Improvement of Input Current Waveforms for a Matrix Converter Using a Novel Hybrid Commutation Method

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Abstract**-- This paper proposes a novel hybrid commutation method and a compensation method for the output voltage error and input current error of a matrix converter in order to improve the input current. The proposed commutation method combines input voltage commutation and load current commutation. There are two conventional commutation methods; one that depends on the polarity of the input line voltage and is called voltage commutation, and one that depends on the polarity of the output current and is called current commutation. However, a problem with voltage commutation is that commutation failure occurs at around an input line voltage of zero. It is difficult to detect the voltage polarity due to dependence on the offset and delay of the sensor. Similarly, current commutation failure occurs at around a load current of zero. The cause of these detection errors are detection delay and the offset of the sensor. However, the proposed commutation method can decrease the commutation failure without the need for a high accuracy sensor, because the current commutation is compensated by the voltage commutation. In addition, a new commutation error compensation method is proposed for the proposed commutation. The output voltage and input current error are compensated at the same time, because the duty ratio of each switch is directly compensated. The proposed method is validated based on the experimental results with a 750 W induction motor and a R-L load. The total harmonic distortion (THD) of the input current and the output current with the proposed hybrid commutation are 3.9% and 2.1%, respectively, and are obtained for an induction motor load with vector control.**

Index Terms**—Commutation, Matrix converter, Error compensation method by commutation**

I. INTRODUCTION

Recently, since a reverse-blocking insulated gate bipolar transistor (IGBT) was developed, there have been many studies for a matrix converter [1-5]. The matrix converter has a lot of advantages for a conventional pulse width modulation (PWM) rectifier and inverter system. For example, high efficiency, compact size, long life time and low input current harmonics can be realized, because of low conduction losses and a controllable input current, and large electrolytic capacitors are not required.

One of the problems of the matrix converter is a commutation method which is the turn-on and turn-off sequence of an AC switch with two IGBT. The switching sequence is controlled to avoid a short circuit of the power supply and an open circuit of the reactive load. If failure of the commutation causes a short circuit, then a large input current flows, and if the commutation failure causes the open circuit of the reactive load, then a large surge voltage occurs in the switching device. In other words, failure of the commutation causes a large snubber circuit, large current devices and waveform distortion.

The commutation sequence has four steps in the conventional method. The sequence is determined by the direction (polarity) of the input voltage (the voltage commutation method), or the direction (polarity) of the load current (the current commutation method). The voltage commutation method or the current commutation method uses a voltage sensor or current sensor and detection circuits for its direction.

To avoid the commutation failure, a high accuracy detection circuit is required. However, a high accuracy detection circuit results in high costs. Some studies have presented methods to avoid commutation failure [6-15]. One of the methods does not pass through the medium voltage of the power supply in the case of switching between the maximum and minimum voltages [15]. However, this method increases the switching losses due to the use of a large voltage difference for switching.

On the other hand, the commutation causes output voltage error and input current error, such as the output voltage error caused by the dead-time in conventional inverters. Compensation methods for the output voltage have been proposed in [13]. However, although conventional method can compensate the output voltage error, there has been no discussion regarding the influence of the input current. Thus, the input current still has waveform distortion.

The input current distortion caused by the commutation failure and the conventional voltage error compensation causes vibration of the input current. Therefore, the loss of a large dumping resistor is required to suppress the vibration of the input current.

This paper proposes a novel hybrid commutation method and a compensation method for the output voltage error including the input current error for the matrix converter. In addition, the influence of the input current by commutation is compensated in order to improve the input current waveforms without the need for a dumping resistor. Although the novel hybrid commutation method uses the direction of the input voltage and load current, the proposed commutation method can drastically suppresses commutation failure without the need for high accuracy sensors. Moreover, since the pulse width is directly compensated by the duty ratio in the proposed error compensation method, the method is very simple, although two types of commutation are used. As a result, the influence of the commutation for the input current can be decreased by the proposed commutation method. This paper shows the validity of the proposed commutation method and error compensation method through the experimental results.

II. HYBRID COMMUTATION METHOD

Fig. 1 shows a basic model of the commutation method with AC switches. The commutation has to simultaneously avoid the short circuit of the power supply and the open circuit of the load. We consider a four step commutation from the voltage souse v_1 to voltage souse v_2 based on Fig. 1.

