Single-step commutation method for three-phase to single-phase matrix converter

Shunsuke Takuma
Nagaoka University of Technology
Nagaoka, Niigata, Japan
takuma_s@stn.nagaokaut.ac.jp

Keisuke Kusaka
Nagaoka University of Technology
Nagaoka, Niigata, Japan
kusaka@vos.nagaokaut.ac.jp

Jun-ichi Itoh
Nagaoka University of Technology
Nagaoka, Niigata, Japan
itoh@vos.nagaokaut.ac.jp

***Abstract*— This paper proposes a single-step commutation method based on an output current direction estimation for a three-phase-to-single-phase matrix converter. Conventional four or two-step commutation causes a commutation failure due to the detection error of grid voltages. In addition, an input current is distorted due to an output voltage error in the low modulation index on a three-phase to single-phase matrix converter. A zero vector to decrease an output current up to zero is proposed to achieve single-step commutation under all region. In the proposed single-step commutation, by modulating only one of two devices in a bi-directional switch and utilizing a zero vector, the commutation failures are avoided completely regardless of the voltage detection error. As experimental results, the input current distortion is 2.3% at 10 kW with the proposed single-step commutation. The input current THD in low modulation index is reduced by 34.9% in comparison with the conventional four-step commutation. The proposed single-step commutation has a considerably simple commutation algorithm.**

Keywords—single-step commutation, three-phase to single-phase matrix converter,

I. Introduction

A lot of studies on electric vehicles (EVs) and plug-in hybrid vehicles (PHEVs) have been accelerated over the past decade. EVs or PHEVs still require the long battery charging time. Therefore, high-power battery chargers with a wide voltage range are researched in order to solve this problem [1-4]. In [5-9], isolated AC-DC converters using a matrix converter as a middle-frequency AC-AC converter connected with the transformer at the primary side have been proposed. The matrix converter volume will be greatly reduced to remove a buffer capacitor compare with other topologies. However, it is necessary to a complex commutation sequence for a safety switching.

Generally, a commutation sequence at the switching timing of the power devices are required for the matrix converters in order to prevent a commutation failure such as short-circuit at a voltage source and open-circuit at a current source. This commutation sequence consists of four times of switching for two bi-directional switches. The conventional commutation methods to utilize the input voltage polarity or the output current direction are proposed [10]. The voltage commutation with a safety operation is required to obtain the relationship of the input voltages clearly. However, the four-step commutation with the voltage polarity or the current direction is a complex commutation algorithm which greatly restricts the applicable control hardware.

An isolated AC-DC converter with a wide voltage range from 200 V to 500 V in CHAdeMO is required. The output voltage of a three-phase to single-phase matrix converter is adjusted by changing a modulation index. When a low modulation index, switching pulses of the matrix converter are narrow compared with a high modulation index. Then, the output voltage error occurs due to short-pulse, which is shorter than dead-time. It is necessary to reduce the number of the commutation step in order to reduce the output voltage error.

In [11-14], a two-step commutation is proposed in order to solve a problem, which is a complex algorism. The two-step commutation is separated into two methods based on the input voltage polarity of the output current direction. The commutation failure still occurs with the two-step voltage commutation at the critical area. On the other hands, the two-step current commutation is suppressed by the commutation failure due to the voltage detection error. However, it is difficult to apply the two-step current commutation for the three-phase to single-phase matrix converter, because the output current direction is changed during one switching period. The high accuracy current sensor or the estimation method is required to obtain the output current direction. In addition, the input current is distorted at the low modulation index, because the conventional two-step commutation still remain the commutation time of one step.

In this paper, the single-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 wide voltage range. The output voltage error by several-step commutation is decreased by the proposed single-step commutation. In addition, the commutation failures do 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 single-step commutation is applied to the three-phase to single-phase matrix converter even in the critical area. The effectiveness of the proposed single-step commutation is confirmed with a 10-kW prototype.

II. Circuit configulation

Figure 1 shows the isolated AC-DC converter with the three-phase to single-phase matrix converter. The matrix converter does not employ a buffer capacitor and an initial charging circuit The proposed circuit consists of a LC filter to eliminate switching ripple, the three-phase to single-phase matrix converter, the middle frequency transformer, a diode rectifier, and a smoothing inductor. In particular, the three-phase grid voltage is converted to a middle frequency single-phase voltage by the matrix converter. Consequently, the volume of the transformer is significantly minimized because this transformer is operated with this middle frequency single-phase voltage. The output voltage is adjusted by the modulation index of the three-phase to single-phase matrix converter.

III. Principle of Single-Step Commutation

A. Single-step commutation on equivarent model

Figure 2 shows the principle of the proposed single-step commutation, which is divided into three modes. As shown in Fig. 2 (a), when the matrix converter starts to transit from V_{max}-phase to V_{mid}-phase with the positive output current, the switch S_{pl}, S_{ml} and S_{nl} turn-onat V_{max}-phase, V_{mid}-phase and V_{min}-phase. At the first step, the switch S_{pl} at V_{max}-phase turns-off and the current commutates from V_{max}-phase to V_{mid}-phase. At the second step, the switch S_{ml} at V_{mid}-phase turns-off and the current commutates from V_{mid}-phase to V_{min}-phase. The output voltage is also changed at single step commutation completely. The switching signal of the one of two devices in the bi-directional switches, is decided by current direction. In this commutation sequence, by applying the modulation of only one of two devices in the bi-directional switches, the short circuit and the open circuit are avoided regardless of the voltage detection error. Therefore, the transition from an input phase to another input phase without any commutation failures is achieved. As shown in Fig. 2 (b), the switching sequence are applied when the output current direction is negative in the same manner.

