A Novel Engine Generator System with Active Filter and UPS Functions Using a Matrix Converter

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Abstract

This paper proposes the application of a matrix converter to a PM generator for power quality compensation, such as reactive power compensation, harmonic current and power interruption. The novel point of this work is that the matrix converter provides reactive power with harmonic current. Simulated and experimental results confirm that the matrix converter can maintain high performance as same as a conventional active filter and an uninterruptible power supply (UPS).

I. Introduction

Recently, renewable resources supplies, such as fuel cells, photovoltaic cells, wind power and engine generators, for distributed power system have been studied intensely. Use of such power supplies means that power quality compensators, such as active filters, reactive power compensators, and uninterruptible power supplies (UPS) are becoming more important for maintenance of a high quality power grid.

Power quality compensators with switching devices are constructed based on a voltage source inverter using six arms. Therefore, conventional power quality compensators require a large electrolytic capacitor in the dc link part of the equipment. The use of a large capacitor hinders downsizing efforts and the lowering of equipment costs. In addition, the high reliability is required for the power compensator and a distributed power system. Therefore the life time of the electrolytic capacitor causes trouble.

On the other hands, ac to ac direct converters have been studied, such as a matrix converter for motor drive applications. Direct converters, which do not have a large electrolytic capacitor and an initial charge circuit, can be used to realize downsizing and lowering of equipment costs, when compared with conventional converters. In this case, the input current of the matrix converter is controlled by only a unity power factor sinusoidal waveform.

This paper proposes the application of a matrix converter to a permanent magnet (PM) generator with power quality compensation. The input current control response of a matrix converter is higher than the conventional voltage type converter, because the input current control works as same as a current type converter.

A control strategy is also proposed for an active filter with UPS function. The proposed control strategy is based on a virtual indirect control method [4], which can clearly separate an input side control and an output side control, such as an indirect matrix converter. Thus, this paper leads a relation between the input and output current. A compensation capacity of this proposed system is also mentioned.

Furthermore, simulated and experimental results are provided for reactive power compensation, UPS operation and active filter operation, using the proposed control method. As a result, the proposed engine generator system has been validated.

II. System Configuration

Figure 1 shows a block diagram of the proposed engine generator system with the matrix converter to compensate power quality. The reactive power and the harmonics in the power grid are compensated by the matrix converter, which generates the same reactive power and harmonics as the load.

Assuming that a matrix converter is applied to one type of distributed power supply with a PM generator, then the matrix converter can supply not only the active power, but also compensate the harmonic current in the power grid, which will realize the maintenance of high power quality without the use of other active filter equipment.

The energy buffer of the matrix converter is used as a PM generator, instead of a large volume capacitor. In the case of compensating active power, such as for power interruption and an unbalanced voltage, a conventional compensator, which consists of a switching device bridge with six arms, requires a large volume capacitor. However, electrolytic capacitors can not be applied to high voltage systems, because there are no high-voltage rated electrolytic capacitors.
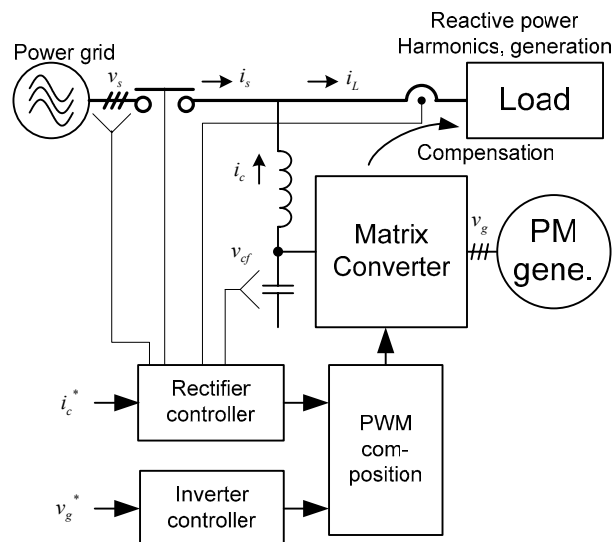

Fig. 1. Block diagram for the engine generator system with a matrix converter.

