Hybrid Commutation Method with Current Direction Estimation for Three-phase-to-single-phase Matrix Converter

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***Abstract*—This paper proposes a hybrid commutation method for a three-phase-to-single-phase matrix converter. Commutation failures in the voltage commutation method result in an increase of grid current distortion (THD), whereas the commutation failures in the current commutation method lead to an increase in snubber capacitor voltage. The proposed commutation method combines the voltage and current commutation methods in order to suppress the commutation failure effects. In particular, the current commutation is operated based on the original estimation method for the high-frequency output current. As experimental results, the proposed commutation method improves the grid current THD by 64%, whereas the snubber capacitor voltage is reduced by 13%.**

Keywords—Hybrid commutation, four-step commutation, Current direction estimation;

I. Introduction

The 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 PHVs 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 ref. [5]-[9], isolated AC-DC converters using a matrix converter as a high-frequency AC-AC converter connected with the transformer at the primary side are 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 require a commutation sequence at the switching timing of the power devices in order to prevent short-circuit at a voltage source and open-circuit at a current source. In Ref. [10]-[13], the conventional commutation method is separated into two types, the voltage commutation method based on the voltage polarity and the current commutation method based on the current direction. The voltage commutation can work reliably if the relationship of the input voltages are accurately obtained. However, commutation failures may occur when two of the input voltage values are almost similar, i.e., at the critical area where the relationship of the input voltage alternates. Consequently, the input current distortions occur due to the commutation failures when the voltage commutation is applied at the critical area.

In Ref. [14], the hybrid commutation method between the voltage commutation and the current commutation has been proposed for a three-phase-to-three-phase matrix converter in order to reduce the number of the commutation failures. In this hybrid commutation method, the detection of the current direction is required for the current commutation. However, in the application of the three-phase-to-single-phase matrix converter connected with the transformer at the primary side, the matrix converter outputs a high-frequency current, the direction of which is difficult to be detected accurately with a general current sensor.

In this paper, the estimation method for the high-frequency current direction of the single-phase-to-three-phase matrix converter is proposed. The purpose of this paper is the reduction of the number of the commutation failures. The original contribution in this paper is the high-frequency current direction estimation based on the carrier of the space vector modulation (SVM). The remainder of this paper is organized as follows; in section II, the configuration of the three-phase to single-phase matrix converter is explained, then in section III the control and analysis for the high-frequency output voltage of the three-phase to single-phase matrix converter are explained. The principle of the current estimation method and the proposed hybrid commutation is explained in section IV. After that, experimental proposed hybrid operations are presented in section V. In addition, a comparison of the characteristics among the voltage and current commutation method is carried out. Finally, the advantages of the proposed commutation are clarified based on these results. the input current THD is 2.9% at 10 kW with the proposed hybrid commutation.

II. CIRCUIT CONFIGURATION

Figure 1 shows the conventional AC-DC converter with a PWM rectifier and an inverter. An Electric capacitor is often used at DC link. Therefore, an initial charge circuit for a DC capacitor is required. Interconnected inductors are required to control input current. These passive components are necessary for the operation of the conventional AC-DC converter.

Figure 2 shows the isolated AC-DC converter applied with the three-phase-to-single-phase matrix converter. The relationship of the input voltages (v_r, v_s, v_t) is required to employ the voltage commutation, whereas the information of the output current direction i_{tr} is necessary for the current commutation. However, due to the detection delay and the gain error of the voltage or current sensor, these commutations usually occur at the intervals when the input voltage polarity changes or at the zero crossing of the output current. The commutation failures with the voltage commutation short-circuit the input side of the matrix converter, which increases the input current distortion. On the other hand, the commutation failures with the current commutation abruptly opens the output side, which increases the snubber capacitor voltage. Therefore, the hybrid commutation method between two commutation methods is proposed in order to reduce the commutation failures.

III. CONTROL METHOD

Figure 3 shows the space vector modulation (SVM) to apply the three-phase to single-phase matrix converter. The SVM is based on the detection of six 60° intervals (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, V1 and V2 are used during the first half of the control period as the positive voltage, whereas V4 and V5 are used during the second half of the control period as the negative voltage. In this control method, the output single-phase voltage has high frequency same as switching carrier. Note that the zero vector V7, V8, and V9 which output the zero voltage, is decided by sector. These duty reference T_1, T_2, and T_z are calculated by (1–3).

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

$$T_2 = \frac{1}{|A|}\begin{vmatrix} V_{1\alpha} & v_\alpha \\ V_{1\beta} & v_\beta \end{vmatrix} \tag{2}$$

$$T_Z = 1-(T_1+T_2)\ \left(\because |A| = \begin{vmatrix} V_{1\alpha} & V_{2\alpha} \\ V_{1\beta} & V_{2\beta} \end{vmatrix}\right) \tag{3}$$

In Figure 2, the switching from the bidirectional switch to another one is only six times per one cycle of the switching carrier. Because, the switching loss is increased when the

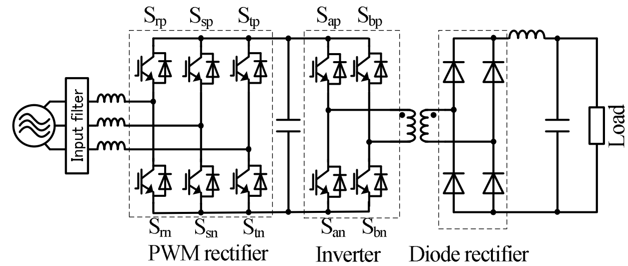


Fig. 1. Conventional AC-DC converter with PWM rectifier and inverter.

