

# High Efficiency Power Conversion Using a Matrix Converter

Jun-ichi Itoh  
Akihiro Odaka  
Ikuya Sato

## 1. Introduction

As demands for energy savings have increased in recent years, inverters are being used in a wider range of applications. Demands for lower cost, smaller size and higher efficiency will continue to further expand the range of inverter applications. However, as a trend toward eco-friendly products increases, some sort of measure is necessary to suppress the harmonics contained in the inverter input current.

Fuji Electric is developing a matrix converter capable of converting an input voltage directly into an arbitrary AC voltage, instead of converting that voltage into a DC voltage as inverters. This matrix converter has higher efficiency, smaller size, longer lifespan and fewer input current harmonics than inverters and has high potential for realizing the abovementioned demands. This paper presents Fuji Electric's matrix converter and the new technologies that enable its practical application.

## 2. Principles of the Matrix Converter

Figure 1 shows the circuit configurations of an inverter and a matrix converter. The inverter is a well-known device that converts an input AC voltage into a DC voltage by a rectifier, and then controls the semiconductor switch of a PWM inverter to convert the DC voltage into the desired AC voltage. A voltage smoothing capacitor is required in the DC link circuit, and an electrolytic capacitor is typically used for this purpose.

On the other hand, the matrix converter arranges semiconductor switches into a matrix configuration and controls them to convert an input AC voltage directly into the desired AC voltage. Since the input AC voltage is not converted to a DC voltage, there is no need for an energy storage device such as an electrolytic capacitor. Bi-directional switches are needed as the semiconductor switches, since an AC voltage is impressed on it.

As can be seen in Fig. 1 (a), the inverter requires a charge-up circuit to suppress the inrush current that flows to the electrolytic capacitor connected to the DC

link circuit. If a diode rectifier is used as the rectifier, a large amount of input current harmonics will be generated and therefore, a DC reactor (DCL) is inserted to reduce the current harmonics in the input current. In a conventional inverter, it is necessary to connect a braking unit to the DC link circuit in order to dissipate the regenerated power from the motor. A PWM rectifier was often used to reduce the input current harmonics and to realize motor regeneration. The matrix converter, on the other hand, is able to realize motor regeneration with almost no input current harmonics. In other words, a single converter unit is able to provide performance equivalent to that of a PWM rectifier and an inverter. Additionally, the charge-up circuit is unnecessary since the large electrolytic capacitor is not needed for the matrix converter. As a result, smaller size and longer lifespan can be achieved. In Fig. 2, a matrix converter system is compared to a conventional system that uses a PWM rectifier and an inverter. The conventional system

