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Extended Feedback Linearisation Control of Non-ideal DCDC Buck Converter in Continuous-conduction Mode

Research paper

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Abstract: This paper presents an extended form of Feedback Linearisation Control (FBLC), which is tested in a non-ideal buck converter in Continuous-conduction Mode (CCM). The FBLC is often used in power electronics to control a non-linear system, due to its advantageous properties. The application of the error integrator shows better steady-state and transient properties, such as a decrease of inrush current. The linearised system has been controlled by the pole placement and the technique is illustrated through an example and simulated via Matlab. The results have been compared by using a classical PID controller, allowing the benefits of FBLC to be highlighted.

Keywords: *DC/DC buck converter • feedback linearisation • inrush current • parasitic • Ackermann*

1. Introduction

Power converters are highly non-linear systems and have variable structures per switching period. These features sometimes make it difficult to design the controller. At the same time, control techniques play important roles in enabling power converters to achieve their maximum efficiency. The main purpose of the control action is to provide a good steady-state and dynamic behaviour, which includes fast response time, efficiency, robustness and invariant behaviour. Furthermore, a good dynamic response can minimise the switching losses of the converters, thereby increasing efficiency.

Numerous linear and non-linear control techniques are available for controlling DC/DC converters. The linear controllers (such as PID controllers) are simple structures and easy to implement but they have problems with robustness, external disturbances, settling or response time (Wibawa et al., 2020). To overcome these disadvantages properties, numerous non-linear control mechanisms are used, such as direct pole placement, sliding mode, fuzzy control, model predictive control, feedback linearisation, etc. (Mumtaz et al,, 2021; Nishtha et al., 2016). The last of these is less frequently mentioned in the literature, but this method has many possibilities.

Feedback linearisation is one of the best techniques for the investigation and design of non-linear systems. This topic is discussed by Salimi and Siami (2015), Zheng and Shuai (2012) and Bhattacharyya et al. (2018). The main idea of this approach is to algebraically transform the non-linear system dynamics into a fully or partially linearised system, thus allowing the feedback control techniques to be applied. This method will not lose the non-linearity of the system at all. Our previous research has shown that using an error integrator to FBCL represents better transient behaviour and can decrease the inrush current at start-up (Csizmadia and Kuczmann, 2021).

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The purpose of this article is to present the FBCL in detail, highlight the benefits of the extra error integrator and investigate the non-ideal system modelling behaviour through a Continuous-conduction Mode (CCM) buck converter example. At the end of the article, the results will be compared with a self-designed PID controller.

2. State-space Model of Buck Converter with Parasitics

The full, detailed model of a buck converter with parasitics is shown in Figure 1.

The averaged state-space model in CCM mode is given by the following expression (which was discussed in Erickson and Maksimovic [2001] and Salimi and Siami [2015]):

$$i_L = \frac{1}{L} - \left(\left(r_{sw} - r_d\right)d + r_d + r_{esl}\right)i_L + v_C - \left(V_i + V_d\right)d + V_d,$$
$$v_C = \frac{1}{C}i_L - \frac{1}{RC}v_C, \tag{1}$$

where v_C and i_L represent the capacitor voltage (output voltage) and inductor current; v_i is the input DC voltage; R,L,C symbolise, respectively, the output load, inductance and capacitance; and d denotes the duty cycle of the converter. The parasitic quantities are symbolised by $r_{sw}, r_d, V_d, r_{esl}$ and r_{esr}, which are the R_{DSon} of the MOSFET switching element, the diode on-state resistance, the diode drop voltage and the last two the parasitic resistance of reactant elements, respectively.

