Isolated Three-Phase AC to DC Converter with Matrix Converter Applying Compensation for Voltage Error by Voltage-based Commutation

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Abstract— **This paper proposes a compensation method for a voltage error by a voltage-based commutation of an isolated AC-DC converter using the matrix converter with a discontinuous current mode (DCM) and a continuous current mode (CCM) for rapid battery charger applications. The isolated AC-DC converter with the matrix converter is expected to be more compact because a medium-frequency AC inductor which is connected to the medium-frequency transformer is used instead of a boost inductor. However, the small medium-frequency inductor causes the input current distortion. In addition, the transmission power error occurs due to the voltage error by the commutation. In this paper, the voltage error caused by the voltage-based commutation is analyzed based on the relationship between the current direction and the three-phase voltage in the initial step of the voltage-based commutation. The two voltage compensations method by the two-level compensation and the linear approximation are combinated. As a result, the input current THD was reduced by 70 % at the boost ratio 1.0.**

Keywords— Three phase AC-DC converter, Matrix converter, Rapid battery charger

I. Introduction

Recently, electric vehicles (EV) and plug-in hybrid vehicles (PHV) may become a trend of automotive technologies as solutions for the energy and environmental problems. The rapid battery chargers are key component to enhance the convenience for users. The rapid battery chargers have important requirement of the reduction for the weight and the size for easy installation and dissemination. Typically, the main power circuit for the rapid battery charger is a medium-frequency isolated AC-DC converter with a PWM rectifier. This conversion method requires boost inductors in the grid AC stage, but it is miniaturization by the high frequency operation [1]. Whereas, a bidirectional AC-DC converter which has the matrix converter and the medium-frequency transformer has been studied actively[2]-[4]. This circuit directly converts from the three-phase AC to the medium-frequency single-phase AC by the matrix converter in grid side. Thus, the efficiency is improved by reduction of a number of conversion stage without a DC-link part. In addition, it has advantage for the size reduction because a large grid-tied inductor and a DC-link capacitor are not necessary.

Some control methods for the matrix converter in the isolated AC-DC converter have been proposed [2]-[9]. In Ref. [2], the switching pattern based on space vector modulation (SVM) is investigated to neglect the effect of the current ripple within one switching cycle. An inductor current is assumed to be constant during one switching cycle. However the large current ripple is occur in the input current because the medium-frequency AC inductor is small. The ripple current gives an error to the current command value because the conventional SVM is based on constant output current during the switching periods. As a result, the input current distortion occurs due to the large ripple current in one switching cycle. Ref. [4] has proposed a switching method that is not affected by current ripple caused by leakage inductance in the switching cycle. However, the current ripple is not canceled strictly because the actual output period of the voltage vector differs due to the voltage error due to the commutation. In this result, the distortion occur in the input current. In Ref. [5], the voltage error is eliminated by adjusting the duty ratio according to the dead-time period when the voltage error is always constant. However the nonlinearly of the voltage error causes the overcompensation when the commutation sequence starts near zero current. The three-level compensation, which includes the zero-voltage period, improves the overcompensation problems. However the three-level compensation has a trade-off relationship between the voltage error due to the commutation and the conversion efficiency.

In this paper, the compensation method of the voltage error is proposed utilizing the voltage-based commutation of the matrix converter. The new contribution of this paper is that the voltage error caused by the voltage-based commutation is reduced by the combination between the two-level compensation and the linear approximation compensation focusing on phase difference between the primary voltage and the secondary voltage. The linear approximation compensation reduces the voltage error without a trade-off with the efficiency. However, the voltage error is not completely eliminated because the error is approximated as linear. The pulse width neglected by the dead-time in the light load region. For these reason, the input current distortion is not compensated completely. In order to improve the distortion, the DC current feedback method is demonstrated to achieve constant instantaneous power of the input/output power. Note that the input current distortion is reduced when the instantaneous power factor is constant. The simulation results show the usefulness of the DC current feedback method.