III. Control strategy

A. Virtual indirect control method

The proposed control strategy is based on a virtual indirect control method with a triangular carrier wave for power grid side control and generator side control, respectively. A feature of this method is that various control methods for a conventional inverter or rectifier can be applied to a matrix converter.

The control algorithm is provided by the inverter part (the generator side), the rectifier part (the power grid side) and a composite pulse width modulation (PWM) generator, which generates the PWM pattern for the matrix converter, as shown in Figure 1. The PWM pattern for the matrix converter is obtained by the switching functions of the inverter and rectifier part.

Figure 2 and 3 shows a model of the indirect matrix converter and the matrix converter, respectively. In this case, the relation between the input voltage and the output voltage of the indirect matrix converter is expressed as

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} S_{up} & S_{un} \\ S_{vp} & S_{vn} \\ S_{wp} & S_{wn} \end{bmatrix} \begin{bmatrix} S_{rp} & S_{sp} & S_{tp} \\ S_{rn} & S_{sn} & S_{tn} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \tag{1}$$

where switching function s is defined that s=1 means switch S is turned on, s=0 means switch S is turned off. Likewise, the relation between the input voltage and the output voltage of the matrix converter is expressed as

$$\begin{bmatrix} v_u \\ v_v \\ v_w \end{bmatrix} = \begin{bmatrix} s_{ru} & s_{su} & s_{tu} \\ s_{rv} & s_{sv} & s_{tv} \\ s_{rw} & s_{sw} & s_{tw} \end{bmatrix} \begin{bmatrix} v_r \\ v_s \\ v_t \end{bmatrix} \tag{2}.$$

Therefore, the PWM pattern for the matrix converter can be converted by

$$\begin{bmatrix} s_{ru} & s_{su} & s_{tu} \\ s_{rv} & s_{sv} & s_{tv} \\ s_{rw} & s_{sw} & s_{tw} \end{bmatrix} = \begin{bmatrix} s_{up} & s_{un} \\ s_{vp} & s_{vn} \\ s_{wp} & s_{wn} \end{bmatrix} \begin{bmatrix} s_{rp} & s_{sp} & s_{tp} \\ s_{rn} & s_{sn} & s_{tn} \end{bmatrix} \tag{3}.$$

As a result, control performance of a matrix converter is exactly same as an indirect matrix converter because the relation between the input voltage and the output voltage is the same. It should be noted that the relation between the input current and the output current is also the same.
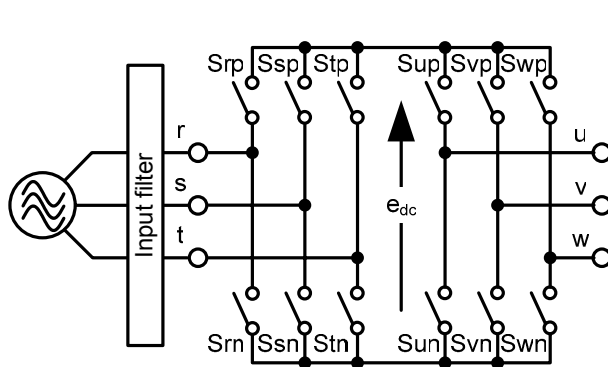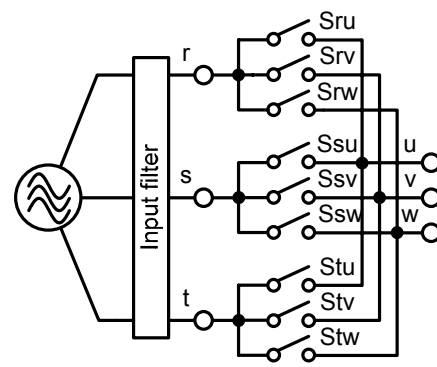

