Quick Response Wide Input Range DC-DC Converter for Renewable Energy System

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Abstract- The switching power supply must deal with much more tasks than ever in the renewable energy system whose implementation is being promoted. For that reason, the digital control switching power supply is recognized as a solution in such a complex system. Although the digital control can realize a higher performance than the analog control, there are issues still need to be improved for further development. The delay time caused by the A-D conversion and processing time influences the dynamic characteristics and transient response. Also, the control precision depending on the quantization error leads to the limit cycle oscillation. These issues must be improved in the digital control. In this paper, the quick response wide input range DC-DC converter has been studied, which meets the demand on the control precision of output voltage, transient response, and dynamic characteristics that are required for the renewable energy system. The proportional gain is changed to a high value at the beginning of the transient state. It is then attenuated smoothly to an initial value, which is set to a low value for steady state. A high proportional gain is used for short time in the transient state. In brief, the proposed method can utilize the feedback gain according to the situation and can meet the demand simultaneously. Therefore, the proposed method is effective in such a complex condition occurring in the renewable energy system.

Keywords DC-DC Converter; Digital Control; Nonlinear Control; Feedback Gain Changing.

1. Introduction

The utilization of the renewable energy has been attracted attention due to growing an amount of the energy consumption and CO2 emission. The renewable energy has some advantages that are its sustainability, low CO2 emission, and disuse of the fossil fuel. On the other hand, the power supply must perform the more flexible operation than ever to optimize the use of the renewable energy because the power generation amount from it always depends on the environmental condition [1-12]. In addition, the power supply plays a role of power flow controller for the demand and supply of energy always changing. The general configuration of the renewable energy system is shown in Fig. 1. There are many components which consume, store, and generate energy. The energy flow and the DC bus voltage are also dynamic. Therefore, the digital control switching power supply attracts attention because it has a capability to meet the advanced and various requirements for the power supply [13-31].

Following items are parts of features of the digital control:

- A superior performance is easily implemented by its flexibility.
- It can communicate with the host and other components via the network.
- It can utilize information.
- Parameters are tuned depending on the condition.

The digital control switching power supply must be developed because the renewable energy system needs solutions to meet the complicated and various requirements which include the energy flow control. It can promote the energy saving.

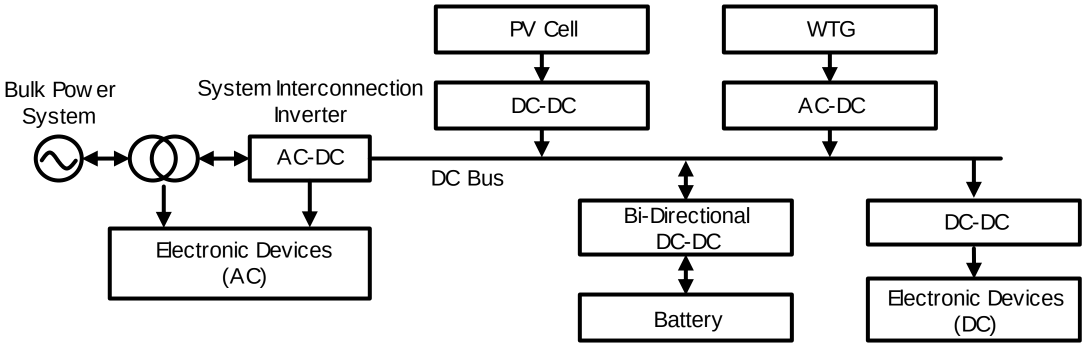


Fig. 1. General configuration of renewable energy system.

However, the delay time, by which the dynamic and transient characteristics of the system are influenced, occurs in the digital control due to the A-D conversion and processing time [29, 30]. Moreover, the quantization error brings limit cycle oscillation which disturbs the output voltage and makes the control precision coarse [31]. The high feedback gain enhances this oscillation. They are one of the issue of the digital control. In terms of the static and dynamic characteristics, the feedback gain should be low to keep the control precision and stability of the system. It should conversely be set to a high value enough to get a quick response. It must be considered additionally that the DC bus voltage fluctuation which always depends on the balance of the demand and supply makes the design of the switching power supply more difficult in the DC powering system. The feedback gain should be changed dynamically taking advantage of the digital control because a proper feedback gain setting is different for the property and condition of the power supply. It can realize a superior control performance to the analog control without breaking the static and dynamic characteristics.

This paper presents the quick response wide input range DC-DC converter for renewable energy system. In the proposed method, the low feedback gain setting for the steady state suppresses the limit cycle oscillation and keeps the stability of the system. The high proportional gain is utilized to return the output voltage to the reference voltage quickly. And then, it is attenuated to the low gain for the steady state smoothly using the exponential function to avoid the shock by gain changing. Namely, the feedback gain can be optimized by such a simple method: the low gain is set in the steady state and the high proportional gain is set for a short time in the transient state. It brings a high performance, which cannot be realized by the analog control.

