Wide Input and Load Integral Gain Changeable Digital Control DC-DC Converter

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Abstract- The aim of this paper is to present an integral gain changeable digital control dc-dc converter with wide input and load regulation characteristics. Since the green energy depends on the environment, wide input regulation characteristics are necessary in dc-dc converters. Additionally, dc-dc converters have an issue that the output voltage of dc-dc converters is increased in the light load condition. When the large feedback gain is used to realize wide regulation characteristics, the stability becomes worse. The proposed method can address all of them using a simple integral gain changeable method. The integral gain is changed quickly by the load current value. The integral changeable function uses a single approximate function which is designed by the stabilization range of output voltage based on the integral control. The proposed method has great regulation characteristics against both of the input voltage and load. Furthermore, it has a superior transient response to the conventional integral gain fixed method. Simulated and experimental results are provided to confirm the effectivity of proposed method.

Keywords dc-dc converter; digital control; integral gain; wide regulation; transient response.

1. Introduction

For the effective use of renewable energy, the hybrid green energy system has been attracting attentions. Although this system can compensate a drawback of renewable energy which changes depending on the environment, the control method of switching power supplies becomes complicated [1]-[4]. Control circuits of power supply system have to monitor a lot of voltages, currents and temperatures to make cooperation with other systems. Therefore, digital control techniques have been studied to apply to dc-dc converters [5]-[9]. The digital control circuit can perform easily parameter tuning to address the change of environment.

DC-DC converters are demanded wide input voltage regulation characteristics to supply the stable dc voltage to the load in this system [10]-[13]. Moreover, dc-dc converters tend to operate frequently in the standby or the energy saving mode for the energy saving [14], [15]. In such a light load condition, the operation mode of reactor current becomes the discontinuous conduction mode (DCM). The dc-dc converter has some problems in the DCM. The output voltage is increased abnormally in the DCM. Besides, it is important for the stable and reliable system to improve the transient response from the energy saving mode to the high power active mode. Digital control dc-dc converters are required not only wide input and load regulation characteristics, but also a quick response.

The large feedback gain can address regulation characteristics. The integral gain of digital PID control is especially essential to regulation characteristics in the DCM. However, the large integral gain has a negative effect on the transient response in the CCM. It is desirable to minimize the integral gain for the CCM considering the stability. A two stage integral gain switchover method has been considered as a basic approach to obtain excellent regulation characteristics [16]. This method changes the integral gain between the CCM and DCM. Since the integral gain of CCM is significantly different from the DCM, this method has to find the accurate switchover point. Moreover, the hysteresis function is necessary to prevent the gain oscillation near the switchover point.

This paper presents a new digital integral gain changeable function which can change the integral gain smoothly and simply. The integral gain is changed quickly by the load current detection. The proposed method uses a single approximate function to determine the integral gain even if input voltage and load are changed to any value. The approximate function is designed by the stabilization range of output voltage based on the integral control. At first, the behavior of integral control is analyzed in Section 2. Section describes the circuit configuration and operation principle of proposed method. In the proposed method, the design of reference bias value of PID control is important. It is a key point to obtain a superior transient response and excellent regulation characteristics with corresponding to changing the input voltage. This design is discussed in Section 4. Finally, it is revealed that the proposed method suppresses the increase of output voltage in the DCM and also shows wide input voltage characteristics. The proposed method has great regulation characteristics with a superior transient response by the appropriate design of reference bias in the PID controller.

2. Behavior of Integral Control Based on Stabilization Range of Output Voltage

The PID control is one of the major feedback control methods to regulate the output voltage in dc-dc converters. Equations (1) and (2) represent the digital feedback value N_{PID} in the PID controller.

$$N_{PID}[n] = N_B - K_P(e_O[n-1] - N_R) - K_I N_I - K_D(e_O[n-1] - e_O[n-2]) \quad (1)$$

$$N_I = \sum(e_O[n-1] - N_R) \quad (2)$$

where n denotes n-th switching period, N_B is the reference bias value, K_P, K_I and K_D are the proportional, integral and differential coefficients, $e_O[n]$ is the digital value of output voltage in n-th switching period, N_R is the desired digital value of $e_O[n]$. $K_I N_I$ means the calculation value of I control. N_B is derived as

$$N_B = N_s(1 + r/R_O)E_O{}^*/E_i \quad (3)$$

where N_s is the numerical digital value corresponding to the switching period T_s, r is the internal loss of dc-dc converter, R_O is the load, $E_O{}^*$ is the desired output voltage and E_i is the input voltage. The proportional (P) and derivative (D) control calculation results are zero in the steady-state. The integral (I) control is especially important in order to realize no steady-state-error of output voltage entirely. This section analyzes the relationship between regulation characteristics of the output voltage and the I control in the buck type dc-dc converter.