II. Circuit Configration And Control Method

Fig. 1 shows the circuit configuration of a bidirectional isolated AC-DC converter. The matrix converter directly converts from the grid frequency in the medium-frequency AC. A DC-link capacitor is not necessarry to the medium-frequency isolated AC-DC converter based on the DAB converter and the matirix converter. Furthermore, the power transmission is realized only with an small inductor L which is connected to the medium-frequency transformer. This circuit does not use the large inductors and a DC inductor. As a result, it is possible to reduce the system volume.

Fig. 2 shows the fundamental voltage vector diagram and the current vector $\mathbf{I_{in}}^*$. In the matrix converter, the input current outputs as a sinusoidal shape, SVM is used to calculate a duty ratio for a converter. SVM is assumed that average output current in each switching cycle is constant. The currnts vectors $\mathbf{I_1}$ and $\mathbf{I_2}$ are close to current command vector. The input current is controlled to follow the input command $\mathbf{I_{in}}^*$ by adjusting the duty ratio of $\mathbf{V_1}$ and $\mathbf{V_2}$ in first half of cycle, and $\mathbf{V_4}$ and $\mathbf{V_5}$ in second half of cycle. However, the large riple current occurs in the transformer current due to a very small transformer leakage inductance in one switching cycle, This current variation, which is so-called "current ripple" in this paper, causes the distortion of the input current and the transmission power error.

Fig. 3 shows the medium-frequency voltage and the current waveforms that are the output of the matrix converter and the secondary of the medium-frequency transformer during the boost mode ($NV_{dc} > \sqrt{2}v_{ac}$) using the ripple cancellation method. In the ripple cancellation method, the amplitude of the current vector during the power transmission period is equaled to the medium-frequency current command value I_{ave}* by changing the output order of negative voltage vector. As a result, the ripple current is equivalently neglected in one switching cycle. The input current distortion is reduced because the effect of the neglecting ripple current. The ripple cancellation method is operated in both DCM ($T_0 > 0$ and $T_a = 0$) and CCM ($T_0 = 0$ and $T_a > 0$).

Fig. 4 shows the control block diagram with the open-loop ripple cancellation method. In the ripple cancellation method,

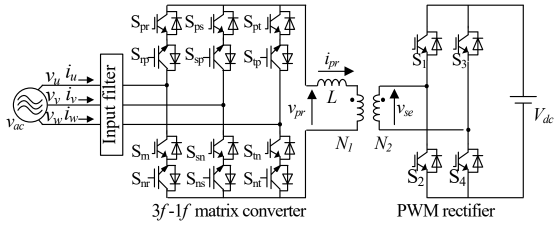


Fig. 1. Circuit configuration of isolated AC-DC converter based on DAB converter and matrix converter. The matrix converter directly generates the medium-frequency AC from the low frequency AC for DAB converter.

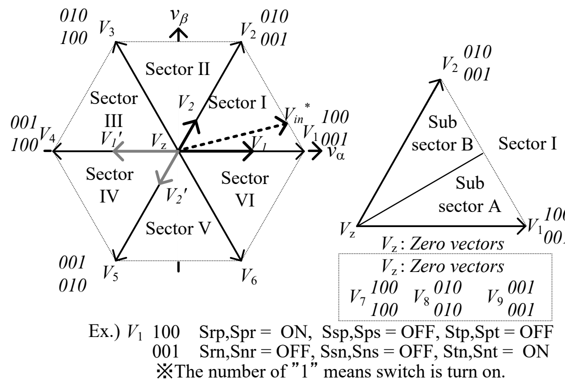
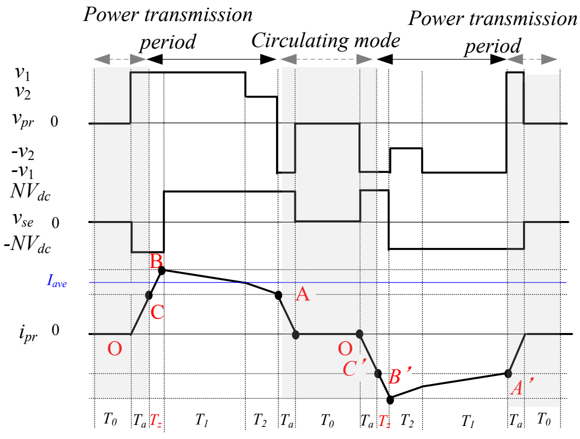
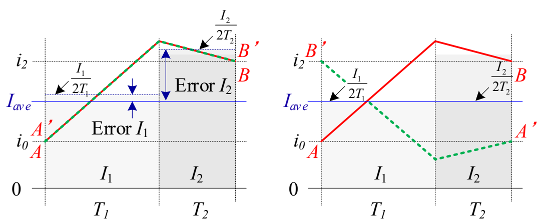