If the output current frequency is lower than the switching frequency such as the three-phase to three-phase matrix converter, a single-step commutation based on the principle is achieved by keeping the same current direction during the switching period. However, the output current direction is changed during half cycle of the switching frequency in the three-phase to single-phase matrix converter. Therefore, the single-step commutation is not used for the three-phase to single-phase matrix converter with the conventional modulation scheme. The zero vector is changed to apply the single-step commutation.

B. Zero vector for single-step commtation

Figure 3 shows the space vector modulation (SVM) to control the input current of the three-phase to single-phase matrix converter. SVM is based on the detection of six 60 deg. intervals (Sector I, II, III, IV, V, and VI) of the input voltages. In addition, the magnitude relationship of the grid voltage is changed at the center of each sector. Therefore, area is defined by

$$Area\begin{cases} A: (n-1)\dfrac{\pi}{3} <= \theta < \dfrac{n}{2}\dfrac{\pi}{3} \\ B: \dfrac{n}{2}\dfrac{\pi}{3} <= \theta < n\dfrac{\pi}{3} \end{cases} \qquad n = 1,2,3,4,5,6 \qquad (1),$$

where n is number of the sector, and θ is the angle of the reference of the input current vector i*.

Output vectors, which are close to the input voltage vector are selected to reduce the input current distortion. In sector I, the positive voltage at the output voltage is outputted to select V_1 and V_2 during the first half of the control period, whereas the negative voltage is outputted to use V_4 and V_5 during the second half of the control period.

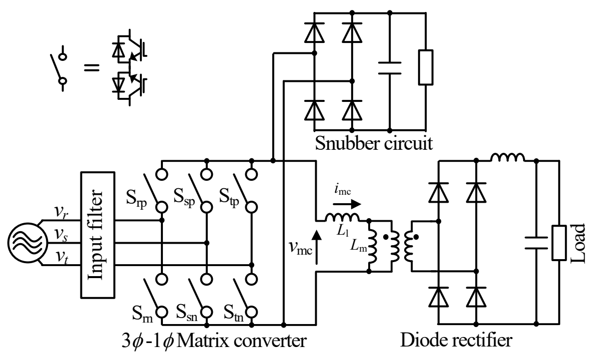


Fig. 1. Isolated AC-DC converter with three-phase-to-single-phase matrix converter. an several-step commutation is required for the operation of the three-phase to single-phase matrix converter.

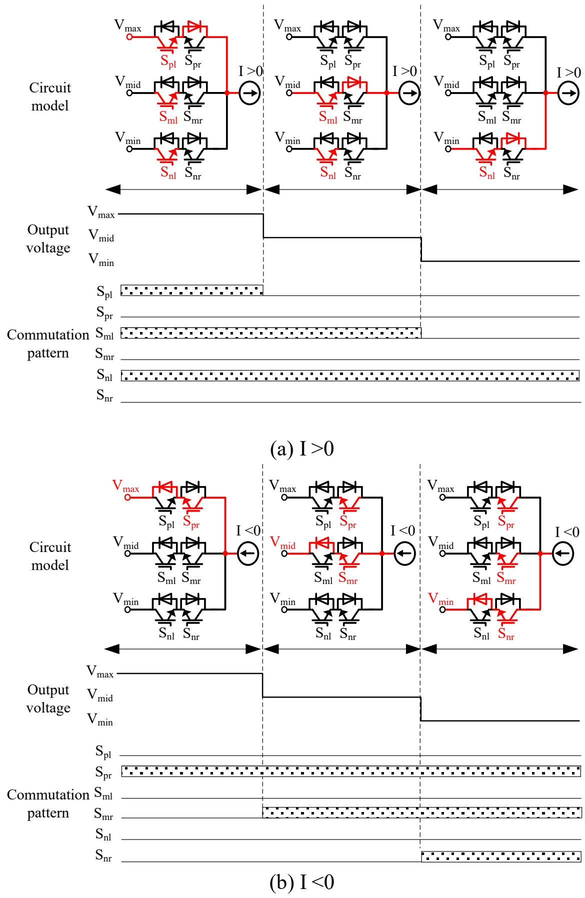


Fig. 2. Switching mode each current direction on equivarent commutation model.

The output voltage of matrix converter at single-phase side has a middle frequency as same as the carrier frequency. 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 (2–4).

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

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

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

Figure 4(a) shows the switching state of the conventional zero vector. The switches of one leg of three-phase to single-phase matrix converter are on to keep the output current path and to output zero voltage. However, the output current direction during zero vector and next vector are mismatched. Therefore, a commutation failure occurs by the switching based on the principle of single-step commutation.

Figure 4(b) shows the switching state of the proposed zero vector for the single-step commutation. The proposed switching state of the zero vector selects to connect the grid and the output side. Therefore, the output current is decreased to zero. The proposed zero vector achieves a safe commutation after zero vector without the change of the current direction because the output current is changed from zero to positive or negative only. Time t_{zero} of reducing current up to zero is expressed by

$$t_{zero} = L_l \frac{i_{mc}}{v_{mc}} \tag{5},$$

where L_l is the leakage inductance of the transformer, i_{mc} is the output current at single-phase side, and v_{in} is the input voltage which is connected to output side.

