Invited Paper

Topics of digital control approaches for future-oriented power converters

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Abstract: This paper presents four topics of digital control approaches to apply future-oriented power converters. The energy flow in power conversion system becomes complex due to the implementation of renewable energy sources. In order to control the energy flow in high performance, the artificial intelligence technologies are expected to be implemented to control the complex power conversion system in the future. The digital control approaches for achieving high performance of switching power converters are proposed as basic researches to apply artificial intelligence technologies. They are discussed and the future research orientations are clarified based on the discussion.

Key Words: digital control, power converter, individual control power conversion system, artificial intelligence, predictive control

1. Introduction

The reduction of CO\textsubscript{2} is a hot topic to protect the environment of the earth in nowadays. The renewable energy has been shown to be an effective means of reducing CO\textsubscript{2} and electricity consumption during peak hour. Also, it can be implemented as non-interruptible power source in the times of disasters. To this end, it is widely implemented in the fields of information communication, transportation, public welfare, etc.

In the conventional power conversion system, since the input power source is only commercial AC power source, thus, the energy is flowed from commercial AC power source to each load in one direction. Sometimes, a bi-direction dc-dc converter is used to drop power from the battery. Still, the energy flow in this system is simple. Since the energy flow is one direction as shown in Fig. 1. Thus, the power conversion units have no necessary to take communication with each other.

Compared with the conventional power conversion system, the energy flow is complex in the power conversion system which implements the renewable energy [1]. The input power supply is not only commercial AC power supply, the solar batteries, wind power generators, fuel cells, etc. are also
implemented as input power sources. A series of ac-dc converters and dc-dc converters are connected to renewable energy sources through the common power line DC-Bus or AC-Bus, as shown in Fig. 2.

![Diagram of a Simple Power Conversion System](image1.png)

**Fig. 1.** Simple power conversion system.

![Diagram of an Integrated Management Control Power Conversion System](image2.png)

**Fig. 2.** Integrated management control power conversion system.

The energy managements for the complex power conversion system are mainly controlled by two control approaches. One is integrated control. The integrated control is a control which takes communication among the units. Based on the information of each unit, the integrated control calculates the optimal operation points in real-time to correspond to the power demand of customer facilities change as time passes, and control the whole power conversion system automatically.

As a kind of integrated control system, home energy management system (HEMS) is implemented for smart grid [2]. The system visualizes how much and the way energy is used at home on the dedicated monitor or other communication devices, to increase the awareness of users about energy conservation. Therefore the power conversion units have necessary to take communication to perform the energy management and the balance of shared power with each power conversion unit. The information line transfers the information of mutual collaboration and/or integrated management of each unit. The information line is commonly formed by the wired or wireless communication.

Furthermore, toward flexible and efficient management of dispersed power sources, [3] proposed a
power packet dispatching system. In this system, electric pulse power is divided into information tags and power packets. Power packets are transferred to loads according to the address information in tags. Since the power packets include not only the power but also the information, different with the HEMS, the information line is eliminated.

The other one is individual control. Figure 3 shows the individual control power conversion system. The individual control mainly focuses on controlling each unit to operate under the rated operating range. As a result, the information line can be eliminated, as shown in Fig. 3. When the units are operated exceed the specified range of conditions, the operation points will be modified by each control circuit. As an example of individual control system, a high voltage direct current (HVDC) feeding system with solar power array and its energy management has been proposed to reduce the energy consumption of data centers [4].

Nowadays, the artificial intelligence (AI) technologies are expected to improve the energy management performance of the individual control power conversion systems. For example, in the renewable energy system, various of energy sources with different characteristics input uncertainly power value to power line through power converters. In the individual control power conversion system, since the power converter units take no communication with each other, the optimal operation points for each unit should be predicted to regulate the balance of the shared power for converters. In this case, the AI technologies can be considered as the most effective way to predict the optimal operation points. The power converters operate under the high switching frequency. It is required to predict the optimal operation points in real-time with high speed. Thus, it is difficult to implement AI technologies to high switching frequency power conversion units directly by the present technology level. Currently, it is important to use simple digital control approaches instead of AI technologies as the predictive control method for predicting the optimal operation points for maximum performance [7–22].

In the individual control power conversion system, a lot of dc-dc converters are integrated in high density and they have to be controlled quickly and systematically for the energy management. Therefore, it is important to implement a quick response digitally controlled dc-dc converter.