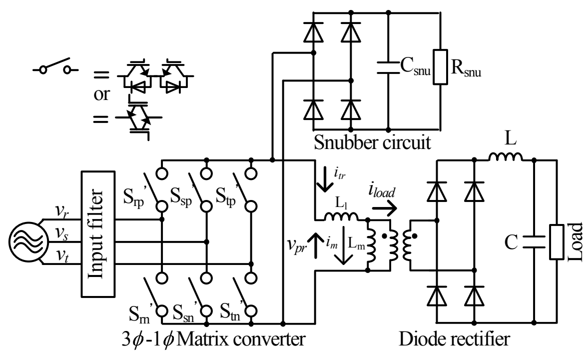


Fig. 2. AC-DC converter with three-phase to single-phase matrix converter. The snubber circuit is absorbed the energy of leakage inductance when the commutation failure occur.

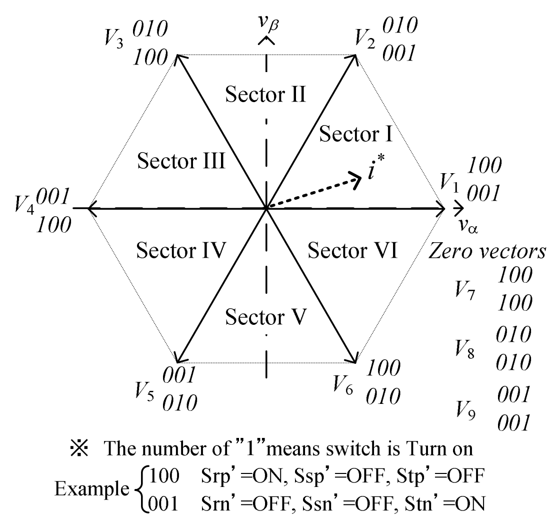
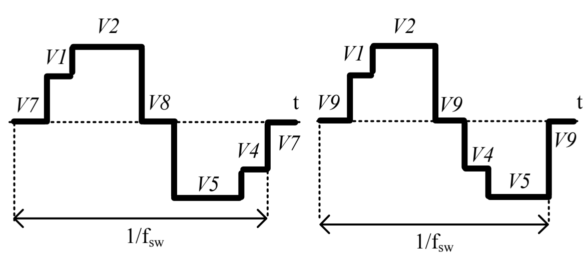


Fig. 3. Space vector modulation.



(a) Method I (b) Method II

Fig. 4. High-frequency output voltage waveforms in sector I.

switching time is larger than six times. The select of output vector is two methods.

Figure 4 (a) and (b) illustrate the output voltage waveforms in sector I. In case of Method I, the output voltage waveform is a point symmetry. On the other hand, the output voltage waveform is a line symmetry by applying Method II. In two Method, the voltage-time product is same under the instantaneous voltage as constant DC. Therefore, an ideal voltage source and high switching frequency is required for the condition which equal to voltage-time product between Method I and Method II.

Figure 5 (a) and (b) show the switching patterns of Method I and II in sector I. In Method I, V8 is used as zero vector. The commutation from S_{rp} to S_{sp} and S_{tn} to S_{sn} is selected, when the output vector is changed from V1, V2 to V8. In other words, the switching device after the commutation does not selected at next commutation. As a results, the switching pulse that is shorter than the commutation time is reduced and the input current distortion is also reduced. However, Method I has a problem. Focus on the filter capacitor C_{tr}, it is discharged during V1 and V4. V2, V8, and V5 are selected after V1 outputs. However, there is only V7 between V4 and V1. As a result, the filter capacitor has the switching ripple component and 300 Hz component. Because, the periods of V2, V5, and V8 depend on duty reference of T_1, T_2, and T_z. It means that output voltage at the high-frequency transformer has 300 Hz components. Therefore, it is possible to conduct the large current by the saturation of the transformer. In order to suppress low order harmonics components of the input current, the filter capacitors value should be large. However, it also increases a volume of the filter C.

In Method II, in order to solve the problem of Method I, the output vector is placed to be the symmetrical waveform. The zero vector is used V9 to connect V2 and V4. Consequently, the filter capacitors are discharged or charged every switching periods. Therefore, the output voltage does not include 300 Hz component in comparison with Method I. The high-frequency transformer is not affected by the low order harmonics components. In this paper, the commutation and the current estimation is discussed based on Method II.