Figure 5 shows the current estimation method to achieve the single-step commutation. The output current is synchronized with the switching carrier by SVM. The switching signal for zero vector is selected to reduce the output current up to zero. The zero current at the output side is necessary until end of the zero vector in order to achieve the single-step commutation under all switching. Actually, the current direction estimation results are synchronized with the negative edge of the zero vector.

Figure 6 shows the transient state during one switching period with proposed single-step commutation. These modes during one switching period in sector I are explained to use the equivalent circuit with the current source at single-phase output side. The output current source is defined as the instantons current of the leakage inductance at the middle-frequency transformer. U-phase, V-phase and W-phase voltage are defined as maximum voltage-phase, middle voltage-phase and minimum voltage-phase.

- $[t_0 - t_1]$ The switching signals of the upper side and the lower side arms are selected to connect the maximum voltage-phase and minimum voltage-phase.
- $[t_1 - t_2]$ The switch S_{rp} turns-off to change output voltage from maximum voltage-phase to minimum voltage-phase at the arm of the upper side.. The current path is also changed by single-step only.
- $[t_2 - t_3]$ The switch S_{sp} and S_{nt} turn-off and the switch S_{nr} turns-on. The current path is also changed from

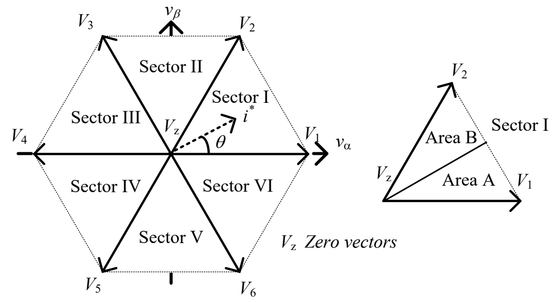
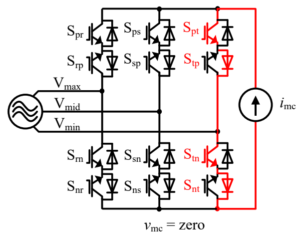
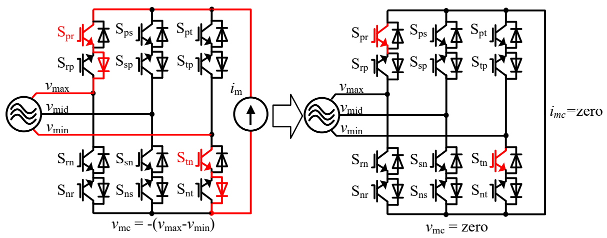


Fig. 3. Space vector modulation.



(a) Conventional method



(b) Proposed method

Fig. 4. Switching state during zero vector. Output current Conventional zero vector

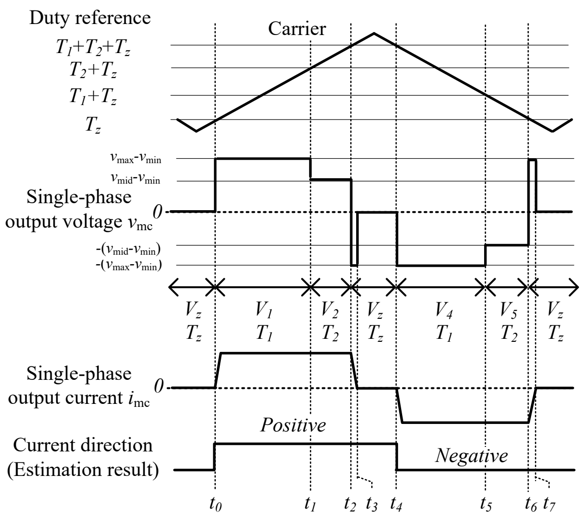


Fig. 5. Estimation principle of current direction. The output current is synchronized the switching carrier by SVM. Therefore, the output current direction is also same relationship.

V_{mid}-current source-V_{min} to V_{min}-current source-V_{max}. As a results, the output current is decreased to zero. This period is calculated by (5).

- [t_3 – t_4] The polarity of the applied voltage of the switch S_{tn} and S_{pt} are reversed biased when the output current is zero. Therefore, the output current keep on zero during zero vector.
- [t_4 – t_5] The switches S_{tn} and S_{pt} turn-off, and the switches S_{nt} and S_{tp} turn-on in same time. If the switching timing has a deference due to the delay of the gate driver and the variation of the switching devices, the commutation failure such as surge voltage by open-circuit and short-current by short-circuit do not occur.
- [t_5 – t_6] The switch S_{rn} turns-off to change output voltage from maximum voltage-phase to minimum voltage-phase at the arm of the lower side. The current path is also changed by single-step only.
- [t_6 – t_7] The switch S_{sn} and S_{tn} turn-off and the switch S_{pt} turns-on. The current path is also changed from V_{mid}-current source-V_{min} to V_{min}-current source-V_{max} in order to obtain the zero current at the output side. The proposed single-step commutation is required to reduce the output current up to zero until next switching.
- [t_7 – t_0] The applied voltage of the switches S_{tn} and S_{pr} is the reversed biased when the output current is zero. Therefore, the output current keep on zero during zero vector. The proposed single-step commutation is achieved by the switching sequence.

C. *Limitation of appling single-step commutation*

The proposed single-step commutation is employed the zero current at the end of the zero vector. The requirement to achieve the proposed single-step commutation is expressed by

$$T_z > L_l \frac{i_{mc}}{v_{mc}} f_c \qquad (6),$$

where f_c is the carrier frequency of SVM to control the three-phase to single-phase matrix converter. The duty of the zero vector is longer than the time of reducing the output current up to zero. The minimum voltage of the output voltage excluded zero voltage is the half of the line to line voltage at grid side.

