as: $[z_1\ z_2\ z_3] = [0\ 0\ 0.1]$ where $z_3 = 1/R = 0.1\Omega^{-1}$. The switching frequency is 200kHz.

- The observer with the structure described in equation (4) and following initial conditions: $\lfloor \hat{z}_1\ \ \hat{z}_2\ \ \hat{z}_3 \rfloor = [1\ 2\ 0.2]$. The acquisition frequency of the observer is 1MHz.

- A sudden change of the load is created at the time t = 0.01s.

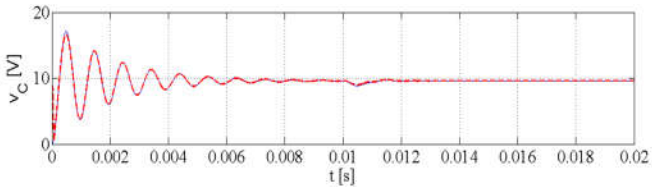

Figure 5. Output voltage estimation

Figure 5 shows the estimation result of the output voltage based on the measurement of the inductor current. It is seen that the estimated voltage in red dotted is well converged to the simulated one in blue continuous.

In addition, a good convergence can be observed for the load resistance in the duration with a sudden change of the load resistance at t = 0.01s, see Figure 6.

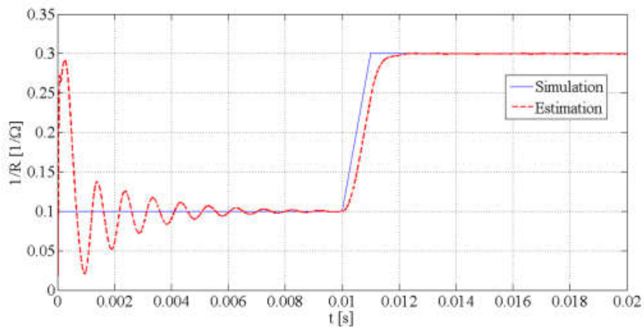

Figure 6. Load resistance estimation

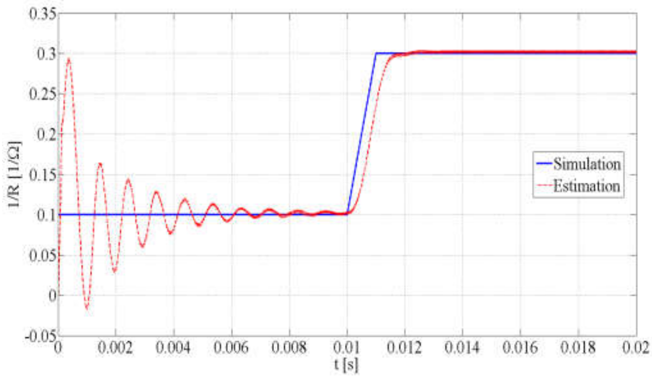

Figure 7. Load resistance estimation with the error of capacitance and inductance

The performance of the observer is also verified in the condition of parameter uncertainty that the parameters used for the observer are reset with 0.7 times of the capacitance and 0.8 times of the inductance compared to those of the system model, respectively. As can be seen in

Figure 7, an adequate convergence is still achieved although there is more fluctuation in the observed signal.

Therefore, it can be concluded that both voltage and resistance are well observed and sufficient to be used for different purposes such as the feedback of converter controller and the input of power management system.

4.2. Control of buck converter without output voltage sensor

To illustrate an application of the estimated results provided by the proposed observer, this section presents a simulation result of controlling the buck converter using the estimated output voltage as the feedback of the controller. The converter is assumed to operate with double-loop control, described in section 2.2, and the reference output voltage of 6V. In addition, there is a sudden change of load at t = 0.5s during the simulation period of 1s.

