Research Papers

Proposal of Phase Shedding Control System for Multiphase PFC Converter

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Abstract

As electric vehicles become more widespread, battery chargers are also becoming more common. A battery charger requires wide-range and high-efficiency operation, which can be achieved by using multi-phase power converters and dynamic phase shedding control. During phase shedding, the state of the power supply undergoes a significant transition, resulting in transient operation. In this technical report, we proposed a new control method that estimates the amount of state transition before and after the phase shedding, thus suppressing transient operation. The validity was confirmed through circuit simulation and verification with actual equipment.

1. Introduction

In recent years, the transition to electric vehicles (EVs) has been accelerating as part of efforts to achieve carbon neutrality. Alongside this shift, battery charging has garnered significant attention, leading to an increasing demand for power factor correction (PFC) converters—AC-DC converters designed to improve power factor during charging.

PFC converters are required to support a wide operating range and achieve high efficiency. One approach to achieving this is the multi-phase design of power converters. By implementing a multi-phase configuration, the current flowing through the switching devices can be distributed, thereby reducing conduction losses. As a result, high efficiency can be achieved in the high-output range (1). However, in the low output range, switching losses become more dominant than conduction losses, leading to decreased efficiency as the number of devices increases. Since the optimal phase varies depending on the output range, dynamic phase shedding control is required (2). However, with conventional phase shedding control, the state of the power converter undergoes a significant transition during phase shedding, resulting in fluctuations in the output voltage corresponding to the amount of state transition.

This paper reports on a new phase shedding control method that estimates and suppresses the state transition of the power converter occurring during phase shedding.

2. Multi-Phase PFC Converter

2.1. PFC Converter

A PFC converter is a device that converts AC power, such as from a commercial power sourcemains power, into DC current and voltage. During the conversion from AC to DC, if the power factor is low, high-frequency noise caused by distortion and reactive power areis generated. When converting power from AC to DC, a low power factor can lead to the generation of reactive power and high-frequency noise due to distortion. In high-power output power supplies, the effects of distortion increases and may affect other devicesbecome more severe, potentially interfering with the operation of other devices. Since a PFC converter includes a power factor correction function, it can reduce distortion and reactive power.Since a PFC converter includes a power factor correction function, it can resolve issues related to reactive power and distortion. Additionally, according to IEC 61000-3-2 regulations, devices such as AC adapters with an output of 75 W or more are required to incorporate a PFC converter, further increasing the demand for PFC converter circuits.

There are various circuit configurationtopologies for PFC converters. In this case, a bridgeless totem-pole PFC converter was selected due to its potential for high efficiency and reduced component count. Figure 1 shows the circuit diagram of the adopted PFC converter. For switches S_{1a} and S_{2a}, GaN-HEMTs were used, as these next-generation power semiconductors exhibit low reverse recovery current. By applying PWM control to switches S_{1a} and S_{2a}, both the input current and output voltage are regulated. The operating modes of a PFC converter generally include Continuous Conduction Mode (CCM), Boundary Conduction Mode (BCM), and Discontinuous Conduction Mode (DCM). To reduce losses during high-power operation, CCM was selected because it minimizes the peak current flowing through the inductor. A control system, as shown in Figure 2, was designed to regulate the CCM-mode PFC converter. The transfer functions of the PFC converter shown in Figure 2, $\Delta I_L/\Delta D$ and $\Delta V_o/\Delta I_L$, are expressed by the following equations (3):

$$\frac{\Delta I_L}{\Delta D} = \frac{V_{ac}}{R_o(1-D)^3} \times \frac{2 + R_o \times C_o \times s}{\frac{L \times C_o}{(1-D)^2}s^2 + \frac{L}{R_o(1-D)^2}s + 1} \quad \cdots ①$$

$$\frac{\Delta V_o}{\Delta I_L} = \frac{V_{ac} \times R_o}{2 \times V_o} \times \frac{1}{R_o \times C_o \times s + 1} \quad \cdots ②$$

where V_{ac} represents the root mean square (RMS) value of the input voltage, V_o represents the RMS value of the output voltage, and D represents the duty ratio.