Fig. 2. Fundamental voltage vector diagram to calculate the duty for the matrix converter.



(a) One switching cycle of the ripple cancel method



(b) Conventional method (c) Ripple cancellation

Fig. 3. Ripple cancellation method in order to simplify duty calculation and minimize reactive power.

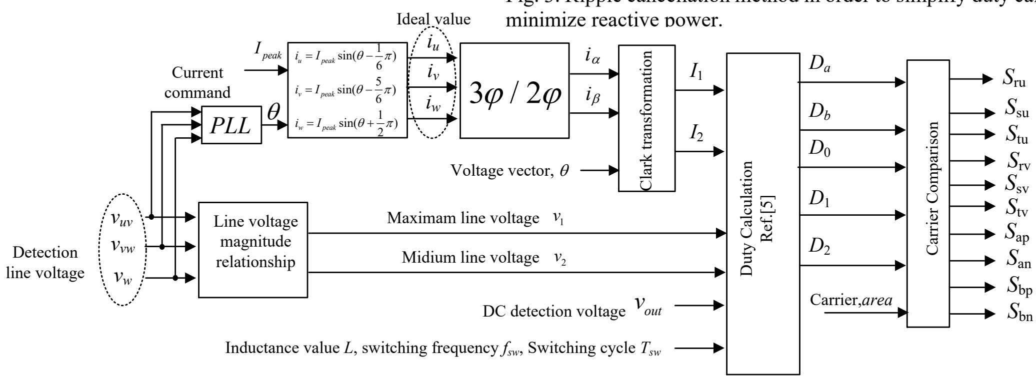


Fig.4 Open-looped control diagram with ripple cancelation method.

the ideal three-phase current values i_u, i_v, and i_w are obtained using the current command value I_{peak} and the system phase θ. The vector magnitudes $\mathbf{I}_1$ and $\mathbf{I}_2$ which are used in SVM are calculated by α-β transformation and Clark transformation for the three-phase current. The calculation of the duty ratio is performed with the formula in Ref. [5].

III. Voltage Error Caused Due to Four-Step Voltage Commutation

The matrix converters need the commutation that prevents short circuits in a power supply and does not open the inductive current pass. The commutation method is separated into a voltage-based commutation and a current-based commutation while satisfying these conditions. In this paper, a four-step voltage-based commutation that does not require a current sensor is applied [10].

Fig. 5 shows the model and the switching sequence of the four-step voltage-based commutation using two bidirectional switches, two voltage sources, and the current source. When the voltage-based commutation is made from the power supply v_a to v_b with the positive load current ($i_{load} > 0$), the changing of the current path from v_a to v_b occurs when S_{1a} is turned-off in the second step. In other words, the output voltage is delayed by the dead-time T_d from ideal timing. Similarly, the commutation from v_a to v_b occurs in the third step under the condition of $v_a < v_b$. The change of the actual output voltage is delayed by $2T_d$. Therefore, the delay of the output voltage due to the voltage-based commutation is not always same and is determined by the voltage condition and the current direction. The compensation of the voltage error is required considering the delay.