At first, the property of the digital PID control are discussed to show a necessity of the proposed method. The operation principle of the proposed method is explained and the discussion about the parameter setting of the proposed method is carried out by clarifying the operation. The comparison between the conventional PID control and proposed method shows the validity of the proposed method. The proposed method can improve undershoot, overshoot, and convergence time of the output voltage by up to 59%, 49%, and 90%. Similarly, the consideration is done under the condition assuming the input voltage fluctuation, which occurs in the renewable energy system. Consequently, it is revealed that the proposed method can solve the issue of the digital control and show a superior transient response to the analog control. The proposed method can be effective in the renewable energy system and contribute the development of the renewable energy system.

2. Properties of Digital PID Control

2.1. Control Precision

The control precision of the digital PID control is discussed in this section. The general configuration of the digital control circuit is depicted in Fig. 2. An output voltage e_O of the DC-DC converter is sent to the A-D converter whose resolution is Q_{AD} bits. The PID controller calculates the on time of the main switch which is expressed as a digital value N_{Ton}. The resolution of the PID controller is Q_{PID} bits. The DPWM signal generator outputs the PWM signal S_{PWM} depending on N_{Ton}. It S_{PWM} has the resolution Q_{DPWM}. The P control whose resolution is Q_P bits is the dominant factor for the control precision in the digital PID control. An influence of the P control on the control precision is considered. The equation of the P control is expressed in Eq. (1).

$$N_{Ton} = N_B - K_P(e_o[n] - N_r) \quad (1)$$

where N_B is the bias value of the PID control. K_P is the coefficient of the P control. $e_O[n]$ is the digital value of the output voltage e_O. N_r is the reference value. The error N_{error} of e_O is expressed as follows.

$$N_{error} = e_o[n] - N_r \quad (2)$$

From Eq. (1) and Eq. (2), the following equation is derived.

$$N_{Ton} = N_B - K_P N_{error} \quad (3)$$

Eq. (4) considers the small change in Eq. (3).

$$N_{Ton} + \Delta N_{Ton} = N_B - K_P(N_{error} - \Delta N_{error}) \quad (4)$$

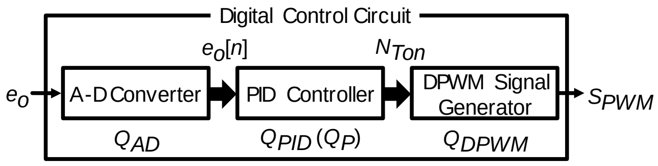


Fig. 2. General configuration of digital control circuit.

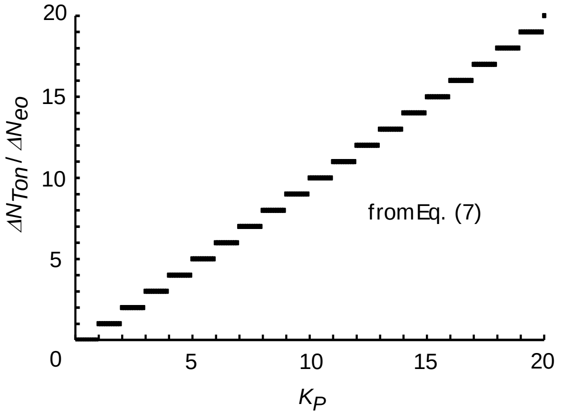


Fig. 3. Relationship between ΔN_{Ton} / ΔN_{eo} and K_P.

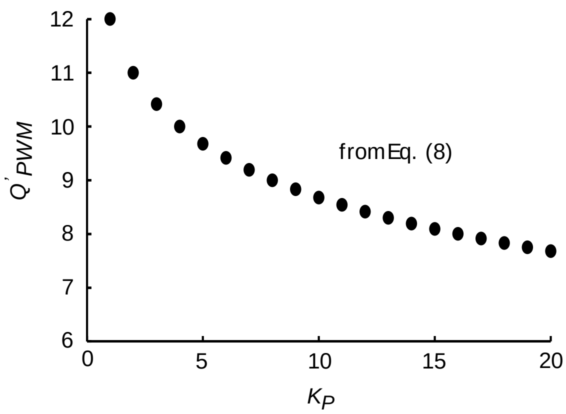


Fig. 4. Relationship between Q'_{PWM} and K_P.

where ΔN_{error} is replaced by

$$\Delta N_{error} = (e_o[n] - N_r) - (e_o[n-1] - N_r)$$
$$= e_o[n] - e_o[n-1] = \Delta N_{eo}. \tag{5}$$

ΔN_{eo} is the small change of $e_O[n]$. The resolution of the P control is expressed by substituting Eq. (5) for Eq. (4).

$$\frac{\Delta N_{Ton}}{\Delta N_{eo}} = K_P \tag{6}$$

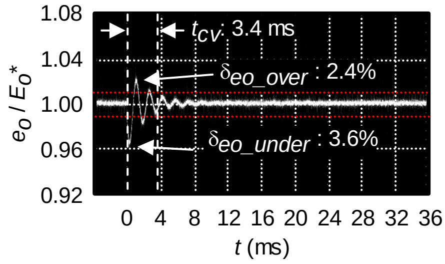


Fig. 5. Transient response of e_O (K_P = 1, K_I = 0.01, and K_D = 1).

