Two-step commutation for Isolated DC-AC Converter with Matrix Converter

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Abstract— **This paper proposes a two-step commutation method for a three-phase-to-single-phase matrix converter. Conventional two-step commutation cannot be applied at all operation regions because a commutation failure due to the detection error of grid voltages still occurs. In the proposed two-step commutation, by modulating only one of two devices in a bi-directional switch and utilizing a zero vector to let the switches naturally turn-off, the commutation failures are avoided completely regardless of the voltage detection error. From experimental results, it is confirmed that the proposed two-step commutation has always safety operation to avoid commutation failure. The input current THD at 10 kW with the proposed two-step commutation is improved by 37% in comparison with the conventional four-step commutation.**

Keywords— Two-step commutation, Current direction estimation, Commutation failure.

I. INTRODUCTION

A lot of studies on Electric vehicles (EVs) and Plug-in hybrid vehicles (PHEVs) have been accelerated over the past decade. Compared to the gasoline vehicle, EVs or PHEVs still faces one of the main challenges, i.e. the long battery charging time. In order to solve this problem, high-power low-profile battery chargers are required [1-4]. In [5-9], isolated AC-DC converters using a matrix converter as a medium frequency AC-AC converter connected with the transformer at the primary side have been proposed. The matrix converter volume is expected to be greatly reduced compared to other topologies which employ a buffer capacitor because the buffer capacitor in the high-power application such as the rapid battery charger usually has to withstand a high current, which increases the capacitor volume.

Generally, the matrix converters are required a commutation sequence at the switching timing of the power devices to prevent short-circuit at a voltage source and open-circuit at inductive components. The conventional commutation method is separated into two types, the voltage commutation method based on the input voltage polarity and the current commutation method based on the output current direction [10-13]. The voltage commutation works reliably if the relationship of the input voltages is accurately obtained. These commutation sequences are the four-step commutation which is divided into the four steps to avoid the open-circuit and the short-circuit. Each step is turned-on or turned-off a switch into the two bi-directional switches depended on the voltage polarity or the current direction. The commutation time which is longer than the switching speed of the switching devices is inserted among the first-step, the second-step, the third-step and the fourth-step. Therefore, the four-step commutation which is the voltage commutation or the current commutation is a complex commutation algorithm which greatly restricts the applicable control hardware. A life time and a reliability of the switching devices are decreased by the commutation failure which is based on the detection error

In order to simplify the control hardware for the matrix converter, two-step commutation methods have been proposed [5-11]. Commutation time in the two-step commutation is half of that in the four-step commutation. This results in a short commutation time with a simpler commutation algorithm. In particular, the two-step commutation in [11] is achieved by zero vectors which is the switching pattern of the additional circuit outputting the zero voltage at the input terminal. Another two-step commutation in [6-10] uses both the voltage polarity and the current direction for the commutation. However, the main problem of these conventional two-step commutations is that either the additional circuit is required or the commutation failures still occurs at the critical area due to a detection error of the input voltage. A solution for this problem is that the commutation method is switched between the conventional two-step commutation and the four-step commutation. However, this solution increases the number of switching step and requires the implement of the two commutation methods.

If the switching pulses are shorter than the dead-time, next commutation sequence starts before present commutation period has been completed and it causes input current distortions. In the low modulation index region, the input current is distorted by the output voltage error due to the conventional several-step commutation. It is necessary to reduce the number of the commutation step in order to reduce the output voltage error.

In this paper, the two-step commutation is proposed for a three-phase to single-phase matrix converter in order to improve the input current total harmonics distortion (THD) in the low modulation index region. The output voltage error is decreased by the proposed two-step commutation due to less commutation. In addition, the commutation failure does not occur regardless of the voltage detection error. The original idea of this paper is to turning-on only one of two devices in the bi-directional switches based on the current direction and to use a voltage vector which let the switches naturally turn-off. Therefore, the proposed two-step commutation is unnecessary to switch between the conventional two-step commutation and another commutation method to prevent the short-circuit at the critical area. The effectiveness of the proposed two-step commutation is evaluated with a 10-kW prototype thought experimental results.

II. CIRCUIT CONFIGURATION AND CONTROL METHOD

Figure 1 shows the isolated AC-DC converter with the three-phase to single-phase matrix converter. The proposed circuit consists of a LC filter to eliminate switching ripple component of the input current, a three-phase to single-phase matrix converter with bi-directional switches, a medium frequency transformer, a diode rectifier, and a smoothing inductor in the output DC side. In particular, the three-phase grid voltage is directly converted to medium frequency single-phase voltage by the matrix converter. Consequently, the volume of the transformer is significantly minimized because this transformer is operated with this medium frequency single-phase voltage.