A. Voltage commutation method

Figs. 2(a) and (b) show the switching sequence using voltage commutation. The switching sequence depends on the direction of the voltage at the switching leg. In this case, the switching operation can be distinguished as IGBT mode (forward bias mode) and diode mode (reverse bias mode). To prevent the short circuit, the voltage commutation must prepare the dead-time between the turn-on and turn-off of the IGBT mode switches. For example, if we assume a switch from S_1 to S_2 in the case of $v_1>v_2$, then the commutation sequence of the voltage commutation is obtained as follows;

Initial condition ON: S_{1a}, S_{1b} OFF: S_{2a}, S_{2b}

Step 1 S_{2a} ON Step 2 S_{1a} OFF

Step 3 S_{2b} ON Step 4 S_{1b} OFF

The commutation failure which creates the short circuit is caused by the changing point of the voltage direction. It should be noted that voltage commutation failure causes not only a distortion of the input current, but also, in the worst case, destroys the switching device by the large input current.

B. Current commutation method

Figs. 2(c) and (d) show the switching sequence using current commutation. The switching sequence depends on the load current direction. The open circuit generates a large surge voltage since the reactive energy of the load is changed to the voltage. To prevent an open circuit, the current commutation must prepare the overlap-time between turn-on and turn-off of the forward current switches.

For example, if we assume a switch from S_1 to S_2 in the case of $i_{load}>0$, then the commutation sequence of the current commutation is obtained as follows;

Initial condition ON: S_{1a}, S_{1b} OFF: S_{2a}, S_{2b}

Step 1 S_{1b} OFF Step 2 S_{2a} ON

Step 3 S_{1a} OFF Step 4 S_{2b} ON

The commutation failure, which makes the open circuit, is caused at around the zero crossing point of the

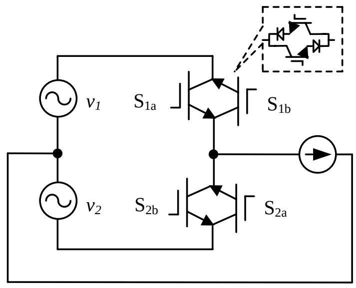
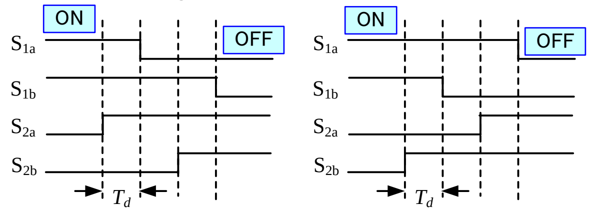
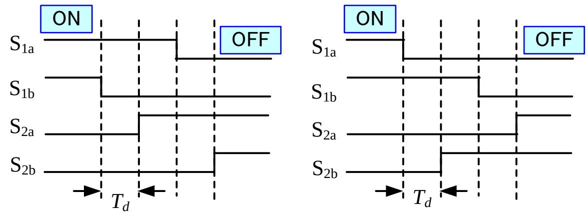


Fig. 1. Commutation model.



(a) Voltage commutation, ($v_1>v_2$). (b) Voltage commutation, ($v_1<v_2$).



(c) Current commutation, ($i_{load}>0$). (d) Current commutation, ($i_{load}<0$).

Fig. 2. Commutation pattern of Fig.1.

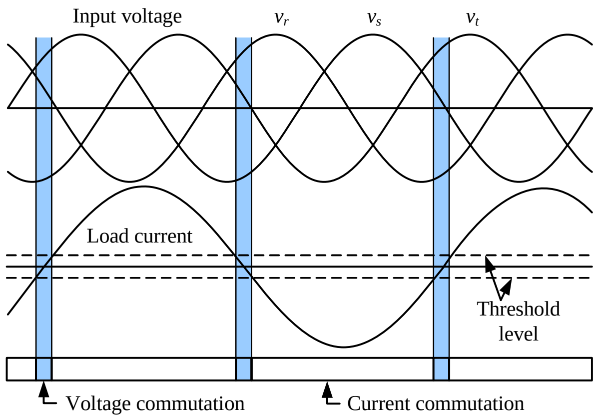
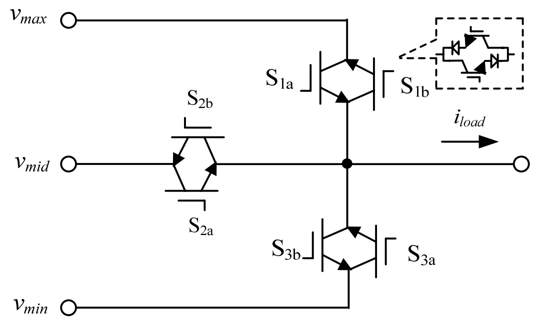