Figure 1 illustrates regulation characteristics of the output voltage E_O in the steady-state taking K_I as a parameter. $E_O{}^*$ is the desired output voltage, I_O is the load current and I_{NB} is the current at the operating bias point. The operating bias point is determined by N_B. N_{PID} is equal to N_B in this point. When the load is changed from the operating bias point, E_O is increased in the light load condition and decreased in the heavy load condition. As shown in Fig. 1, the wide regulation characteristics are realized by increasing K_I.

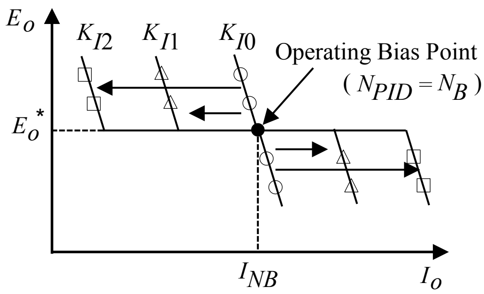


Fig. 1. Regulation Range.

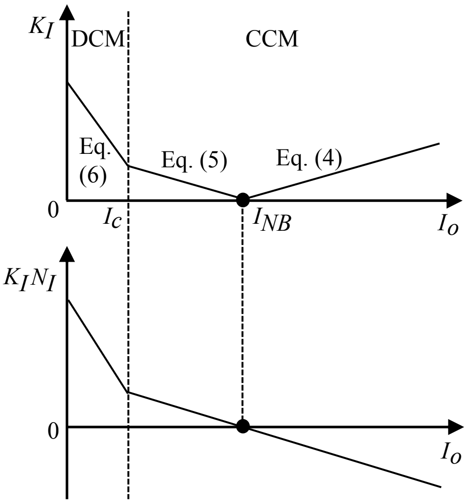


Fig. 2. Pattern diagram of stabilization range of E_O based on K_I and $K_I N_I$.

Figure 2 shows the pattern diagram of stabilization range of E_O based on the I control. I_c is the critical current. According to [17], the relationship between I_O and K_I for the output voltage stabilization is obtained as follows.

$$K_I \geq -\frac{N_B}{2^Q - 1} + \frac{N_s}{E_i\left(2^Q - 1\right)}\left(rI_O + E_O{}^*\right),\ I_O > I_{NB} \quad (4)$$

$$K_I \geq \frac{N_B}{2^Q - 1} - \frac{N_s}{E_i\left(2^Q - 1\right)}\left(rI_O + E_O{}^*\right),\ I_c < I_O \leq I_{NB} \quad (5)$$

$$K_I \geq \frac{N_B}{2^Q - 1} - \frac{2LN_s I_O}{T_{on}E_i(2^Q - 1)\left\{\left(E_i / E_O{}^*\right) - 1\right\}},\ I_O \leq I_c \quad (6)$$

where Q is a bit number of integral control part, L is the

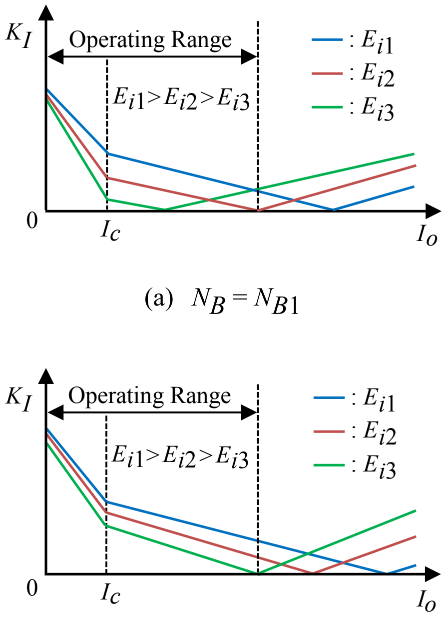


Fig. 3. Stabilization range of E_O when N_B is changed (N_{B1} < N_{B2}).

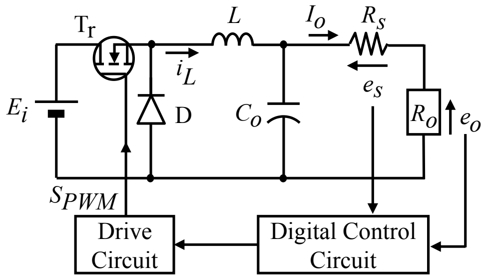


Fig. 4. Digital control buck type dc-dc converter.