A. Voltage commutation compensation during DCM operation under boost condition

Fig. 6 shows the operation waveforms of the voltage-based commutation during the DCM under the boost mode. The relationship of the voltage magnitude is $v_u > v_v > v_w$. The voltage error of the matrix converter by the voltage-based commutation is determined by the voltage magnitude and the current direction. The two-level compensation using two compensation values is used for the dead-time compensation as a feed forward method. The two-level compensation eliminates the voltage error caused by the dead-time [5]. The actual pulse width differs from the ideal pulse width by the dead-time. The voltage error is eliminated by adding the dead-time compensation to the duty. The voltage output periods T_2 and T_b change by the dead time T_d due to the voltage commutation. The period T_2 becomes longer by T_d, while the period T_b becomes shorter by T_d. Therefore, the actual output periods T_2' and T_b' are expressed as (1) in the DCM operation.

$$\begin{cases} T_b' = T_b + T_d \\ T_2' = T_2 - T_d \end{cases} \quad \text{.......................................}(1)$$

However, the overcompensation occurs by the two-level compensation near zero current, which results in the input current distortion.

B. Voltage commutation compensation from DCM to CCM operation

Fig. 7 shows the linear approximation compensation method. The operation has the phase difference φ between the primary and the secondary voltages. The phase difference φ is affected by the voltage error when the operation mode

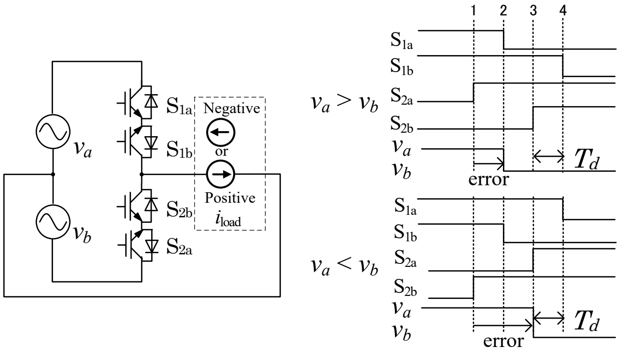
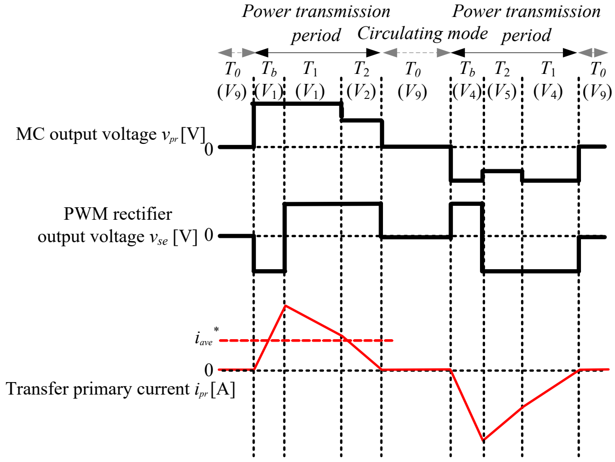
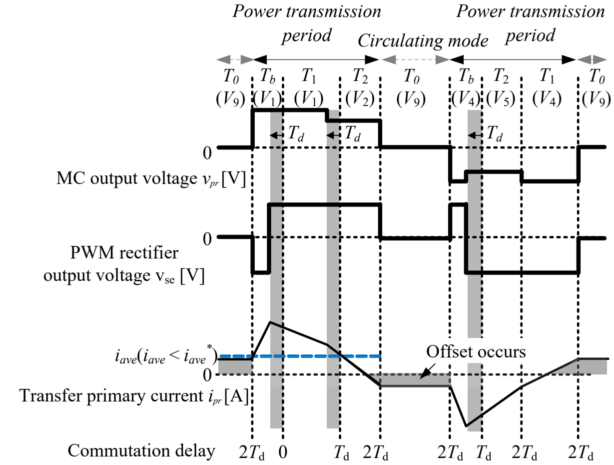


Fig. 5. Commutation model and mechanism of voltage error.



(a) Ideal commutation



(b) Voltage commutation

Fig. 6. Middle frequency waveformsunder DCM.

