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Simple Fuzzy PID Controllers for DC-DC Converters

K.-W. Seo* and Han Ho Choi†

Abstract – A fuzzy PID controller design method is proposed for precise robust control of DC-DC buck converters. The PID parameters are determined reflecting on the common control engineering knowledge that transient performances can be improved if the P and I gains are big and the D gain is small at the beginning. Different from the previous fuzzy control design methods, the proposed method requires no defuzzification module and the global stability of the proposed fuzzy control system can be guaranteed. The proposed fuzzy PID controller is implemented by using a low-cost 8-bit microcontroller, and simulation and experimental results are given to demonstrate the effectiveness of the proposed method

Keywords: Converter, Fuzzy system, PID control, Microcontroller, Uncertainty, Stability analysis

1. Introduction

A bunch of control algorithms for DC-DC converters have been proposed in the literature. However, it is not easy to precisely control DC-DC converters because of load or parameter variations. To get around this problem, many researchers [1-7] have proposed numerous control algorithms which are robust to load or parameter variations. Recently, several researchers such as [8-13] have presented fuzzy control design methods. The fuzzy control theory gives an alternative approach for collecting human knowledge and dealing with nonlinearities or uncertainties. The fuzzy modeling and control methods have succeeded in controlling uncertain systems that cannot be easily handled by conventional control methods [14-16]. Almost all the previous fuzzy control design techniques such as [8-13] are based on heuristics-based fuzzy approach which is essentially model free. Though the previous methods [8-13] may yield satisfactory performances, they have two significant drawbacks as pointed out in [12]. There is no systematic design technique. And analysis of stability and performance of the control system is not easy. Considering these facts, a fuzzy PID control design method for a buck converter is proposed. The PID parameters are determined based on the common control engineering knowledge that transient performances can be improved if the P and I gains are big and the D gain is small at the beginning [18, 19]. Unlike the previous fuzzy control design methods [8-13], the global stability of the proposed control system can be guaranteed. By using the results of [20] the asymptotic stability is shown. Finally, the proposed fuzzy controller is implemented by using an inexpensive 8-bit microcontroller. Via simulations and experiments it is shown that the proposed method can be successfully used to control a buck converter under input voltage and load variations.

† Corresponding Author: Div. of EEE, Dongguk Univ.-Seoul, Korea. (hhchoi@dongguk.edu)
* Div. of EEE, Dongguk Univ.-Seoul, Korea. (hhchoi@dongguk.edu)
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2. System Description

A buck converter shown in Fig. 1 can be represented by the following dynamic equation [3, 4] :

$$\begin{aligned} \dot{i}_L &= -\frac{1}{L}v_C + \frac{E}{L}u_d \\ \dot{v}_C &= \frac{1}{C}i_L - \frac{1}{RC}v_C \end{aligned} \tag{1}$$

where i_L, v_C, u_d represent the input inductor current, the output capacitor voltage, the discrete-valued control input taking values in the set $\{0,1\}$, and E, L, C, R are the external source voltage value, the inductance of the input circuit, the capacitance of the output filter, the output load resistance, respectively. We will assume that the inductor current is never allowed to be zero, i.e. the converter is in continuous conduction mode.

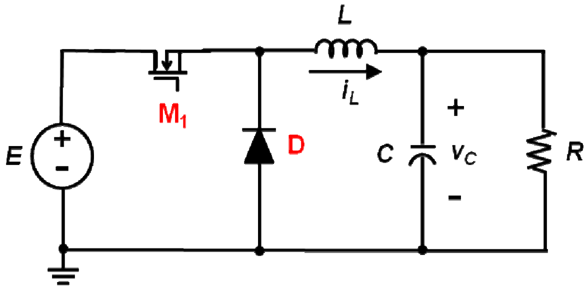

Fig. 1. Topology of buck converter.

After all, the design problem can be formulated as designing a fuzzy PID controller for the above model (1).

3. Control Design and Stability Analysis

3.1 Conventional PID controller

By introducing the duty ratio input function $u(\cdot)$ ranging on the interval [0, 1] and the following variables :

$$z_1 = \int_0^t e d\tau,\quad z_2 = e = V_r - v_C,\quad z_3 = \frac{d}{dt}e = -\dot{v}_C,$$
$$v = \frac{E}{LC}\left(\frac{V_r}{E} - u\right)$$

we can obtain the following approximate averaged model from (1)

$$\dot{z} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\frac{1}{LC} & -\frac{1}{RC} \end{bmatrix} z + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} v$$

where $z = [z_1, z_2, z_3]^T$, and V_r is the desired reference output voltage such that $E > V_r > 0$.