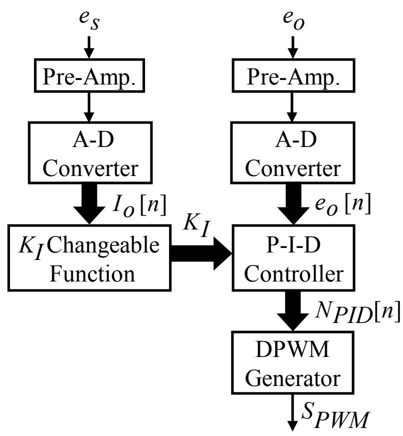


Fig. 5. Proposed control circuit.

energy storage reactor and T_{on} is the on-time of main switch. When K_I is smaller than the value of solid line, E_O cannot be kept to E_O*, that is, the solid line shows minimum required values for the output voltage regulation. The large value of K_I is required in the DCM compared with the CCM. The sign of $K_I N_I$ is different between Eqs. (4) and (5) in the CCM.

From Eqs. (4) through (6), the stabilization range of E_O based on K_I is affected by E_i and N_B as shown in Fig. 3. N_{B1} and N_{B2} are obtained by substituting E_{i1} and E_{i2} into (3), respectively. When it is assumed that E_{i1} is larger than E_{i2}, N_{B1} is smaller than N_{B2}. Minimum required values of K_I are changed by N_B. It is found that N_B is an important value to design K_I changeable function.

3. Circuit Configuration and Operation Principle

Figure 4 shows the digital control buck type dc-dc converter. C_O is the output smoothing capacitor, R_O is the load, T_r is the main switch and D is the fly wheel diode. e_S is the voltage corresponding to I_O and it is detected by the sensing resistor R_S. The proposed control circuit detects e_O and e_S.

The proposed control circuit configuration is described in Fig. 5. e_O converts the digital value $e_O[n]$ by the A-D converter. The digital PID controller receives $e_O[n]$ and calculates $N_{PID}[n]$. $N_{PID}[n]$ is fed into the digital PWM (DPWM) generator, and it outputs the signal S_{PWM} to the main switch. e_S is detected for K_I changeable function through the A-D converter and converted to the digital value $I_O[n]$. The proposed method changes K_I by I_O. To address the variation of E_i and avoid any complex calculation, K_I changeable function is a single approximate function using a logarithm function as Eq. (7) in order to satisfy the stabilization range of E_O in Fig. 3.

$$K_I = \alpha \cdot \ln(I_O) + \beta \tag{7}$$

where α and β are constant values. The proposed method does not have to use multiple expressions even if E_i is changed. Furthermore, the input voltage detection circuit including an A-D converter is not necessary. Equation (7) is drawn using minimum required values of K_I at three points of I_O in the DCM, criticality and CCM, respectively.

As mentioned in Section 2, the stabilization range of E_O and the sign of $K_I N_I$ are changed by N_B and E_i. Due to this, two different K_I changeable functions are prepared using different values of N_B in the next section.

4. Design and Performance Characteristics of K_I Changeable Function

As circuit and control parameters, E_i is usually 20V, E_O* is 5V, the switching frequency is 100kHz, L is 183μH, C_O is

530μF, R_s is 0.05Ω, r is 0.42 Ω, I_c is 0.1A and the rated current is 1A. The A-D converter is 11bits and its sampling frequency is 100kHz. N_s is 2000 and Q is 15. The variation range of E_i is considered from 16V to 24V. K_P and K_D are unity in the PID controller. The A-D converter and PID controller are implemented by the DSP (TMS320C6713-225). The XILINX Virtex-5 FPGA is utilized for the DPWM.

4.1. Design of K_I Changeable Function

Figure 6 shows K_I changeable function and the stabilization range of E_o when N_B is 543. The solid line is K_I changeable function and dashed lines are the stabilization range of E_o in each input voltage. The variation of E_i is not considered in this design. Thus, N_B is calculated by substituting 20 for E_i and 5 for R_o into Eq. (3). In this case, the sign of $K_I N_I$ is different by E_i in the CCM. The approximate function is drawn by values of K_I at 0.01A, 0.1A and 1A. α is -0.002 and β is 0.005 in K_I changeable function.

When N_B is 676, the stabilization range of E_o indicates different characteristics as shown in Fig. 7. E_i and R_o are substituted 16 and 5 into Eq. (3) for the calculation of N_B. The sign of $K_I N_I$ is the same in all operation range even if E_i is changed. α is -0.002 and β is 0.008 in Fig. 7 using the same way as the previous one.