The relationship between ΔN_{Ton} / ΔN_{eo} and K_P which means the resolution of the P control is described in Fig. 3 according to Eq. (7). It gets coarse as K_P increases. The relationship among resolutions Q_{AD}, Q_P, and Q_{DPWM} is as follows.

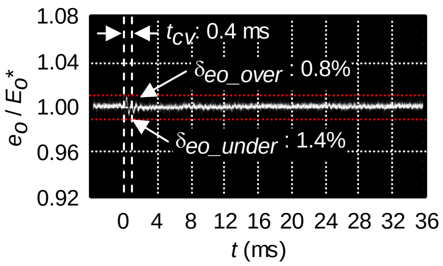
$$2^{Q_P} = \frac{2^{Q_{AD}}}{[K_P]} = 2^{Q'_{DPWM}} \tag{8}$$

where Q'_{DPWM} is a pseudo resolution of DPWM signal generator. Q_{DPWM} is influenced by K_P because the DPWM signal generator outputs the PWM signal S_{PWM} using N_{Ton}. Q_{DPWM} becomes, for example, one fourth ($Q'_{DPWM} = Q_{DPWM}$ - 2) when K_P is set to 4 (= 2^2) in case of $Q_{AD} = Q_{DPWM}$. Fig. 4 describes this relationship between Q'_{PWM} and K_P using Eq. (8). Q'_{DPWM} is decreased when K_P is set to a large value as illustrated in Fig. 4. Namely, K_P should be set to 1 to control e_O precisely.

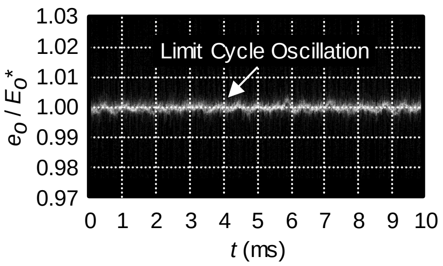
2.2. Transient Response

It is revealed that the high proportional gain set by a large K_P brings worsening of Q'_{DPWM} and the control precision of e_O. Figs. 5 and 6 are the transient response of e_O in the case of the different feedback gain. E_O^* / E_i^* is 0.25. The load resistance R / R^* changes stepwise from 5 to 1. The time constant τ_{LC} of the LC filter in the buck type DC-DC converter is about 440 μs. The evaluation items are the undershoot δ_{eo_under} and overshoot δ_{eo_over} of e_O, and the convergence time t_{CV} when e_O converges within plus or minus 1% of reference voltage E_O^*. Fig. 5 shows the transient response of e_O when K_P, K_I, and K_D are set to 1, 0.01, and 1 to get good regulation characteristics. K_I and K_D are the coefficient of the integral and differential control. K_D is set to 1 not to be susceptible to a noise. The transient response is slow since the feedback gain depends on the static characteristics.

While, the transient response of e_O is shown in Fig. 6 when K_P, K_I, and K_D are set to 10, 0.01, and 4 for a quick response. Although a quick response is realized, the disturbance on e_O caused by the limit cycle oscillation occurs in steady state.



(a) Overview.



(b) Enlarged view in steady state.

Fig. 6. Transient response of e_O (K_P = 10, K_I = 0.01, and K_D = 1).

From the above, a quick response and the control precision of e_O are contrary to each other in the digital control DC-DC converter. It cannot be improved by only the feedback gain setting. Furthermore, the influence of the delay time makes the design difficult.

3. Operation Principle of Proposed Method

Fig. 7 illustrates the block diagram of the digital control buck type DC-DC converter. Symbols represent circuit parameters: E_i is an input voltage. e_O is an output voltage. D is a flywheel diode. T_r is a main switch. R is a load. C is an output smoothing capacitor. L is an energy storage reactor. The scheme of digital controller is in Fig. 8. e_O is sent to the A-D converter through the pre-amplifier. It is converted to the digital value $e_O[n]$ by the A-D converter. $e_O[n]$ is used for the PID control calculation and the proportional gain changing. N_{Ton} is set to the PWM generator to count the on time. The PWM signal generator outputs the PWM signal S_{PWM} which is sent to the drive circuit. Fig. 9 depicts the mechanism of the proportional gain changeable function. The proportional gain changer changes K_P from K_{P_st} to K_{P_tr} suddenly to realize a quick response of e_O when e_O exceeds the threshold voltage V_{th1}or V_{th2}. K_{P_tr} is set to a large value which ignores the stability margin because it is used for a short time in the transient state. After that, K_P is attenuated according to following function.

$$K_P = K_{P\_tr} e^{-\lambda t} \tag{9}$$

In (9), an exponential function is used to decrease K_P gently.