D. *Implementation for single-step commutation*

Table I shows the switching table for the proposed single-step commutation. The switching table depends on the sector, area, and the selected output vector. The switching pulse of the same vector is changed by the sector. In addition the switching pulse is changed by area because maximum-phase, medium voltage-phase and minimum voltage-phase are also changed. According to the principle of the single-step commutation as shown in Fig. 2, the gate signals are 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 7 shows the gate signal generation for the proposed single-step commutation. The complex commutation algorism as the four-step commutation does not required because only single-step commutation using a

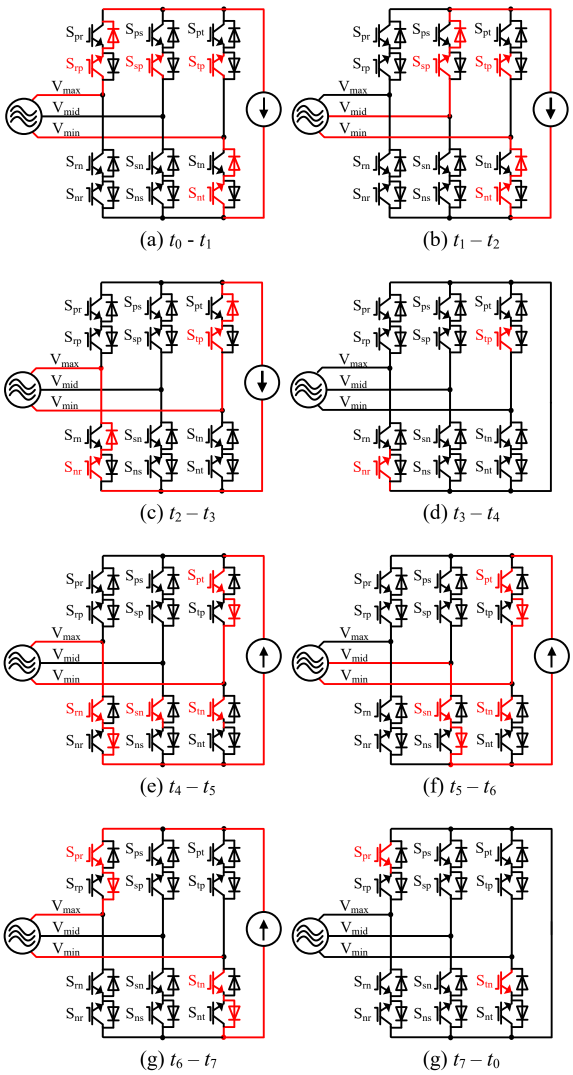


Fig. 6. Switching state during one carrier frequency.

switching table and the current direction estimation. The three-phase current reference is converted by Clarke transformation for SVM. As shown in Fig. 3, the switching signal is selected by the sector and the vector based on the αβ current reference according to Table I. As shown in Fig. 5(a), the current direction estimation is updated at the negative edge of the zero vector. The one of two devices S_{xl} or S_{xr} 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. The assignment of the gate signal depending on the current direction is express by

$$\begin{cases} S_{xl} = S_x & S_{xr} = 0 & i_{load} > 0 \\ S_{xl} = 0 & S_{xr} = S_x & i_{load} < 0 \end{cases} \quad \text{x=p,m,n} \qquad (7),$$

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_{mc}. S_x is the switching signal of the bi-directional switch according to Table I. 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.

TABLE I. SWITCHING TABLE FOR SINGLE-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	Area A	111	011	001	010	010	001	111	101	100	001	001	100	111	110	010	100	100	010
		001	001	100	111	110	010	100	100	010	111	011	001	010	010	001	111	101	100
	Area B	101	111	001	010	010	100	110	111	100	001	001	010	011	111	010	100	100	001
		001	001	010	011	111	010	100	100	001	101	111	001	010	010	100	110	111	100

Example) Sector: I Area: A Vector: V_1

$$\begin{bmatrix}111\\001\end{bmatrix}=\begin{bmatrix}S_{rp}=\mathrm{ON} & S_{sp}=\mathrm{ON} & S_{tp}=\mathrm{ON}\\ S_{rn}=\mathrm{OFF} & S_{sn}=\mathrm{OFF} & S_{tn}=\mathrm{ON}\end{bmatrix}$$

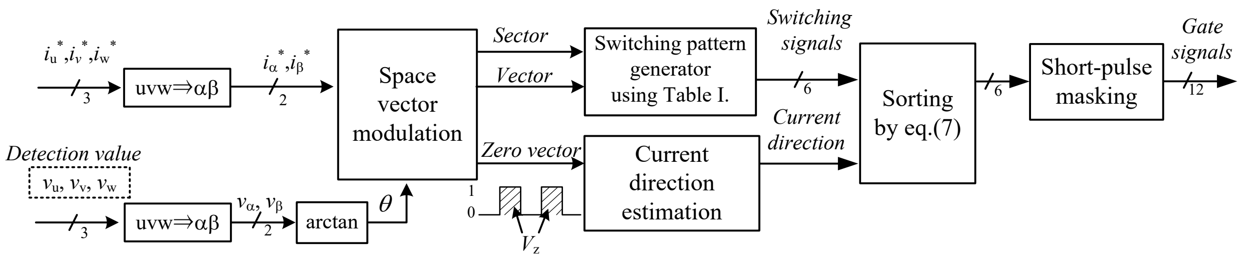


Fig. 7. Signal generation for proposed single-step commutation.