III. TWO-STEP COMMUTATION METHOD

A. Problem of conventional commutation method

Figure 2 shows the equivalent circuit at each arm of the matrix converter. The equivalent circuit consists of the three voltage sources (maximum-phase-voltage V_{max}, middle phase-voltage V_{mid}, minimum phase-voltage V_{min}), current source which represents as the current at the transformer, and three bi-directional switches. Figure 2(b) and 2(c) show the transition situation from V_{max} to V_{mid} with the four-step voltage commutation and the conventional two-step commutation. If the actual voltage polarity does not agree with the detection voltage polarity, the short-circuit via the grid occurs in the commutation state of the four-step voltage commutation or in the steady state of the conventional two-step commutation after turning-on S_{mr}

B. Principle of two-step commutation

Figure 3 depicts the principle of the proposed two-step commutation, which is divided into two modes. Figure 3(a) shows the transition from an input phase to another input phase, whereas Figure 3(b) shows the transition from zero-vector state to an input phase. As shown in Fig. 3 (a), when the matrix converter starts to transit from

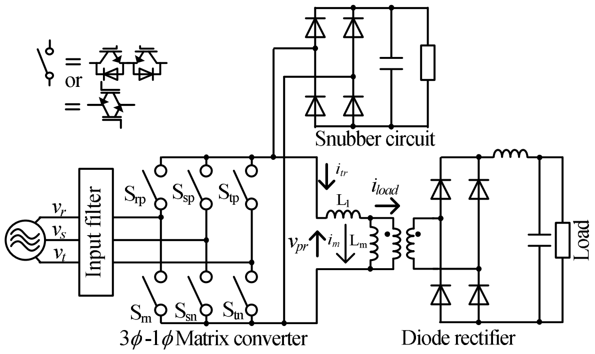


Fig. 1. Isolated AC-DC converter with three-phase-to-single-phase matrix converter.

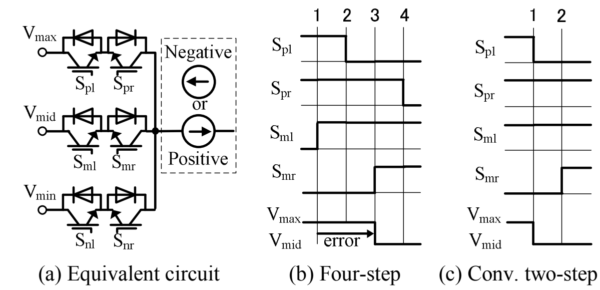


Fig. 2. Conventional commutation step; If the acutal voltage does not agree with the detection voltage, the short-circuit occur by the commutation failure

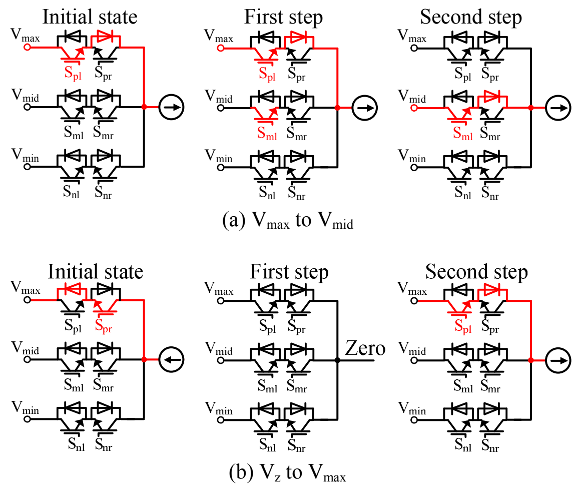


Fig. 3. Proposed commutation sequence. The commutation step is always two-step by proposed sequence.

V_{max}-phase to V_{mid}-phase in case of the positive output current, only the switch S_{pr} is on at V_{max}-phase. At first step, only the switch S_{mr} at V_{mid}-phase turns-on. Then, at second step, the switch S_{pr} turns-off and the current commutates from V_{max}-phase to V_{mid}-phase. In this commutation mode, the short-circuit and the open-circuit are avoided regardless of the voltage detection error by the modulation of only one of two devices in the bi-directional switches. Therefore, the transition from an input phase to another input phase without any commutation failures is achieved. The initial state is on state of S_{pl} and then similar switching sequence are applied when the output current direction is negative. The initial state of the equivalent commutation model for each arm is express by (1)

$$\begin{cases} S_{xl} = 1 & S_{xr} = 0 \quad i_{load} > 0 \\ S_{xl} = 0 & S_{xr} = 1 \quad i_{load} < 0 \end{cases} \quad \mathrm{x = p, m, n} \tag{1}$$

where subscript x indicates p (V_{max}-phase) or m (V_{mid}-phase) or n (V_{min}-phase) depend on the output line to line voltage V_{pr}. If the output voltage of the matrix converter is V_{max}-V_{min}, x of the upper side arm is p. In addition, x of the lower side arm is n.

Figure 4 shows the output voltage error of the commutation operation with the proposed two- step commutation. The output voltage is delayed by one-step time at the commutation from the high voltage phase to the low voltage phase because the current flow does not change until the second step. In contrast, the output voltage error does not occur when the commutation from the low voltage phase to the high voltage phase because the current flow changes after the first step. In last case, the output voltage is delayed by one-step time when the commutation from the zero vector to any vector. The reason is because the output voltage is zero when all switches is turned-off at first step after the zero vector.