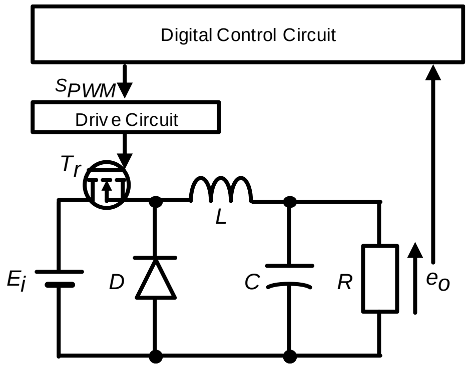


Fig. 7. Block diagram of digital control buck type dc-dc converter.

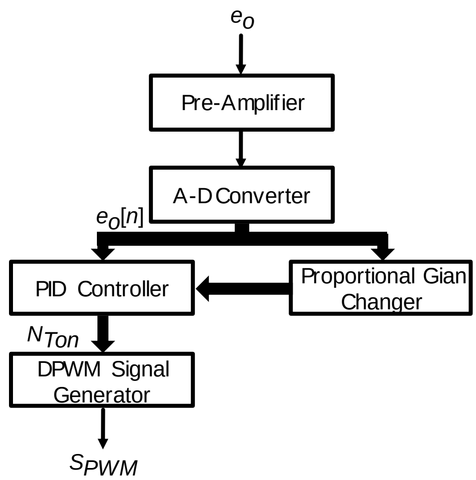


Fig. 8. Scheme of digital controller.

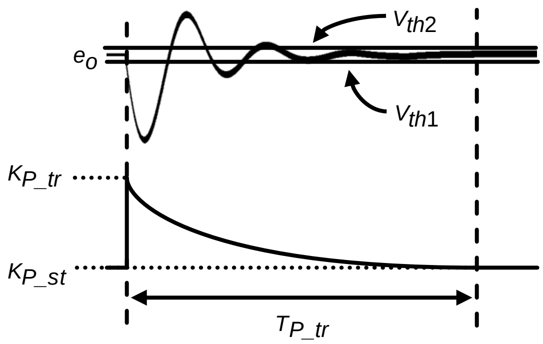


Fig. 9. Mechanism of the proportional gain changeable function.

λis an arbitrary constant which is derived as follows.

$$K_{P\_tr} e^{-\lambda T_{P\_tr}} = K_{P\_st} \qquad (t = T_{P\_tr}) \tag{10}$$

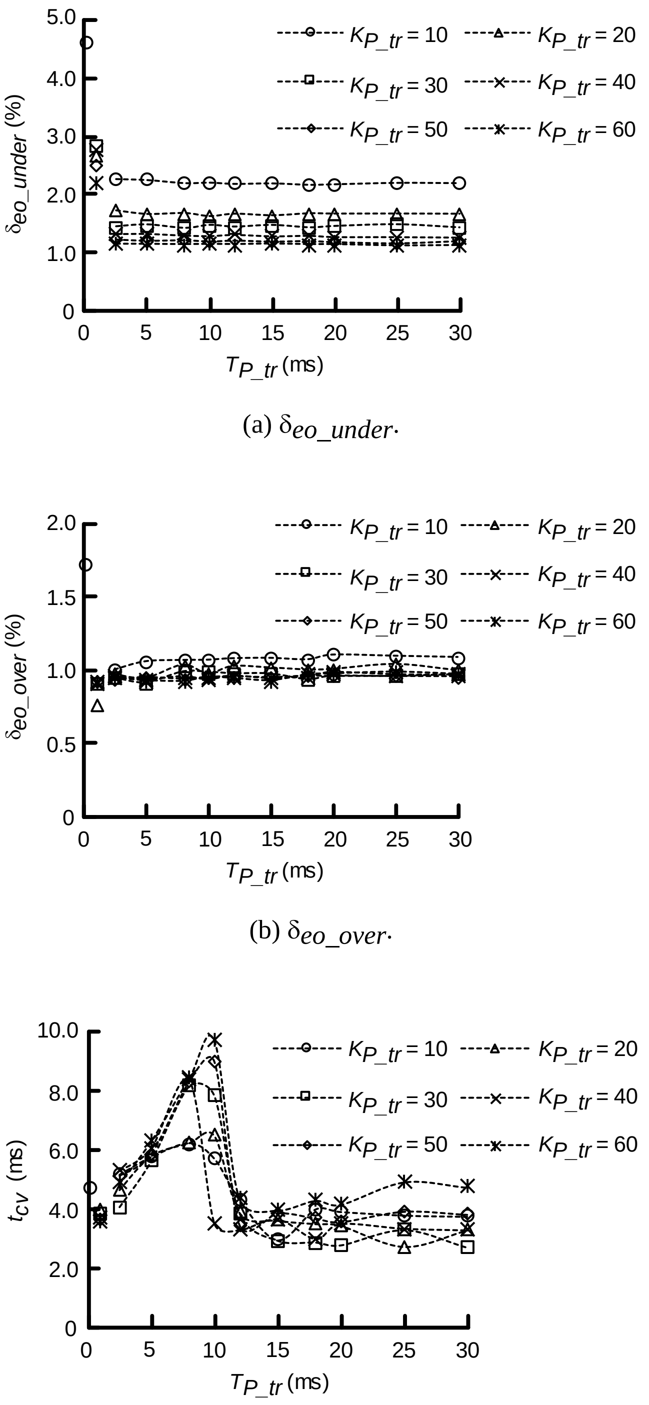
$$\lambda = -\frac{1}{T_{P\_tr}} \ln \frac{K_{P\_st}}{K_{P\_tr}} \tag{11}$$