If we set the auxiliary input variable v as the following conventional PID controller

$$v = -K^P e - K^I \int_0^t e d\tau - K^D \frac{d}{dt}e \tag{2}$$

or equivalently $v = -K^P z_2 - K^I z_1 - K^D z_3$ then the closed-loop control system is given by

$$\dot{z} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -K^I & -(K^P + \frac{1}{LC}) & -(K^D + \frac{1}{RC}) \end{bmatrix} z \tag{3}$$

and the characteristic function of the closed-loop control system is given by the following third-order polynomial

$$s^3 + (K^D + \frac{1}{RC})s^2 + (K^P + \frac{1}{LC})s + K^I \tag{4}$$

which is stable as long as

$$(K^P + \frac{1}{LC})(K^D + \frac{1}{RC}) > K^I, K^P > 0, K^I > 0, K^D > 0$$

3.2 Fuzzy PID control law

The common control engineering knowledge given in [18, 19] implies that transient performances can be improved if the P and I gains are big and the D gain is small when the error is big, thus reflecting on this knowledge we try to modify the conventional PID controller (2). The proposed fuzzy PID control input v is determined by a set of fuzzy rules of the following form

Rule i : IF e is F_i, THEN

$$v = -K_i^P e - K_i^I \int_0^t e d\tau - K_i^D \frac{d}{dt}e$$

where $F_i (i = 1, \cdots, 2n-1)$ are fuzzy sets, $n > 1$, $r = 2n-1$ is the number of fuzzy rules, and K_i^P, K_i^I are positive constants. F_i is characterized by membership functions m_i. We assume that the fuzzy set F_n covers $e=0$, F_i covers more negative e than $Fi+1$ does for $1 \le i \le n-1$, and $Fi+1$ covers more positive e than Fi does for $n \le i \le 2n-2$. The membership functions m_i with $n = 3$ are shown in Fig. 2. In this figure, ZO ($F3$) stands for zero, NB($F1$) for negative big, NS($F2$) for negative small, PS($F4$) for positive small, PB($F5$) for positive big.

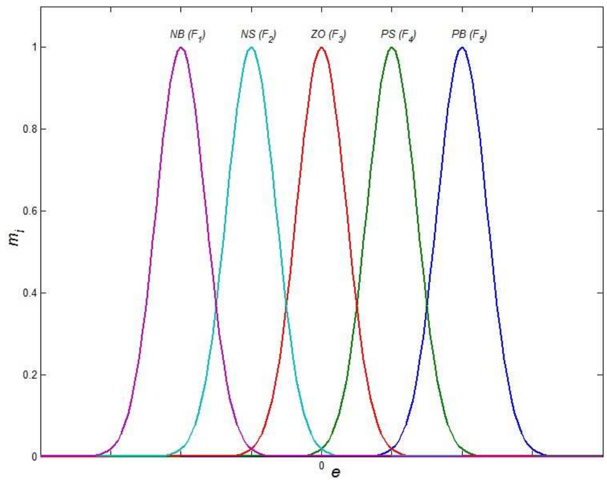

Fig. 2. Membership functions with n=3

The common control engineering knowledge implies that in order to improve transient performances we need to set the gains as

$$\begin{aligned} &K_1^P \ge K_2^P \ge \cdots \ge K_{n-1}^P \ge K_n^P > 0, \\ &K_{2n-1}^P \ge K_{2n-2}^P \ge \cdots \ge K_{n+1}^P \ge K_n^P > 0, \\ &K_1^I \ge K_2^I \ge \cdots \ge K_{n-1}^I \ge K_n^I > 0, \\ &K_{2n-1}^I \ge K_{2n-2}^I \ge \cdots \ge K_{n+1}^I \ge K_n^I > 0, \\ &K_1^D \ge K_2^D \ge \cdots \ge K_{n-1}^D \ge K_n^D > 0, \\ &K_{2n-1}^D \ge K_{2n-2}^D \ge \cdots \ge K_{n+1}^D \ge K_n^D > 0, \end{aligned} \tag{5}$$