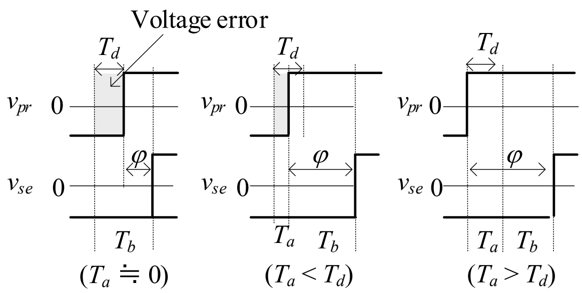


Fig. 7. Linear approximation compensation method.

switches from DCM to CCM. The voltage error by the phase difference φ between the primary and the secondary voltages occurs when the operating mode is switched from DCM to CCM. The amount of the voltage error is nonlinear when the

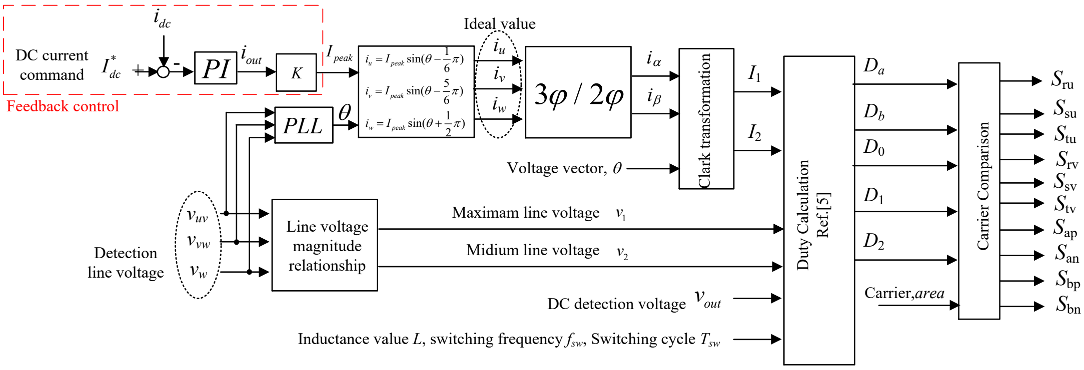


Fig. 8. Feedback loop control diagram with ripple cancelation method.

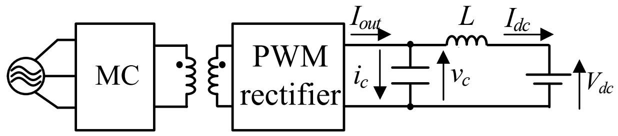
commutation begins near zero current [11]-[12]. The current direction at the start of the commutation changes due to the application of the two-level compensation. For this reason, the two-level compensation causes the overcompensate. The phase difference is greatly affected by the transmission power in the circuit configuration of isolated AC-DC converter based on the DAB converter and the matrix converter. The error of the voltage output period based on the voltage error seems to change the phase of the primary side and the secondary side in the operation of the DAB converter. In addition, the phase difference of the DAB converter causes a large transmission power error even if the voltage error is small. In a voltage-source PWM rectifiers, the compensation performance is improved by adjustment of the threshold current [13]. However, the threshold current always changes in the matrix converter because the instantaneous voltage fluctuates at six times of the grid frequency. Due to this, the linear compensation is applied for the phase difference φ under following three conditions. 1) Boundary conditions with DCM (T_a => 0), 2) The duty ratio T_a is less than dead-time ($T_a < T_d$), 3) The duty ratio T_a is longer than dead-time ($T_a > T_d$). The linear approximation compensation amount $\Delta\varphi$ is expressed as

$$\Delta\varphi = \begin{cases} T_d & (T_a \geq 0) \\ T_d - T_a & (0 < T_a < T_d) \\ 0 & (T_a > T_d) \end{cases} \quad (2)$$

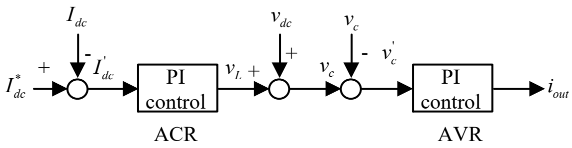
In chapter III-A,B, we examined the two-level compensation method and the linear approximation method in order to reduce the voltage error that occurs in the DCM or changed operation mode from DCM to CCM during the commutation. However, the voltage error is difficult to compensate for the voltage output period shorter than the dead time. In addition, the linear approximation method does not sufficiently reduce the voltage error. Thus, the input current distortion is remind by these reasons.