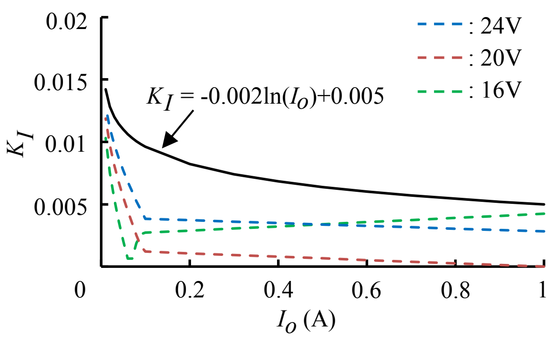


Fig. 6. K_I changeable function when N_B is 543.

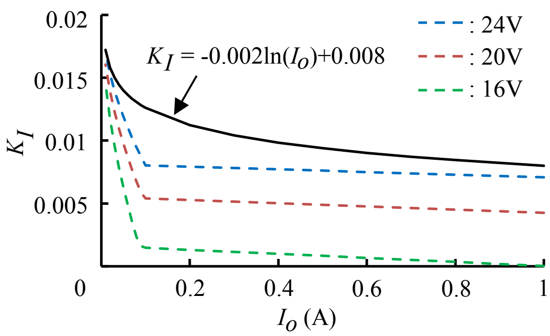


Fig. 7. K_I changeable function when N_B is 676.

4.2. Performance Characteristics

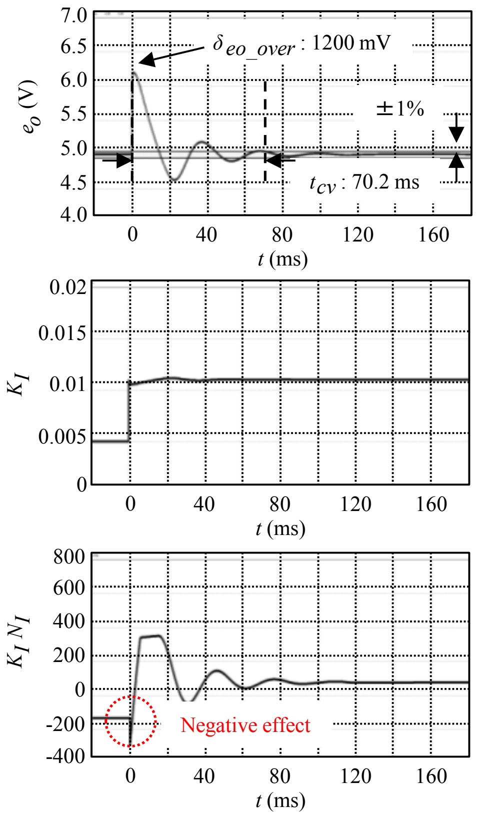
The transient response from the CCM to DCM is discussed by simulated and experimental results to evaluate the impact on the difference of two designs. t_{cv} is the time which e_o converges within 1% from the desired voltage. δ_{eo_over} and δ_{eo_under} the overshoot and undershoot of e_o. δ_{iL_over} is the overshoot of i_L.

Figure 8 shows the transient response of proposed method when N_B is 543. The load step change is from 1A (CCM) to 0.05A (DCM) and E_i is 16V. When the load step change is occurred, K_I is changed to the large value by K_I changeable function in Fig. 6. $K_I N_I$ is the negative value in the CCM. On the other hand, $K_I N_I$ shows the positive value in the steady-state of DCM. $K_I N_I$ has to increase to suppress the overshoot of e_o after the load step change. Since $K_I N_I$ is the negative value before the load step change, the increase of K_I has a negative effect on $K_I N_I$ and the transient response. δ_{eo_over} and t_{cv} are 1120mV and 54.8ms in the experimental result. This negative effect can be solved by increasing N_B.