From Figure 2, it can be observed that the control system of the PFC converter consists of two major control loops. Among these, the inner loop is responsible for power factor correction control, while the outer loop is for output voltage control. In addition to these loops, disturbances at the frequency of the commercial power supplymains power are always multiplied into the control system after the output voltage compensator. Each loop interferes with the others, and disturbances from the commercial power supplymains frequency also interfere with output voltage control. Therefore, it is necessary to properly design each control compensator to prevent interference between the loops and the disturbances.

Taking these control design methods into account and aiming to accommodate high output, we worked on implementing a multiphase PFC converter.

Figure 3 shows the circuit diagram of the multiphase PFC converter. The validation of the multiphase system was conducted using the simplest two-phase PFC converter. Power factor correction for the first phase is handled by switches S_{1b} and S_{2b}, while switches S_{3b} and S_{4b} manage power factor correction for the second phase. Full-wave rectification is performed using switches S_{5b} and S_{6b}. Additionally, a current balance control mechanism has been introduced to ensure that the current flowing through each phase remains uniform.

By implementing a multiphase configuration, the current flowing through each phase can be reduced, which in turn lowers conduction losses. Additionally, through interleaved operation, inductors L_1 and L_2 can be replaced with a coupled inductor, thereby canceling out the DC superimposed magnetic flux and enabling a reduction in the size of the inductor (4).

Figure 1 Circuit diagram of single-phase Totem-pole bridgeless PFC converter

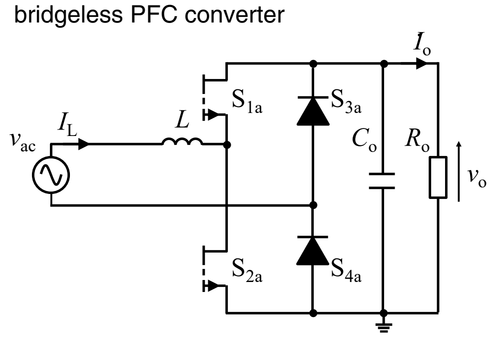


Figure 2 Block diagram of PFC converter

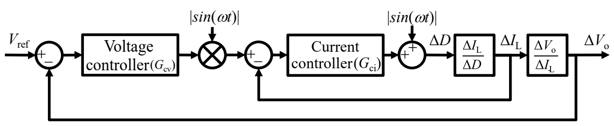
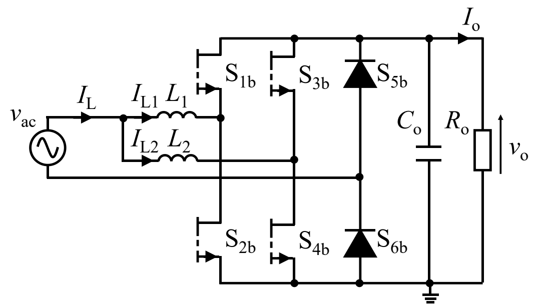


Figure 3 Circuit diagram of multiphase PFC converter



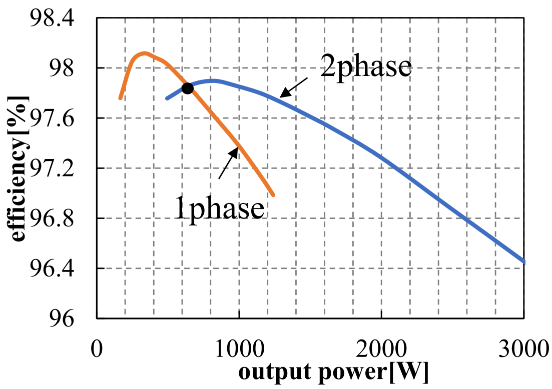
2.2. Phase Shedding Control

By adopting a multi-phase configuration, efficiency at high output can be improved.high-efficiency drive operation can be achieved in the high-output range. However, a drawback of this approach is that the number of switching devices increases, leading to greater switching losses. In the low-output range, where switching losses dominate over conduction losses, efficiency deteriorates. Therefore, it is necessary to implement phase shedding according to the output.Therefore, it is necessary to operate with appropriate phase shedding based on the output.

Figure 4 shows the efficiency curve of the PFC converter used in this study. When the output power exceeds approximately 600 W, conduction loss becomes the dominant factor, and the converter operates with higher efficiency in two-phase drive mode. Therefore, phase shedding is necessary around 600 W. However, if the phase shedding threshold is set at exactly 600 W, there is a risk of chattering. To prevent this, the threshold should implementincorporate hysteresis.