IV. COMMUTATION METHOD

A. Voltage commutation

The voltage commutation requires only the input voltage polarities. The voltage detection of the input side is always equipped to measure the voltage condition. Therefore, the additional voltage sensor is not required for the voltage commutation. However, the voltage commutation has some disadvantage. One is that the commutation failure is caused by detection error of the input voltage polarity in nearly two line to line voltages.

Figure 6 shows the equivalent commutation model for a matrix converter. The initial state of the switching devices on the commutation model is following:

S1a, S1b : ON   S2a, S2b : OFF

the steady state after the commutation is following:

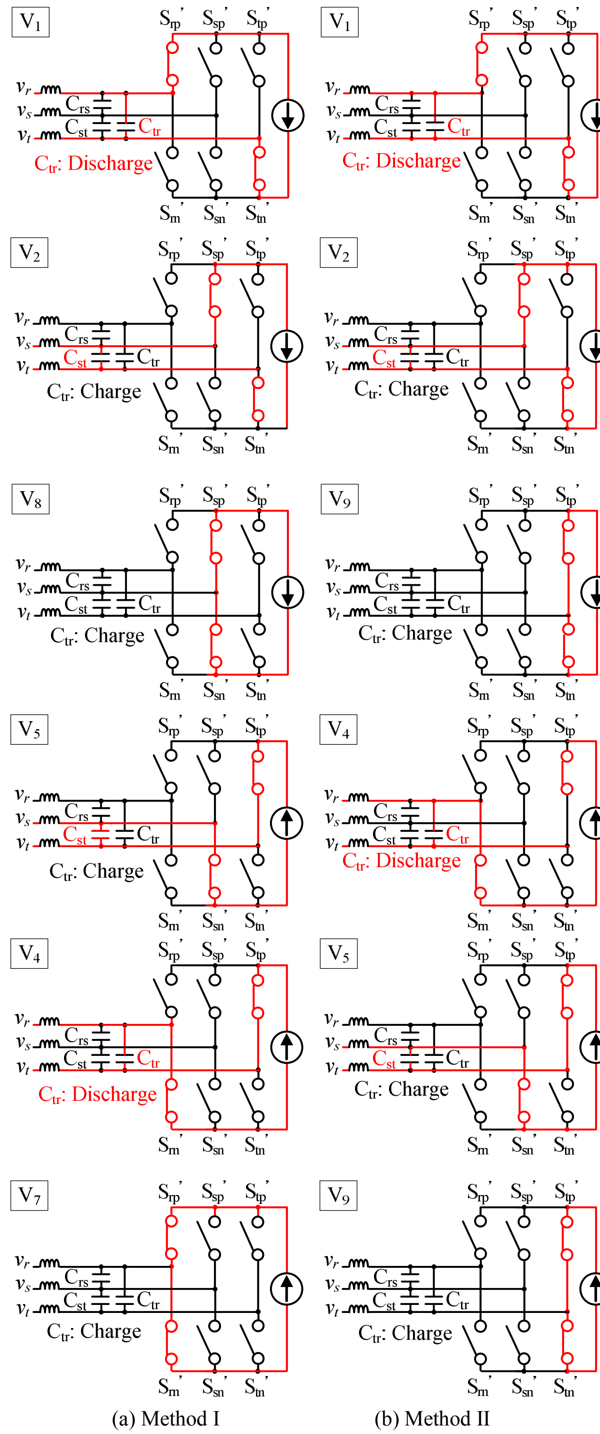


Fig. 5. Switching pattern in sector I

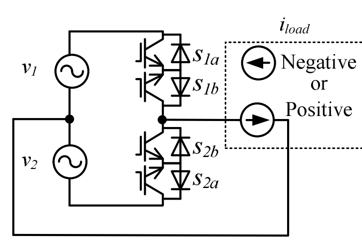


Fig. 6. Commutation model.

S1a, S1b : OFF   S2a, S2b : ON

B. Current estimation for current commutation

The current commutation method requires only the current direction not the instantaneous current value. Therefore, the direction of the high-frequency current can be estimated without the fast-response-time current sensor. The estimation principle for the current direction is based on the control method of the matrix converter. The high frequency of the output voltage is determined by the carrier of SVM and the duty reference. The output voltage has positive and negative periods during one cycle of the carrier. Similarly, the output current direction also has positive and negative periods during one cycle of the carrier.

Figure 7 shows the relationship between the carrier of SVM and the estimated current direction. At the beginning of the half carrier period, the current direction alternates during commutation after the zero voltage period. Therefore, the output current direction of matrix converter at single-phase side changes sign after the half carrier period.

Figure 8(a) and (b) show a four-step commutation with the current commutation in order to prevent an open-circuit. When the current direction does not change during commutation, the current commutation succeeds, and no surge voltage occurs at the output side of the matrix converter. Therefore, the snubber capacitor voltage does not increase.