A SISO non-linear system can be given by:

$$\begin{cases} \dot{x} = f(x) + g(x)u, \\ y = h(x), \end{cases} \tag{2}$$

where

$$f(x) = \begin{bmatrix} -\frac{1}{L}\left(r_d + r_{esl}\right)i_L + v_c + V_d \\ \frac{1}{C}i_L - \frac{1}{RC}v_C \end{bmatrix}$$
$$g(x) = \begin{bmatrix} -\frac{1}{L}\left(r_{sw} - r_d\right)i_L - V_i - Vd \\ 0 \end{bmatrix}$$
$$y = h(x) = u_C \tag{3}$$

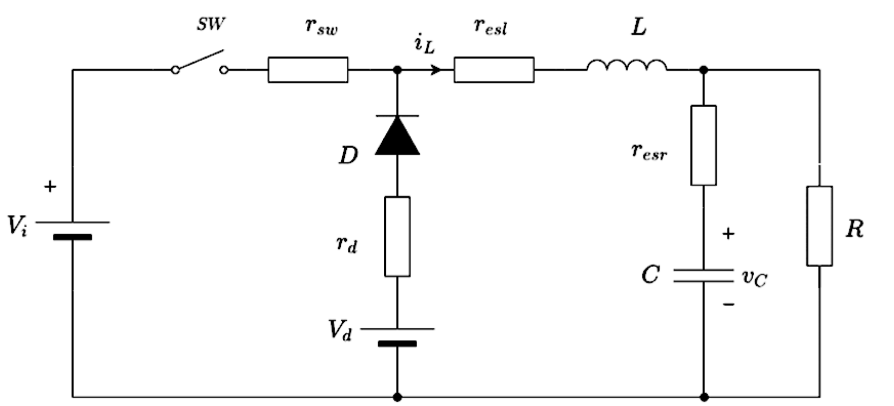

Fig. 1. Buck converter including parasitics.

3. Exact Feedback Linearisation

The feedback linearisation method is discussed in detail by Isidori (1995). The investigated SISO system is given in the form corresponding to Eq. (3). Let us differentiate the output functions by time until the input function appears in the expressions:

$$\dot{y} = \frac{\partial h}{\partial x} f(x) + \frac{\partial h}{\partial x} g(x), \tag{4}$$

where $L_f h$ and $L_g h$ mean the Lie derivative of $h(x)$ along $f(x)$ and $g(x)$, respectively.

Differentiating y continuously until $L_g L_f h(x) \equiv, L_g L_f^{r-1} h(x) \neq 0$, a relative degree of the system is equal to r. As a result of this, we get an integral line, i.e. $z_1 = y$, $z_2 = \dot{y}$, $z_3 = \dot{y}$, etc., whose r^{th} element is:

$$y^{(r)} = L_f^r h(x) + L_g L_f^{(r-1)} h(x) u. \tag{5}$$

Define v as new input:

$$v = L_f^r h(x) + L_g L_f^{(r-1)} h(x) u. \tag{6}$$

This u input is the new input of the system. From this, the original input can be obtained:

$$u = \frac{-L_f^r h(x) + v}{L_g L_f^{(r-1)} h(x)}. \tag{7}$$

The state-space description of the whole system is:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \\ \dot{z}_3 \\ \vdots \\ \dot{z}_r \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix}}_{A} \begin{bmatrix} z_1 \\ z_2 \\ z_{r-1} \\ \vdots \\ z_r \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ 0 \\ \vdots \\ 0 \\ 1 \end{bmatrix}}_{B} v. \tag{8}$$

The linear controller is designed for matrix *A* and vector *B*. *A* and *B* are always of this shape, and the number of rows depends on the number of state variables.

In the case of buck converter, the controlled quantity is the output (capacitor) voltage; so, the non-linear coordinate transformation is given by:

$$\boldsymbol{T}(x) = \begin{bmatrix} h(x) \\ L_f h(x) \end{bmatrix} = \begin{bmatrix} v_C \\ \frac{1}{C} i_L - \frac{1}{RC} v_C \end{bmatrix}. \tag{10}$$

The new control input is given by applying Eq. (8):

$$u = \frac{-L_f^2 h(x) + v}{L_g L_f h(x)}, \tag{11}$$

where

$$L_g\left(L_f h(x)\right) = -\frac{1}{LC}\left(\left(r_{sw} - r_d\right)i_L - V_i - Vd\right),$$
$$and \tag{12}$$
$$L_f^2 h(x) = L_f\left(L_f h(x)\right) = -\frac{1}{LC}\left(\left(r_d + r_{esl}\right)i_L + v_C - V_d\right) + \frac{1}{RC^2}i_L - \frac{1}{R^2C^2}v_C$$