Phase shedding allows wide-range and highly efficient operation. However, in conventional control systems, phase shedding induces significant state transitions in the power converter, leading to output voltage fluctuations proportional to the magnitude of the state transition.However, phase shedding in conventional control systems causes a significant transition in the state of the power converter, resulting in output voltage fluctuations corresponding to the amount of state transition. The greater the fluctuation in output voltage, the larger the capacitor with fluctuation suppression functionality needs to be, which is a disadvantage. Therefore, it is necessary to minimize fluctuations in the output voltage corresponding to the amount

Figure 4 Efficiency curves of PFC converter measured at each phase



of state transition as much as possible. In DC-DC converters, control methods for improving this issue have been proposed [(5)]. Since the response speed of output voltage control in PFC converters must be designed to be lower than the mains frequency of commercial power supplies, fluctuations in output voltage become more significant pronounced compared to DC-DC converters. However, this issue has not been investigated.

3. Proposed Phase Shedding Control

In this study, a new control system and operational flow were developed to suppress fluctuations during the phase shedding in the PFC converter. Figure 5 illustrates shows the new control system, while Figure 6 presents the operational flow of the control. For phase shedding, the output power of the PFC converter is first checked. At this time, the output power is obtained by multiplying the respective sensor values from the output voltage sensor and the output current sensor installed in the circuit. If the calculated output power value exceeds the shedding threshold, S_1 is toggled. Then, the state transition quantity of the power converter is calculated. The amount of state transition is determined from the deviation between the current value output from each phase before phase shedding $I_{o\ phase\ before}$ and the current value output from each phase after phase shedding $I_{o\ phase\ after}$. Io phase before and Io phase after are calculated using the following equation.

$$I_{o\ phase\ before} = \frac{I_{o\ before}}{N_{before}} \cdots ③$$

$$I_{o\ phase\ after} = \frac{I_{o\ after}}{N_{after}} \cdots ④$$

$I_{o\ before}$ and N_{before} represent the sensor value of the output current and the number of phases before phase shedding, respectively, while Io_after and Nafter represent the sensor value of the output current and the number of phases after phase shedding, respectively.

The reason for using the current values output from each phase to estimate the amount of state transition was to accurately capture the difference in states before and after phase shedding. In a multi-phase system, each phase is connected in parallel, making it difficult to estimate the amount of state transition before and after phase shedding using either the input voltage or output voltage. In the case of input current, it oscillates at the frequency of the commercial power supply. When sensing the states before and after the shedding, only the instantaneous values of the current can be sensed. The input current value sensed at the timing of the shedding changes. Additionally, if the transition occurs at the zero-crossing point, the amount of state transition becomes extremely small, potentially leading to incorrect sensing. Therefore, it is difficult to use the input current to estimate the amount of state transition. When using the output current flowing through each phase, estimation can be performed using Equations ③ and ④, allowing for the estimation of the amount of state transition while considering both changes in output power and changes in the number of phases. Therefore, the current values output from each phase were used to estimate the amount of state transition.

When the calculation of the amount of state transition is complete, S_2 is turned on, and feedforward (hereinafter, FF) control is initiated. If S_2 is turned off at the moment output voltage fluctuation suppression is confirmed, another state transition of the power converter occurs according to the FF value, causing output voltage fluctuations. Therefore, during FF control, the FF value must be gradually reduced to prevent significant output voltage fluctuations. By turning off S2 when the FF value reaches zero, no state transition occurs, allowing FF control to be stopped while keeping the control system stable.

The validity of the proposed FF control was confirmed through circuit simulation and testing with actual equipment.

Figure 5 Proposed phase shedding control system

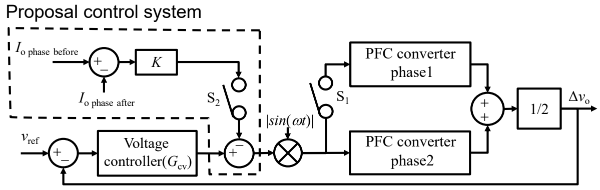
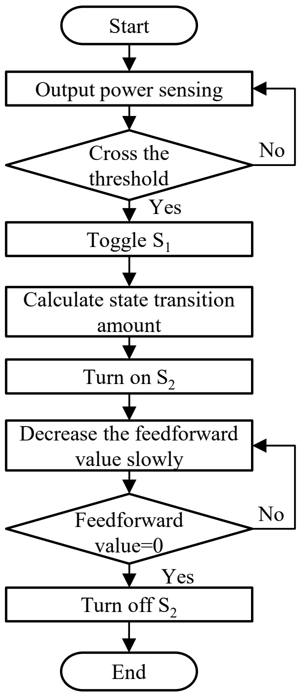