Figure 5 shows the proposed two-step commutation sequence. The output voltage error due to the dead time is considered. The delay of one-step time occurs from the first step to the second step as shown in Fig. 2 (a) when the matrix converter transits from an input phase to another input phase in the positive output current. In the transition from the zero-vector state to another input phase, all switches have to be turned-off at the first step. Similarly, the delay of one-step time occurs from the first step to the second step as shown in Fig. 2 (b). Consequently, the compensation for the voltage error due to the delay of one-step time of the proposed two-step commutation is similar to that in the back-to-back converter, which is significantly simpler than the output voltage error compensation in the four-step commutation.

Figure 6 shows the half-cycle operation of one switching period including commutation in sector I. The relationship of phase-voltage is $v_r > v_s > v_t$.

(i) Initial state: V_1

S_{rp} and S_{nt} are on, whereas the output current direction is positive. Therefore, S_{pr} and S_{tn} can only conduct the current through the diode connected anti-parallel with the switching devices.

(ii) Commutation state V_1 to V_2

At first step, S_{sp} is turned-on. The current flow does not change because the R-phase voltage is higher than the S-phase voltage.

At second step, S_{rp} is turned-off. The output voltage is changed from V_{max}-phase to V_{mid}-phase. This matrix converter successfully outputs vector V_2

(iii) Commutation state V_2 to V_{zero}

At first step, S_{tp} and S_{nr} is turned-on, whereas the output current direction is still positive. At second step, S_{sp} and S_{nt} is turned-off. The output voltage polarity is changed to be opposite of the output current. Thus, the output current quickly decreases to zero. When the output

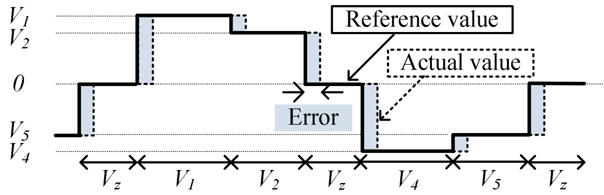
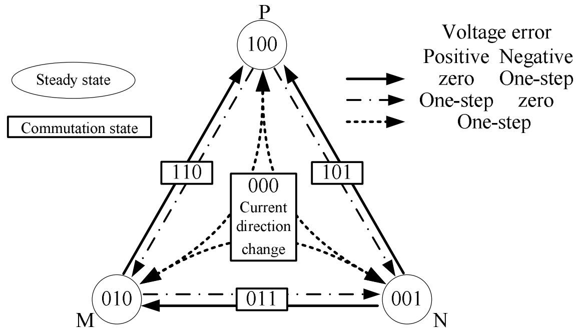


Fig. 4. Output voltage error with proposed two-step commutation.



Current direction	(S_1,S_2,S_3)	$(S_{1P},S_{1N},S_{2P},S_{2N},S_{3P},S_{3N})$
Positive	1 0 0	1 0 0 0 0 0
Negative	1 0 0	0 1 0 0 0 0

Fig. 5. Proposed two-step commutation sequence.

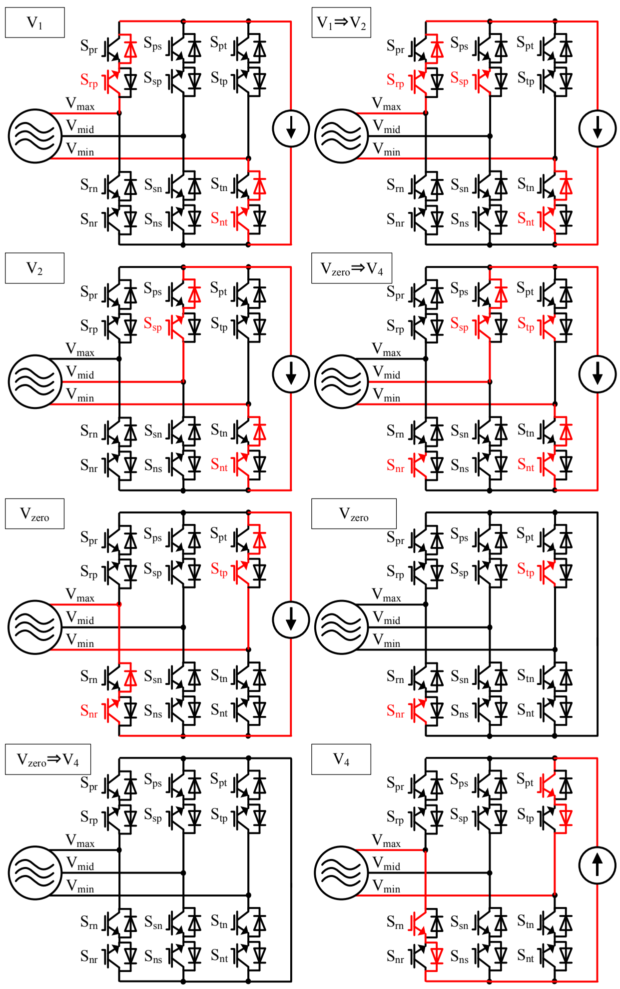


Fig. 6. Transition situation during half cycle one switching period.

current reaches zero, the output voltage also becomes zero, i.e. zero-vector state.