Figure 8(c) and (d) show the commutation failure with the current commutation. The problem is that the commutation after the zero voltage period itself changes the current direction. Therefore, the commutation failure occurs regardless of the result of the proposed current direction estimation. In the 1st step of the proposed commutation, the output of the matrix converter is opened and the output current is abruptly blocked. Thus, a surge voltage occurs and is absorbed by the snubber circuit which protects the matrix converter. Consequently, the snubber capacitor voltage increases due to the commutation failures with the current commutation method. The current commutation failures can be reduced by employing the voltage commutation method at the commutation after the zero voltage period, i.e., the hybrid commutation method.

C. Proposed hybrid commutation method

Figure 9 shows the hybrid commutation between the voltage commutation and the current commutation, which has the four-step commutation. In the critical area, the current commutation is applied to avoid a grid from a short circuit. On the other hand, the voltage commutation is applied in the uncritical area because the surge voltage is caused by the current commutation in entire area. Proposed commutation is to avoid commutation failure. However, the output voltage of the three-phase to single-phase matrix converter of two commutations has the voltage error by each commutation. The amplitude of the input current is affected by the error of output power because the input current is decreased when output voltage is increased under the constant output power. Therefore, the error compensation is required for the constant output voltage against same duty reference.

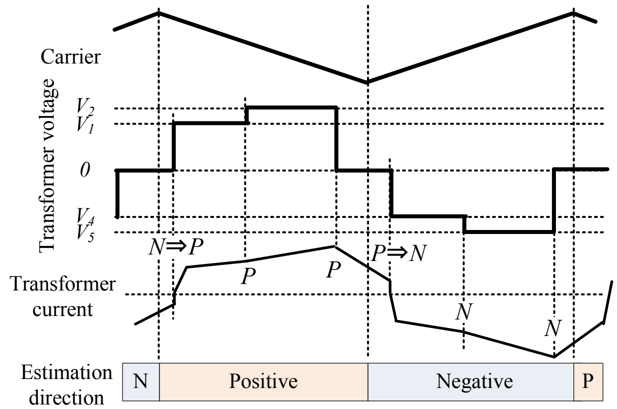


Fig. 7. Estimation principle of current direction. The output voltage is syncnonized the switching carrier by SVM. Therefore, the output current direction is also same relationship.

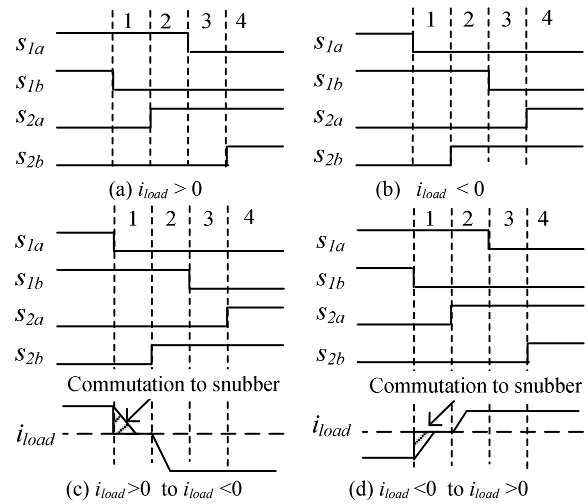


Fig. 8. Four-step commutation with current commutation method. When current direction is changed, the current commutation is failure.

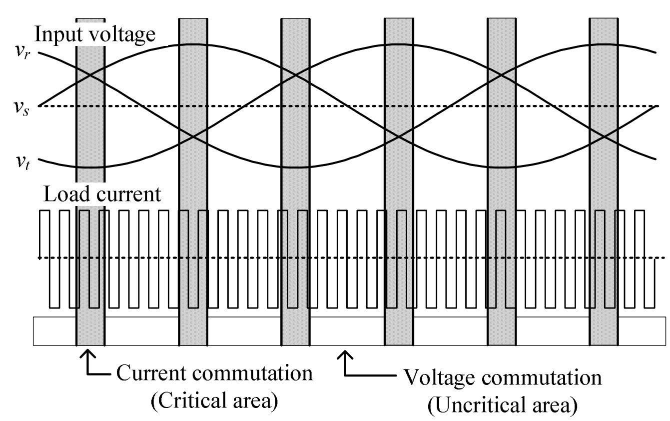


Fig. 9. Proposed commutation method. In the critical area, the current commutation is applied to avoid short-circuit. In the uncritical area, the voltage commutation is applied to reduce the surge voltage.

D. Output voltage error of hybrid commutation method

Figure 10(a) and (b) show the output voltage error of the three-phase to single-phase matrix converter with the voltage commutation method in each current direction. If the current direction is positive, the output voltage is changed from v_1 to v_2 at the second step. In comparison with the ideal step without commutation, the period of v_2 is decreased by one commutation step. Figure 9(b) shows the error voltage under the negative current direction and same voltage relation as Figure 9(a). In the second step, the load current remains to flow with v_1. At the third step, the output voltage is changed by turning on of S2b.

