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

Kazuhiro Kajiwara*, Hidenobu Tajima*, Fujio Kurokawa*

* Graduate School of Engineering, Nagasaki University, 1-14 Bunkyo-machi, Nagasaki, 852-8521, Japan  
  (bb52311101@cc.nagasaki-u.ac.jp, amsky1306@gmail.com, fkurokaw@nagasaki-u.ac.jp)

‡ Corresponding Author; Kazuhiro Kajiwara, Graduate School of Engineering, Nagasaki University,  
1-14 Bunkyo-machi, Nagasaki, 852-8521, Japan,  
Tel: +81 95 819 2553, bb52311101@cc.nagasaki-u.ac.jp

Received: 03.11.2015 Accepted: 08.12.2015

**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 given by the integral range of output voltage based on the integral control. At first, the behavior of integral control is analyzed in Section 2. Section 3 describes the circuit configuration and operation principle of the 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.

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

\[
N_I = \sum(e_o[n-1] - N_R) \tag{2}
\]

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

\[
N_B = N_s(1 + r/R_o)E_o^* / E_i \tag{3}
\]

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 \( K_I \).

Figure 2 shows the pattern diagram of stabilization range of \( E_o \) based on \( K_I \) and \( K_I N_I \).

\[
K_I = \frac{N_B}{2^Q - 1} \left( \frac{N_s}{E_i(2^Q - 1)} \right) (rI_o + E_o^*), \quad I_o > I_{NB} \tag{4}
\]

\[
K_I = \frac{N_B}{2^Q - 1} \left( \frac{N_s}{E_i(2^Q - 1)} \right) (rI_o + E_o^*), \quad I_c < I_o \leq I_{NB} \tag{5}
\]

\[
K_I = \frac{N_B}{2^Q - 1} \left[ \frac{2LN_s I_o}{T_{on} E_i(2^Q - 1)} \left( \frac{E_i}{E_o^*} - 1 \right) \right], \quad I_o \leq I_c \tag{6}
\]

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 ($N_{B1} < N_{B2}$).

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 $K_iN_I$ 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 $SPWM$ 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.

$$K_I = \alpha \cdot \ln(I_o) + \beta$$

where $\alpha$ and $\beta$ 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 $K_iN_I$ 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, Rs is 0.05Ω, r is 0.42Ω, Ic 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 \( K_P N_I \) 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. \( \alpha \) is -0.002 and \( \beta \) 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 \( K_P N_I \) is the same in all operation range even if \( E_i \) is changed. \( \alpha \) is -0.002 and \( \beta \) 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.](image)

\[ K_I = -0.002 \ln(I_o) + 0.005 \]

![Fig. 7. \( K_I \) changeable function when \( N_B \) is 676.](image)

\[ K_I = -0.002 \ln(I_o) + 0.008 \]

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. \( \delta_{eo\_over} \) and \( \delta_{eo\_under} \) are the overshoot and undershoot of \( e_o \). \( \delta_{iL\_over} \) is the overshoot of \( iL \).

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. \( K_P N_I \) is the negative value in the CCM. On the other hand, \( K_P N_I \) shows the positive value in the steady-state of DCM. \( K_P N_I \) has to increase to suppress the overshoot of \( e_o \) after the load step change. Since \( K_P N_I \) is the negative value before the load step change, the increase of \( K_I \) has a negative effect on \( K_P N_I \) and the transient response. \( \delta_{eo\_over} \) 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 \( K_P N_I \) is positive values in both of the CCM and the DCM. Thus, \( K_I \) and \( K_P N_I \) are smoothly changed in the load step change without the negative effect. \( \delta_{eo\_over} \) is 470mV and \( t_{cv} \) is 44.8ms in the experimental result. \( \delta_{eo\_over} \) 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), \( \delta_{eo\_under} \) is 950mV, \( t_{cv} \) is 4.8ms and \( \delta_{iL\_over} \) 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, \( K_P N_I \) becomes quickly small value after the transient response, \( \delta_{eo\_under} \) and \( \delta_{iL\_over} \) are suppressed. \( \delta_{eo\_under} \) is 790mV, \( t_{cv} \) is 7.5ms and \( \delta_{iL\_over} \) is 550mA in Fig. 11(b). Although \( t_{cv} \) is not shortened owing to the improvement of stability in the CCM, \( \delta_{eo\_under} \) and \( \delta_{iL\_over} \) 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...
Fig. 8. Transient response of proposed method in step change of $I_o$ from 1A to 0.05A when $N_B$ is 543.

Fig. 9. Transient response of proposed method in step change of $I_o$ from 1A to 0.05A when $N_B$ is 676.
Fig. 10. Transient response in step change of $I_o$ from 0.05A to 1A $K_I$ is fixed to 0.022.

Fig. 11. Transient response of proposed method in step change of $I_o$ from 0.05A to 1A when $N_B$ is 676.
is changed. It is revealed that wide regulation characteristics of the proposed method shows a superior transient response to the conventional integral gain fixed method by appropriate design. Thus, the proposed method does not have to design the hysteresis function. Thus, 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.

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 hysteretic 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