Fig. 3. Proposed commutation method.

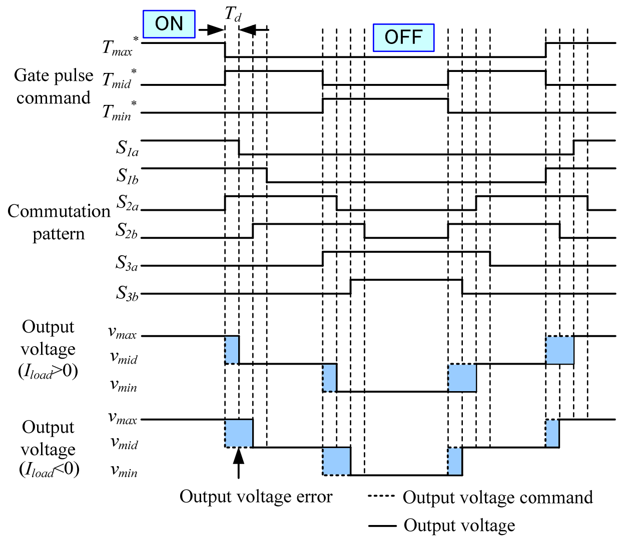
load current. It should be noted that current commutation failure causes not only a vibration of the output voltage, but also, in the worst case, destroys the switching device by a large surge voltage. In particular, failure of the current commutation continually occurs, because the wrong load current due to the commutation failure cannot flow in the right direction. In addition, the current commutation requires a reverse hysteresis characteristic to that of the current polarity signal.

C. Hybrid commutation method

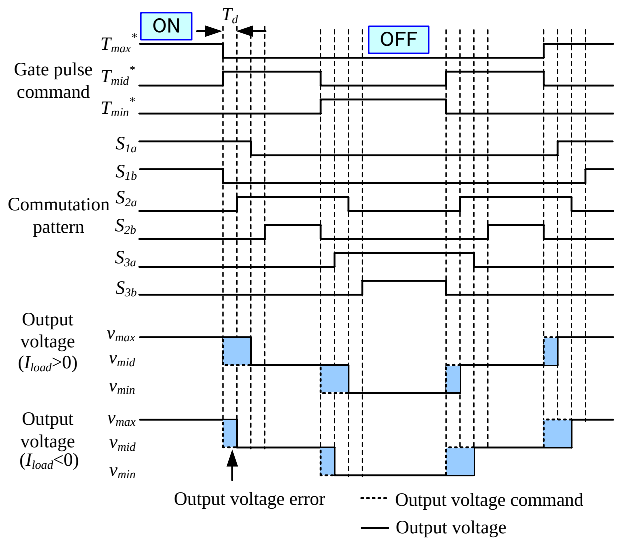
Fig. 3 shows the principle of the proposed hybrid commutation method. As previously discussed, the voltage commutation is in danger of failing at around a voltage difference of zero, and the current commutation is



(a) Configuration of a matrix converter.



(b) Voltage error in the case of voltage commutation.



(c) Voltage error in case of current commutation.

Fig. 4. Voltage error by commutation.

in danger of failing at around a load current of zero. Thus, the proposed method combines both the voltage commutation and the current commutation as follows.