4. Controller Design

The controller was designed by Ackermann's formula, which is based on the work of Bajoria et al. (2016) and a control tutorial for Matlab and Simulink. To determine the poles, we started from a rule of thumb; so, the poles of the system (*p*) were moved to:

$$p = -\frac{1}{5\tau}, \tag{13}$$

where τ is the time constant of the system. In the case of buck converter, the time constant (τ) is equal with that in Eq. (8):

$$\tau = RC = 10\Omega \cdot 10\mu F = 0.0001s. \tag{14}$$

Based on the simulations, the final values of the poles are obtained:

$$p = \left[-1/0.00005; -1/0.0005; -1/0.00005\right]. \tag{15}$$

From this, the feedback gain matrix is obtained:

$$k^T = \left[1.8750 \cdot 10^9, 7.5000 \cdot 10^4, 1.5625 \cdot 10^{13}\right]. \tag{16}$$

The block scheme of the whole system is shown in Figure 2.

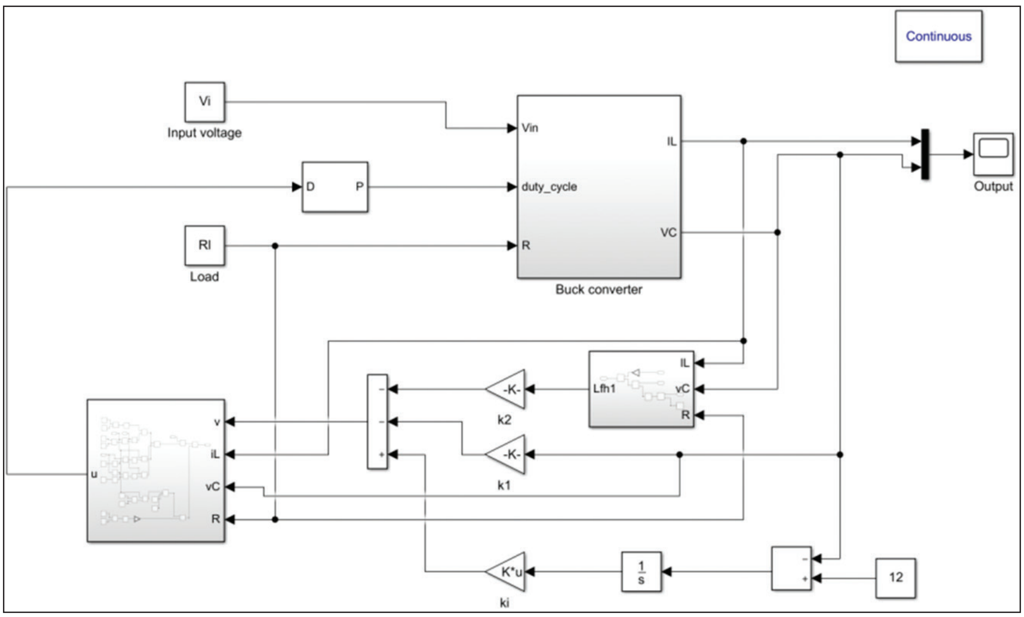

Fig. 2. Matlab Simulink model of the system with error integrator.

5. Simulation Results

The properties of the presented controller are testified by MATLAB Simulink. Its details are specified in Table 1. For better comparability, the parameters have been derived from the work of Salimi and Siami (2015). To demonstrate the beneficial properties of feedback linearisation control (FBLC), we also designed a PID controller, which is based on the work of Wibawa et al. (2020) and Huifang et al. (2019). The PID controller parameters are listed in Table 2.

To investigate the proposed controller, the following tests have been conducted:

- Start-up test;
- Dynamic response for step/sudden load resistance change; and
- Dynamic response for step/sudden for step/sudden input voltage change.