Fig. 2. Indirect converter

Fig. 3. Matrix converter

B. Active filter control with UPS function

Figure 4 shows a control block diagram for rectifier control. This system has two operation modes for harmonic current compensation such as an active filter, and power interruption compensation such as UPS. Detection of power interruption is used in the same way as the conventional method, which detects the magnitude of the input voltage. When a power interruption has occurred, the matrix converter works as the voltage power source. The selector shown in Figure 1 selects the current command for UPS mode and active filter mode.
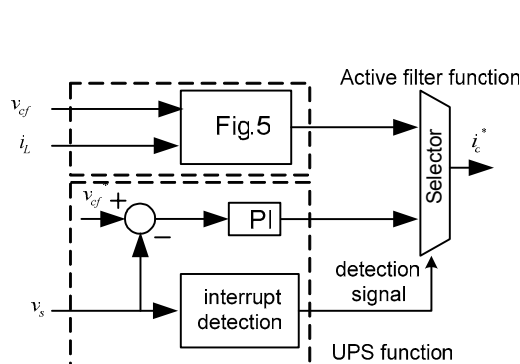

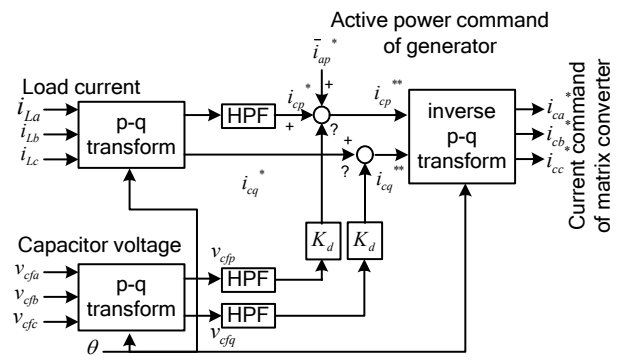Fig. 4. Block diagram for rectifier control.

Fig. 5. Block diagram for reactive power compensation with damping control for the input current.

Figure 5 shows a control block diagram for the active filter function. The input current commands are calculated using the load current. It should be noted that the control method of the rectifier part is

the same as a current type converter. In this controller, the load current is converted to a p-q frame, which is a rotating frame based on the voltage vector of the power grid. Therefore, the values of the p-axis represent the active current and those of the q-axis represent the reactive current.

There are two difference points for application of the control method to a conventional power grid compensator, described as follows:

1) Active power command of the PM generator is added to the active current command.

2) Damping control [5] of the input current is applied to the active and reactive current command calculation, as shown in Figure 5.

The current commands with damping control are obtained using equation (4). A high pass filter (HPF) is used to extract the harmonic current from the capacitance voltage. The cut off frequency of the HPF depends on the harmonics extraction frequency.

$$i_c^{**} = i_c^* - K_d \frac{ST}{1+ST} v_{cf}$$

(4)

where, ic** is the compensated current command, ic* is the original current command, T is the time constant, Vcf is the capacitor voltage, and Kd is the damping gain.

C. Input current control method of matrix converter

In this chapter, we discuss the input current control method for the matrix converter based on the indirect matrix converter. The theories of the indirect converter are entirely equivalent to the matrix converter because the matrix converter is controlled based on the virtual indirect control method in this proposed system. In this case, for example, when Srp, Stn, Sup, Svp, and Swn are turned on in the indirect matrix converter as shown in Figure 2, R phase is connected to U, V phase, and T phase is connected to W phase. Likewise, when Sru, Srv, Stw are turned on, R phase is also connected to U, V phase, and T phase is also connected to W phase in the matrix converter. Thus, the connection between the input terminal and the output terminal of the matrix converter is the same as converter indirect matrix converter.