C. Voltage commutation compensation with DC current feed-back control

This chapter describes the problem of the linear approximation, which is the problem of the feedforward compensation, and the DC current feedback compensation, which solves the problem of not being able to compensate the output of the pulses below the dead time. The instantaneous power of the input/output power becomes constant due to the DC current feedback. When the instantaneous power is constant, the input current distortion does not occur under the power factor is constant. Due to this, the problem of the voltage error is solved without the compensation by the feedforward.



(a) Circuit configuration with DC side.



(b) Control diagram.

Fig. 9. Circuit configuration and Control diagram with DC current feedback.

Fig. 8 shows a block diagram with the feedback control. In Fig. 4, the maximum input current value I_{peak} is the command value, whereas in the feedback control, the DC current I_{dc} is used as the command. The current peak value is calculated by a PI control and the output of the conversion gain. The duty ratio is calculated by the equation in Ref. [5].

Fig. 9 shows the circuit configuration and the control block diagram for the DC current feedback control. The aim of this compensation method is to keep the instantaneous power of the input and the output power constant with the direct current feedback. The input current distortion will disappear under the constant instantaneous power and unity power factor.

Fig. 9(a) shows the circuit configuration on the DC side. The DC side circuit configuration has a LC filter between the DC voltage source (battery side) and the PWM rectifier.

Fig. 9(b) shows the control block diagram. The automatic current regulator (ACR) and the automatic voltage regulator (AVR) are applied to control the DC current. The PWM rectifier output current is summation of the DC current I_{dc} and the capacitor current I_c. Furthermore, the capacitor current I_c is zero in the steady-state. Thus, the PWM rectifier output current I_{out} and the DC current I_{dc} are equal in the steady state ($I_{out} \fallingdotseq I_{dc}$). In addition, the conversion gain K shown in Eq. (3) is provided to convert the PI output value I_{out} to the maximum input current value I_{peak}.

$$K = \frac{\hat{I}_{peak}}{\hat{I}_{dc}} \quad (3)$$

$\hat{I}_{peak}$ is the maximum value of the input current and $\hat{I}_{dc}$ is the output current at the rated operation. Note that these conditions are considered in the steady state without the conversion losses. The configuration from the output of the conversion gain to the duty calculation is the same as in the open-loop.

IV. Experimental Verification

Table 1 shows the experimental conditions. Note that the rated power is 6 kW, the switching frequency is 50 kHz, and the four-step voltage-based commutation is applied to prevent the commutation failures such as short-circuiting of the input voltage. One-step cycle of the four-step voltage-based commutation is set to 250 ns.

Fig. 10(a) shows the primary side voltage, current, and the secondary side voltage in the DCM region without the compensation. The transmission power command is 2.0 kW. From the experimental waveform, the voltage-based commutation operation of the matrix converter causes the voltage error in the output voltage because the transformer current has the current offset during the zero-voltage period.

Fig. 10(b) shows the primary side voltage, current, and the secondary side voltage with the two-level compensation. The transformer current was zero in synchronization with the zero-voltage period by suppressing the output voltage error by the two-level compensation.

Fig. 11 shows the primary-side voltage, current, and the secondary-side voltage without the compensation at the transmit power command is 2.0 kW. The input current waveform is greatly distorted. This is caused by the nonlinear voltage error in the phase difference φ between the primary and the secondary voltages when the operating mode is switched from DCM to CCM.

Fig. 12 shows the primary-side voltage, current, and the secondary-side voltage with linear approximation compensation. The input current distortion is reduced by adding the error compensation based on Eq. (2) to the phase difference φ.

Fig. 13 shows the input/output voltage and the current waveform of the matrix converter and the rectifier at the rated conditions under the boost ratio of 1.0. The input voltage and the current are in the phase and controlled at THD of 5.0% or less at the power factor of 1.0.