where T_{P_tr} is the duration of the proportional gain changing.

4. Verification of Proposed Method

4.1. Parameter Setting of Proportional Gain Changing

The parameter setting of the proportional gain changing is discussed considering the transient characteristics in the simulation. Fig. 10 indicates the transient characteristics of the proposed method. The circuit parameter and evaluation items are the same as Section 2 excluding t_{cv}. In Fig. 10, t_{cv} means the time when e_o converges plus or minus 0.5% of $E_o{}^*$. In the simulation, V_{th1} and V_{th2} are set to plus or minus 0.4% of $E_o{}^*$ in order to realize the ideally work of the gain changer. δ_{eo_under} and δ_{eo_over} are suppressed as the proportional gain changing duration T_{P_tr} increases. The tendency of t_{cv} changes around T_{P_tr} = 10 ms. It is discussed according to the transient response of the proposed method under changing T_{P_tr} shown in Fig. 11. K_{P_tr} is set to 30 in this figure. The operation of the proposed method can be confirmed. K_P is suddenly changed at the beginning of the transient state and is attenuated exponentially according to T_{P_tr}. When T_{P_tr} is 1 ms, t_{cv} becomes long because it is too short to cover the disturbance of e_o in the transient state. The disturbance of e_o in the transient state is covered by the proportional gain changing in the case of T_{P_tr} = 5 ms and 10 ms. However, the P control is dominant and an error of e_o is small for the proportional gain changing duration. It takes a long time for the summation value N_I of an error of e_o enough to fill up the steady state error in the I control. In other words, it is necessary that an error of e_o is almost accumulated in the resistor of the I control, whose output value reaches a final value, at the end of the proportional gain changing. Hence, exceeds plus or minus 0.5% of $E_o{}^*$ and t_{cv} gets long in the case of T_{P_tr} = 5 ms and 10 ms. When N_I at the end of the proportional gain changing is compared with its final value, the differences are 1240 and 420, respectively. Likewise, N_I is small value (= 160) enough to regulate e_o quickly as T_{P_tr} is set to 14 ms.



(a) δ_{eo_under}.

(b) δ_{eo_over}.

(c) t_{cv}.

Fig. 10. Transient characteristics of proposed method.

Fig. 12 depicts the transient characteristics taking K_{P_tr} as a parameter when T_{P_tr} is set to 14 ms. From Fig. 12, it is confirmed that a quick response is obtained around K_{P_tr} = 30. As a result, T_{P_tr} = 14 and K_{P_tr} = 30 are chosen in the proposed method.

4.2. Comparison between Proposed Method and Conventional PID Control

The transient responses of e_o in the proposed method and the conventional PID control are shown in Figs. 13 and 14. Note that is K_P decreased in the proportional gain changing duration according to Eq. (12) because the exponential function is impossible to be implemented into the DSP used in the experiment.

$$K_P = K_{P\_tr} - \frac{K_{P\_tr} - K_{P\_st}}{T_{P\_tr}} t \tag{12}$$

The circuit parameter and evaluation items are as well as Section 2. In the simulation and experiment of this comparison, V_{th1} and V_{th2} are set to plus or minus 1.2% of $E_o{}^*$ to keep the operation of the gain changer as ideally as possible and avoid a malfunction by a noise. The simulation and experimental results illustrated in Figs. 13 and 14 are almost matched in each method. In the experimental result, the proposed method can improve δ_{eo_under}, δ_{eo_over}, and t_{cv} by 54%, 38%, and 71% compared with the conventional PID