(iv) Commutation state V_{zero} to V_4

At first step, S_{tp} and S_{nr} can safely turned-off because the output current has become zero. At second step, $\underline{S_{rn}}$ and S_{pt} is turned-on and the matrix converter outputs the negative voltage.

In consequence, the proposed two-step commutation operates the matrix converter without any commutation failures regardless of the detection voltage error at the input voltage.

IV. INPLEMENT OF TWO-STEP COMMUTATION

A. Input current control for matrix converter

Figure 7 shows the space vector modulation (SVM) applied to the three-phase to single-phase matrix converter. The operation mode of SVM is divided by every 60 deg. (Sector I, II, III, IV, V and VI) of the input voltages. Output vectors which are close to the input voltage vector are selected. In sector I, V_1 and V_2 are used during the first half of the control period as the positive voltage, whereas V_4 and V_5 are used during the second half of the control period as the negative voltage. Note that the zero vector V_z which outputs the zero voltage, is decided by the sector. These duty reference T_1, T_2, and T_z are calculated by

$$T_1 = \frac{1}{|A|}\begin{vmatrix} v_\alpha & V_{2\alpha} \\ v_\beta & V_{2\beta} \end{vmatrix} \tag{2}$$

$$T_2 = \frac{1}{|A|}\begin{vmatrix} V_{1\alpha} & v_\alpha \\ V_{1\beta} & v_\beta \end{vmatrix} \tag{3}$$

$$T_Z = 1-(T_1+T_2)\left(\because |A| = \begin{vmatrix} V_{1\alpha} & V_{2\alpha} \\ V_{1\beta} & V_{2\beta} \end{vmatrix}\right) \tag{4}$$

B. Current direction estimation

Figure 8 shows the current estimation method to achieve the proposed two-step commutation. The current direction estimation is required for reducing the current sensor which has the high current ratio and the wide bandwidth. The output current is synchronized with the switching carrier by SVM. The switching signal for the zero vector is selected to reduce the output current up to zero. In order to achieve the two-step commutation, the zero current timing at the output side is necessary until

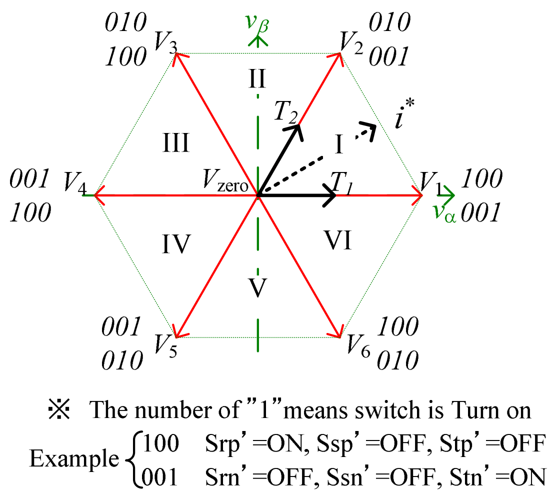


Fig. 7. Space vector modulation.

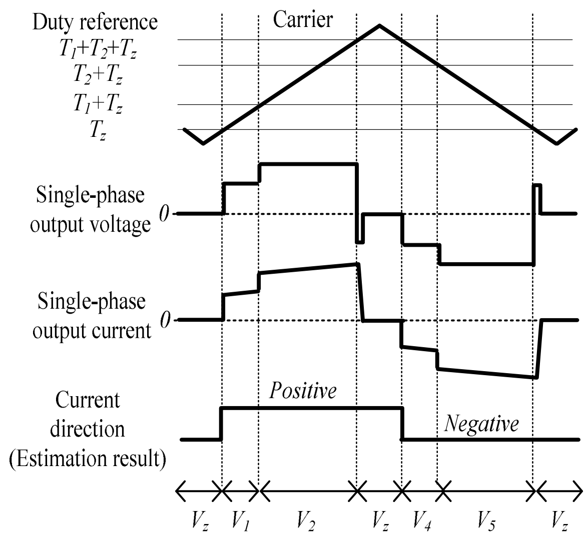


Fig. 8. Estimation principle of current direction. The output current is synchronized the switching carrier by SVM. Therefore, the output current direction is also same relationship.

end of the zero vector. The output voltage is clamped at the grid voltage during the zero vector when the output current thought via grid voltage. After that, the output current and voltage are also zero. The current direction estimation is achieved to keep the zero current at the output side until end of the zero vector.

C. Inplementation of proposed two-step commutation

Table I shows the switching table for the proposed two-step commutation. The switching table depends on the sector and the selected output vector. The switching pulse of the same vector is changed by the sector. According to the principle of the proposed two-step commutation as shown in Fig. 3, the gate signals are

TABLE I. SWITCHING TABLE FOR TWO-STEP COMMUTATION.