Figure 4 shows the timing chart of digital feedback control. In this figure, $ADC$ in the block indicates the A-D conversion. $CO$ indicates the control operation of digital controller. $T_{ADC}$ is the time of A-D conversion and $T_{CO}$ is the time of control operation. Normally, the sampling period $T_{samp}$ is set to the same with switching period $T_s$ for suppressing the cost of digital controller. It is expected the switching on-time $T_{on}[n]$ can be determined after the sampling timing as soon as possible. However, it takes the time of $T_{ADC}$ and $T_{CO}$ to calculate the $T_{on}[n]$. Then the preset of
$T_{on}[n]$ also takes some time. As a result, the $T_{on}[n]$ which determines the switching off-timing, is applied in the next switching cycle. The period from the sampling timing to the switching off-timing can be considered as the delay time, which is shown as $T_{delay}$ in this figure. The delay time gives a negative influence on the stability and transient response [5–7].

Fig. 4. Timing chart of digital feedback control.

Many digital control approaches have been suggested to suppress the influence of delay time and improving the transient response [8–16]. Furthermore, these approaches are useful to suppress the mutual interference. [8] proposed a digital fast P control for improving the stability and transient response. The digital control part in this approach is divided into fast P control and slow ID control. The A-D sampling period in fast P control is significantly shorten compared with the conventional PID control. [11] proposed a digital peak current mode control approach. A simple peak current detector is proposed to decrease the cost of peak current detection. A good transient response can also be obtained in this approach.

Several advanced predictive control approaches for high performance prediction of optimal operation points for individual control system have also been suggested [15, 17–19]. The optimal operation point in each converter is important to keep the balance of shared power of converters. A static model control approach to predict the output current is presented in [15], which dissipates the sensing-resistor. The optimal operation point for improving the transient response can be calculated based on the information of the output voltage and predicted output current. A novel predictive control approach for boundary conduction mode (BCM) PFC converter has been presented in [19]. In the proposed approach, the inductor current is predicted by analytical equations instead of being detected by a sensing-resistor or sensing-circuit. The optimal operation point can be calculated without the detection of inductor current. These predictive control approaches can eliminate the sensing-resistor or sensing-circuit, so the efficiency can be improved and the cost can be reduced.

In the future, by the developing of AI technologies, it is expected that the optimal operation for not only the power conversion units but also for the entire system can be predicted. By implementing the AI technologies to the power conversion system, the optimal operation point can be fixed automatically, which dissipates the unwanted efficiency reduction and cost demand-over [21, 22].

2. Digital control approaches

Four important digital control approaches will be explained to apply the future-oriented power converters.
2.1 Fast P control

In order to suppress the influence of delay time of A-D conversion and improve the transient response, a digital fast proportional (P) control approach has been presented in [8]. Different with the conventional PID control, the digital control parts in this approach are divided into the fast P control and the slow integral-differential (ID) control. The P control is set by an A-D converter with high sampling frequency and low resolution. An A-D converter with high sampling frequency and high resolution is set for slow ID control.

Figure 5 shows a schematic diagram of digital fast P controlled buck dc–dc converter. $E_i$ indicates the input voltage, $e_o$ is the output voltage, $R$ is the load, $T_r$ is the main switch. Conventionally, the $e_o$ is controlled by the PID control. The error occurs when the sampled $e_o$ is different with the desired reference voltage, and it is modified by PID control. Theoretically, the P control modifies the error by the present information of $e_o$. By operating the P control in high speed, the delay time caused by A-D conversion can be suppressed. On the other hand, the I control modifies the error by the past information of $e_o$, which leads to a phase delay. Thus, the transient response cannot be improved even if we operate the I control in high speed. Due to these reasons, the digital control part is divided to the fast P control and slow ID control in the proposed approach. In the digital control circuit, the output voltage is converted to digital value with an 8 bit A-D converter and it is sent to the fast P control. Simultaneously, the $e_o$ is converted to digital value with an 11 bit A-D converter and it is sent to the slow ID control. The calculation process of the fast P and slow ID controls which determine the suitable digital value of switching on-time is separated and processed in parallel. Then a PWM signal with suitable duty ratio is generated in PWM generator, and it drives the dc–dc converter via drive circuit.