- Zero crossing point of the load current: voltage commutation
- Others: current commutation

Therefore, the proposed hybrid commutation method can decrease the commutation failure without the need for a high accuracy detection circuit. Two type hybrid

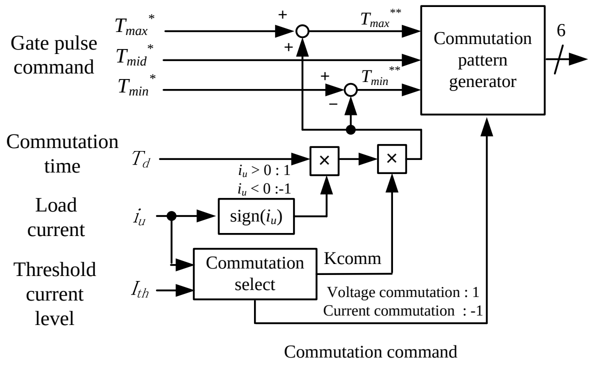


Fig. 5. Proposed commutation error compensation.

commutation methods can be considered, one that actively uses the voltage commutation, and one that actively uses the current commutation. However, the current preference of a hybrid commutation is better than the others for a decrease in commutation failure when the output frequency is lower than the input frequency, because the number of commutation method changes decreases.

III. ERROR COMPENSATION METHOD BY COMMUTATION

A. Voltage error by commutation

Fig. 4(a) shows an equivalent circuit for one phase of the matrix converter. The symbols, v_{max}, v_{mid}, and v_{min} in Fig. 4(a), indicate the maximum, medium, and minimum voltage of the power supply, respectively. Figs. 4(b) and (c) show the relation between the output voltage and gate pulses of the matrix converter. The output voltage error occurs as shown by the shadowed part in Figs. 4(b) and (c). In the case of voltage commutation in the dead-time period, which means that both IGBT mode switching devices are turned-off, the output voltage determines the direction of the load current.

The pulse width using the voltage commutation of the matrix converter can be expressed by Eq. (1).

$$\begin{cases} T_{\max} = T_{\max}^* - T_d \\ T_{\mathrm{mid}} = T_{\mathrm{mid}}^* \\ T_{\min} = T_{\min}^* + T_d \end{cases} \qquad \begin{cases} T_{\max} = T_{\max}^* + T_d \\ T_{\mathrm{mid}} = T_{\mathrm{mid}}^* \\ T_{\min} = T_{\min}^* - T_d \end{cases} \tag{1}$$

$$(i_{load} > 0) \qquad\qquad (i_{load} < 0)$$

where T_{max} represents the turned-on time of the switch connecting with the maximum voltage, T_{mid} represents the turned-on time of the switch connecting with the medium voltage, T_{min} represents the turned-on time of the switch connecting with the minimum voltage, T_d represents the commutation time of one step, the suffix '*' represents the command, and i_{load} is the load current.

From Eq. (1), the voltage error can be determined by Eq. (2).

$$v_{Vcomm} = v^* - (v_{\max} - v_{\min}) T_d f_s \mathrm{sign}(i_{load}) \tag{2}$$

where, y=sign(x) means

y=1 when x>0, y=-1 when x<0.

Similarly, in the case of current commutation, the voltage error during the overlap-time of the forward IGBT depends on the load current direction. In this case, the pulse width of the matrix converter can be expressed by Eq. (3).

$$\begin{cases} T_{\max} = T_{\max}{}^{*} + T_d \\ T_{\mathrm{mid}} = T_{\mathrm{mid}}{}^{*} \\ T_{\min} = T_{\min}{}^{*} - T_d \end{cases} \qquad \begin{cases} T_{\max} = T_{\max}{}^{*} - T_d \\ T_{\mathrm{mid}} = T_{\mathrm{mid}}{}^{*} \\ T_{\min} = T_{\min}{}^{*} + T_d \end{cases} \tag{3}$$

$$(i_{load} > 0) \qquad\qquad (i_{load} < 0)$$

From Eq. (3), the voltage error can be determined by Eq. (4)

$$v_{Icomm} = v^{*} + (v_{\max} - v_{\min}) T_d f_s \mathrm{sign}(i_{load}) \tag{4}$$

The input current distortion is generated by the conventional error voltage compensation method since the output voltage is compensated by Eqs. (2) or (4). Specifically, the voltage error adds to the voltage command. However, this method only compensates the output voltage without consideration for the input current. In this case, the voltage error compensation causes vibration of the input current. Consequently, a large dumping resistor loss is required to suppress the vibration of the input current.