Sector	I			II			III			IV			V			VI		
Vector	V_1	V_2	V_z	V_2	V_3	V_z	V_3	V_4	V_z	V_4	V_5	V_z	V_5	V_6	V_z	V_6	V_1	V_z
Switching signal	100 001	010 001	001 100	010 001	010 100	001 010	010 100	001 100	100 010	001 100	001 010	100 001	001 010	100 010	010 001	100 010	100 001	010 100

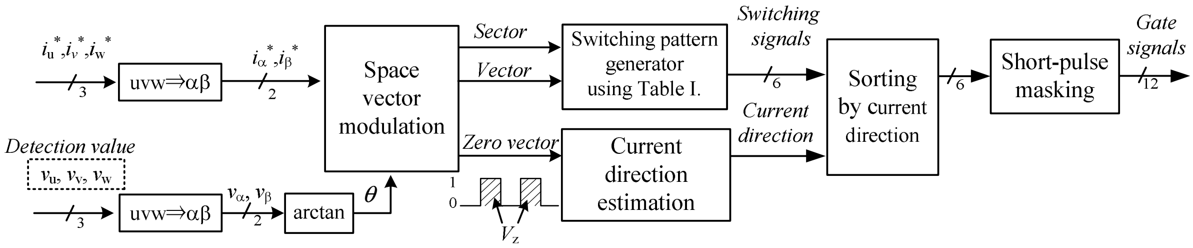


Fig. 9. Signal generation for proposed two-step commutation.

decided for the six bidirectional switches. For example, the output vector V_1 is selected in the sector I, S_{rp}, S_{tp} and S_{tn} are turned-on. S_{sp}, S_{rn} and S_{sn} are turned-off.

Figure 9 shows the gate signal generation for the proposed two-step commutation which requires the complex commutation algorism as the four-step commutation because the proposed two-step commutation only uses a switching table and the current direction estimation. The one of two devices in the bi-directional switches is operated by the gate signals depending on the current direction. Another one of that is turned-off during half cycle of the switching frequency. Finally, the short-pulse in the gate signals is masked because the short-pulse wide more than the sum of the raise time and the turn-on delay time required between the switching and next switching on the three-phase to single-phase matrix converter.

V. Experimental Results

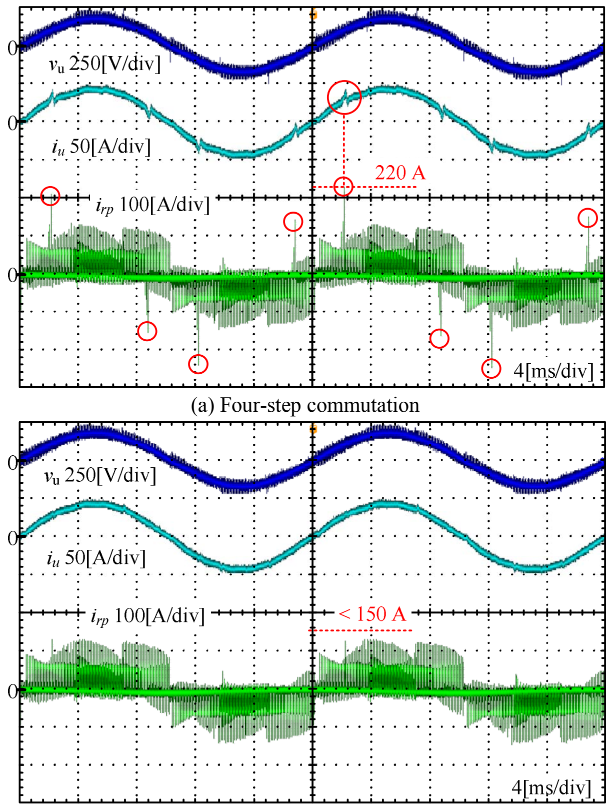
Table II shows the experimental conditions for 10 kW. The switching devices at the three-phase to single-phase matrix converter uses IGBT (MITSUBISHI ELECTRIC: CM400C1Y-24S). The one-step time t_d is decided by the switching characteristics of IGBT. The sum of the raise time and the turn-on delay time of this IGBT is shorter than 1.0 µs. Therefore, the one-step time sets to 1.0 µs.

Figure 10 (a), (b) shows the experimental waveforms of the three-phase to single-phase matrix converter at 10 kW with the four-step commutation method based on the grid voltage polarity (voltage commutation) and with the proposed two-step commutation method respectively. The commutation failure applying the voltage commutation occurs in the regions where the relationship of the grid voltages changes. As a result, the surge current is approximately 220 A. Consequently, the life time and the reliability of the switching devices is decreased. In addition, the input current is distorted by the commutation failure. The proposed method based on estimation of the output current direction achieves to avoid short-circuit at the grid voltage. Consequently, the input current distortion is low value by 2.9%. In addition, surge current is always suppressed by the proposed two-step commutation.

Figure 11(a)-(b) show the experimental waveforms with the four-step voltage commutation, and the extended waveforms at high modulation index, respectively. The input current has low THD by 4.9% and high-power

TABLE II. EXPERIMENTAL CONDITION.