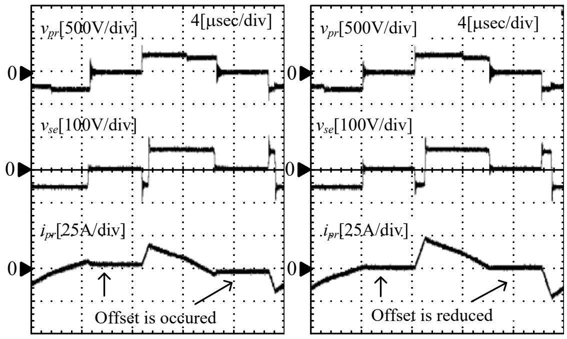
V. Simlation Verification

Fig. 14(a) shows the simulation results without the voltage error compensation. From the simulation waveform, a large input current distortion occurs due to the influence of the non-linear voltage error on the phase difference between the primary and the secondary side voltage when the operation mode is switched from DCM to CCM. The phase error between the primary and the secondary side occurs during the voltage-based commutation. In addition, the large input current distortion occure due to the large difference of the transmission power between DCM and CCM.

Fig. 14(b) shows the simulation waveforms with the feedforward compensations that uses the two-level compensation and the linear approximation compensation. In addition, the transmission power error during CCM is improved and the distortion of the input current is reduced by

Table 1. Experimental parameters.

Quantity	Symbol	Value
Rated power	P	6.0 kW
Three-phase AC voltage	v_{ac}	200 V
DC voltage	V_{dc}	Max 100 V
Input frequency	f	50 Hz
Carrier frequency	f_{sw}	50 kHz
Leakage inductance	L	21 μH
Turn ratio of transformer	N_1:N_2	3.3:1
Input filter	L_f	0.19 mH
	C_f	10 μF
Dead-time	T_d	250 ns



(a) Without compensation (b) With compensation

Fig. 10. Waveforms of matrix converter and rectifier.

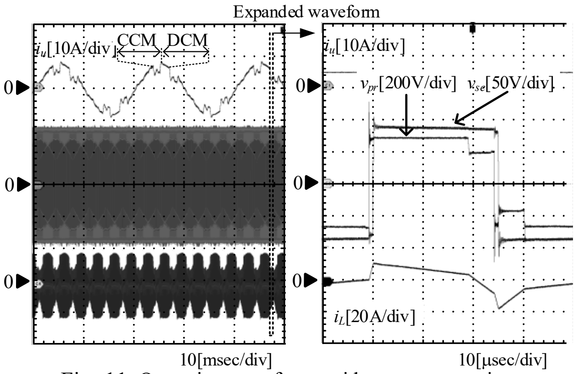


Fig. 11. Operation waveforms without compensation.

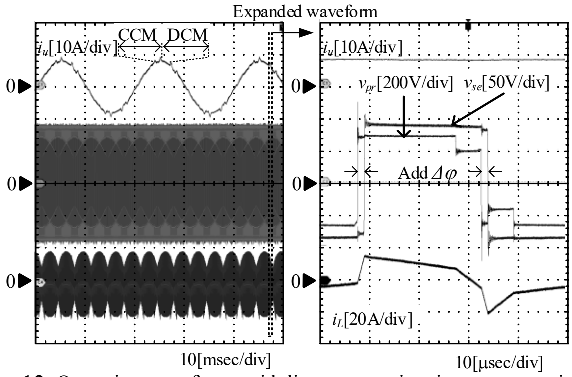


Fig. 12. Operation waveforms with linear approximation compensation.

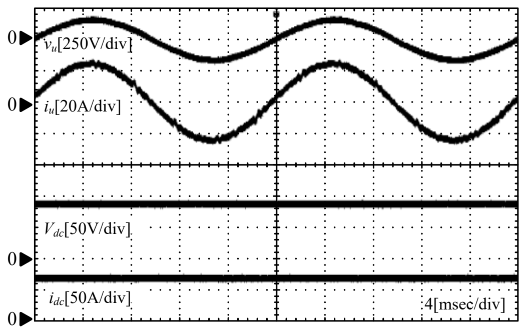


Fig.13. Input and output waveforms of matrix converter with rated operation.

adding the error correction shown in Eq. (2) to the phase difference.

Fig. 14(c), it is demonstrated that the input current THD is improved by the feedback compensation. However, the compensation is not enough because of low feedback gain. The optimization of the feedback gain will be revealed with stability analysis in future works.