B. Proposed compensation method

In this paper, the voltage error is directly compensated by the duty ratio according to Eqs. (1) and (3). In particular, the commutation method is changed by the magnitude of the load current for the proposed commutation. Therefore, the compensation duty ratio is obtained by Eq. (5).

$$\begin{cases} T_{\max}{}^{**} = T_{\max}{}^{*} + T_d \mathrm{sign}(I_{load}) K_{comm} \\ T_{\min}{}^{**} = T_{\min}{}^{*} - T_d \mathrm{sign}(I_{load}) K_{comm} \end{cases} \tag{5}$$

where K_{comm} represents a commutation method flag, if the voltage commutation is used, then K_{comm} = 1, if the current commutation is used, then K_{comm}=-1.

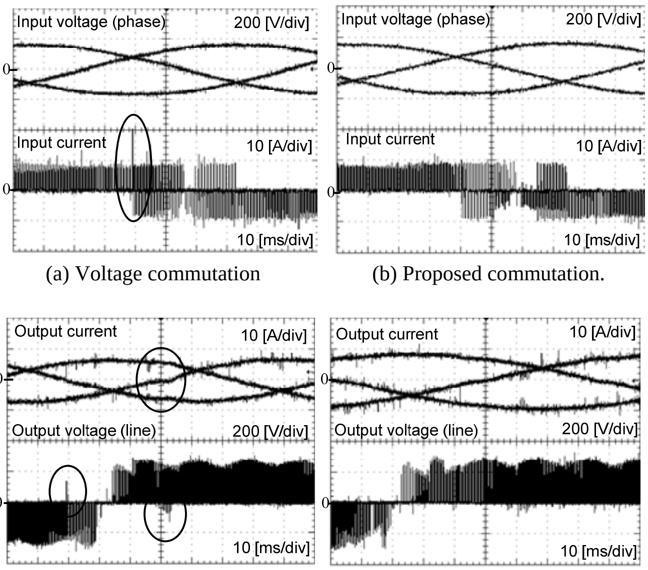
Fig. 5 shows the control block of the proposed compensation method for commutation error. Although the proposed commutation method uses two types of commutation (voltage commutation and current commutation), the compensation block is almost the same as the conventional dead-time compensation in the inverter. That is, the proposed compensation method is very simple. The commutation selection is achieved by the magnitude of the load current.

IV. EXPERIMENTAL RESULTS

Table 1 shows the experimental conditions of the proposed commutation and the compensation method. A control method for the matrix converter applies the virtual indirect control method used in [3]. This method

TABLE1 EXPERIMENTAL PARAMETERS.

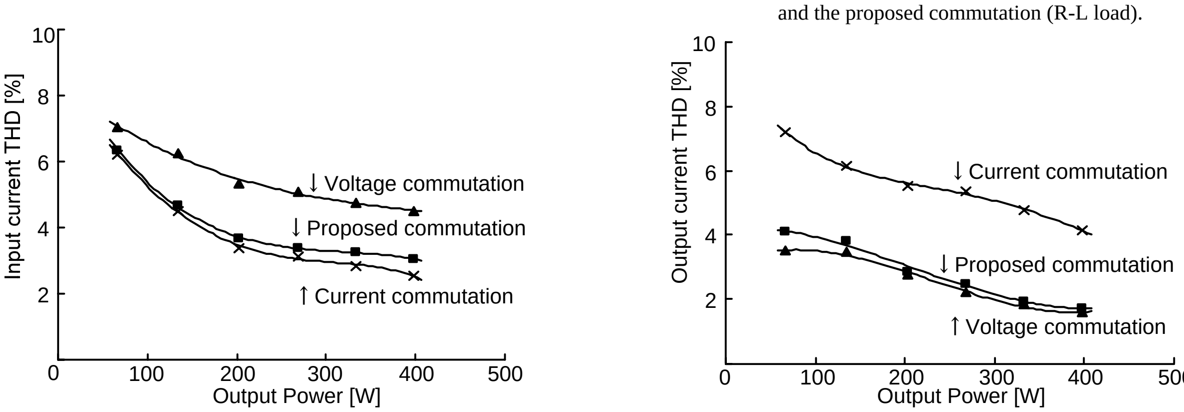
Input voltage	200[V]	LC filter	2 [mH]
Input frequency	50[Hz]		6.6 [μF]
Cut-off frequency	1.3[kHz]	Commutation time	2.5[μs]
R-L load	V/f control	750[W] Motor	Vector control
Output frequency	20[Hz]	Motor speed	600[rpm]
Threshold current level		±1.1 [A]	



(a) Voltage commutation (b) Proposed commutation.