Finally, the short-pulse in the gate signals is masked because the short-pulse wide t_d 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. However, the input current is distorted by the output voltage error due to the masking of the short-pulse. The output voltage error with the proposed single-step commutation is minimum compared with other multi-step commutation methods.

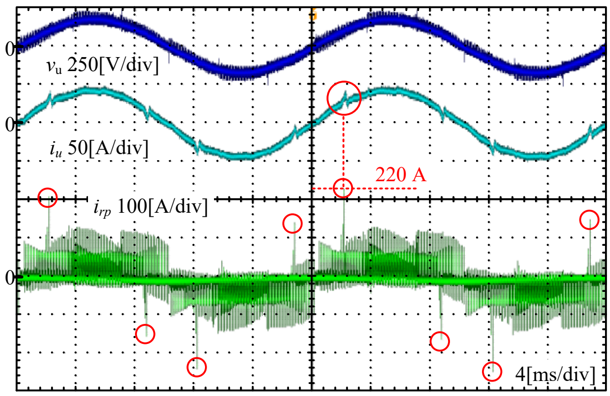
IV. EXPERIMENTAL RESULT

Table II shows the experimental conditions for 10-kW prototype. The output voltage range is from 200 V to 500 V. The switching devices at the three-phase to single-phase matrix converter are IGBTs (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 of the proposed single-step commutation and the conventional four-step commutation is 1.0 μs. The output voltage error compensation by several-step commutation is applied to the three-phase to single-phase matrix converter with the conventional four-step commutation.

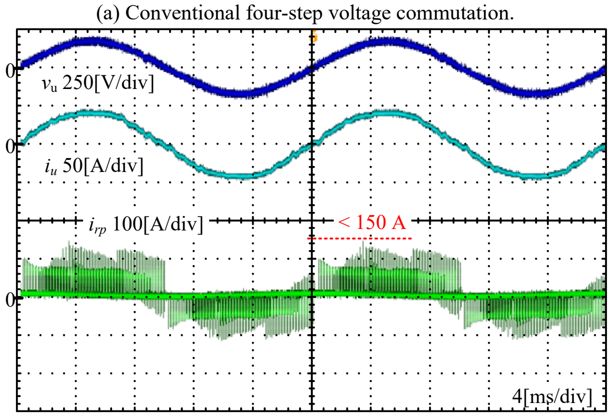
Figure 8 show the gird voltage and current waveforms and the current at the lower switching devices of the three-phase to single-phase matrix converter at 10 kW with the delay time 50 μs of the voltage detection on FPGA. As shown in Fig. 8 (a), the commutation failure with the four-step voltage commutation occurs in the regions, where the relationship of the grid voltages changes. As a result, the surge current at the lower switching devices is approximately 220 A. Consequently, the life time and the reliability of the switching devices are decreased. In addition, the input current is distorted by the commutation failure. As shown in Fig. 8 (b), the proposed single-step commutation based on the current direction estimation achieves to avoid short-circuit. It confirms from this result that the proposed single-step commutation method operates the matrix converter without any commutation failures regardless of the input voltage detection error. Consequently, the input current distortion is 2.9%. In addition, the surge current at the lower

TABLE II. EXPERIMENTAL CONDITIONS.

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%)
Commutation time	t_d	1.0 μs/step