Fig.1 Inverter and matrix converter

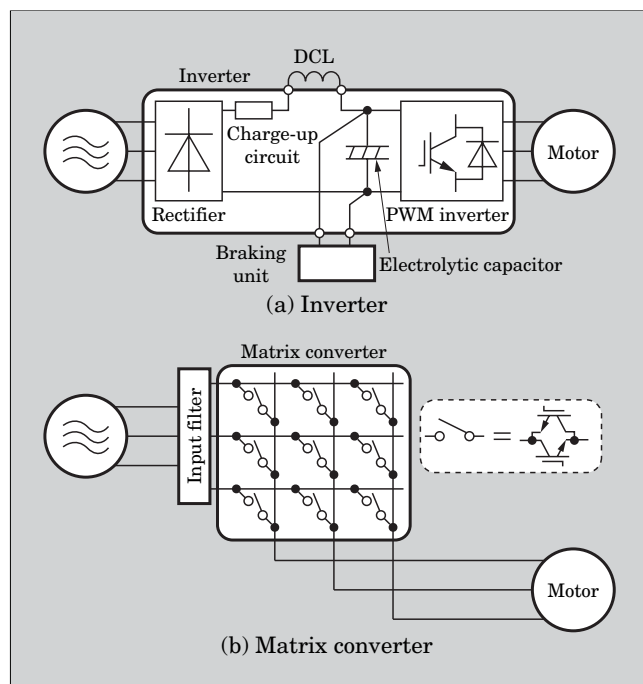
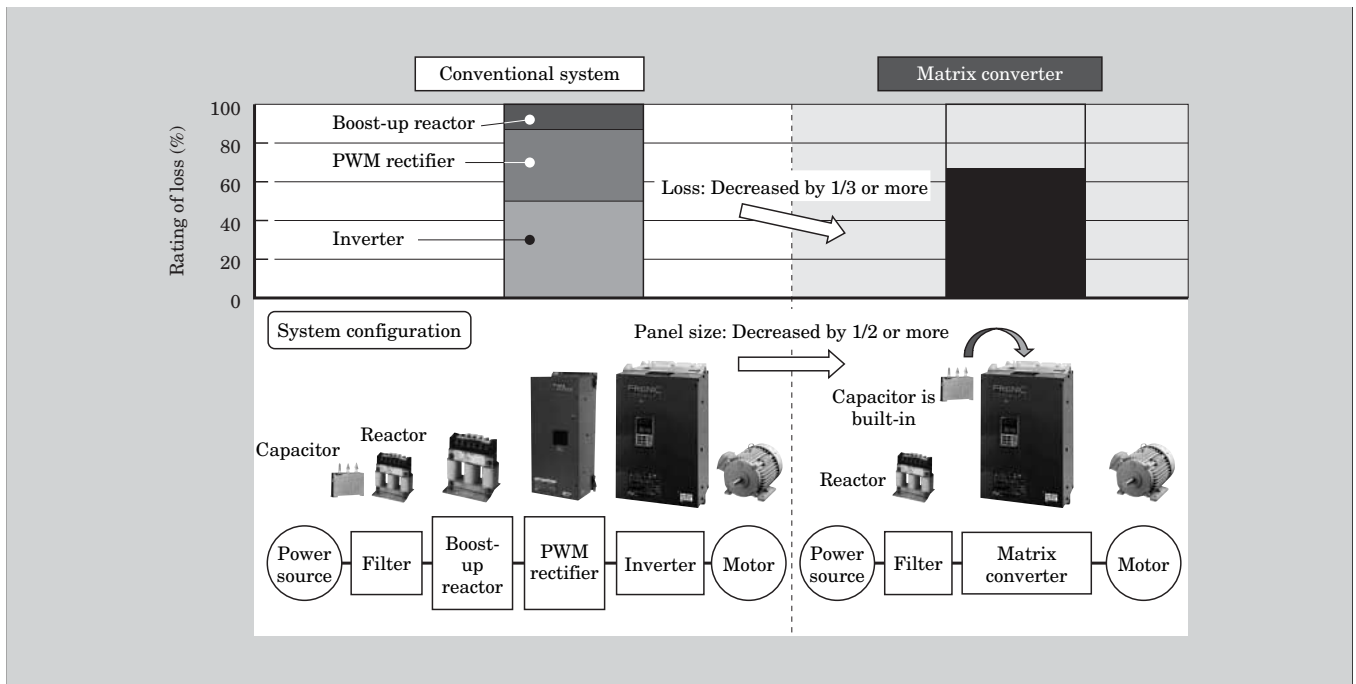


Fig.2 Comparison of the matrix converter with the conventional system



needs a filter capacitor, a filter reactor and a boost-up reactor in addition to a main unit. The matrix converter system, however, only needs a main unit and a filter reactor. Therefore, the configuration becomes simple and a panel size of the system can be reduced by 1/2 or more. In addition, since the matrix converter uses one-stage AC-AC direct conversion, a low loss system can be realized, achieving at least 1/3 lower loss than in the conventional system.

### 3. New Technologies for the Practical Application of Matrix Converters

The circuit configuration and operating principles of the matrix converter have been known for some time, but there are many problems in achieving practical application. The new technologies that solved these problems are introduced below.