Figure 6 indicates power flow of the indirect matrix converter. The input side converter operates as a current source rectifier, and the output side converter operates as a voltage source inverter in the indirect matrix converter. Therefore, the maximum value of the input current depends on magnitude of the DC link current.
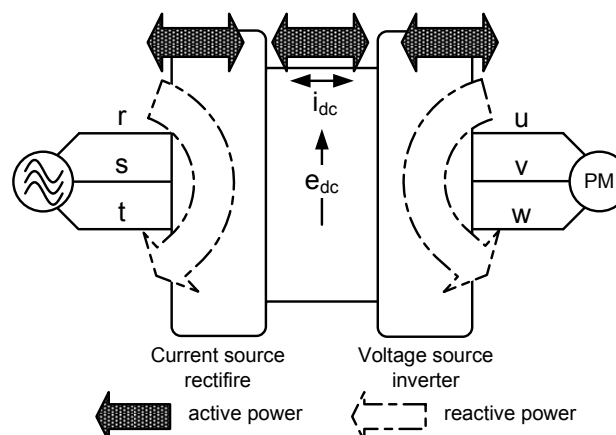

Fig. 6. Power flow of AC/DC/AC converter.

The reactive power of the load side does not affect the DC link stage because the reactive power is generated by free wheeling mode. In addition the DC link stage only transmits the active power on the load. It is similar to control a matrix converter with the virtual indirect control method. The indirect matrix converter does not have an energy buffer. Therefore, the DC link current is determined by the output current and the load power factor of the voltage source inverter. The load power factor is

calculated using the voltage commands and the output current of the inverter. As a result, the DC link current is given by

$$
\begin{aligned}
i_{img\_dc} &= i_{out\_max} \cdot \cos\theta_{out} \\
&= i_{out\_max} \cdot \frac{v_\alpha^* \cdot i_{out\alpha} + v_\beta^* \cdot i_{out\beta}}{\sqrt{(v_\alpha^{*2} + v_\beta^{*2})(i_{out\alpha}^2 + i_{out\beta}^2)}}
\end{aligned}
\tag{5}
$$

where v_α^* and v_β^* are the output voltage commands of the inverter, $i_{out\alpha}$ and $i_{out\beta}$ are the output current, i_{out_max} is the peak value of the output current, and suffix α and β mean on a rest frame.

The control range of the input current is constrained by $\sqrt{3}/2$ times of the DC link current because the DC link current has ripple between $\sqrt{3}/2 i_{img\_dc}$ and i_{img_dc}. The current source rectifier uses a triangular carrier in order to generate PWM pulse. Thus, the input current commands are normalized by $\sqrt{3}/2$ times of the DC link current. Finally, the modulation index of the input current is obtained by

$$
\begin{aligned}
i_c^{**} &= \frac{i_c^*}{\frac{\sqrt{3}}{2} * i_{img\_dc}} \\
&= \frac{2}{\sqrt{3}} \cdot \frac{i_c^*}{i_{out\_max}} \cdot \frac{\sqrt{(v_\alpha^{*2} + v_\beta^{*2})(i_{out\alpha}^2 + i_{out\beta}^2)}}{v_\alpha^* \cdot i_{out\alpha} + v_\beta^* \cdot i_{out\beta}}
\end{aligned}
\tag{6}
$$

where i_c^{**} is the modulation index of the input current, i_c^* is the input current command.

By using the virtual current source type rectifier with the modulation index as shown in Equation (6), the input current of the matrix converter is able to be controlled by an open loop controller though there is no auto current regulator for the input side.

IV. Reactive Power Compensation range

The power factor of the input side of the matrix converter deteriorates according to magnitude of compensated reactive power, because the input current of the matrix converter not only contain the active power but also the reactive power to compensate the power grid. As described in previous chapter, a behavior of a matrix converter can be basically discussed as same as an indirect matrix converter. In case of an indirect matrix converter, if the input power factor becomes low, then a DC voltage would decrease. That is, the matrix converter can not control the motor connected to the output side because the output voltage of the inverter is constrained by the DC link voltage. Accordingly, we have to carefully choose the reactive power compensated in a load including the output voltage of the matrix converter.