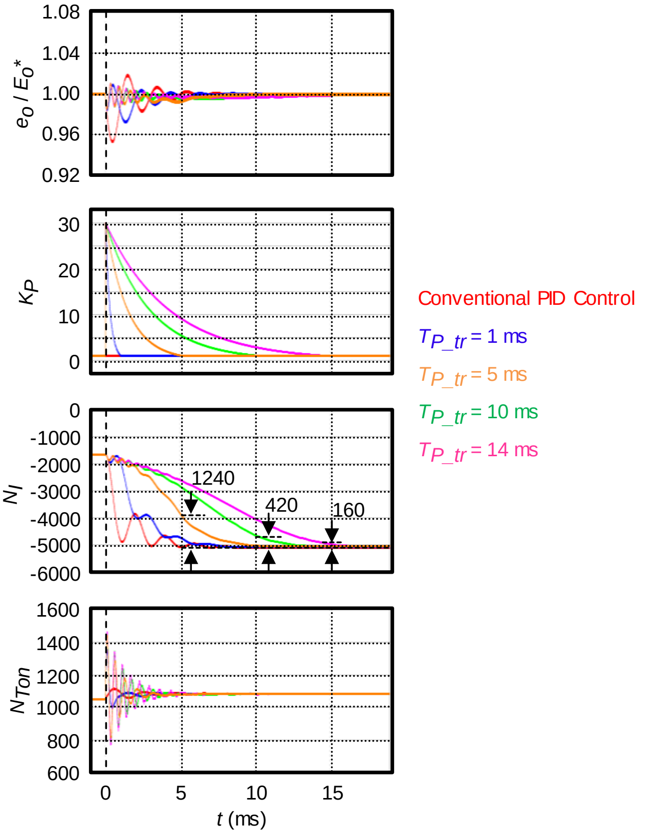
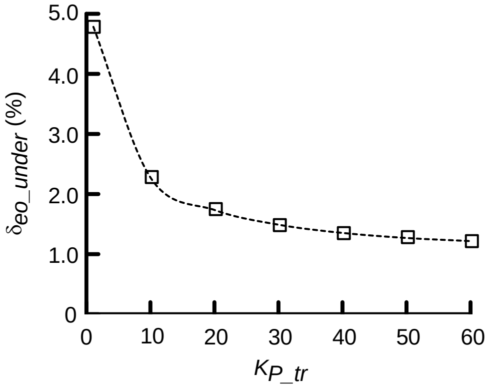


Fig. 11. Transient response of proposed method under changing T_{P_tr}.

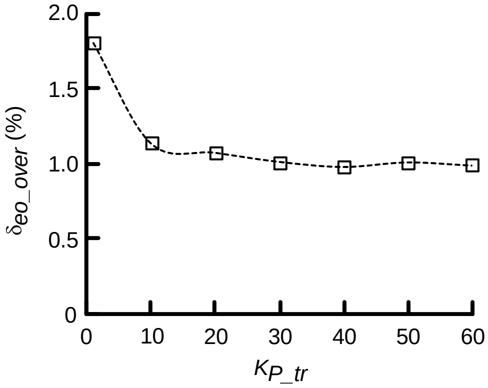
control. e_o is disturbed by limit cycle oscillation since K_P in the experiment is higher than that in the simulation due to the difference of the attenuation function as it is decreasing. Eventually, it will disappear when K_P returns to K_{P_st}.

Next, the input voltage fluctuation which occurs in the renewable energy system is assumed. In concrete, the transient responses of e_o in the proposed method and the conventional PID control are compared under the conditions which are E_i / E_i^* = 0.8 and 1.2. These are in Figs. 15 through 18. The proposed method shows a superior transient response in both case. When E_i / E_i^* is equal to 0.8, δ_{eo_under}, δ_{eo_over}, and t_{cv} are improved by 59%, 47%, and 90%. Moreover, δ_{eo_under}, δ_{eo_over}, and t_{cv} are improved by 60%, 25%, and 80% when E_i / E_i^* is equal to 1.2.

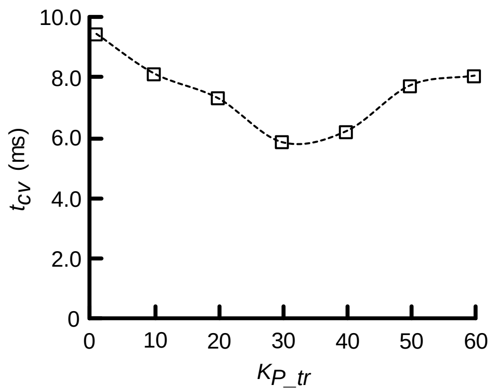
In the renewable energy system, E_i sometimes goes down to E_i / E_i^* = 0.6. Figs. 19 and 20 are the transient response of e_o assuming this condition in the proposed method and the conventional PID control. τ_{LC} and K_I are set to 1.5 ms and 0.025 to keep the stable operation and regulation of e_o in this case. V_{th1} and V_{th2} are set to plus or minus 0.5% of E_o^* since δ_{eo_under} of the conventional PID control is about 1% in these simulation and experiment. The proposed method can



(a) δ_{eo_under}.