Fig. 15 shows the comparison of the input current THDs among each compensation method. The input current THD is redeced by 70% due to applying the feedforward compensation. Howevere, more improvement is required less than 0.4 p.u. due to the insufficient compensation of the linear approximation method In the simulation results, it seems that the DC current feedback compensation is better than the feedforward compensation at 0.2 p.u. or more. However, the gain of the PI controller is set to very high-response in the simulation. The optimization of the controller, which applies the feedback compensation in parallel to the feedforward compensation, is needed in future works.

VI. Conclusions

In this paper, the compensation method of the voltage error was proposed utilizing the voltage-based commutation of the matrix converter. The voltage error caused by the voltage-based commutation was investigated by using the two-level compensation and the linear approximation compensation methods. The experimental results showed that the compensations were effective in reducing the input current distortion. THD of the input current was improved by up to 70%. However, the voltage error compensation was not completely reduced in light load due to the linear approximation. Therefore, the DC current feedback compensation was demonstrated by the simulation to reduce the influence of the voltage error and insensitive less than the dead time. The simulation results showed that the voltage error was improved compared to the method using the feedforward compensation.

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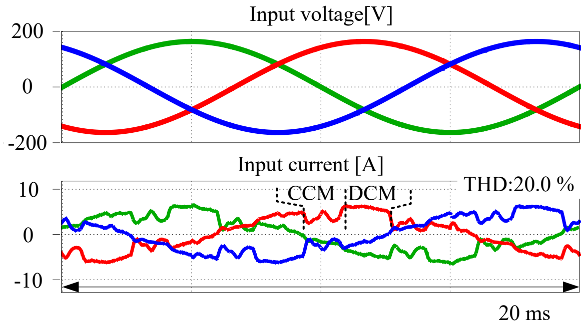
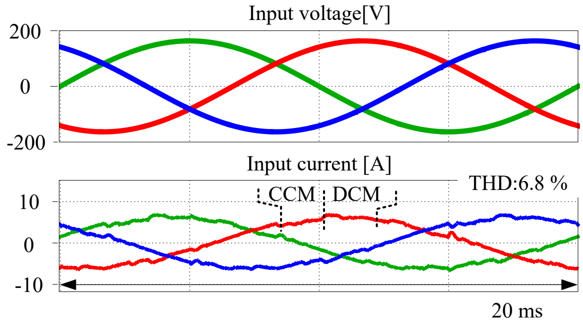
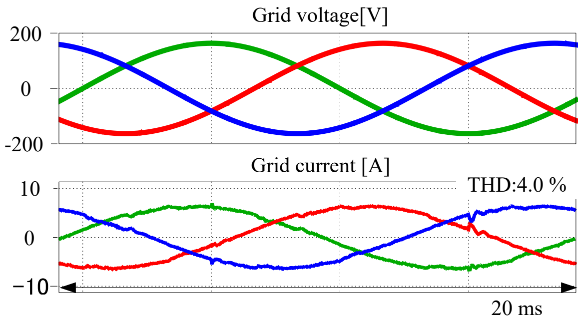


(a) Without compensation



(b) With feedforward compensation
(Two-level compensation + linear approximation compensation)



(c) Feedback compensation

Fig. 14. Simulation result of the operation mode switching from DCM to CCM.

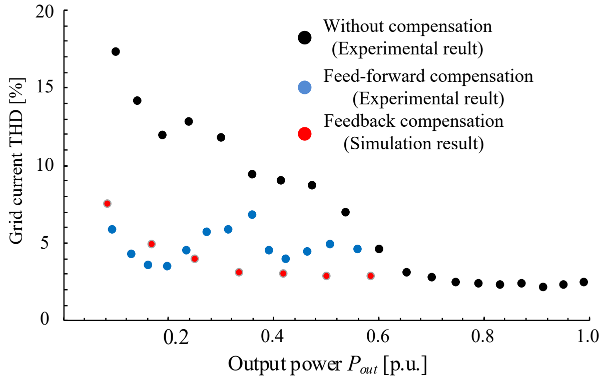


Fig. 15. THD characteristics (boost ratio 1.0).

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