In this chapter, we examine the relations between the maximum compensated reactive power and the output voltage of the matrix converter. The maximum output voltage of the matrix converter is obtained using

$$
V_{out} = \frac{\sqrt{3}}{2} V_s \cdot \cos\theta_{in}
\tag{7}
$$

where V_s is the power grid voltage, $\cos\theta_{in}$ is the input power factor of the matrix converter.

In case of the indirect matrix converter, the input current of the matrix converter is also depended on the output power factor and the magnitude of the output current because the input current is determined by the DC link current. Therefore, when the matrix converter compensates reactive power, the input apparent power is obtained using Equation (8).

$$
S_{in} = V_s \cdot I_{out} \cdot \cos\theta_{out}
\tag{8}
$$

where I_{out} is the output current(RMS), $\cos\theta_{out}$ is the output power factor of the matrix converter.

The input power factor of the matrix converter is given using the apparent power leaded by Equation (8), and reactive power compensated in a load. As the result, the input power factor is obtained using Equation (9).

$$
\cos\theta_{in} = \frac{\sqrt{S_{in}^{2} - Q_{load}^{2}}}{S_{in}}
$$

$$
= \frac{\sqrt{(V_s \cdot I_{out} \cdot \cos\theta_{out})^2 - Q_{load}^{2}}}{V_s \cdot I_{out} \cdot \cos\theta_{out}} \tag{9}
$$

where S_{in} is the input apparent power of matrix converter, Q_{load} is reactive power for compensation.

Finally, the relation among the output voltage V_{out}, the reactive power of the load Q_{load} and the load power factor $\cos\theta_{out}$ for compensation is expressed using Equation (10).

$$
\left|Q_{load}\right| = I_{out} \cdot \cos\theta_{out} \cdot \sqrt{(V_s + \frac{2}{\sqrt{3}} \cdot V_{out})(V_s - \frac{2}{\sqrt{3}} \cdot V_{out})} \tag{10}
$$

Figure 7 shows the compensation range of reactive power, using Equation (10) under constant output current I_{out} and constant input voltage V_s. The ability as a reactive power compensator increases in the domain of low output voltage and high power factor.
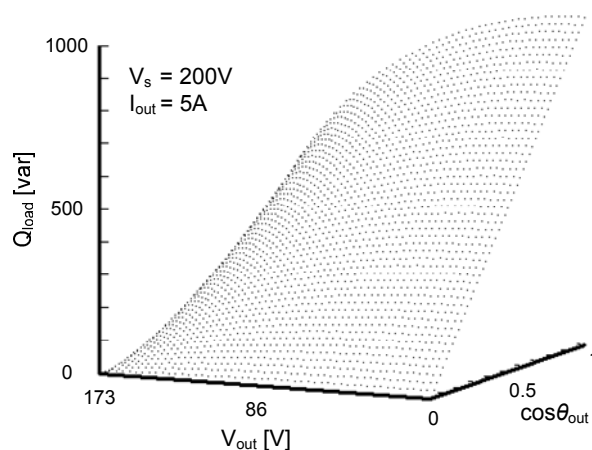

Fig. 7. Compensation range of reactive power.

V. Simulation results

Table 1 shows the simulation parameters used to confirm the basic operation of the proposed system. The simulation assumes that the commutation of the matrix converter is the ideal, that is, the commutation time is zero. In this system, the active power is divided between the power grid and the PM generator. The ratio of the active power (power distribution ratio) between the power grid and the PM generator is set to almost 7:3.

Table. 1. Simulation parameters.

Power grid voltage	200[V]
Power grid frequency	50[Hz]
Carrier frequency	10[kHz]
Power distribution ratio (Power grid :PM generator)	7:3
LC filter Cut of frequency	1.6[kHz]
LC filter Damping factor	0.22
Load (UPS, Active filter operation)	Diode bridge (R=75Ω, DCL=200 mH)
(reactive power compensation)	R=25Ω,L=50 mH

Figure 8 shows the simulation results for reactive power compensation. At the middle of the horizontal axis, reactive power compensation is initiated and the unity input power factor can then be obtained. The serving active power of the power grid is decreased, because the PM generator is supported by the active power. It should be noted that we also confirmed that the proposed system can compensate the power factor of the power grid for capacitor load.