![Digital Control Circuit](image)

Fig. 5. Block diagram of proposed approach and scheme of A–D converters.

Figure 6 shows the timing chart of conventional PID control, proposed fast P control, ID control and slow ID control. The A-D sampling period in conventional PID control is $T_{P,samp}$, which is equal to the switching period $T_s$. The A-D sampling period in fast P control is $T_{P,samp}$, which is equal to $T_s/M_p$. $M_p$ is the sampling number of fast P control. The A-D sampling period in slow ID control can be regulated to 2 or 3 times of $T_s$. Since the sampling period is shorten by the fast P control, the influence of A-D conversion delay time can be suppressed. To this end, the transient response can be improved in the proposed approach.

To verify the performance of proposed approach, a buck dc–dc converter was implemented and tested. As the specifications of prototype, the input voltage $E_i$ is 20 V and the desired output voltage $E_o$ is 10 V. The switching frequency $f_s$ is 100 kHz. The digital controller selects the Xilinx Spartan3AN (XC3S700AN).

Figure 7 shows the experimental transient responses of the conventional PID control and proposed fast P control when output current is step changed from 0.5 A to 1 A. The undershoot of $e_o$ is over 760 mV and the convergence time is over 3.80 ms in conventional PID control, as shown in Fig. 7. In
the proposed approach, the overshoot is 460 mV and the convergence time is improved to 0.69 ms, as shown in Fig. 8. The improvement rate in convergence time is 81.8%.

From these results, it is confirmed that compared with the conventional PID control, the proposed fast P control can keep the superior transient response, the effect of delay time in A-D conversion is suppressed.

![Fig. 6. Timing chart of each control approach.](image1)

![Fig. 7. Transient response of conventional PID control in case of step change from 1 A to 0.5 A.](image2)

![Fig. 8. Transient response of proposed approach in case of step change from 1 A to 0.5 A.](image3)
2.2 Peak current mode control

Another useful control approach to improve the transient response of power conversion units is the peak current mode control. Recently, several advanced peak current mode control techniques have been suggested in [10–12]. A digital peak current mode phase-shifted full-bridge dc-dc converter for the data center has been presented in [11].

Figure 9 shows a schematic diagram of digital peak current mode controlled phase-shifting full-bridge dc-dc converter. $E_i$ indicates the input voltage, $e_o$ is the output voltage, $R$ is the load, $i_T$ is the current of transformer, $I_o$ is the output current, $Q_1$ to $Q_4$ indicate the main switch of primary side, $Q_5$ and $Q_6$ indicate the main switch of secondary side, $T$ is the transformer. The $e_o$ is sent to the digital control circuit and the PWM signal is generated. The PWM signal drives the full-bridge dc-dc convert via drive circuit. The voltage across the primary side of transformer $e_T$ should also be detected and sent to the digital control circuit. The full-bridge dc-dc converter is controlled based on the information of $e_o$ and $e_T$.

Figure 10 shows the configuration of digital control circuit for the phase-shifted full-bridge dc-dc converter. $S_{DH}$ and $S_{DL}$ are generated by the delay circuit. $S_{DH}$ and $S_{DL}$ indicate the sampling start signals of A-D conversion for $i_T$ in mode 1 and mode 2. Then, $S_H$ and $S_L$ indicate the peak current detection of $i_{T_{\text{max}}}$ and $i_{T_{\text{min}}}$, respectively. At last, $S_H$ and $S_L$ determine the timing for turning off $S_4$ and $S_3$, respectively.

![Digital peak current mode controlled phase-shifted full-bridge dc-dc converter](image)

**Fig. 9.** Digital peak current mode controlled phase-shifted full-bridge dc-dc converter.

![Control circuit configuration for phase-shifted full-bridge dc-dc converter](image)