#### 3.1 Technology for realizing a reverse blocking IGBT

Table 1 shows the bi-directional switches that are used in matrix converter. An AC voltage is impressed on the bi-directional switches. Because conventional semiconductor switch such as IGBTs do not have reverse blocking capability, diodes for reverse blocking are needed as shown in Table 1 (a). The problem with this diode, however, was that it increased on-state loss and decreased efficiency.

In order to solve this problem, Fuji Electric is developing a new IGBT having reverse blocking capability (RB-IGBT). Under a reverse bias, the conventional IGBT generates a large leakage current because its depletion region extends to the dicing surface at the chip side, where severe strain exists after the mechani-

Table 1 Bi-directional switches

	(a)	(b)
Bi-directional switch		
Number of devices	IGBT × 2, diode × 2	RB-IGBT × 2
On-state voltage	≈ 4 V	≈ 2 V

cal dicing process. In the newly developed RB-IGBT, a deep isolation region is formed in the dicing area to prevent expansion of the side surface of the depletion region and to ensure the reverse-blocking capability. Recent advances in IGBT manufacturing technology have enabled the realization of this device. The RB-IGBT has the same basic structure as the conventional IGBT, and thus their characteristics are also similar. Moreover, the reverse recovery characteristic of the RB-IGBT is approximately the same as that of the conventional diode.

Figure 3 compares the loss of matrix converters with each of bi-directional switches shown in Table 1 (a) and 1 (b). By using the RB-IGBT, the on-state loss of a series-connected diode is eliminated and although the switching loss remains nearly the same, on-state loss can be reduced by approximately 30%.

#### 3.2 Protection technology

Figure 4 shows the commutation and protection circuit of the matrix converter. Commutation is the

Fig.3 Comparison of the matrix converter losses

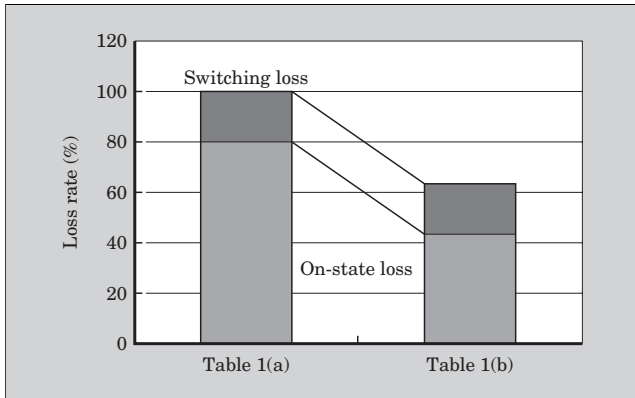
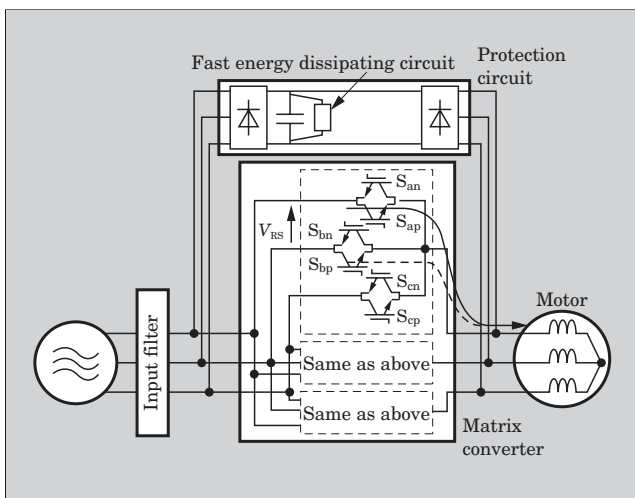