Figure 11(a) and (b) show the output voltage error with the voltage commutation method during one cycle. According to Figure 10, the error of output voltage is decided. The relationship of duty reference of T_1 and T_2 is changed by each 30° of the grid voltage. Therefore, the amplitude of the output vector against each duty reference is changed. Therefore, the error compensation is changing by the amplitude relationship between T_1 and T_2. The output voltage compensation due the voltage commutation is expressed as follows:

$$\begin{cases} T_1' = T_1 - T_d \\ T_2' = T_2 \\ T_Z' = 1-(T_1'+T_2') \end{cases}, \quad \begin{cases} T_1' = T_1 \\ T_2' = T_2 - T_d \\ T_Z' = 1-(T_1'+T_2') \end{cases}, \qquad (4)$$

$$(T_1 > T_2) \qquad\qquad (T_1 < T_2)$$

Figures 12(a) and (b) show the output voltage error with the current commutation method in positive current direction. If v_1 is larger than v_2, the output voltage is changed from v_1 to v_2 at the third step. In comparison with the ideal step without commutation, the period of v_2 is decreased by two commutation steps. Figure 11(b) shows the error voltage when v_2 is larger than v_1. At the second step, the output voltage is changed by turning on of S2a.

Figures 13(a) and (b) show the output voltage error with the current commutation during one cycle. The error compensation of the current commutation is expressed as following:

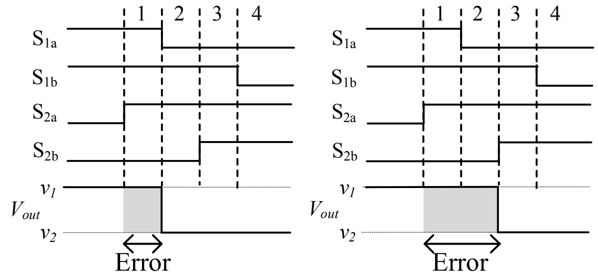
$$\begin{cases} T_1' = T_1 + T_d \\ T_2' = T_2 \\ T_Z' = 1-(T_1'+T_2') \end{cases}, \quad \begin{cases} T_1' = T_1 \\ T_2' = T_2 + T_d \\ T_Z' = 1-(T_1'+T_2') \end{cases}, \qquad (5)$$

$$(T_1 > T_2) \qquad\qquad (T_1 < T_2)$$

The error compensation for the proposed hybrid commutation is expressed as equation (6) in combination with equation (4) and equation (5).

$$\begin{cases} T_1' = T_1 - K_{comm} T_d \\ T_2' = T_2 \\ T_Z' = 1-(T_1'+T_2') \end{cases}, \quad \begin{cases} T_1' = T_1 \\ T_2' = T_2 - K_{comm} T_d \\ T_Z' = 1-(T_1'+T_2') \end{cases}, \qquad (6)$$

$$(T_1 > T_2) \qquad\qquad (T_1 < T_2)$$



(a) $i_{load} > 0$. $v_1 > v_2$ (b) $i_{load} < 0$. $v_1 > v_2$

Fig. 10. Output voltage error by voltage commutation.

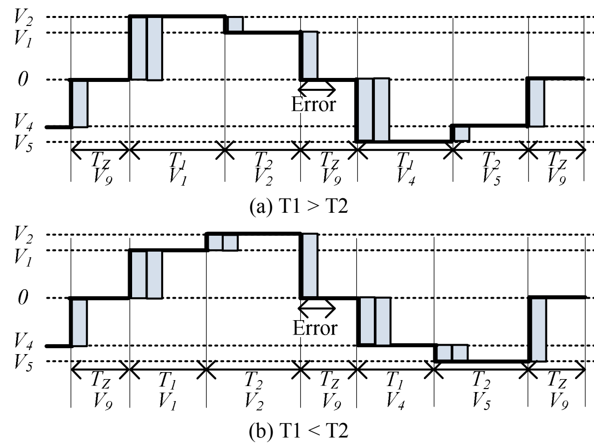
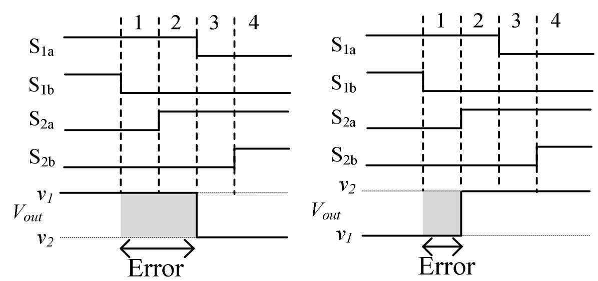


Fig. 11. Relation among space vectors and output voltage error with voltage commutation



(a) $i_{load} > 0$. $v_1 > v_2$ (b) $i_{load} > 0$. $v_1 < v_2$

Fig. 12. Output voltage error by current commutation.