**Fig. 10.** Control circuit configuration for phase-shifted full-bridge dc-dc converter.
Figure 11 shows A-D converters for \( i_T \) in the mode 1 and mode 2. They are consisted of passive RC integrator and comparator. \( V_{th-H} \) is set to be higher than the bias voltage \( V_B \) in the RC integrator and the \( V_{th-L} \) is lower than \( V_B \). The \( S_{DH} \) and \( S_{DL} \) are generated in the delay circuit based on the calculated \( N_{PID} \). When \( S_{DH} \) is operating under on state, \( v_{rc-H} \) is \( V_B \), as shown in Fig. 11(a). The \( v_{rc-H} \) increases during the period which \( S_{DH} \) is turned off. When the \( v_{rc-H} \) reaches \( V_{th-H} \), \( S_H \) is turned off. \( S_H \) indicates the peak current detection of \( i_T \) in mode 1. Similarly, as shown in Fig. 11(b), \( v_{rc-L} \) is \( V_B \) when \( S_{DL} \) is the on state. \( v_{rc-L} \) decreases when \( S_{DL} \) is turned off. \( S_L \) is turned off when \( v_{rc-L} \) becomes lower than \( v_{th-L} \). The \( S_L \) indicates the peak current detection of \( i_T \) in mode 2.

Figure 12 shows the operation waveforms of the proposed approach. At first, \( T_{DH} \) and \( T_{DL} \) are determined by the PID calculation \( N_{PID} \). The operation is switched to mode 1 when \( S_2 \) is turned off. The sampling of \( i_T \) is started at the moment that \( S_{DH} \) is switched to off state. \( i_{T_{max}} \) is detected when \( v_{rc-H} \) becomes higher than \( V_{th-H} \), and \( S_H \) is turned off. The \( S_4 \) is turned off instantaneously when the \( i_{T_{max}} \) is detected. Similarly, the detection of \( i_{T_{min}} \) in the mode 2 can be achieved when \( S_{DL} \) is turned off. When \( i_{T_{min}} \) is detected and \( S_L \) is turned off, \( S_4 \) is turned off. In this way, the proposed approach can realize the peak current detection in real time. It can be applied to the phase-shifted full-bridge dc-dc converter.

In order to demonstrate the effectiveness of proposed method, a phase-shifted full-bridge dc-dc converter was implemented and tested. As the specifications of the prototype, the input voltage \( E_i \).
is 380 V and the desired output voltage $E_o$ is 12 V. The output power is 800 W. The switching frequency is 135 kHz. The digital controller selects the FPGA(XC3S700AN-4FGG484C). $V_B$ is 1.5 V, $V_{th,H}$ is 1.65 V, $V_{th,L}$ is 1.35 V, $i_{T_{max}}$ is 5.67 A and $i_{T_{min}}$ is -5.67 A.

Figure 13 shows the transient responses when the $I_o$ is step changed from 25 % to 50 % in both of the conventional PID control and proposed approach. In this case, the $E_i$ is 380 V. As shown in Fig. 13(a), the convergence time of $e_o$ converged within 1 % of the desired voltage is 390 μs in the conventional PID control. The convergence time of $e_o$ is improved to 200 μs in the proposed approach, as shown in Fig. 13(b). On the other hand, the undershoot of $e_o$ is 1.2 % in both of the conventional PID control and proposed approach. Although the undershoot of $e_o$ is not improved, the convergence time of $e_o$ is improved by 48.7 % in the proposed approach.

Figure 14 shows transient responses when $E_i$ is 300 V. In this case, the convergence time is 370 μs in conventional method and it is suppressed to 200 μs in the proposed approach. The undershoot is also 1.2 % in this case.

It is confirmed that the convergence time of $e_o$ is significantly improved even if $E_i$ is changed. The superior transient response can also be achieved in the proposed approach.

Fig. 13. Transient response when step change of $I_o$ is from 25 % to 50 % and $E_i$ is 380 V.

Fig. 14. Transient response when step change of $I_o$ is from 25 % to 50 % and $E_i$ is 300 V.

### 2.3 Sensorless static model control

Previously, a reference and/or bias modification model digital control approach is presented for improving the transient response of dc-dc converter [13, 14]. Although the existing proposed approaches
achieve the superior transient response compared to the conventional digital PID control, the power loss occurs because the current is detected using the additional sensing-resistor.

In order to eliminate the power loss caused by sensing-resistor, [15] proposed a schematic diagram of sensorless static model controlled dc-dc converter, as shown in Fig. 15. $i_o$ is the output current. Different with the previous model control, only the output voltage $e_o$ is detected and sent to digital control circuit. The $i_o$ is predicted by the analytical equations. Therefore, the sensing-resistor and A-D converter for $i_o$ can be eliminated.