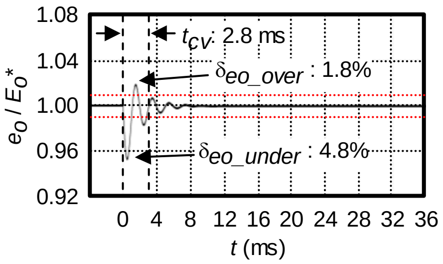
(b) δ_{eo_over}.



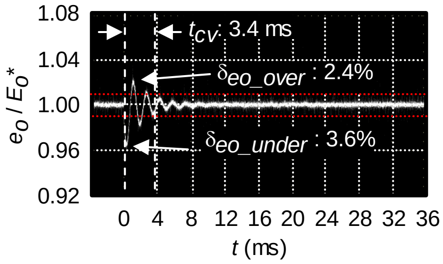
(c) t_{cv}.

Fig. 12. Transient characteristics of proposed method taking K_{P_tr} as parameter when T_{P_tr} is set to 14 ms.

similarly realize a superior response to the conventional PID control in this condition. e_o is completely suppressed within plus or minus 1% of E_o^* in the proposed method. When E_i drops down to the allowed minimum voltage, the proposed method can realize a quick response compared with the

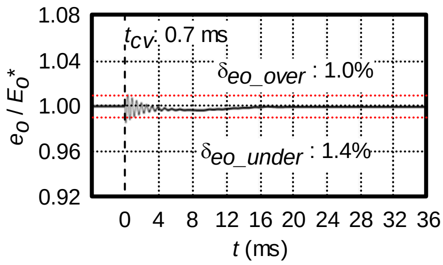


(a) Simulation.

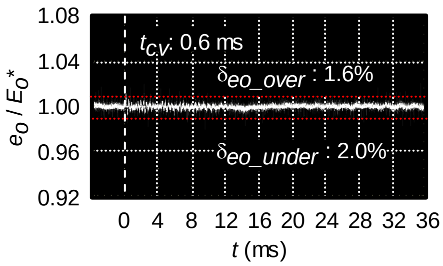


(b) Experiment.

Fig. 13. Transient responses of e_o in conventional PID control.

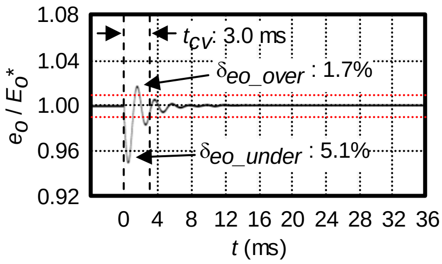


(a) Simulation.

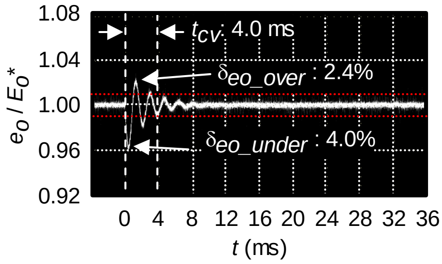


(b) Experiment.

Fig. 14. Transient responses of e_o in proposed method.

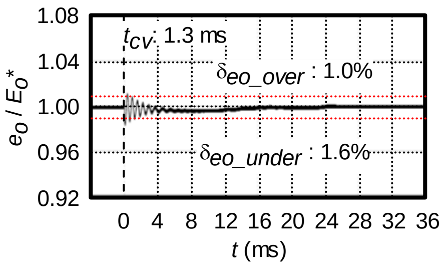


(a) Simulation.

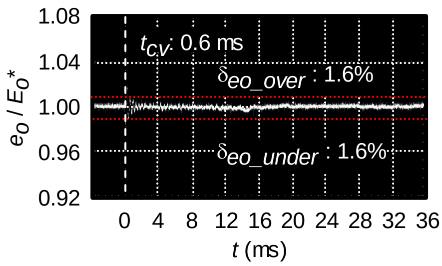


(b) Experiment.

Fig. 15. Transient responses of e_o in conventional PID control ($E_i / E_i^* = 0.8$).

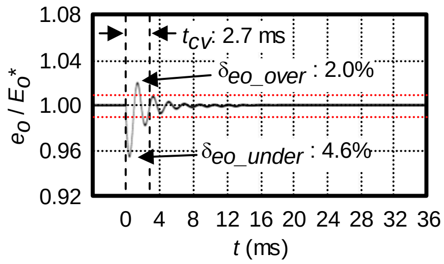


(a) Simulation.