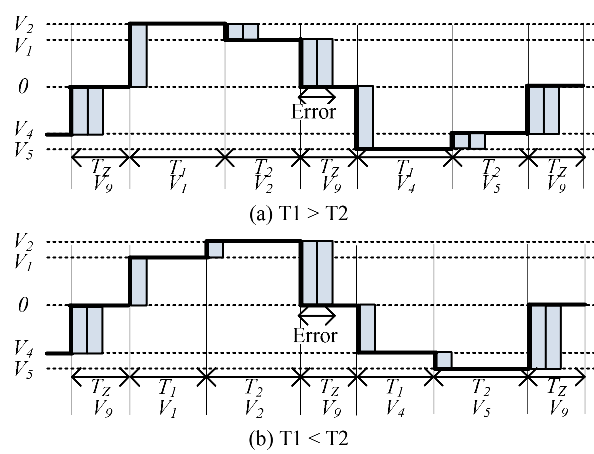


Fig. 13. Relation among space vectors and output voltage error with current commutation.

In case of the voltage commutation, K_{comm} =1. In case of the current commutation, K_{comm} =-1. The error compensation for each commutation can be achieved.

V. Experimental Results

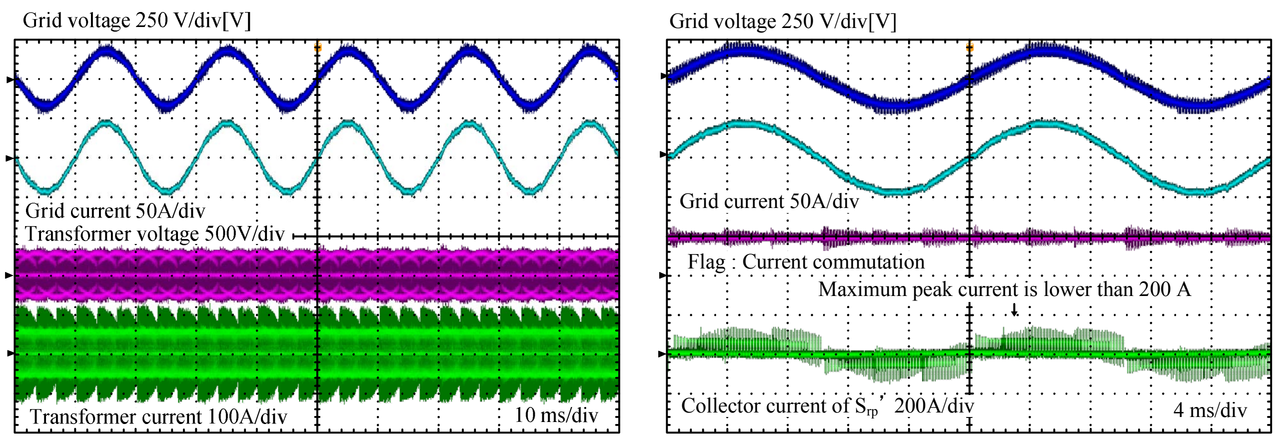
Table I shows the experimental conditions for 10kW. The switching devices at the three-phase to single-phase matrix converter are IGBT (CM400C1Y-24S). The commutation time t_d is decided by switching characteristics of IGBT. The sum of the raise time and turn on delay time of this IGBT is shorter than 1.0 μs. Therefore, the commutation time set 1.0 μs.

Figures 14–15(a) show the experimental waveforms of the single-phase-to-three-phase matrix converter at 10kW with the current commutation method and with the voltage commutation method, respectively. The commutation failures with the current commutation method occur at the zero-crossing points in the matrix converter output current. The matrix converter output current is abruptly blocked and the surge voltage occurs which increases the snubber capacitor voltage. Meanwhile, the commutation failures with the voltage commutation method occur when the relationship of the grid voltages changes due to the delay or detection error of the voltage sensor. Therefore, the input side of the matrix converter is shorted and the input current distortion increases.

TABLE I. Experimental conditions.

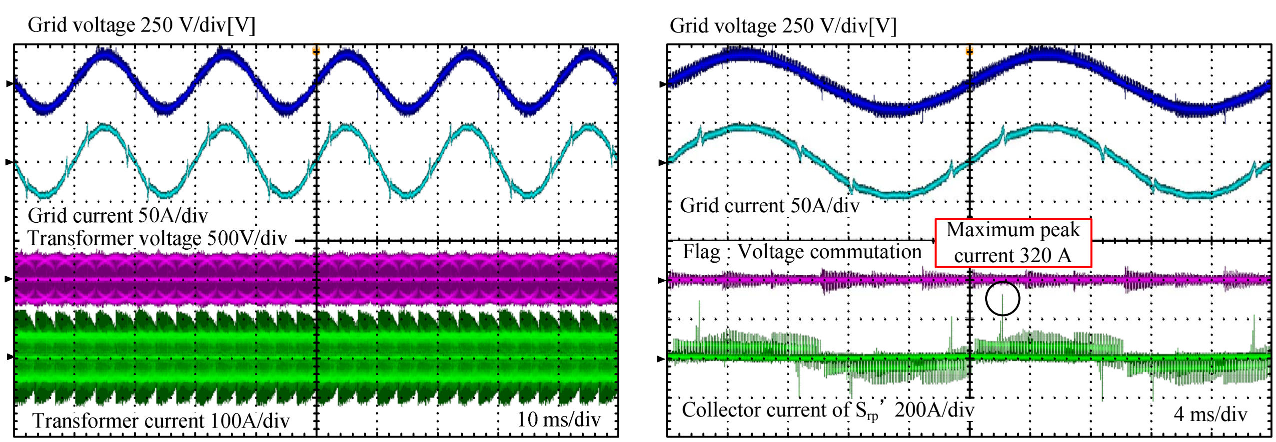
Element	Symbol	Value
Rated output power	P_{out}	10 kW
Three-phase AC voltage	v_{ac}	200 V
Input frequency	f	50 Hz
Carrier frequency	f_c	10 kHz
Leakage inductance	L_l	0.4 μH
Magnetic inductor	L_m	0.8 mH
Turn ratio of transformer	N_1:N_2	1:2.4
Input filter	$L_f(\%Z)$	0.4 mH(2.8%)
	$C_f(\%Y)$	11 μF(4.2%)
Output inductor	L	1.3 mH
Output capasitor	C	35 μF
Commutation time	T_d	1.0 μs
Snubber resister	R_{snu}	68 kΩ
Snubber capacitor	C_{snu}	1.0 μF