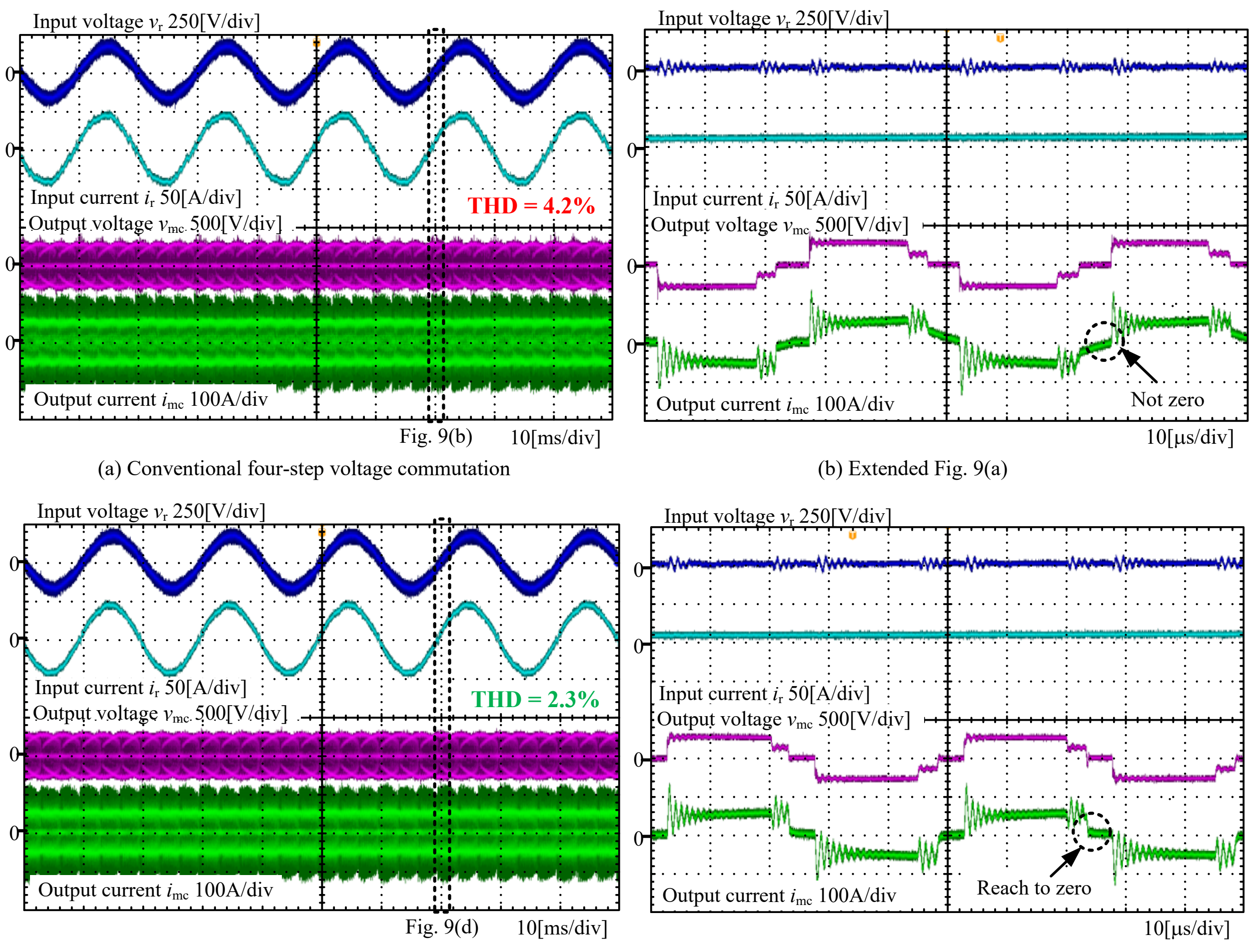


(a) Conventional four-step voltage commutation.



(b) Proposed single-step commutation.

Fig. 8. Operation waveforms at rated power of 10 kW.



(a) Conventional four-step voltage commutation

(b) Extended Fig. 9(a)

(c) Proposed single-step commutation

(d) Extended Fig. 9 (c)

Fig. 9. Waveforms with conventional four-step voltage commutation and proposed single-step commutation undet high modulation index (MI = 0.85) at rated power of 10 kW. The conventional four-step method results in a high current THD of 4.2% compared with the current THD of the proposed single-step commutation. the output current with the proposed single-step commutation is decreased to zero quickly.

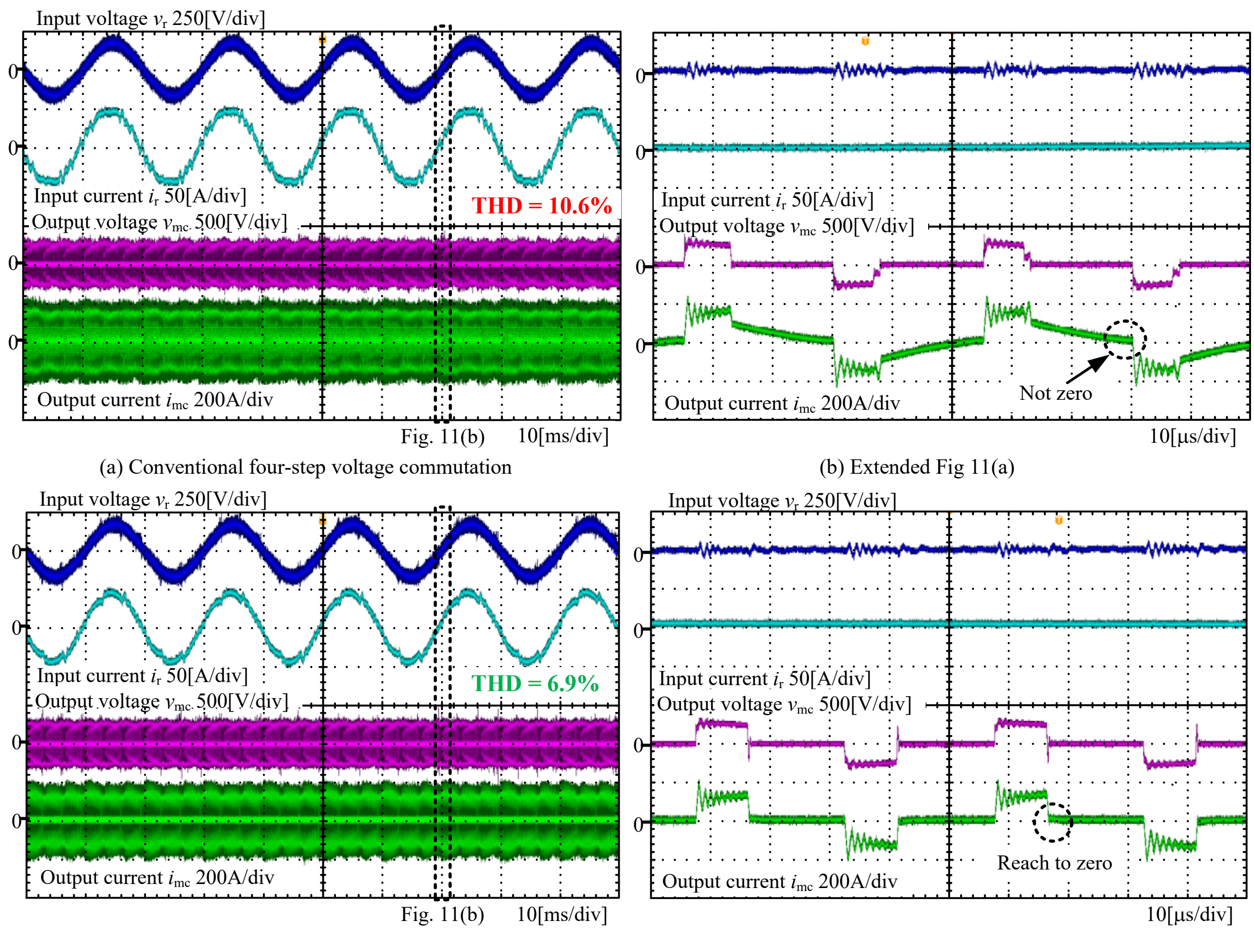
switching devices is always suppressed by the proposed single-step commutation.