By taking the weighted average of the IF-THEN rule outcome, we can obtain the final PID control input

$$v = -\sum_{i=1}^{r} h_i(e)\left[K_i^P e + K_i^I \int_0^t e\, d\tau + K_i^D \frac{d}{dt}e\right] \tag{6}$$

where $h_i = m_i / \sum_{j=1}^{r} m_j$ is the normalized weight of each IF-THEN rule and it satisfies $h_i \geq 0, \sum_{h=1}^{r} h_i = 0$. It should be noted that unlike the previous heuristics-based fuzzy methods [8-13] the proposed method does not requires a computationally burdensome defuzzification module to obtain a crisp value of the variable v because in the proposed method outcome of each IF-THEN fuzzy rule uses a scalar rather than a fuzzy set for the variable v. Thus the proposed method is much simpler than the previous heuristics-based fuzzy methods [8-13]. Fig. 3 shows a block diagram of the proposed control algorithm.

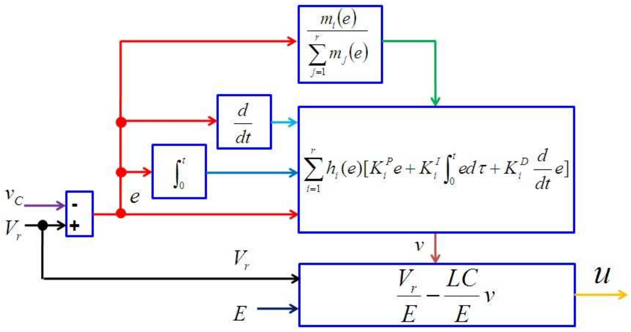

Fig. 3. Block diagram of the fuzzy control algorithm.

3.3 Stability condition

Using (3) and (6), the following error dynamics can be obtained :

$$\dot{z} = \sum_{i=1}^{r} h_i(e)\begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -K_i^I & -(K_i^P + \frac{1}{LC}) & -(K_i^D + \frac{1}{RC}) \end{bmatrix} z \tag{7}$$

which leads to the following third-order characteristic function

$$s^3 + b_2 s^2 + b_1 s + b_0 \tag{8}$$

with

$$b_2 \in \left[K_0^D + \frac{1}{RC}, K_n^D + \frac{1}{RC}\right], \quad b_1 \in \left[K_n^P + \frac{1}{LC}, K_0^P + \frac{1}{LC}\right], b_0 \in \left[K_n^I, K_0^I\right] \tag{9}$$

where $K_0^P = \max\{K_1^P, K_r^P\}$, $K_0^I = \max\{K_1^I, K_r^I\}$, and $K_0^D = \min\{K_1^D, K_r^D\}$. By [20] it can be shown that the characteristic function (8) with (9) is stable if

$$(K_n^P + \frac{1}{LC})(K_0^D + \frac{1}{RC}) > K_0^I > 0 \tag{10}$$

This proves the following theorem.

Theorem : Consider the closed-loop system of (1) with the fuzzy PID control law (6). Then, the asymptotic stability of $z = 0$ is guaranteed as long as the PID parameters satisfy the condition (10).

4. Experimental Results

Consider a buck converter (1) with the parameters given in Table 1. We assume that $r = 5$ and the membership functions are given by the Gaussian ones $m_i = \exp[-\sigma(e-W_i)^2]$ where $W1 = -W5 = -10$, $W2 = -W4 = 0.75W1$, $W3 = 0, \sigma = 1/W_1^2$. It should be noted that the Gaussian membership function is a very prevailing one for specifying fuzzy sets because of its smoothness and concise notation. Let the fuzzy PID parameters be given by

$$K_1^P = K_5^P = 36000,\ K_2^P = K_4^P = 14400,\ K_3^P = 9000,$$
$$K_1^I = K_5^I = 2.916E9,\ K_2^I = K_4^I = 1.1664E9, K_3^I = 0.729E9,$$
$$K_1^D = K_5^D = 2250,\ K_2^D = K_4^D = 3600,\ K_3^D = 9000$$

We can obtain the following fuzzy PID control law satisfying the stability condition (10)

$$u = \frac{V_r}{E} - \frac{LC}{E}\sum_{i=1}^{5} h_i(e)\left[K_i^P e + K_i^I \int_0^t e\, d\tau + K_i^D \frac{d}{dt}e\right] \tag{11}$$

Table 1. Parameters for experiment.