![Fig. 15. Sensorless static model control dc-dc converter.](image)

Figure 16 shows the configuration of sensorless static model control. The $e_i$ and $e_o$ are converted to digital value $e_i[n-1]$ and $e_o[n-1]$. Then the $e_i[n-1]$ and $e_o[n-1]$ are sent to the $i_o$ prediction part, the $i_o$ is calculated based on the $e_i[n-1]$, $e_o[n-1]$ and the digital value of switching on-time during (n-1)th switching period $T_{on}[n-1]$. The predicted $i_o$ is indicated by $i_{o,pre}[n]$.

Figure 17 shows the relationship between the reference of PID control $T_{on,model}[n]$ and output current $i_o$. The $i_{o,pre}[n]$ in continuous conduction mode (CCM) and discontinuous conduction mode (DCM) which is shown in Fig. 17, are derived as follows:

$$i_{o,pre,CCM}[n] = \frac{T_{on}[n-1](e_i[n-1] + V_D) - N_{Ts}(e_o[n-1] + V_D)}{r N_{Ts}}$$  

$$i_{o,pre,DCM}[n] = \frac{(e_i[n-1] - e_o[n-1])(e_i[n-1] + V_D)T_{s}^2 T_{on}[n-1]}{2L(e_o[n-1] + V_D)}$$

where $V_D$ is the forward voltage of diode, $N_{Ts}$ is the digital value of switching period, $r$ is the parasitic resistance of converter.

In the model control part, the $T_{on,model}[n]$ is calculated based on the $e_i[n]$ and $i_{o,pre}[n]$. $T_{on,model}[n]$ in CCM and DCM are derived as follows:

$$T_{on,mod,CCM}[n] = \frac{N_{Ts}}{e_i[n-1] + V_D}(E_o^* + r i_{o,pre,CCM}[n] + V_D)$$

$$T_{on,mod,DCM}[n] = N_{Ts} \sqrt{\frac{2L i_{o,pre,DCM}[n](E_o^* + V_D)}{(e_i[n-1] + V_D)(e_i[n-1] - E_o^*)T_s}}$$

where $E_o^*$ is the desired output voltage value.

Simultaneously, the switching on-time $T_{on,PID}[n]$ is determined by the PID calculation of $e_o[n]$. The final switching on-time is the summary of $T_{on,PID}[n]$ and $T_{on,model}[n]$.

$$T_{on}[n] = T_{on,mod}[n] + T_{on,PID}[n]$$

Furthermore, an attenuation function $T_{on,tr}[i]$ is implemented to improve the transient response, as shown in Fig. 18. The $T_{on,tr}[i]$ is expressed as follows.

$$T_{on,tr}[i] = K_1 - iK_2T_s$$
Fig. 16. Configuration of sensorless static model control.

Fig. 17. Relationship between $T_{on}$ model $[n]$ and $i_o$.

Fig. 18. Operation principle of attenuation function for transient improvement.

The $T_{on-tr}[i]$ does not work in the steady-state. When a step change occurs, a large bias can be added by the $T_{on-tr}[i]$. In this way, the undershoot of $e_o$ can be significantly improved. In order to verify the effectiveness of proposed sensorless static model control, a buck dc-dc converter was designed and tested. The input voltage $e_i$ is 20 V and the desired output voltage $E_o^*$ is 5 V. The rated output current is 1 A. The inductance $L$ is 196 $\mu$H. The output capacitance $C_o$ is 891 $\mu$F. The internal resistance $r$ is 0.18 $\Omega$. The forward voltage of diode $V_D$ is 0.26 V.
Figure 19 shows the experimental transient responses of the conventional PID control and proposed sensorless static model control. The undershoot of $e_o$ is over 7.6% and the convergence time is 6.4 ms in conventional PID control, as shown in Fig. 19(a). In Fig. 19(b), it is shown that the undershoot of $e_o$ is decreased to 1.1% and the convergence time is improved to only 0.07 ms. The improvement rate in undershoot of $e_o$ and convergence time is 85.5% and 98.9%, respectively. Therefore, the improvement of transient response is huge.

From these results, it is confirmed that the proposed sensorless static model control can achieve a superior transient response compared with the conventional PID control. Since the sensing-resistor of inductor current is eliminated, a higher efficiency can be achieved in the proposed approach.