Fig.4 Commutation and protection circuit

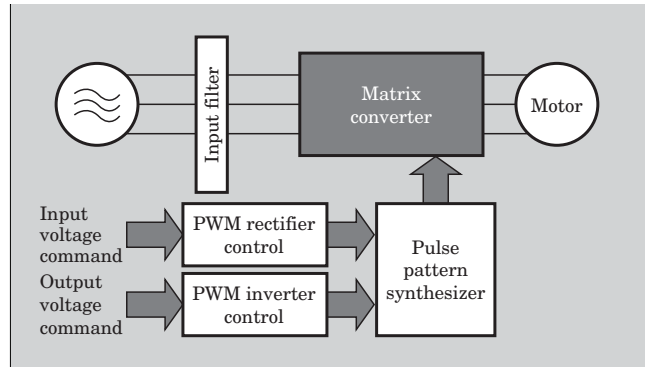


process wherein the current flowing to a switch  $S_a$ , for example, is transferred by turning on a switch  $S_b$  and turning off a switch  $S_a$  so as to transfer that current to switch  $S_b$ . The switch must be controlled, so that there is no short circuit and the load current is not interrupted. If the load current is interrupted, a large surge voltage is impressed upon the semiconductor switch and the switch is damaged.

Therefore, similar to the conventional PWM inverter, dead time is provided to prevent a short circuit condition and surge voltage generated during this dead time interval is absorbed by a protection circuit. As a result, loss increases and the protection circuit grows in size, as it requires a large electrolytic capacitor to absorb energy. This reduces the advantage of the matrix converter.

The commutation problem is solved by controlling the two RB-IGBTs that compose a bi-directional switch independently. In other words, by keeping a reverse-biased switch constantly in its on-state, the device is made to behave the same as the freewheeling diode in the conventional PWM inverter, and the load current is not interrupted. The forward-biased switch is turned-on and off with dead time and controlled similar to a conventional PWM inverter to prevent a

Fig.5 Control method for the matrix converter



short circuit condition. For example, in Fig. 4, if  $v_{RS} > 0$ ,  $S_{an}$  and  $S_{bp}$  are reverse biased and therefore are always turned-on, while  $S_{ap}$  and  $S_{bn}$  are turned-on and off with dead time. As a result, while short circuit conditions are being prevented, interruption of the load current is also prevented and the current is commutated safely. In addition, a protection circuit is necessary to protect the device from overcurrent and/or overvoltage. An electrolytic capacitor is generally used in the protection circuit to absorb energy stored in the load. However, using the electrolytic capacitor for the protection circuit reduces the advantage of the matrix converter. To overcome the problem, a new protection circuit is developed. The new protection circuit dissipates the load energy quickly without absorbing the energy to the capacitor. As a result, the electrolytic capacitor is not necessary.

### 3.3 Control technology

With the matrix converter, simultaneous control of the output voltage and input current is possible, but simultaneous and independent control is not easy to implement. The control method becomes complicated because switching one bi-directional switch in order to output a certain voltage causes the change of the input current condition. The higher speed, higher performance and lower cost of control devices in recent years, however, have made it possible to realize even complicated control with ease. In the conventional control method for a matrix converter, the pulse pattern for each bi-directional switch is calculated directly from the condition for obtaining the desired AC output voltage and the condition in which the input current becomes a sinusoidal wave. This control method is unique to the matrix converter and is capable of outputting various pulse patterns. However, since the pulse pattern is calculated directly, it is difficult to control the input current and the output voltage independently.

Then, a new control method was developed, and is shown in Fig. 5. This method is based on the virtual indirect control of a virtual PWM rectifier and a virtual PWM inverter. The matrix converter pulse pattern is obtained by synthesizing the pulse patterns of the