Input Voltage (E)	10 [V]
Desired output voltage (V_r)	5 [V]
Input inductance (L)	1[mH]
Output capacitance (C)	10 [μF]
Nominal load resistance (R)	20 [Ω]
PWM frequency (f_s)	20 [kHz]

Fig. 4 shows a schematic diagram of the above fuzzy PID control law. To demonstrate the effectiveness of the proposed control algorithm, an experimental test bed is constructed by using the circuit diagram of Fig. 5. The general purpose 8- bit microcontroller ATmega128 from ATMEL was used to implement the proposed control algorithm. The ATmega128 microcontroller operates at 16MHz and it supports embedded control oriented features such as two 8-bit PWM channels, 53 programmable input output lines, four flexible timer/counters with compare modes, an 8 channel 10-bit successive approximation ADC (Analog to Digital Converter). The conversion time of the

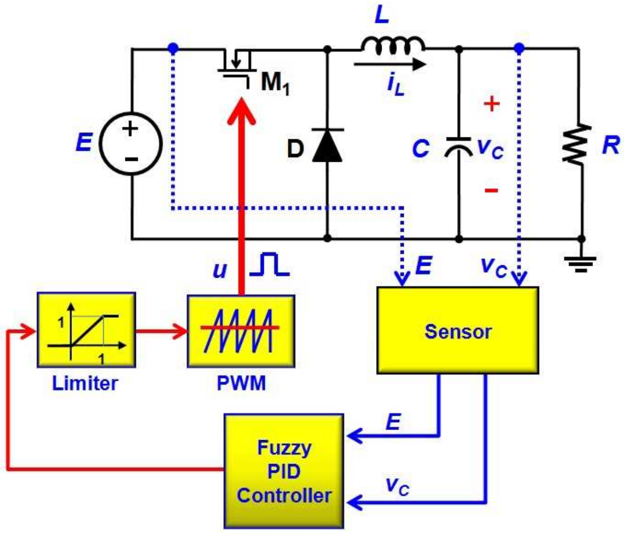

Fig. 4. Schematic diagram of the proposed control system. .

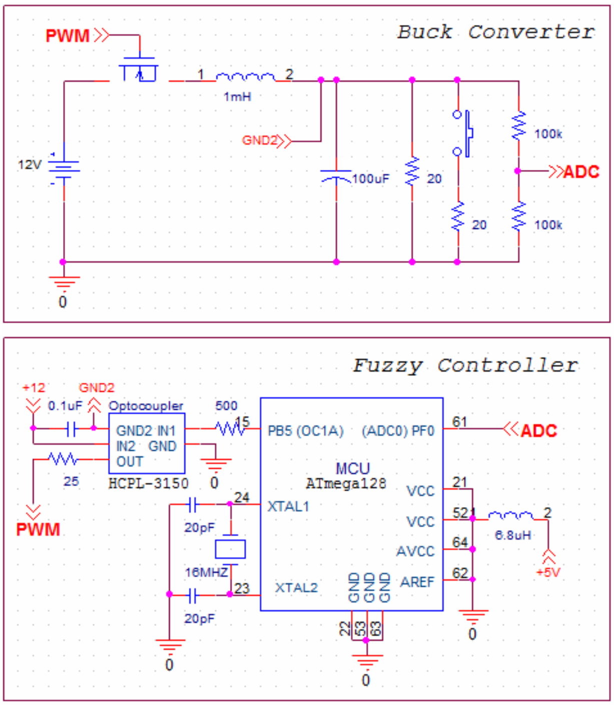

Fig. 5. Circuit diagram showing the ATmega128 microcontroller connected to a buck converter.

ADC is 13 - 260 μsec. It should be noted that the previous heuristics-based fuzzy control methods of [4, 5, 7-9, 12] require computationally burdensome defuzzification procedures to determine control input values while the proposed method requires no defuzzification module, thus the proposed method is simple and it can be easily implemented by means of a low-cost 8-bit microcontroller. Figs. 6-11 given below were obtained by a Tektronix TDS5104B digital oscilloscope. Fig. 6 shows the experimental results (i_L and v_C) when the proposed fuzzy PID controller is applied to the converter under load variation.