Figures 14–15(b) show the collector current of S_{rp}. The



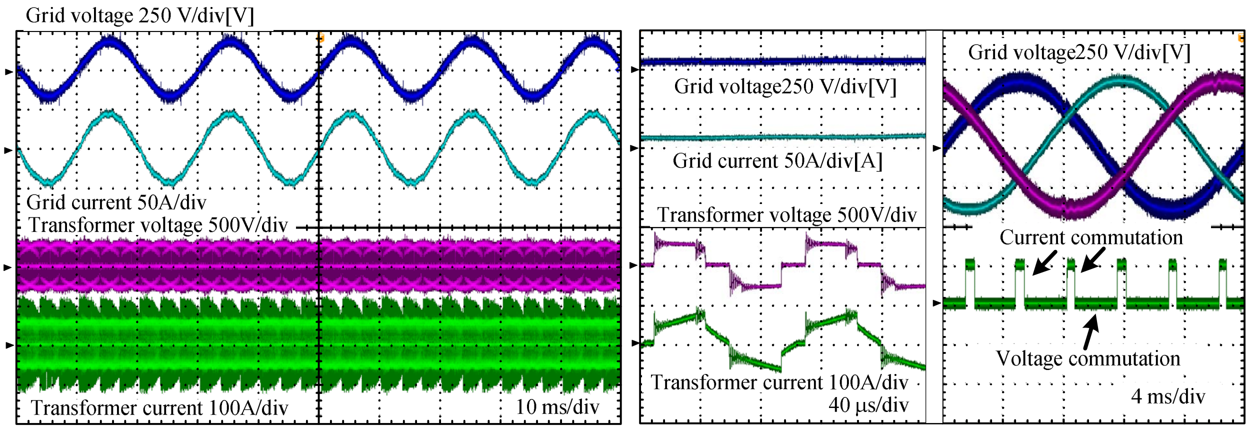
(a) Operation waveforms at 10kW (b) Collector current

Fig. 14. Current commutation method. The large current due to short-circuit is nothing by the current commutation. Therefore, the low gird current THD is achieved.



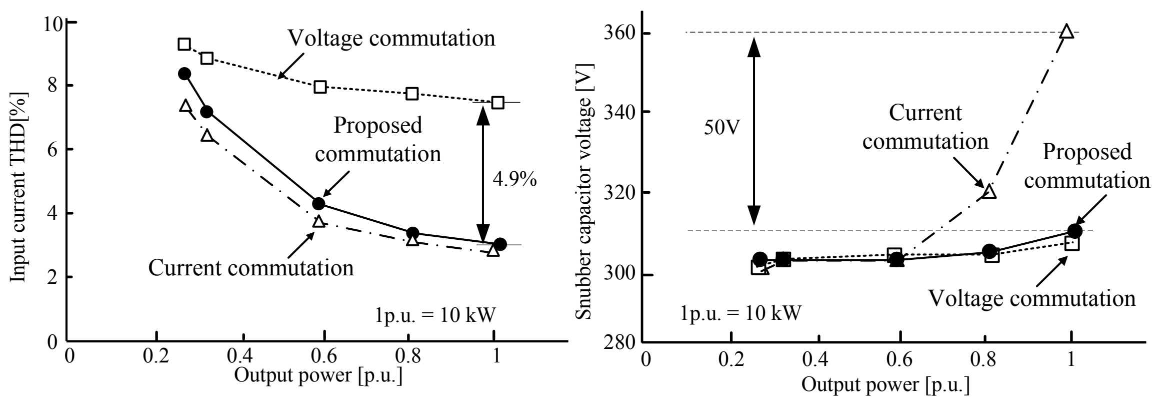
(a) Operation waveforms at 10kW (b) Collector current

Fig. 15. Voltage commutation method. In the critical area, the grid current is distorted. Because, short-circuit of the voltage source occur by the commutation failure. The maximum peak current at S_{rp} is 320 A.