Figure 6 Control flowchart



4. Result

A circuit simulator was used to switch the number of phases from one to two during steady-state operation at an output power of 1100 W. Figure 7 shows the results of verifying the effect of FF control in this scenario. With the proposed FF control implemented, the control system operated with a deviation from the target value due to the influence of the FF term. However, when power factor correction control was active, the amplitude of the output voltage fluctuation caused by phase shedding was reduced to approximately one-third.

Next, FF control was implemented in the actual equipment to verify whether similar effects could be achieved with the

Figure 7 Verification results of ff control using circuit simulator

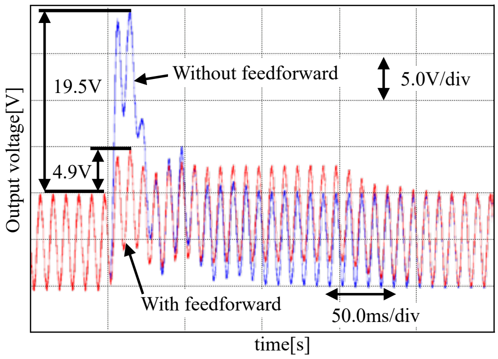


Figure 8 Measurement results from actual equipment under low load fluctuations

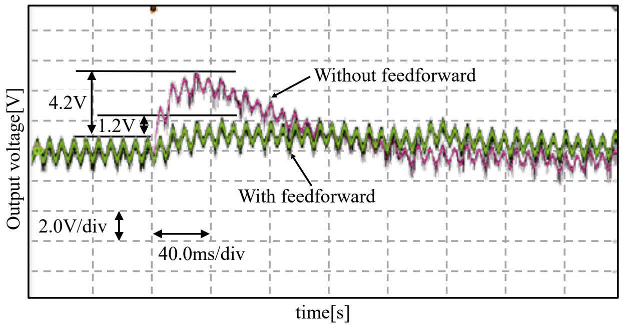
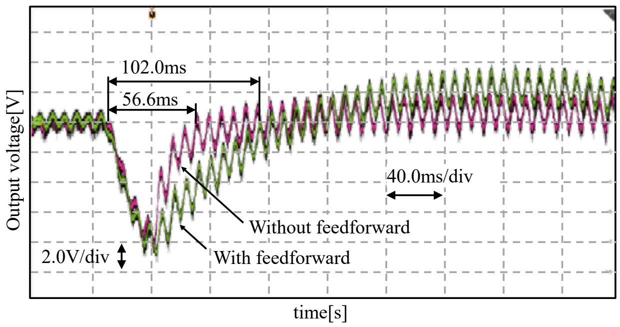


Figure 9 Measurement results from actual equipment under high load fluctuation



small model. The results of the effectiveness verification on the actual equipment are shown in Figure 8. When the number of phases was changed from one to two during operation at an output power of 40 W, the output voltage was suppressed to approximately one-third by FF control, as shown in Figure 8, similar to the simulation results. However, when the output power was varied from 40 W to 80 W and the number of phases was changed from one to two, the time required to track the target value increased, as shown in Figure 9.

This is because the fluctuation that occurred before the feedforward (FF) control was initiated due to the load variation could not be suppressed, and the FF control started while fluctuations were still present. As a result, the time required to track the target valuesettling time became longer. Therefore, by optimizing the time from load variation to the initiation of FF control, it is expected that output voltage fluctuations can be suppressed in the same manner as under low-load variation conditions.

5. Conclusion

In this technical report, we presented the structure and effects of a phase shedding control system for a multiphase PFC converter. By utilizing output current sensor values to estimate the amount of state transition before and after phase shedding, we were able to account for both changes in output power and the number of phases. Based on this estimated state transition, we constructed a feedforward control system, which successfully reduced output voltage fluctuation amplitude to approximately one-third when phase shedding occurred under low-load variation conditions. These results confirm the effectiveness of the proposed method.

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