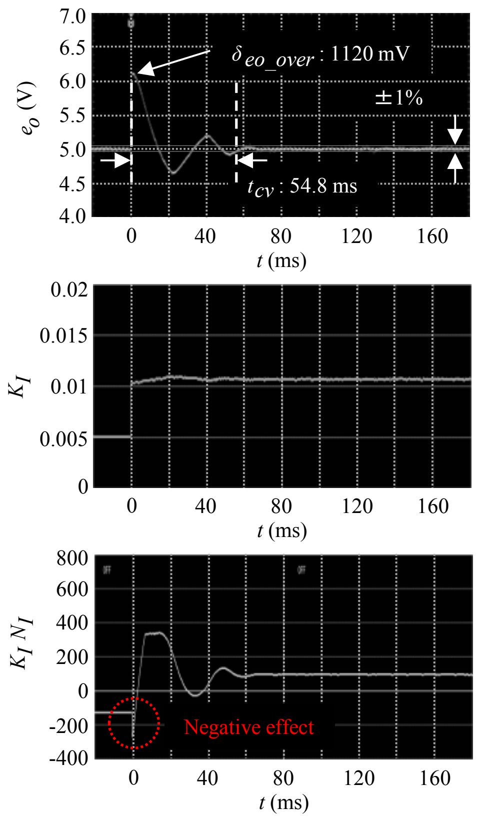
Figure 9 indicates the transient response of proposed method in the same load step change with Fig. 8 when N_B is 676. It is shown that $K_I N_I$ is positive values in both of the CCM and the DCM. Thus, K_I and $K_I N_I$ are smoothly changed in the load step change without the negative effect. δ_{eo_over} is 470mV and t_{cv} is 44.8ms in the experimental result. δ_{eo_over} and t_{cv} are improved by 58% and 23% compared with Fig. 8. It is confirmed that N_B is an important parameter in the transient response, and the design of Fig. 7 is better than that of Fig. 6. N_B has to be determined by the minimum value in the range of variation of E_i.

Figures 10 and 11 compare the transient response in the load step change from 0.05A (DCM) to 1A (CCM). In Fig. 10, K_I is fixed to 0.022 in order to obtain the good regulation characteristics in any load condition. As shown in Fig. 10(b), δ_{eo_under} is 950mV, t_{cv} is 4.8ms and δ_{iL_over} is 990mA. In contrast, Figure 11 shows the transient response of proposed method when N_B is 676. Since the proposed method can change K_I to the small value in the CCM, the stability is improved. Additionally, $K_I N_I$ becomes quickly small value after the transient response, δ_{eo_under} and δ_{iL_over} are suppressed. δ_{eo_under} is 790mV, t_{cv} is 7.5ms and δ_{iL_over} is 550mA in Fig. 11(b). Although t_{cv} is not shortened owing to the improvement of stability in the CCM, δ_{eo_under} and δ_{iL_over} are improved by 17% and 44%, respectively. As a result, the proposed method shows a superior transient response to the conventional method using fixed value of K_I.

Figures 12 and 13 indicates load and input voltage

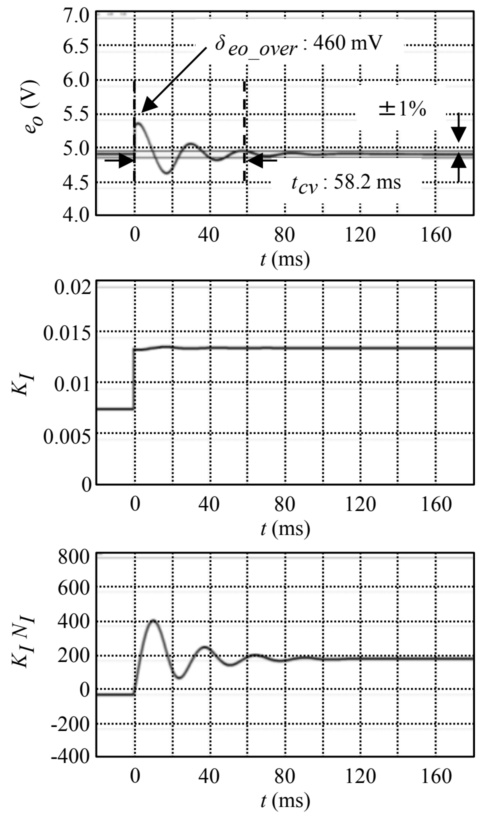


(a) Simulated result.

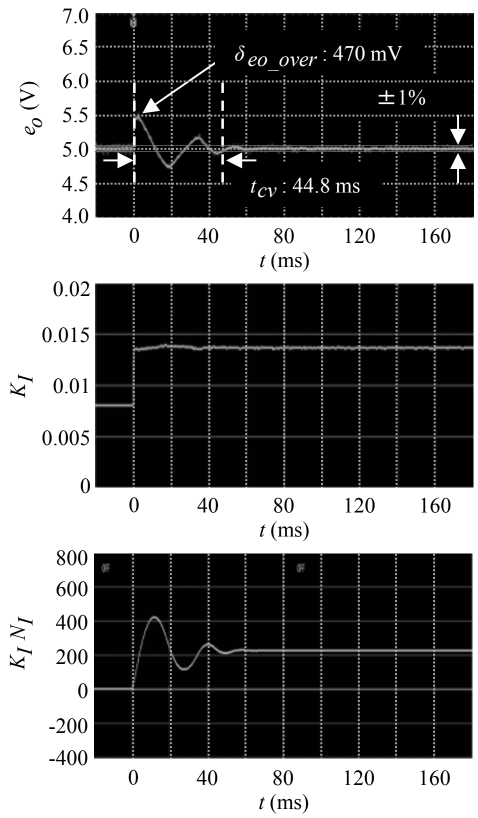


(b) Experimental result.