Element	Symbol	Value
Three-phase AC voltage	v_{ac}	200 V
Input frequency	f	50 Hz
Rated output power	P_{out}	10 kW
Carrier frequency	f_c	20 kHz
Leakage inductance	L_l	0.4 µH
Turn ratio of transformer	N_1:N_2	1:2.4
Input filter	$L_f(\%Z)$	350 µH(2.3%)
	$C_f(\%Y)$	11 µF(4.7%)
Output filter	L	1.3 mH
	C	30 µF
Commutation time	t_d	1.0 µs

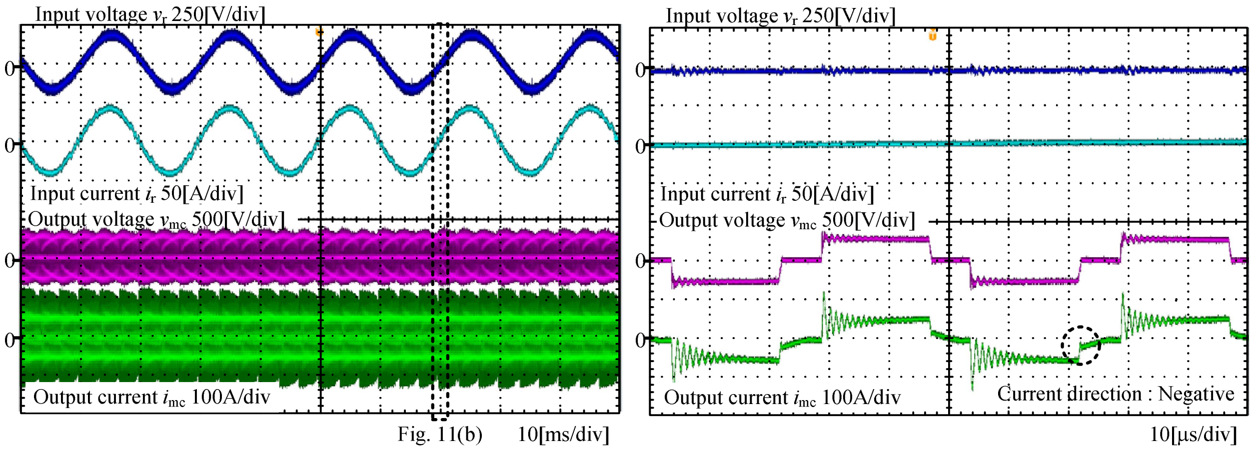


(b) Two-step commutation

Fig. 10. Conparison of device current at matrix converter at rated 10 kW.

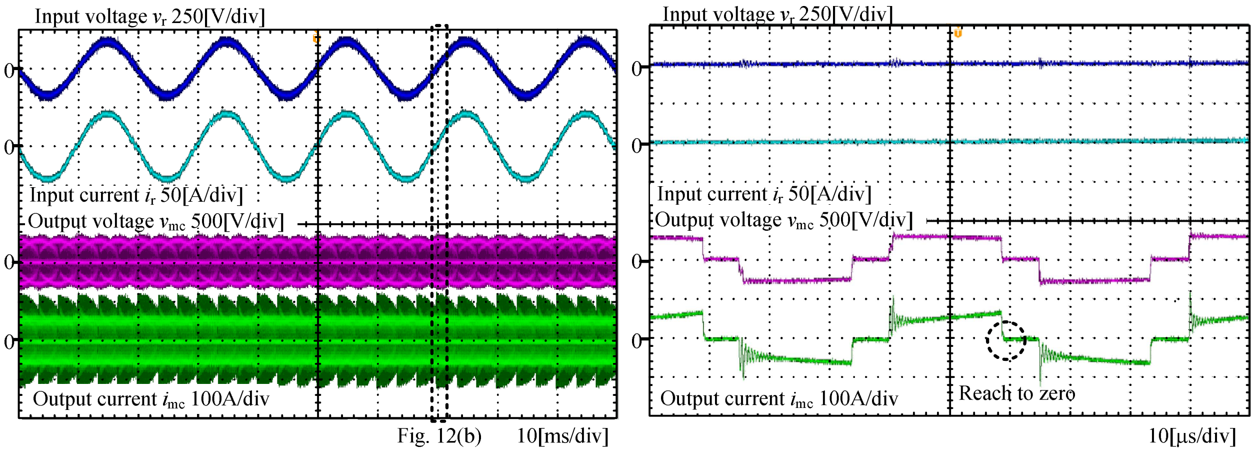
factor as 0.99. However, the output current does not zero at zero vector.

Figure 12(a)-(b) show the experimental waveforms with the proposed two-step commutation, and the extended waveforms at high modulation index,



(a) Input and output waveforms of matrix converter (b) Extended Fig 11(a)

Fig. 12. Four-step voltage commutation with high modulation index (MI = 0.85) at rated power 10 kW.



(a) Input and output waveforms of matrix converter (b) Extended Fig12 (a)

Fig. 13. Proposed two-step voltage commutation with high modulation index (MI = 0.85) at rated power 10 kW.

respectively. It is clear that the output current at the zero vector state quickly decreases to zero. Therefore, the surge voltage due to the output current does not occur when all switches turn-off. It confirms from this result that the proposed two-step commutation method operates the matrix converter without any commutation failures regardless of the input voltage detection error.