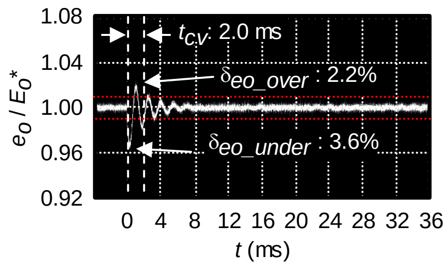


(b) Experiment.

Fig. 16. Transient responses of e_o in proposed method ($E_i / E_i^* = 0.8$).

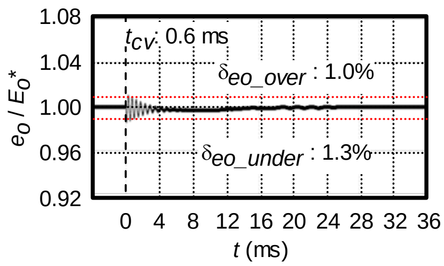


(a) Simulation.

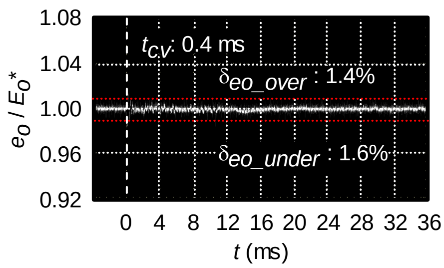


(b) Experiment.

Fig. 17. Transient responses of e_o in conventional PID control (E_i / E_i^* = 1.2).

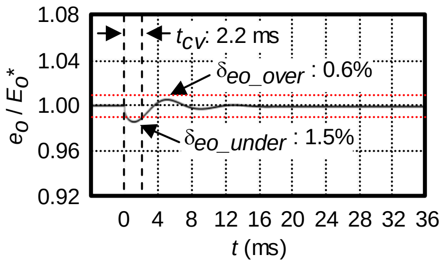


(a) Simulation.

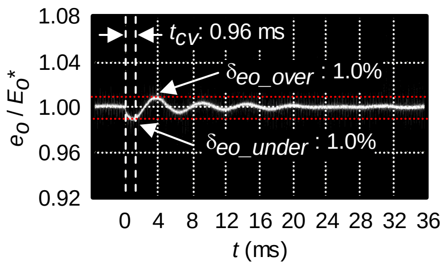


(b) Experiment.

Fig. 18. Transient responses of e_o in proposed method (E_i / E_i^* = 1.2).

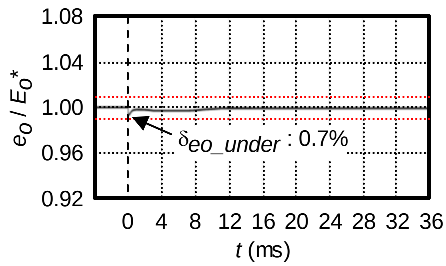


(a) Simulation.

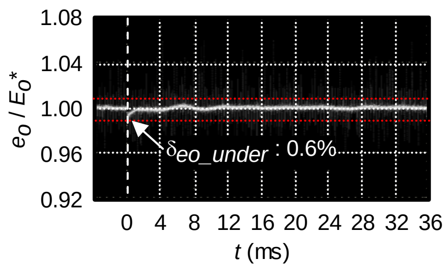


(b) Experiment.

Fig. 19. Transient responses of e_o in conventional PID control (E_i / E_i^* = 0.6).



(a) Simulation.



(b) Experiment.

Fig. 20. Transient responses of e_o in proposed method (E_i / E_i^* = 0.6).

conventional PID control as well as any other condition of E_i. As a result, the proposed method can be effective to improve the transient response without breaking the static and dynamic characteristics in the renewable system.

5. Conclusion

In this paper, it is revealed that the conventional PID control cannot improve the control precision of output voltage, transient response, and dynamic characteristics simultaneously. The quick response wide input range DC-DC converter for renewable energy system taking advantage of the digital control is proposed as a solution to this issue. The feedback gain is changed depending on the situation of the DC-DC converter to realize a superior transient response to the conventional PID control keeping the static and dynamic characteristics. The conclusion of this paper is as follows:

1) The issue of the feedback gain setting in the conventional PID control is clarified. It cannot perform good performance in the control precision of output voltage, transient response, and dynamic characteristics simultaneously.
2) The feedback gain changeable control DC-DC converter which changes the proportional gain for a short time in the transient state is proposed and is implemented.
3) The parameter of the proportional gain changing is verified from the transient characteristics and waveform of the transient response to realize a quick response.
4) The proposed method shows its validity in the consideration of the input voltage fluctuation which appears in the renewable energy system.
5) In the experiment, the undershoot, overshoot, and convergence time of the output voltage is improved by up to 59%, 49%, and 90%, respectively

The proposed method will be implemented and be validated in the renewable energy system as the large-scale demonstration in future. Also, the proposed method can contribute the energy management and energy flow control in the renewable energy system utilizing the information.

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