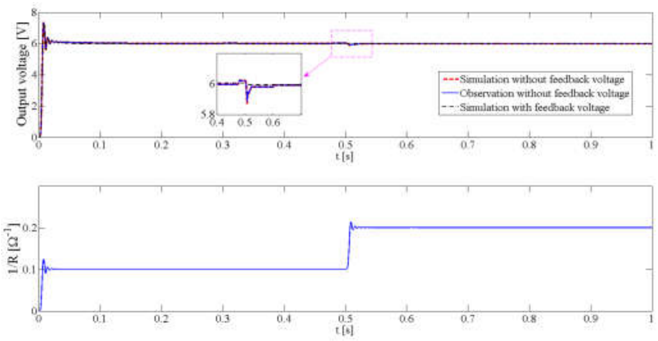

Figure 8. Output voltage response of the controller with estimated voltage feedback

As can be seen in Figure 8, a good response of output voltage is obtained during the converter operation from the initial stage through an event of load change at t = 0.5s. This is evidence to show that the estimated output voltage can be efficiently used for the feedback of voltage controller.

5. CONCLUSION

The estimation of load resistance and output voltage has been investigated in this paper. A constant gain observer has been designed and applied to the buck converter which operates in a closed double-loop structure. The output voltage and the load resistance are estimated on the basis of the available measurement of the inductor current. The performance of the observer is validated by simulation of the converter in the condition that there is a sudden variation in the load resistance. The estimated voltage is also successfully applied as the feedback of the controller. Further study will focus on applying the estimation result of resistance to the power management system of microgrids. The estimation method for other parameters of the buck converter will also be the future work for the condition monitoring and improvement of the controller performance.

APPENDIX

Table 1. Parameters of the DC-DC buck converter

Parameters	Variables	Value
Input voltage	V_{in}, V	12
Inductance	L, μH	240
Inductor resistance	R_L, Ω	0.4
Output capacitor	C/μF	100

REFERENCES

[1]. L. Ren, C. Gong, 2021. *Parameter identification based on linear model for buck converters.* Electrical Engineering, vol. 103, no. 1, pp. 293-302.

[2]. Z. Cen, P. Stewart, 2016. *Condition parameter estimation for photovoltaic buck converters based on adaptive model observers.* IEEE Transactions on Reliability, vol. 66, no. 1, pp. 148-160.

[3]. Gabriel Rojas-Dueñas, Jordi-Roger Riba, Manuel Moreno-Eguilaz, 2020. *Nonlinear Least Squares Optimization for Parametric Identification of DC–DC Converters*. IEEE Transactions on Power Electronics, vol. 36, no. 1, pp. 654-661.

[4]. M. Ahmeid, M. Armstrong, S. Gadoue, M. Al-Greer, P. Missailidis, 2017. *Real-Time Parameter Estimation of DC-DC Converters Using a Self-Tuned Kalman Filter.* IEEE Transactions on Power Electronics, vol. 32, no. 7, pp. 5666-5674.

[5]. R. K. Chauhan, C. Phurailatpam, B. S. Rajpurohit, F. M. Gonzalez-Longatt, S. N. Singh, 2017. *Demand-side management system for autonomous DC microgrid for building.* Technology and Economics of Smart Grids and Sustainable Energy, vol. 2, no. 1, p. 4.

[6]. X. Feng, K. L. Butler-Purr, T. Zourntos, 2018. *Real-time electric load management for DC zonal all-electric ship power systems.* Electric Power Systems Research, no. 154, pp. 503-514.

[7]. Himanshu, R. Khanna, 2012. *Various control methods for DC-DC buck converter*. in 2012 IEEE Fifth Power India Conference, Murthal, India.

[8]. Y. Yin, J. Liu, A. Marquez, X. Lin, J. I. Leon, S. Vazquez, L. G. Franquelo, L. Wu, 2020. *Advanced Control Strategies for DC-DC Buck Converters With Parametric Uncertainties via Experimental Evaluation.* IEEE Transactions on Circuits and Systems I: Regular Paper, vol. 67, no. 12, pp. 5257-5267.

[9]. V. Utkin, 2013. *Sliding mode control of DC/DC converters.* Journal of the Franklin Institute, vol. 350, no. 8, pp. 2146-2165.

[10]. J. P. Gauthier, I. A. Kupka, 1994. *Observability and observers for nonlinear systems.* SIAM Journal on Control and Optimization, vol. 32, no. 4, pp. 975-994.

[11]. H. Hammouri, M. Farza, 2003. *Nonlinear observers for locally uniformly observable systems.* ESAIM. COCV, vol. 9, pp. 353-370.

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