Figure 13 shows the characteristics of the input current THD with each commutation method at the high modulation index. The input current THD of the proposed two-step commutation is similar to one of the conventional four-step commutation. The commutation step is decreased by the proposed two-step commutation to keep the performance of input current control.

Figure 14(a)-(b) show the experimental waveforms with the conventional four-step voltage commutation, and the extended waveforms at low modulation index, respectively. The input current is distorted by the masking of the short-pulse.

Figure 15(a)-(b) show the experimental waveforms with the proposed commutation, and the extended waveforms at low modulation index, respectively. It confirms from this result that the proposed two-step commutation method operates the matrix converter

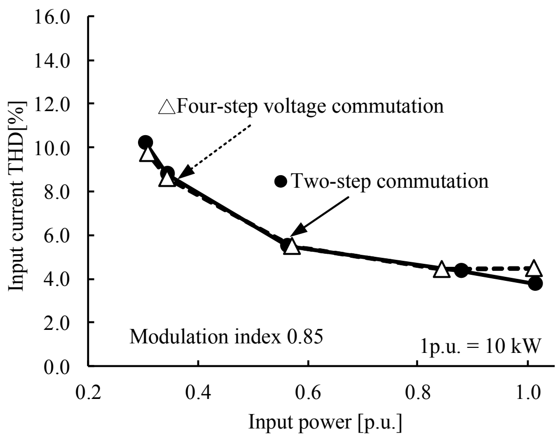
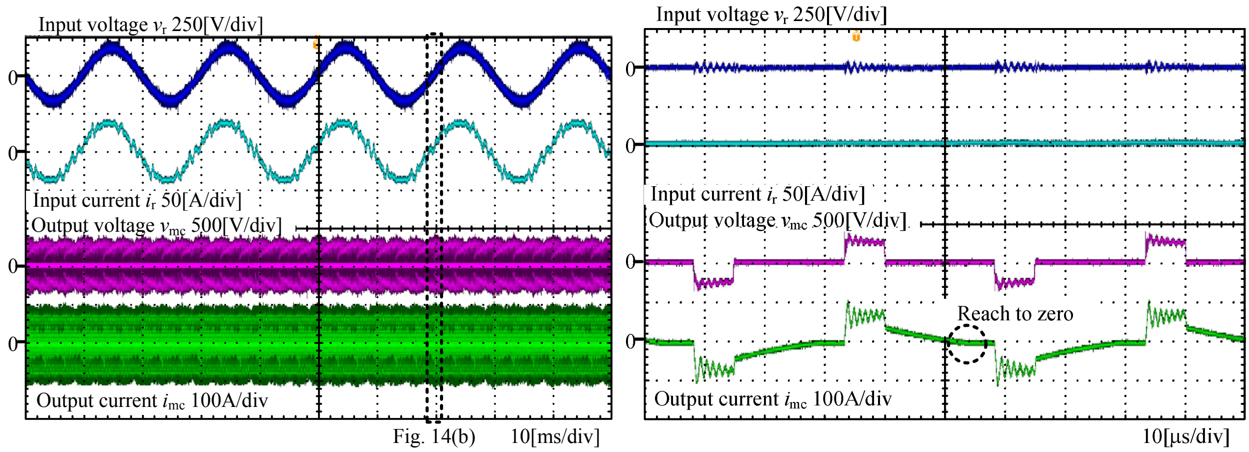


Fig. 11. Comparison of grid current THD at high modulation index. The input current THDs of the proposed two-step commutation and the conventional four-step commutation are also same.

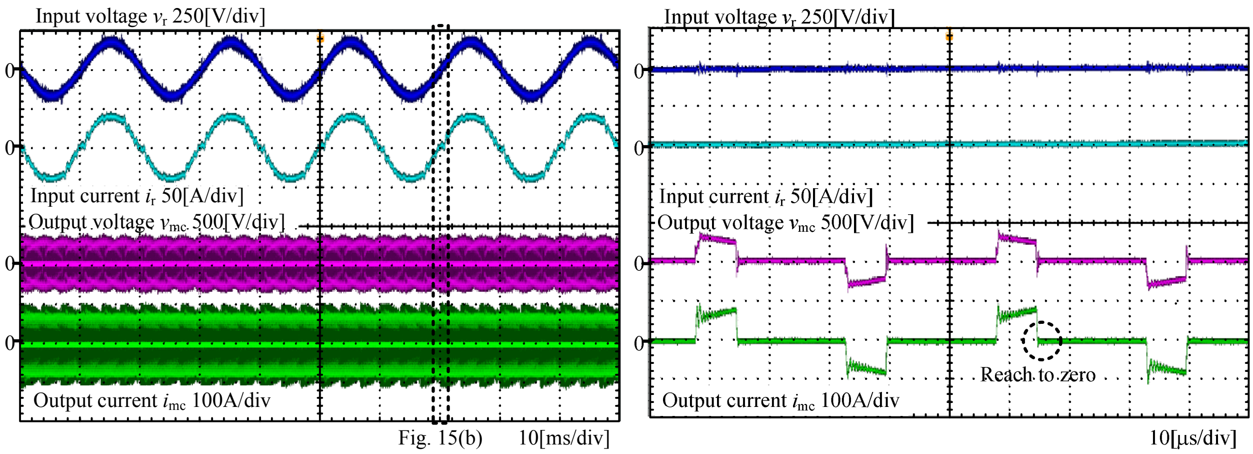
regardless of the modulation index.