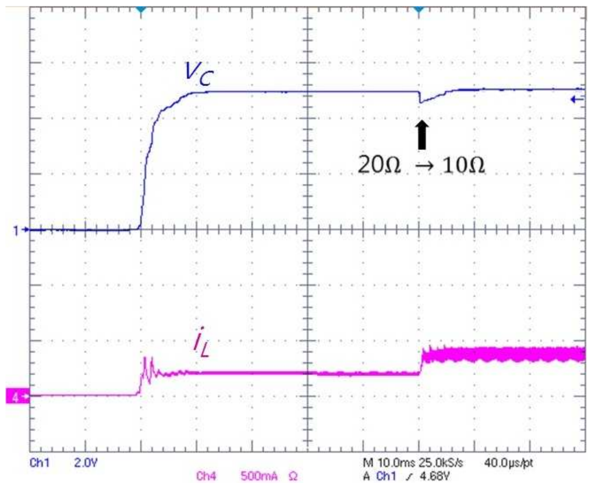

Fig. 6. Experimental results with the proposed fuzzy PID controller (11) under load variation.

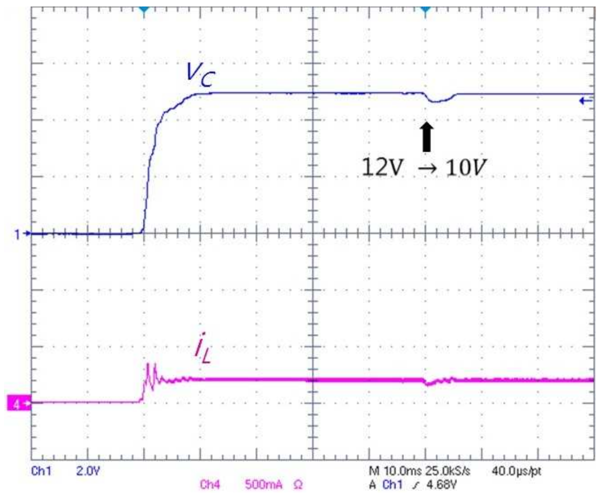

Fig. 7. Experimental results with the proposed fuzzy PID controller (11) under input voltage variation.

The load resistor (R) is suddenly changed from 20[Ω] (nominal value) to 10[Ω] (50% of nominal value). The system behavior under input voltage variation is also tested and the results (i_L and v_C) are shown in Fig. 7. The input voltage is step changed from 10[V](nominal value) to 7.5[V] (25% of nominal value).

For comparisons, we consider the following non-fuzzy PID controller

$$u = \frac{V_r}{E} - \frac{LC}{E}[K_1^P e + K_1^I \int_0^t e d\tau + K_1^D \frac{d}{dt} e] \qquad (12)$$

Figs. 8 and 9 show the experimental results with (12) under the same conditions as Figs. 6 and 7. Figs. 8(a) and 9(a) illustrate the input inductor current (i_L). Figs. 8(b) and 9(b) show the output capacitor voltage (v_C). We also experiment with the following non-fuzzy PID controller (13)

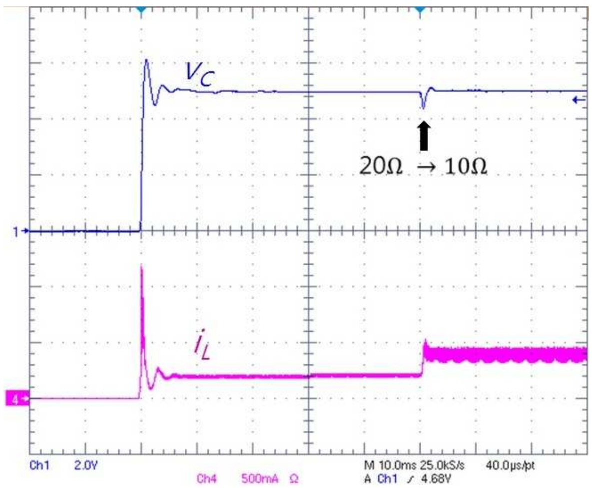

Fig. 8. Experimental results with the conventional non-fuzzy PID controller (12) under load variation.

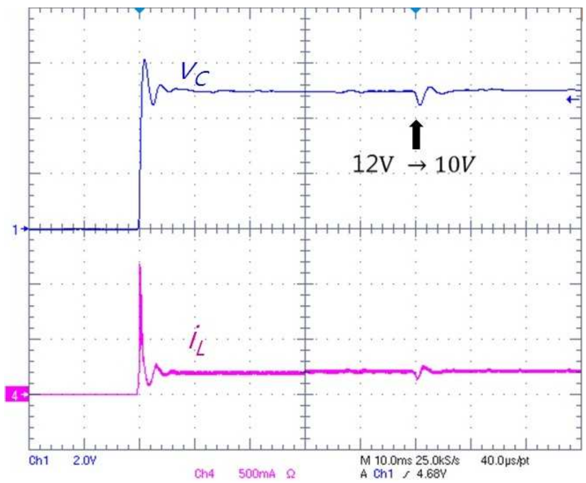

Fig. 9. Experimental results with the conventional non-fuzzy PID controller (12) under input voltage variation.