Fig.6 Principle of the virtual indirect control method

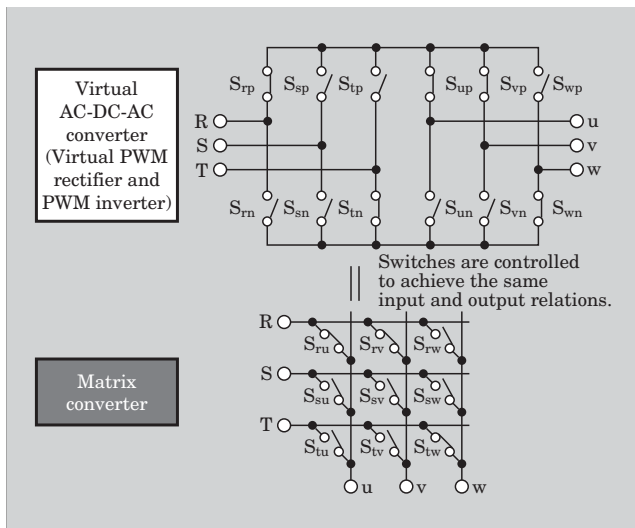


Fig.7 Input and output waveforms

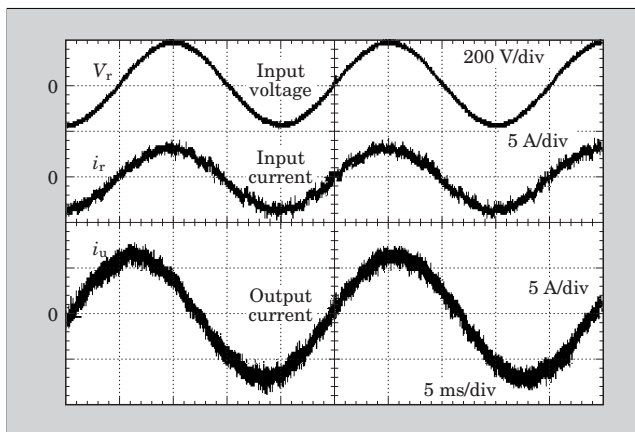
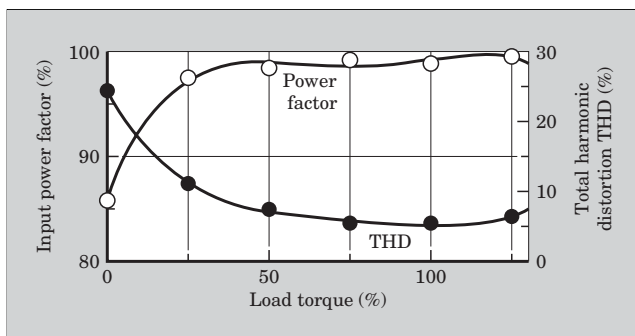


Fig.8 Input power factor and THD vs. load torque



virtual PWM inverter and the virtual PWM rectifier. This method enables the input current and output voltage to be controlled independently. In addition, since this control method can be implemented as a direct extension of the control of the conventional PWM inverter, techniques developed in the past can be applied largely without change. The virtual indirect method controls the input current and output voltage, and as shown in Fig. 6, assumes a virtual converter comprised of a virtual PWM rectifier and a virtual

Fig.9 Acceleration and deceleration characteristics (100 r/min → 1,200 r/min → 100 r/min)

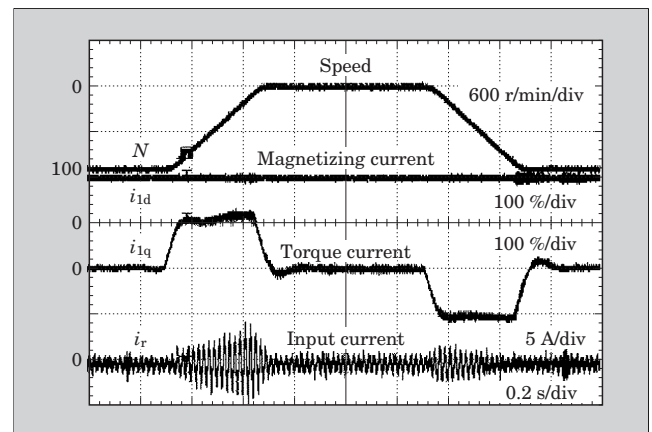
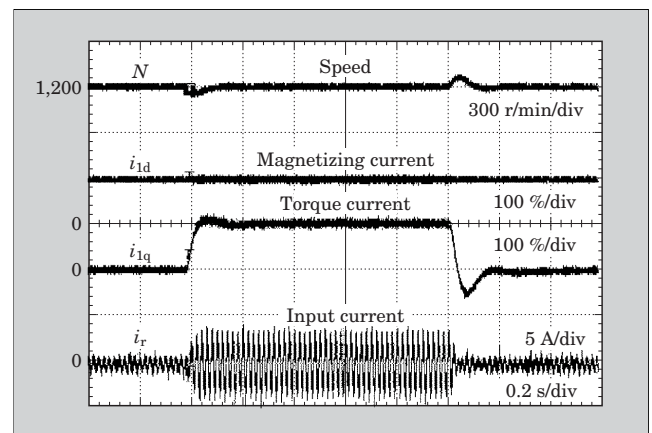