Fig. 8. Transient response of proposed method in step change of I_o from 1A to 0.05A when N_B is 543.

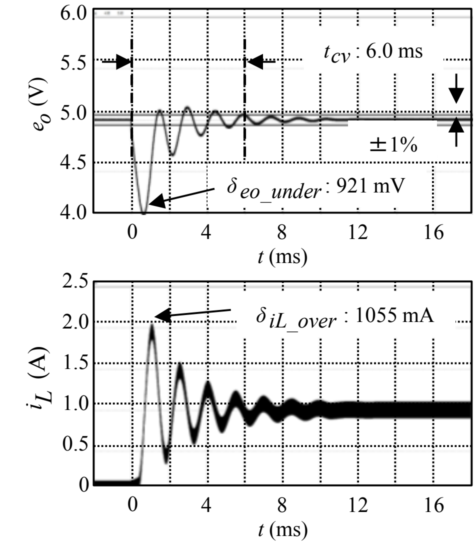


(a) Simulated result.

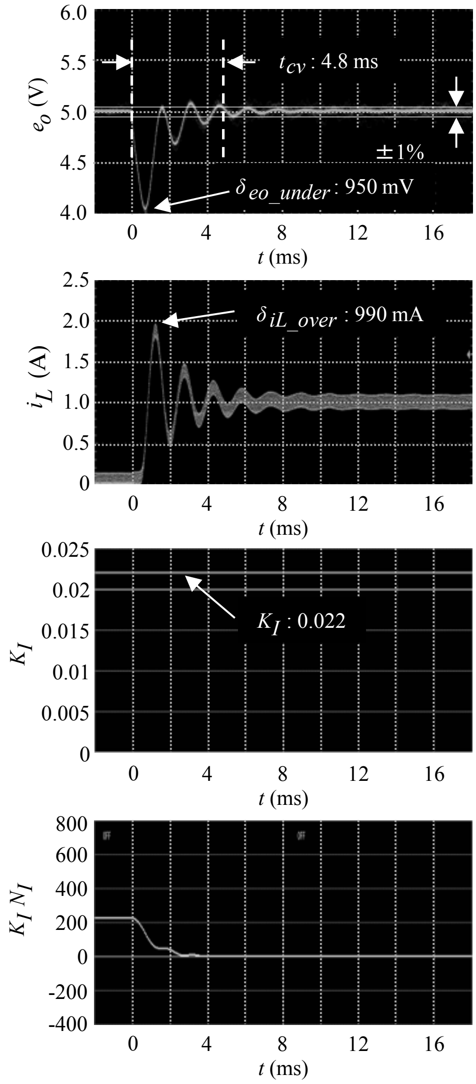


(b) Experimental result.

Fig. 9. Transient response of proposed method in step change of I_o from 1A to 0.05A when N_B is 676.

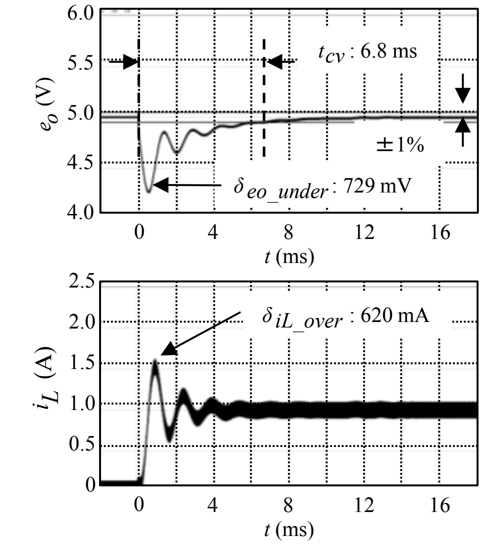


(a) Simulated result.