Figure 9(a)-(b) show the input and output waveforms of the matrix converter with the four-step voltage commutation, and the extended waveforms at the high modulation index, respectively. The input current has low THD by 4.9% and high-power factor as 0.99. However, the output current does not zero at the end of the zero vector.

Figure 9(c)-(d) show the input and output waveforms of the matrix converter with the proposed single-step commutation, and the extended waveforms at the high modulation index, respectively. It is clear that the output current during the zero vector quickly decreases to zero. Therefore, the output current direction is not changed at the commutation after the zero vector. The proposed single-step commutation is achieved under all switching without the change of the current direction by switching.

Figure 10 shows the characteristics of the input current distortion with each commutation method at the high modulation index. The commutation step is greatly decreased by the proposed single-step commutation to keep the performance of the input current control. The input current THD of the proposed single-step commutation is lower than one of the conventional four-step commutation under entire region. The output power range ,which is lower than THD 5.0% input current is extended by 33.3%.

Figure 11(a)-(b) show the input and output waveforms of the matrix converter with the conventional four-step voltage commutation, and the extended waveforms at low modulation index, respectively. The output voltage error against the output voltage RMS is large compared to the high modulation index. Therefore, the input current is distorted due to the output voltage error by the masking of the short-pulse.



(a) Conventional four-step voltage commutation

(b) Extended Fig 11(a)

(c) Proposed single-step commutation

(d) Extended Fig12 (c)

Fig. 11. Waveforms with conventional four-step voltage commutation and proposed single-step commutation undet low modulation index (MI = 0.35) at rated power of 10 kW.

Figure 11(c)-(d) show the input and output waveforms of the matrix converter with the proposed commutation, and the extended waveforms at low modulation index, respectively. It confirms from this result that the proposed single-step commutation method operates the matrix converter regardless of the modulation index. The zero current during the zero vector for the proposed commutation is achieved.

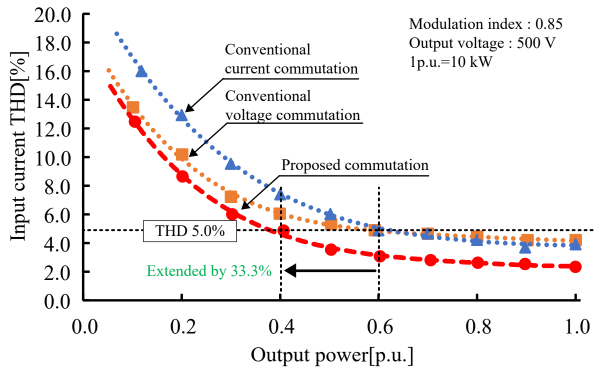


Fig. 10. Comparison of grid current THD with each commutation method at low modulation index. The output power range with low THD is extended of 33.3% by the proposed single-step commutation.

Figure 12 shows the distortion characteristics of each commutation methods at the low modulation index. The input current THD of the proposed single-step commutation is 7.7% at 10 kW. In the low modulation index, the proposed single-step commutation has the high performance in comparison with the conventional four-step commutation at entire loads.

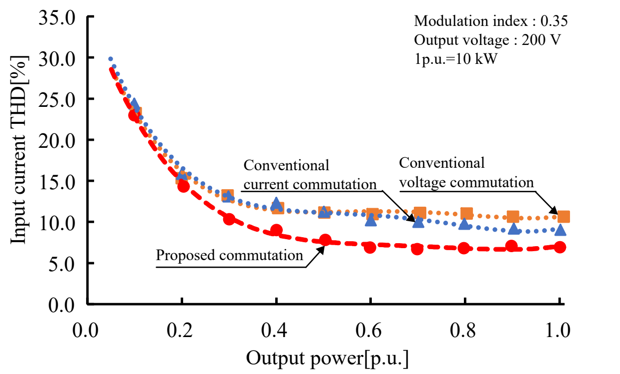


Fig. 12. Comparison of grid current THD with each commutation method at low modulation index. The input current THD is improved by 37 % with the proposed two-step commutation in comparison with the conventional four-step commutation.

Figure 13 shows the THD characteristics of each commutation methods against the modulation index at a rated power of 10 kW. The input current THD of the proposed single-step commutation is the lowest with the value of 2.9% at 10 kW in the high modulation index. In the low modulation index, the input current THD of the conventional four-step commutation is more than 11%. If the switching pulses are shorter than the dead-time, the output voltage error occurs. As a results, the input current is distorted. On the other hand, the proposed commutation is completed only single-step. Therefore, the input current keeps low distortion under all modulation index. It is confirmed that the input current THD with the proposed single-step commutation method is improved by 34.9% compared to the conventional four-step voltage commutation method with the low modulation index. In addition, the output voltage range is also improved by 28.6% with the low THD.