Table 1. Buck converter parameters.

Sign	Value
R	10Ω
L	$2000\ \mu H$
C	$10\ \mu F$
r_{sw}	0.1Ω
r_d	$1m\Omega$
V_d	$0.8V$
r_{esl}	0.2Ω
r_{esr}	0.1Ω
V_{in}	$32V$
V_o	$12V$
I_o	$1.2A$
f_{sw}	100 kHz

Table 2. PID controller coefficient.

Parameter	Value
P	0,00155
I	8.3
D	1.473×10^{-7}

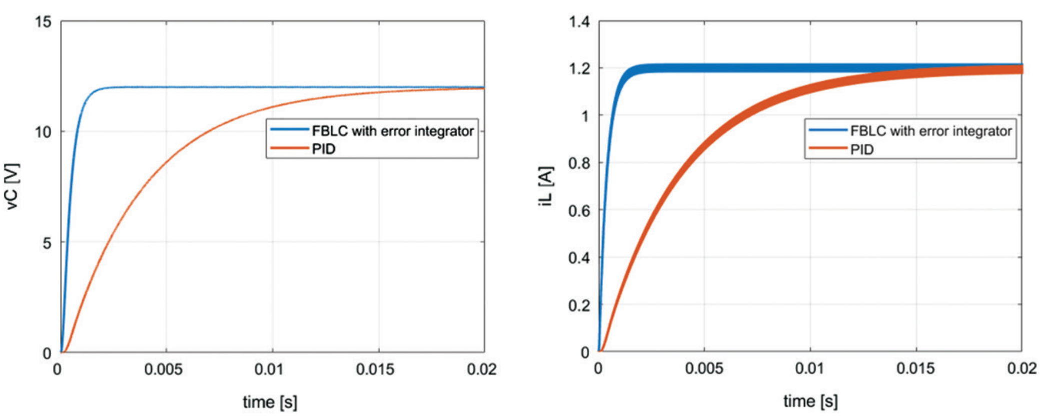

Fig. 3. Capacitor voltage and inductor current during start-up.

5.1. Start-up test

The start-up test was made by nominal parameters. The response of the proposed controller during start-up is shown in Figure 3. It is clear from the simulation result that the error integrator eliminates the inrush current, and the settling time became extremely short (<5 ms). The nominal inductor current is shown in Figure 4.

5.2. Dynamic tests

To investigate the response of controllers for the load change, the load resistor value is changed between 10 Ω and 20 Ω, with a 0.05 s period time. The responses of the output voltage and inductor current to load changes are shown in Figure 5. In a similar way, the responses to changes in input voltage were tested: the input voltage was changed between 32 V and 45 V, with a 0.05 s period time. The responses are shown in Figure 6. The dynamic properties of the proposed controller are equally good in comparison with the results obtained by Salimi and Siami (2015).

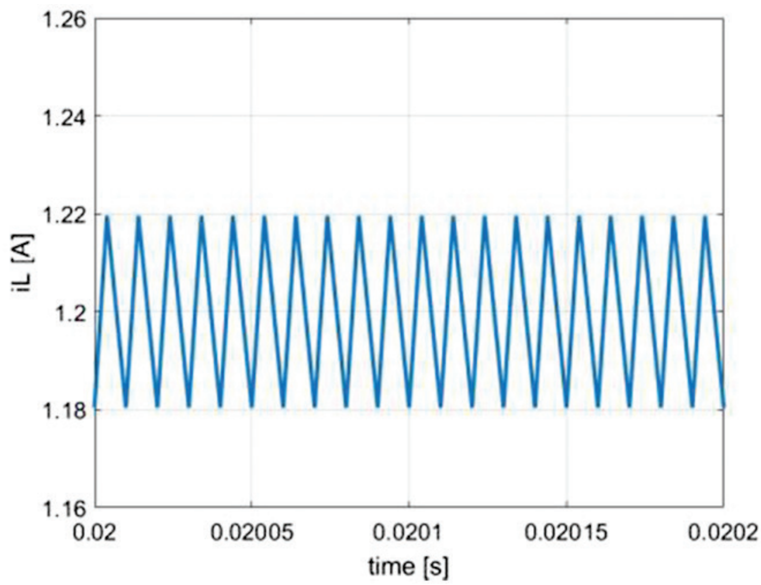

Fig. 4. Inductor current ripple in nominal condition (FBLC). FBLC, Feedback linearisation control.