$$u = \frac{V_r}{E} - \frac{LC}{E}[K_3^P e + K_3^I \int_0^t e d\tau + K_3^D \frac{d}{dt} e] \qquad (13)$$

Figs. 10 and 11 show the experimental results with (13) under the same conditions as Figs. 6 and 7. The PID gain of (12) corresponds to that of the fuzzy Rule 1 for the case that *e* is NB, thus as shown in Figs. 8 and 9 the non-fuzzy PID controller (12) gives fast responses with big overshoot. Since the PID gain of (13) uses that of the fuzzy Rule 3 for the case that *e* is ZO, as shown in Fig. 10 and 11 the non-fuzzy PID controller (13) yields no overshoot at the cost of slow responses. The proposed fuzzy PID controller guarantees fast responses as well as no overshoot under load perturbation and input voltage variation, i.e. the proposed fuzzy PID controller can easily incorporate the advantages of the non-fuzzy PID controllers. From experimental results, it can be concluded that the proposed fuzzy PID controller gives good performance and it can be successfully used to reject input voltage and load variations.

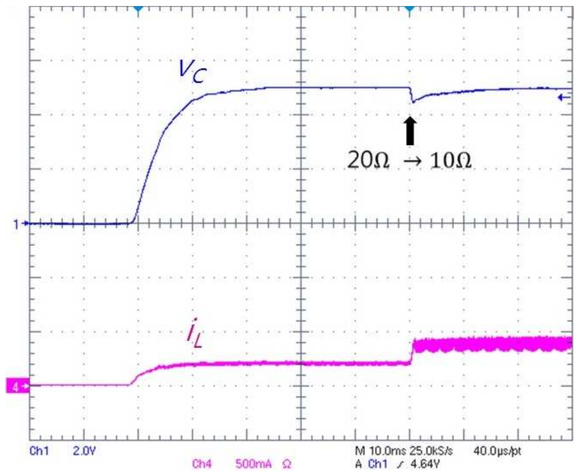

Fig. 10. Experimental results with the conventional non-fuzzy PID controller (13) under load variation.

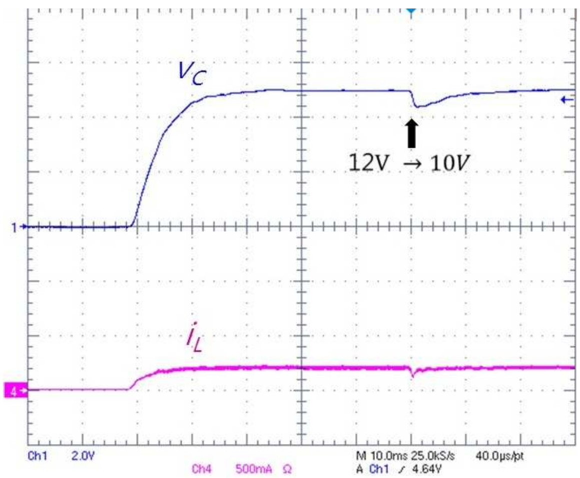

Fig. 11. Experimental results with the conventional non-fuzzy PID controller (13) under input voltage variation.

5. Conclusion

In this paper, a fuzzy PID controller for a buck DC-DC converter was proposed to achieve robust performance. Also, we analytically derived the stability condition which the PID gains should satisfy in order to guarantee the asymptotic stability of the closed-loop control system. Finally, the proposed control scheme was verified by experimental results. It should be noted that fuzzy PID controllers for boost converters, buck-boost, Cuk converters can be designed by using the similar formulations given in this paper

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K.-W. Seo received the B.S. and M.S. degree in Elec. Eng. from Dongguk University, Seoul in 2010 and 2012, respectively. He is now with Samsung Elec., Suwon. His research interests are in the field of microprocessor-based control.

Han Ho Choi received the B.S. degree in Control and Instrumentation Engineering from Seoul National Univ., Seoul, Korea, and the M.S. and Ph.D. degree in Electrical Engineering from KAIST in 1988, 1990, and 1994, respectively. He is now with the Div. of EEE, Dongguk Univ.-Seoul. His research interests include control theory and its application to real world problems.