(c) Current commutation. (d) Proposed commutation.

Fig.6. Experimental results for voltage commutation, current commutation and the proposed commutation (R-L load).



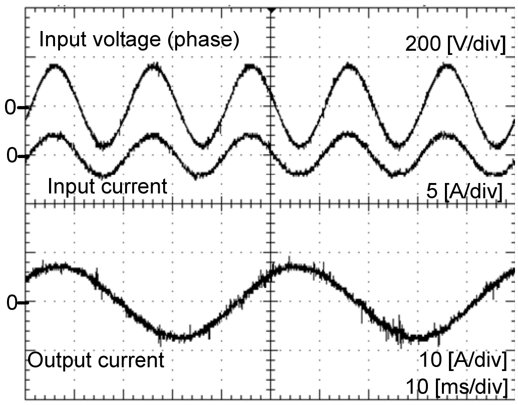
(a) Comparison of the input current THD. (b) Comparison of the output current THD.

Fig.7. THD for the input and output current (R-L load).

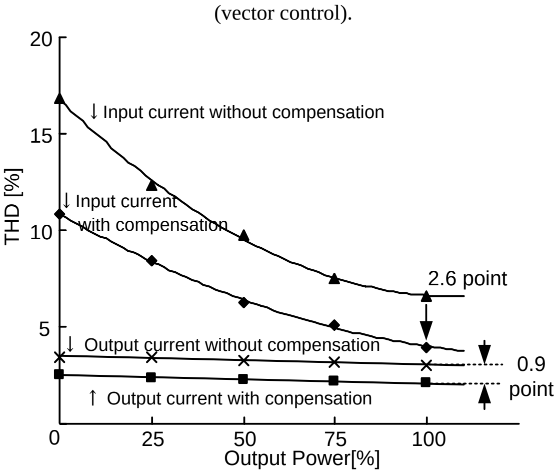
can clearly separate the input current control strategy and the output voltage control strategy. The change level between the voltage commutation and the current commutation was set to 20% of the rated current for a 750 W induction motor. The changing level is dependent on the accuracy of the load current sensor.

Fig. 6 shows a comparison of the voltage commutation, the current commutation and the proposed hybrid commutation. The large rush current caused by the commutation failure occurs at a point where the maximum voltage changes to the medium voltage as circled of Fig. 6(a). On the other hands, the proposed hybrid commutation changes smoothly without the rush current at the voltage change point. A surge voltage and zero crossing distortion occurs during current commutation as shown in the circled area of Fig. 6(c). In contrast, there is no surge voltage or current distortion for the proposed hybrid commutation. Therefore, the proposed commutation method is valid for suppression of the commutation failure.

Fig. 7 shows the comparison of the total harmonic distortion (THD) for the input and the output current using a R-L load. The voltage commutation deteriorates the THD of the input current, because the commutation failure of the voltage commutation triggers the current vibration in an input L-C filter, which is connected to the input side of the matrix converter. In contrast, the current commutation increases the THD of the output current, because the commutation failure leads to the distortion of

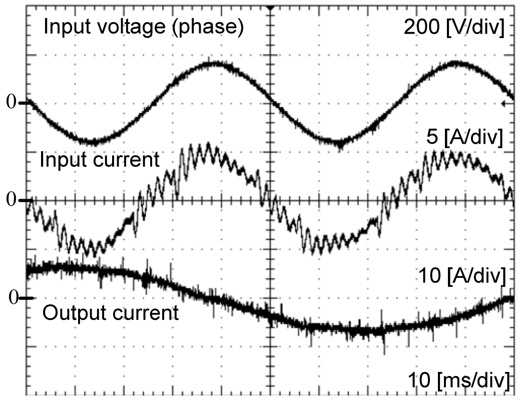


(a) Waveform for the proposed hybrid commutation (vector control).