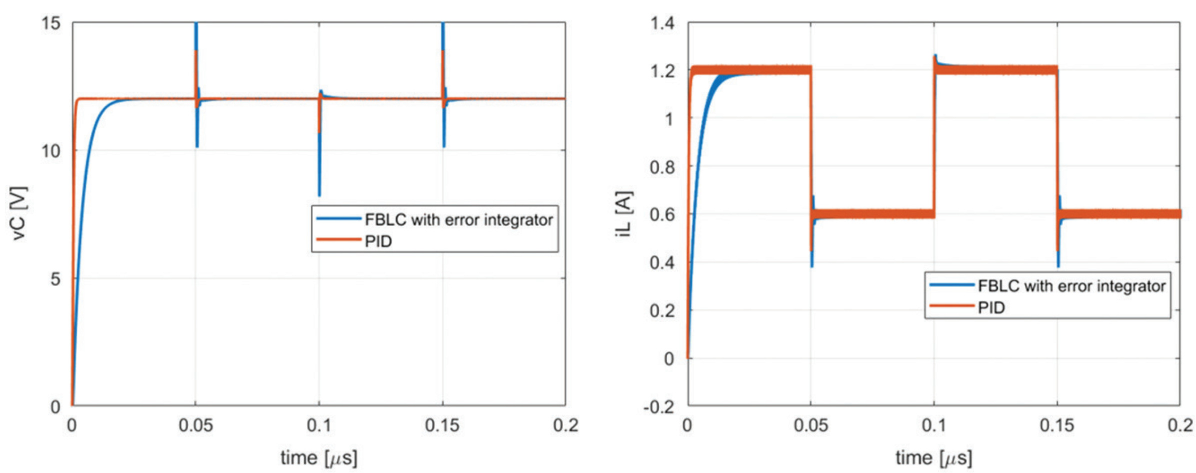

Fig. 5. Inductor current and capacitor voltage response to load changes.

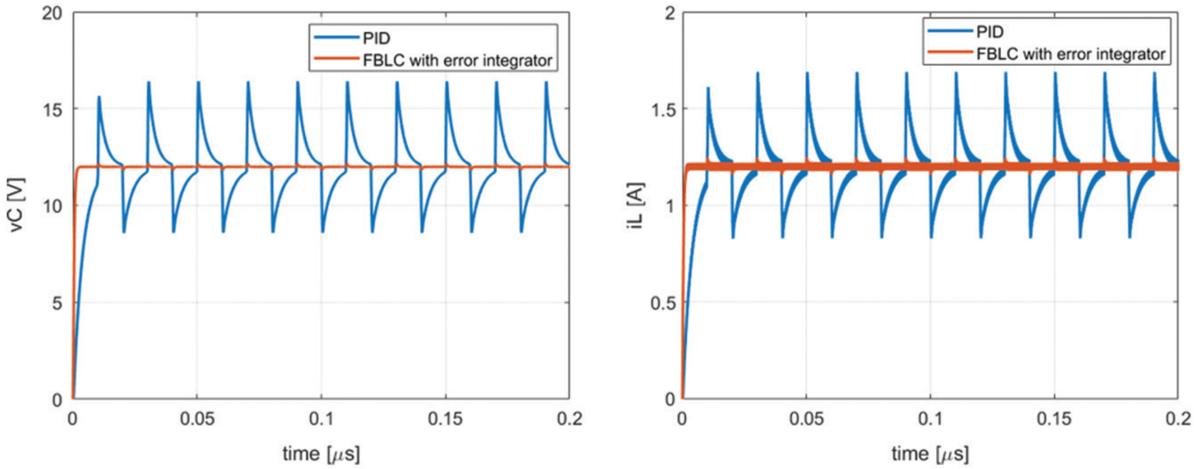

Fig. 6. Capacitor voltage and inductor current response to input voltage changes.