Figure 16 shows the distortion characteristics of each commutation methods at the low modulation index. The input current THD of the proposed two-step commutation is 7.7% at 10 kW. In the low modulation index, the proposed two-step commutation has the high performance in comparison with the conventional four-



(b) Input and output waveforms of matrix converter (b) Extended Fig 14(a)

Fig. 15. Four-step voltage commutation with high modulation index (MI = 0.30) at rated power 10 kW.



(b) Input and output waveforms of matrix converter (b) Extended Fig 14(a)

Fig. 16. Proposed two-step voltage commutation with high modulation index (MI = 0.30) at rated power 10 kW.

step commutation at entire loads.

Figure 17 shows the output voltage error of each commutation method. the output voltage error is less than 0.4% regardless of the modulation index. It is clear that the proposed two-step commutation method is unnecessary to compensate the output voltage error.

Figure 18 shows the distortion characteristics of each commutation methods against the modulation index at rated 10 kW. The input current THD of the proposed two-step commutation is 7.7% at 10 kW. The output voltage range is extended by 36% in case of same input current THD.

VI. CONCLUSIONS

In this paper, the two-step commutation was proposed in the three-phase to single-phase matrix converter. Compared to the conventional two-step commutation, the proposed two-step commutation is always the safety operation regardless of the voltage detection error. In addition, the commutation algorithm of the proposed two-step commutation is much simpler than the conventional commutation. On the other words, the simple control hardware is employed for the matrix converter with the proposed two-step commutation. The

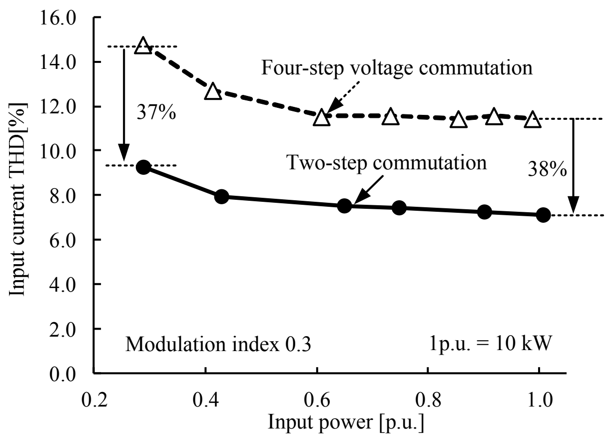


Fig. 14. Comparison of grid current THD with each commutation method at low modulation index. The input current THD is improved by 37 % with the proposed two-step commutation in comparison with the conventional four-step commutation.

input current THD with the proposed two-step commutation is improved by 38% at the low modulation index.

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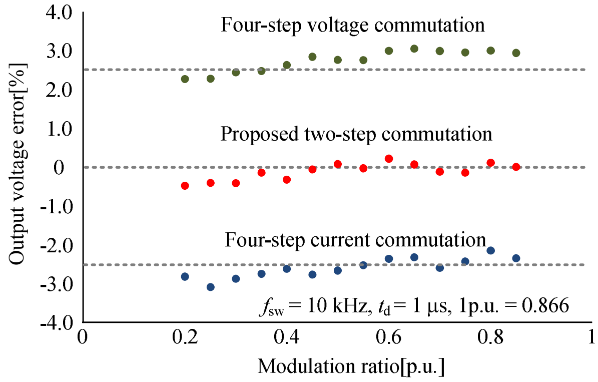

Fig. 17. Comparison of output voltage error.

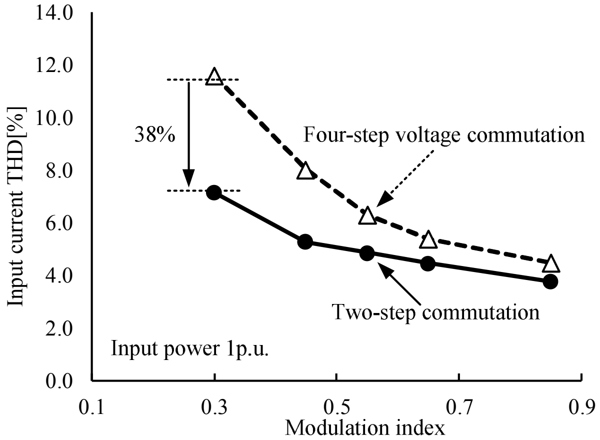

Fig. 18. Comparison of grid current THD with each commutation method at entire modulation index.