(a) Operation waveforms at 10kW (b) Extended waveforms of Fig. 15(a) (c) Commutation flag

Fig. 16. Proposed hybrid commutation method.



(a) Grid current THD against load (b) Snubber capacitor voltage against load

Fig. 17. Comparison of grid current THD and snubber capacitor voltage with each commutation method. By the application of the proposed commutation, the low grid current THD and suppression of the snubber capacitor voltage can be achieved.

collector current at the critical region of the grid voltage is abruptly increased with the voltage commutation. It is caused by the commutation failure based on delay of the voltage detection. Consequently, the input current is distorted. The switching devices can be broken by the large current due to short-circuit. In contrast, in current commutation, the collector current of S_{rp} is lower than 200 A. the current commutation works reliably when the relationship of the input voltages are not accurately obtained.

Figure 16(a)-(c) show the experimental waveforms with the proposed hybrid commutation method, the extended waveforms, and the regions where the current commutation method and the voltage commutation method are alternated, respectively. The current commutation method is applied at the regions where the relationship of the grid voltages changes, whereas the voltage commutation method is applied at the other regions. Therefore, the proposed hybrid commutation method effectively suppresses the commutation failures without any additional fast-response-time current sensors.

Figure 17(a) shows the distortion characteristics of each commutation methods. The input current THD of the current commutation method is the lowest with the value of 2.7% at 10 kW because the commutation failures with the current commutation method do not affect the input current distortion of the matrix converter. On the other hand, the input current THD with the voltage commutation method is the highest with the value of 7.6% at 10kW. It is confirmed that the input current THD with the proposed hybrid commutation method is reduced by 64% compared to the voltage commutation method.

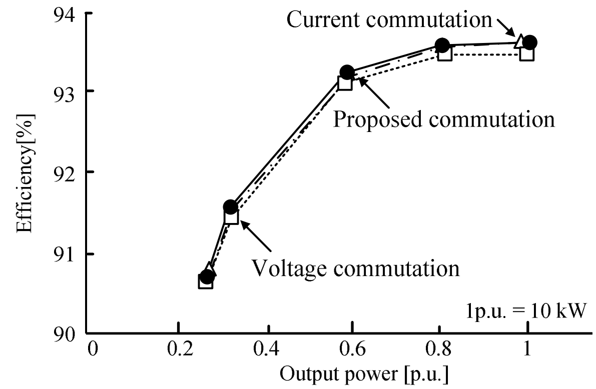
Figure 17(b) shows the snubber capacitor voltage characteristics of each commutation methods. The snubber capacitor voltage with the current commutation method becomes the highest because the commutation failures with the current commutation method abruptly block the matrix converter output current. In contrast, the snubber capacitor voltage is decreased by 13% by applying the proposed hybrid commutation method. The proposed hybrid commutation method contributes to not only the reduction of the voltage stress on the snubber capacitor but also reduce the additional switching loss caused by the commutation failure.

Figure 18(a) shows the efficiency characteristics of each commutation methods. The maximum efficiency among three commutation method is 93.6% with the current commutation at 10kW. However, the efficiency of other commutation methods is over than 93.5%. Therefore, the efficiency characteristics over the wide load range is not affected by the commutation method.

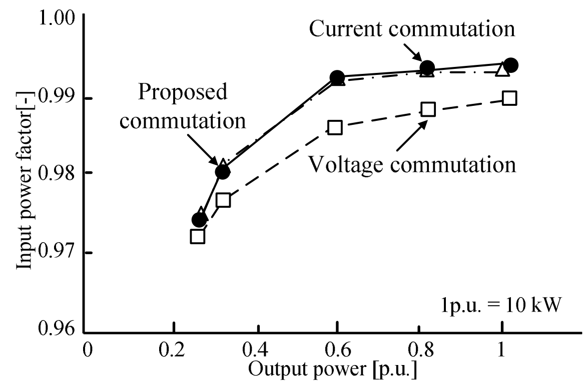
Figure 18(b) shows the input power factor of each commutation methods. Input power factor is almost same between the proposed hybrid and current commutation. In the proposed hybrid commutation method, the low grid current THD and suppression of the snubber capacitor voltage is achieved to keep the efficiency and high input power factor.

VI. CONCLUSIONS

In this paper, the hybrid commutation method with the current estimation for the single-phase-to-three-phase matrix converter in isolated AC-DC converter was proposed. The proposed commutation is alternated between the voltage commutation and the current commutation to reduce the number of the commutation failure. The experiment confirmed that with the proposed hybrid commutation method, a low input current THD of 2.9% and a low snubber capacitor voltage of 13% in comparison with the current commutation at rated power were achieved. The short-circuit of gird is suppressed by the current commutation with the current direction estimation method.



(a) Efficiency against load



(b) Input power factor against load

Fig. 18. Comparison of efficiency and Input power factor with each commutation method. These characteristics among three commutaion methods is almost same.

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