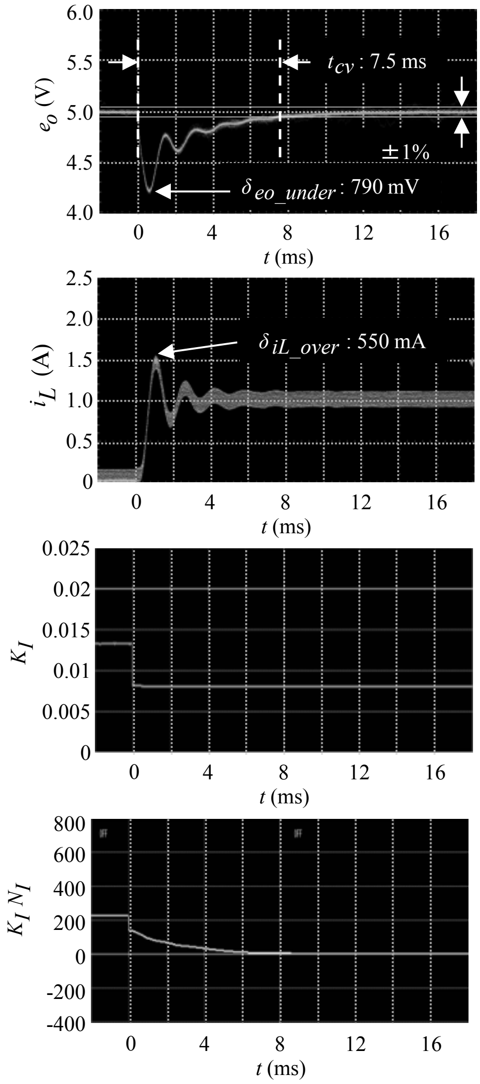


(b) Experimental result.

Fig. 10. Transient response in step change of I_O from 0.05A to 1A K_I is fixed to 0.022.



(a) Simulated result.



(b) Experimental result.

Fig. 11. Transient response of proposed method in step change of I_O from 0.05A to 1A when N_B is 676.

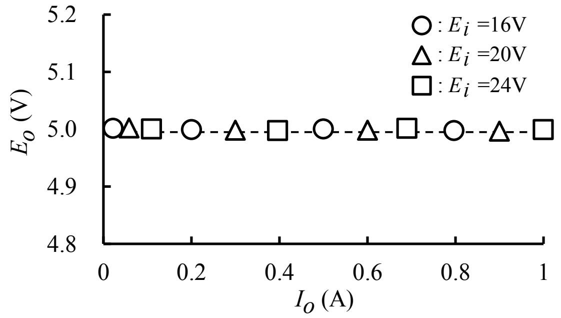


Fig. 12. Load regulation characteristics of proposed method.

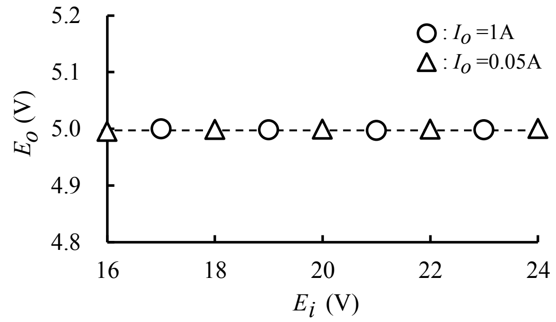


Fig. 13. Input voltage regulation characteristics of proposed method.

regulation characteristics of the proposed method when N_B is 676. Since K_I is changed to the minimum required values in Fig. 7, E_o is not increased in the DCM. Moreover, excellent regulation characteristics are realized even if E_i is varied from 16V to 24V. The proposed method shows wide input voltage and load regulation characteristics using the simple integral gain changeable control. It is verified that the proposed method is effective to improve both of regulation characteristics and transient response.

5. Conclusion

The simple integral gain changeable digital control dc-dc converter is presented for the wide input and load. The proposed method detects the load current to change the integral gain. The integral gain is determined by minimum required values of the stabilization range of output voltage based on the integral control. A single approximate function is used for the integral gain changeable function. Thus, the proposed method does not have to design the hysteresis function and use the switchover of operation expressions. It is important that the reference bias value of PID control be designed by the minimum value in the variation range of input voltage to avoid worsening the transient response. The proposed method shows a superior transient response to the conventional integral gain fixed method by appropriate design. Furthermore, the proposed method can keep the desired output voltage in the DCM even if the input voltage is changed. It is revealed that wide regulation characteristics are obtained in the proposed method. The proposed method is effective for the realization of high stability and reliable green energy system because it can improve both of regulation characteristics and the transient response.

References

[1] H. H. Abdeltawab and Y. A. R. I. Mohamed, "Market-oriented energy management of a hybrid wind-battery energy storage system via model predictive control with constraint optimizer," *IEEE Trans. on Industrial Electronics*, vol. 62, no. 11, pp. 6658–6670, Nov. 2015.