2.4 Predictive control for BCM PFC converter

The predictive control approach can also be implemented to the power factor correction (PFC) converter. When the PFC converter operates under boundary conduction mode (BCM), it is necessary to detect the zero-crossing point of inductor current. Conventionally, the zero-crossing is detected by a sensing-resistor or a sensing-circuit. The sensing-resistor causes a reduction of efficiency and the sensing-circuit causes an increase in cost.

In order to solve the problems in detection of zero-crossing point, [19] presented a novel predictive control approach for BCM PFC converter. Figure 20 shows the predictive controlled BCM PFC converter. $e_{ac}$ indicates the alternating input voltage. $i_{ac}$ indicates the input current. $e_i$ is the full rectification of $e_{ac}$. $e_o$ is the output voltage. In the proposed approach, the zero-crossing point is predicted by the analytical equations of inductor current. Thus, neither sensing-resistor nor sensing-circuit is needed. The PFC converter is only controlled by the information of $e_i$ and $e_o$.

Figure 21 shows the operation waveforms of BCM PFC converter. When the PFC converter operates under BCM, there are two operation states: state I ($T_i$: ON, D: OFF) and state II ($T_i$: OFF, D: ON). The inductor current in operating state I $i_{L1}(t)$ and the inductor current in operating state II $i_{L2}(t)$ are derived as follows:

$$i_{L1}(t) = K_1 + K_2(t_0) \exp\{-\alpha_1(t - t_0)\}$$  \hspace{1cm} (7)

$$i_{L2}(t) = G_1 + [G_2(t) \cos\{\omega_2(t - t_1) + G_3(t_1) \sin\{\omega_2(t - t_1)\}] \exp\{\alpha_2(t - t_1)\}$$  \hspace{1cm} (8)

where the $K_1$, $K_2$, $\alpha_1$, $G_1$, $G_2$, $G_3$, $\omega_2$, $\alpha_2$ in Eq. (7) and Eq. (8) are expressed by the parameters of PFC converter.

Figure 22 shows the diagram of the proposed predictive control for BCM PFC converter. The switching on-time $T_{on}$ is determined by PID control of the digital output voltage $e_o[n]$. Then, the peak value of inductor current is obtained by substituting the $T_{on}$ into Eq. (7). The peak value is subsequently used as the initial value of Eq. (8). The $i_{L2}(t)$ is zero at the zero-crossing point. The switching off-time $T_{off}$ can be obtained by solving Eq. (8). In this way, the optimal switching off-time for realizing the prediction of zero-crossing point can be obtained.
In order to demonstrate the effectiveness of the proposed predictive digital control approach, a single-phase PFC boost converter was implemented and tested. The $e_{ac}$ is 100 V_{rms} and the desired output voltage is 400 V_{dc}. The $L$ is 1.2 mH. The output power is 30 W and the output capacitance is 15 μF.

Figure 23 shows the experimental waveforms of inductor current and gate-source voltage of MOSFET. It is shown that the zero-crossing point is predicted successfully and the PFC converter operates under BCM in the proposed approach.

Figure 24 shows the experimental waveforms of input voltage $e_{ac}$ and input current $i_{ac}$. It is found the $i_{ac}$ is controlled to a sinusoidal waveform that in phase with $e_{ac}$. Therefore, a high power factor
Experimental waveforms of inductor current and gate-source voltage.

Experimental waveforms of input current and input voltage.

0.993 and a low total harmonic distortion (THD) of $i_{ac}$ 9.7% is achieved in proposed predictive control.

3. Conclusion

The energy flow in power conversion system becomes complex due to the implementation of renewable energy sources. As a complex power conversion system, the individual control power conversion system will be a mainstream in the future. Several digital control approaches are presented to control the power converters in the individual control system. Fast P control and peak current mode control are presented to suppress the influence of delay time. The convergence time is improved by 81.8% in the fast P control. The convergence time is improved by 48.7% in the peak current mode control.

Furthermore, two predictive control approaches are presented to predict the optimal operation points of power converters. The sensorless static model control predicts the output current. The predictive control for BCM PFC converter predicts the zero-crossing point of inductor current. The efficiency of power converters can be improved by the two predictive control approaches because the optimal point as desired current/voltage is predicted by analytical equations instead of being detected by a sensing-resistor.

The digital control approaches are considered as the basic research of artificial intelligence technologies. The artificial intelligence technologies are expected to be implemented to control future-oriented power converters. The combination of digital control approaches and artificial intelligence technologies can be considered as the future research objectives.

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