Fig.10 Impact load torque characteristic (0 % → 100 % → 0 %)



PWM inverter.

The virtual indirect control method is based upon the principle that states, “in a three-phase power converter, if the final input and output connection relations are made equal, then the input and output waveforms will not depend on circuit topologies.” In Fig. 6 for example, if there exist intervals during which the virtual rectifier turns on switches  $S_{rp}$  and  $S_{tn}$ , and the virtual PWM inverter turns on switches  $S_{up}$ ,  $S_{vp}$  and  $S_{wn}$ , then the input and output connection relations will be such that R-phase is connected to U-phase and V-phase, and T-phase is connected to W-phase. Consequently, the matrix converter similarly turns on switches  $S_{ru}$ ,  $S_{rv}$  and  $S_{tw}$ . As a result, R-phase is connected to U-phase and V-phase, and T-phase is connected to W-phase, and the operation of the matrix converter becomes same as that of the conventional PWM system.

Figure 7 shows waveforms of the matrix converter with the virtual indirect control method. The load is an induction motor. Unity power factor of the input is observed, and good sinusoidal waveforms were obtained for both the input and output currents.

Figure 8 shows the input power factor and total

harmonic distortion (THD) of the input current versus load torque. The input power factor is more than 99 % at 50 % load torque or higher. THD of the input current is also less than 10 % at 50 % load torque or higher.

Figures 9 and 10 show waveforms of the acceleration-deceleration characteristic and impact load torque characteristic, respectively, in the case of using the vector control method for the induction motor control. The magnetizing current remains constant even when the torque current changes, and it can be verified that vector control achieves good results, similar to those of the conventional motor control. Moreover, during deceleration it can be seen that input current increases and power is regenerated.

#### 4. Conclusion

New technology that enables the practical application of matrix converters has been introduced. Although not discussed in this paper, technical development is also underway to overcome the following basic limitations of the matrix converter.

- (1) Since this is an AC-AC direct conversion method, the maximum voltage that can be output as a sinusoidal wave is limited to 0.866 times the input voltage.
- (2) Since there is energy storage device, the matrix converter is susceptible to input voltage distur-

bances such as power failures.

Elevators and cranes, which require the regenerative operations, are suitable targets where the matrix converter is applied. Moreover, since the input current has low harmonic content, the matrix converter holds promise as a means to lessen current harmonics. Future application is also expected to fields that use PWM rectifiers and inverters, such as in a flywheel energy storage system. The RB-IGBT is expected to achieve even higher breakdown voltages and larger current capacity in the future, similar to that of the conventional IGBT. Along with these trends, the range of applications of the matrix converter is also expected to expand, and we intend to do our best to provide solutions.

#### References

- (1) Takei, M. et al. The Reverse Blocking IGBT for Matrix Converter with Ultra-Thin Wafer Technology. Proceedings of the 15th International Symposium on Power Semiconductor Devices & ICs (ISPSD). 2003, p.156-159.
- (2) Roy, M. et al. The MBS (MOS Bidirectional Switch), a new MOS switch with reverse blocking voltage. EPE99-Lausanne. 1999.
- (3) Oyama, J. et al. New Control Strategy for Matrix Converter. Proceeding of Power Electronics Society Conference. 1989, p.360-367.