[2] D. B. W. Abeywardana, B. Hredzak, and V. G. Agelidis, "Single-phase grid-connected LiFePO4 battery-supercapacitor hybrid energy storage system with interleaved boost inverter," *IEEE Trans. on Power Electronics*, vol. 30, no. 10, pp. 5591–5604, Oct. 2015.

[3] Y. Kang, C. Chiu, M. Lin, C. Yeh, J. Lin,and K. Chen, "Quasiresonant control with a dynamic frequency selector and constant current startup technique for 92% peak efficiency and 85% light-load efficiency flyback converter," *IEEE Trans. on Power Electronics*, vol. 29, no. 9, pp. 4959-4969, Sept. 2014.

[4] S. A. Khajehoddin, M. Kaeimi-Ghartemani, P. K. Jain, and A. Bakhshai, "DC-bus design and control for a single-phase grid-connected renewable converter with a small energy storage componet," *IEEE Trans. on Power Electronics*, vol. 28, no. 7, pp. 3245-3254, Oct. 2012.

[5] M. Vulovic, D. Boroyevich and P. Mattavelli, "Digital gain-scheduled control of a high frequency parallel resontant dc-dc converter," in *Proc. IEEE Applied Power Electronics Conference and Exposition*, Feb. 2012, pp.1814-1820.

[6] S. Chae, Y. Song, S. Park and H. Chung "Digital current sharing method for mulitiphase dc-dc converters using the peak input voltage," in *Proc. IEEE Energy Conversion Congress and Exposition*, pp.1307-1311, Sept. 2011.

[7] L. Corradini and P. Mattavelli "Modeling of multisampled pukse width modulators for digitally controlled dc-dc converters," *IEEE Trans. on Power Electronics*, vol. 23, no. 4, pp. 1839-1847, July 2008.

[8] J. Lee, J. Shin and B. H. Cho "A digital predictive critical conduction mode buck converter control method," in *Proc. IEEE Applied Power Electronics Conference and Exposition*, Feb. 2012, pp.709-714.

[9] Z. Zhao and A. Prodic, "Limit-cycle oscillations based auto-tuning system for digitally controlled dc-dc power supplies," *IEEE Trans. on Power Electronics*, vol. 22, no. 6, pp. 2211-2222, Nov. 2007.

[10] S. Lim, J. Ranson, D. M. Otten, and D. J. Perreault, "Two-stage power conversion architecture suitable for wide range input voltage," *IEEE Trans. on Power Electronics*, vol. 30, no. 2, pp. 805–816, Feb. 2015.

[11] R. Guo, Z. Liang, and A. Q. Huang, "A family of multimodes charge pump based dc–dc converter with high efficiency over wide input and output range,"

IEEE Trans. on Power Electronics, vol. 27, no. 11, pp. 4788–4798, 2012.

[12] K. A. Cho, S. H. Ahn, S.B. Ok, H. J. Ryoo, S. R. Jang and G. H. Rim “Design of LCC resonant converter for renewable energy systems with wide-range input voltage,” in *Proc. IEEE Power Electronics and Motion Control Conference*, Jun. 2012, pp. 1221-1228.

[13] Hao Cheng, K. M. Smedley, and A. Abramovitz, “A wide-input-wide-output (WIWO) dc-dc converter,” *IEEE Trans. on Power Electronics*, vol. 25, no. 2, pp. 280–289, Feb. 2010.

[14] O. Trescases and W. Yue, “A survey of light-load efficiency improvement techniques for low-power dc-dc converters,” in *Proc. IEEE Power Electronics and Asia (ICPE& ECCE)*, May 2011, pp.326-333.

[15] T. Ueno, T. Miyazaki, T, Ogawa and T. Itakura, “A 600 mA, constant on-time controlled DC-DC converter with 67% conversion efficiency at an output current of 23 μA,” in *Proc. IEEE Applied Power Electronics Conference and Exposition*, Mar. 2014, pp.1932-1935.

[16] F. Kurokawa and S. Higuchi, “Control characteristics of dc-dc converter using digital integral gain switchover function,” in *Proc. IEEE International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Jun. 2012, pp. 1320-1323.

[17] H. Matsuo, F. Kurokawa, K. Imamura, K. Imamura and K. Tanaka, “Regulation characteristics of the DC-DC converter with digital current-injected control circuit,” in *Proc. IEEE International Telecommunications Energy Conference*, Sept. 1992, pp. 455-462.