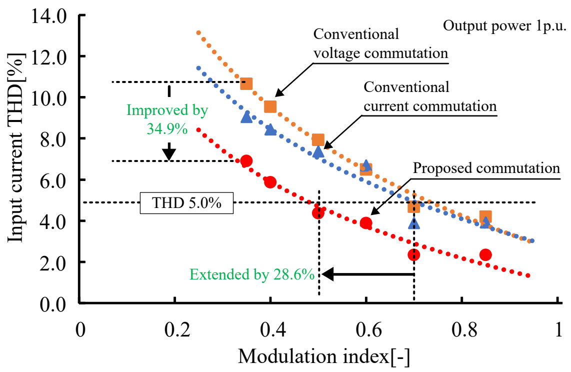


Fig. 13. Comparison of grid current THD with each commutation method. The input current THD is improved by 34.9 % with the proposed single-step commutation in comparison with the conventional four-step commutation.

V. Conclusion

In this paper, the single-step commutation was proposed to improve the input current distortion in the three-phase to single-phase matrix converter. Compared to the conventional four-step commutation, the input current THD was reduced by 34.9% with the proposed single-step commutation at low modulation index. the output voltage range was also improved by 28.6% with the low THD, which is lower than 5.0%. In addition, the commutation algorithm of the proposed single-step commutation was much simpler than the conventional several-step commutation. On the other words, the simple control hardware is employed for the matrix converter with the proposed single-step commutation.

References

[1] M. Pahlevaninezhad, P. Das, J. Drobnik, P. K. Jain and A. Bakhshai, "A New Control Approach Based on the Differential Flatness Theory for an AC/DC Converter Used in Electric Vehicles," in IEEE Transactions on Power Electronics, vol. 27, no. 4, pp. 2085-2103, April 2012.

[2] Kohei Aoyama, Naoki Motoi, Yukinori Tsuruta, and Atsuo Kawamura,"High Efficiency Energy Conversion System for Decreaces in Electric Vehicle Battery Terminal Voltage",IEEJ Journal of Industry Applications, vol.5, no.1, pp.12-19, 2016.

[3] S. Kim and F. S. Kang, "Multifunctional Onboard Battery Charger for Plug-in Electric Vehicles," in IEEE Transactions on Industrial Electronics, vol. 62, no. 6, pp. 3460-3472, June 2015.

[4] Fuka Ikeda, Toshihiko Tanaka, Hiroaki Yamada, and Masayuki Okamoto,"Constant DC-Capacitor Voltage-Control-Based Harmonics Compensation Algorithm of Smart Charger for Electric Vehicles in Single-Phase Three-Wire Distribution Feeders",IEEJ J. Industry Applications, vol.5, no.5, pp.405-406, 2016.

[5] R. Huang and S. K. Mazumder, "A Soft-Switching Scheme for an Isolated DC/DC Converter With Pulsating DC Output for a Three-Phase High-Frequency-Link PWM Converter," in IEEE Transactions on Power Electronics, vol. 24, no. 10, pp. 2276-2288, Oct. 2009.

[6] Mahmoud A. Sayed, Kazuma Suzuki, Takaharu Takeshita, Wataru Kitagawa : "PWM Switching Technique for Three-phase Bidirectional Grid-Tie DC-AC-AC Converter with High-Frequency", IEEE Transactions on Power Electronics, 2016

[7] R. Garcia-Gil, J. M. Espi, E. J. Dede and E. Sanchis-Kilders, "A bidirectional and isolated three-phase rectifier with soft-switching operation," in IEEE Transactions on Industrial Electronics, vol. 52, no. 3, pp. 765-773, June 2005.

[8] M. A. Sayed; K. Suzuki; T. Takeshita; W. Kitagawa, "PWM Switching Technique for Three-phase Bidirectional Grid-Tie DC-AC-AC Converter with High-Frequency Isolation," in IEEE Transactions on Power Electronics , vol.PP, no.99, pp.1-1

[9] A. K. Singh; E. Jeyasankar; P. Das; S. Panda, "A Single-Stage Matrix Based Isolated Three Phase AC-DC Converter with Novel Current Commutation," in IEEE Transactions on Transportation Electrification , vol.PP, no.99, pp.1-1

[10] S. Tammaruckwattana, Chenxin Yue, Y. Ikeda and K. Ohyama, "Comparison of switching losses of matrix converters for commutation methods," 2014 16th European Conference on Power Electronics and Applications, Lappeenranta,

[11] M. Ziegler and W. Hofmann, "Semi natural two steps commutation strategy for matrix converters," PESC 98 Record. 29th Annual IEEE Power Electronics Specialists Conference (Cat. No.98CH36196), Fukuoka, 1998, pp. 727-731 vol.1.

[12] L. Linhart, J. Lettl and J. Bauer, "Matrix converter two-step commutation method limitations," Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010, Ohrid, 2010, pp. T3-53-T3-58.

[13] X. Ma, H. Dong and J. Zhao, "Research on a novel two-step commutation strategy for matrix converter based on the value of input voltage," 2016 Chinese Control and Decision Conference (CCDC), Yinchuan, 2016, pp. 6988-6993.

[14] Hongwu She, Hua Lin, Bi He and Haiming Shou, "A novel voltage-controlled commutation method for matrix converter," 2007 International Conference on Electrical Machines and Systems (ICEMS), Seoul, 2007, pp. 38-42.