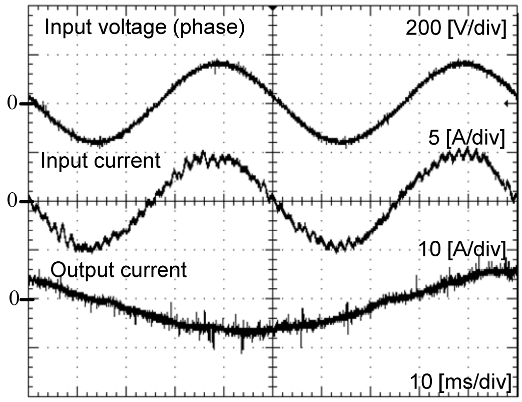


(b) THD for the input and output current (vector control).

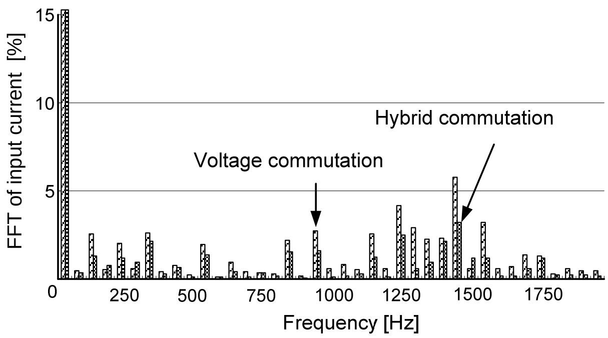
Fig. 8. Experimental results using a motor load with vector control.



(a) Waveform for voltage commutation.



(b) Waveform for the proposed hybrid commutation.



(c) Frequency spectrum of the input current.

Fig. 9. Experimental results under the motor load without a dumping resistor in the input filter.

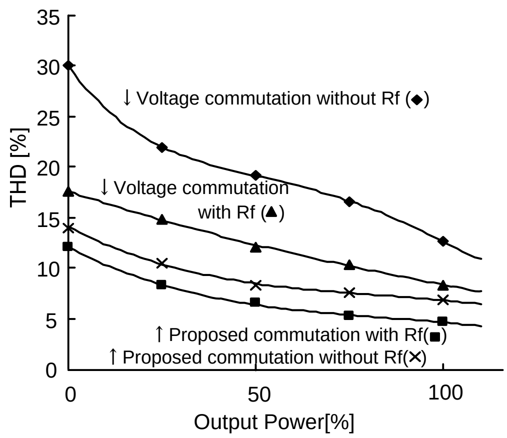


Fig. 10. Comparison of the THD of the input current for the voltage and hybrid commutation under a motor load.

the output voltage. In the proposed hybrid commutation, low THD is obtained for the input and output currents. These results confirm that the proposed method has both advantages of voltage and current commutation.

Fig. 8(a) shows the waveforms for the input and output current, using vector control with an induction motor of 750 W. THD are obtained for the input current and the output current, using the proposed hybrid commutation, and are 3.9% and 2.1% at the rated load, respectively.

Fig. 8(b) shows the comparison between the THD of the hybrid commutation with or without the proposed commutation error compensation methods. The THD for input current is improved by 2.6 point by application of the proposed commutation error compensation method. Therefore, the proposed commutation error compensation method is valid for decreasing the distortion of the input current.

Fig. 9 shows the waveforms of the input and output current and frequency spectrum of the input current without a dumping resistor in the input filter, and for a motor load controlling V/f control. A dumping resistor with large volume is required, because the commutation failure of the voltage commutation causes the vibration of the input current. By applying the proposed commutation, the vibration can be suppressed without the need for a dumping resistor.

Fig. 10 shows the comparison between the THD of the voltage commutation and the hybrid commutation with or without a dumping resistor. This result also uses a motor load with V/f control. The experimental results given in Fig. 10 indicate that the proposed hybrid commutation method without a dumping resistor is better than the conventional voltage commutation with a dumping resistor.

These experimental results confirm the validity of the proposed commutation method and commutation error compensation method.