6. Conclusions

This research describes a closed-loop control of buck converter using exact feedback linearisation. Compared to previous work (e.g., Csizmadia and Kuczmann, 2021), the non-ideal state-space model does not give many different results. The controller retains its positive benefits, such as better transient behaviour and reduced inrush current, due to the error integrator.

In further research, this extended FBCL method will be applied to another DCDC converter (boost) and experimental tests will be performed. Further, the ideal state-space model is expected to make the controller design easier and faster.

References

Nishtha, B., Rajesh, N. and Savita, N. (2016). Overview of different control schemes used for controlling of DC-DC converters," *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, 2016, pp. 75-82, doi: 10.1109/ICEPES.2016.7915909.

Mumtaz, F., Yahaya, N. Z., Meraj, S. T., Singh, B., Kannan, R., Ibrahim, O. (2021). Review on Non-isolated DC-DC Converters and their Control Techniques for Renewable Energy Applications. *Ain Shams Engineering Journal*, 12(4), 3747–3763.

Wibawa, U., Mardiana, E. and Ardhenta, L. (2020). Design and performance analysis of PID controller for extended output voltage buck-boost converter. In: *2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS), 2020,* pp. 31-36, doi: 10.1109/EECCIS49483.2020.9263458.

Salimi, M. and Siami, S. (2015). Closed-Loop control of DC-DC buck converters based on exact feedback linearization. In: *2015 4th International Conference on Electric Power and Energy Conversion Systems (EPECS)*, Sharjah, 2015, pp. 1–4, doi: 10.1109/EPECS.2015.7368537.

Zheng, H. and Shuai, D. (2012). Nonlinear control of Boost converter by state feedback exact linearization. In: *24th Chinese Control and Decision Conference (CCDC)*, Taiyuan, 2012, pp. 3502–3506, doi: 10.1109/CCDC.2012.6244559.

Bhattacharyya, D., Padhee, S. and Pati, K. C. (2018). Modeling of DC–DC Converter Using Exact Feedback Linearization Method: A Discussion. *IETE Journal of Research*, doi: 10.1080/03772063.2018.1454345.

Csizmadia, M. and Kuczmann, M. (2021). Feedback linearization with integrator of DCDC buck converter taking into account parasitic elements.

In: *2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC)*, 2021, Conference on Gridding and Polytope Based Modelling and Control (GPMC), pp. 97–101, doi: 10.1109/PEMC48073.2021.9432632.

Erickson, R. W. and Maksimovic, D. (2001). *Fundamentals of Power Electronics,* 2nd ed. Springer, New York.

Isidori, A. (1995). *Nonlinear Control Systems*. London: Springer.

Bajoria, N., Sahu, P., Nema, R. K. and Nema, S. (2016). Overview of different control schemes used for controlling of DC-DC converters. In: *2016 International Conference on Electrical Power and Energy Systems (ICEPES)*, Bhopal, 2016, pp. 75–82, doi: 10.1109/ICEPES.2016.7915909.

Time-Response Analysis of a Boost Converter Circuit, Control Tutorial for Matlab & Simulink (https://ctms.engin.umich.edu/CTMS/index.php?aux=Activities_BoostcircuitA)

Wibawa, U., Mardiana, E. and Ardhenta, L. (2020). Design and performance analysis of PID controller for extended output voltage buck-boost converter. In: *2020 10th Electrical Power, Electronics, Communications, Controls and Informatics Seminar (EECCIS)*, 2020, pp. 31–36, doi: 10.1109/EECCIS49483.2020.9263458.

Xu, H., Cheng, M., Zhang, F. (2019). Modeling and simulation of non-ideal buck converter in CCM. In: *IOP Conference Series: Earth and Environmental Science*. 300. 042098. doi: 10.1088/1755-1315/300/4/042098.