V. CONCLUSIONS

This paper proposes a novel hybrid commutation method that combines voltage commutation and current commutation and a compensation method based on the duty ratio. The advantages of the proposed commutation are;

- realization of low THD for the input current and output current at the same time,
- compensation of the input current error by the commutation using the voltage error from the commutation.
- suppression of the vibration of the input current without the need for a dumping resistor.

The THD of the input current and the output current using the proposed hybrid commutation was 3.9% and 2.1%, respectively, obtained with an induction motor load using vector control. The snubber capacity can be decreased and the reliability of the switching device can be improved using the proposed commutation method.

REFERENCES

[1] J.Oyama, T.Higuchi, E.Yamada,T Koga, T. Lipo: ” New Control Strategy for matrix converter ” Proceedings of Power Electronics Society conference, pp360-367, 1989.

[2] P. W. Wheeler, J. Rodriguez, J. C. Clare, L. Empringham: ”Matrix Converters: A Technology Review” IEEE Transactions on Industry Electronics Vol. 49, No. 2, pp274-288, 2002.

[3] J.Itoh, I.Sato, H.Ohguchi, K,Sato, A.Odaka, N.Eguchi:「A Control Method for the Matrix Converter Based on Virtual AC/DC/AC Conversion Using Carrier Comparison Method」IEEJ Vol.124-D No.5,2004(in Japanese).

[4] H.Hara, E.Yamamoto, M.Zenke, K.Kan, T.Kume“An Improvement of Output Voltage Control Performance for Low Voltage Region of Matrix Converter” Proc. of IEEJapan IAS 2002, pp.I-313-316 (1-48), 2004 (in Japanese)

[5] J.Oyama, X. Xia, T.Higuchi, K.Kuroki , E.Yamada,T Koga: 「VVVF On-line Control of Matrix converter」 IEEJ Vol.116-D No.6,2004(in Japanese).

[6] J.Itoh, H.Tajima, H.Ohsawa:「Induction Motor Drive System using V-connection AC Chopper」IEEJ Vol.123-D No.3,2003(in Japanese)

[7] J. Mahlein, J. Igney, J. Weigold, M. Braun, O. Simon, “Matrix Converter Commutation Strategies With and Without Explicit Input Voltage Sign Measurement,” IEEE Trans. on Industrial Electronics, Vol.49, No.2, pp.407-414, 2002.

[8] P. W. Wheeler, D. A. Grant, “Optimized input filter design and low-loss switching techniques for a practical matrix converter,” IEE Proceedings of Electric Power Applications, Vol.144, No.1, pp.53-60, Jan., 1997.

[9] K. G. Kerris, P. W. Wheeler, L. Empringham, and J. C. Clare,“Implementation of a Matrix Converter Using p-Channel MOS-Controlled Thyristors,” IEE Conference on Power Electronics and Variable Speed Drives, London, September 2000

[10] L.Empringham, P.W.Wheeler, J.C.Clare, “Intelligent Commutation of Matrix Converter Bi-directional Switch Cells using Novel Gate Drive Techniques,” Proc. of IEEE Power Electronics Specialists Conference 1998 (PESC98), pp.707-713, 1998

[11] M. Ziegler and W. Hofman, “Performance of a two step commutated matrix converter for ac-variable-speed drives,” Proc. of EPE 1999,No.258 (CD-ROM)

[12] P W Wheeler, J C Clare, L Empringham, “A MCT BASED MATRIX CONVERTER WITH MINIMIZED COMMUTATION TIMES AND ENHANCED WAVEFORM QUALITY,” IEE Conference Publication (Institute of Electrical Engineers), Vol.487, pp.206-210 (2002)

[13] H.ohguchi, J.Itoh, I.Sato, A.Odaka, H.kodachi, N.Eguchi: “An Improvement Scheme of Control Performance for Matrix Converter” Proc. of EPE 2004

[14] M. Ziegler and W. Hofmann, “Semi natural two steps commutation strategy for matrix converters,” in Proc. IEEE PESC’98, pp.727–731, 1998.

[15] Lixiang Wei, T.A.Lipo, Ho Chan,” Robust voltage commutation of the conventional matrix converter,” Power Electronics Specialist Conference, 2003. PESC '03. 2003 IEEE 34th Annual Volume 2, 15-19 June 2003 Page(s):717 - 722 vol.2