Figure 9 shows the results for active filter operation, which means harmonic current compensation of the power grid. The harmonic current causes a diode rectifier. The harmonic compensation is started in the middle of the horizontal axis. As a result, a good sinusoidal current waveform is obtained in the power grid. In addition, the simulation results confirm that the damping control can suppress the oscillation of the LC filter to the input current of the matrix converter. However, the oscillation depends on LC filter in the grid current is slightly remaining.

Figure 10 shows the UPS operation with active filter, which represents power interruption compensation by the PM generator system. The output voltage is smoothly changed from the power grid to the PM generator. The output voltage is controlled by a proportion and integration (PI) controller during the power interruption. That is, the output voltage regulator is immediately applied when the power interruption occurs. A good sinusoidal voltage waveform is also obtained in this case.
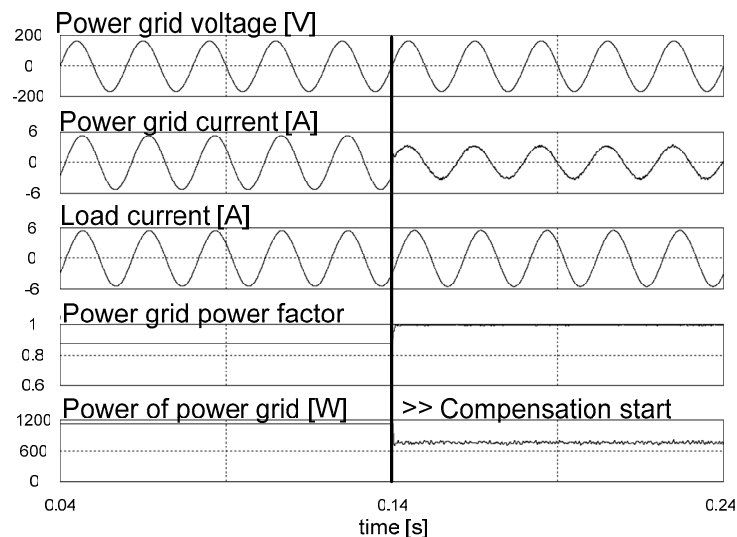

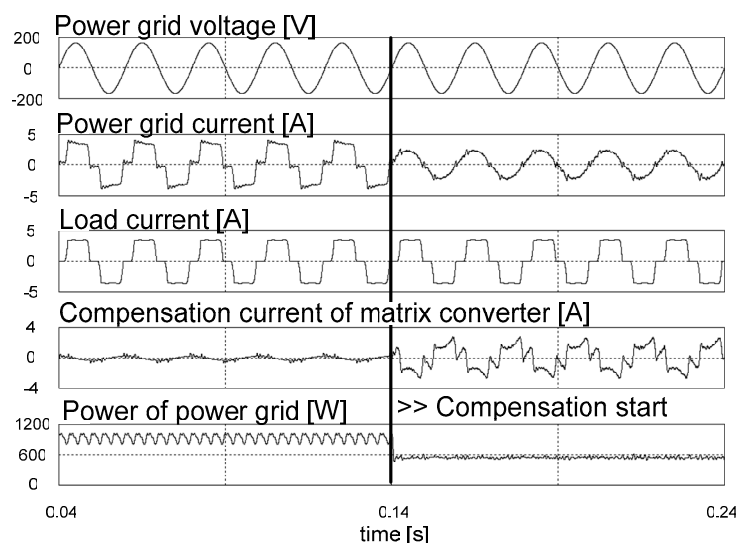Fig. 8. Simulation results of reactive power compensation with an R-L load

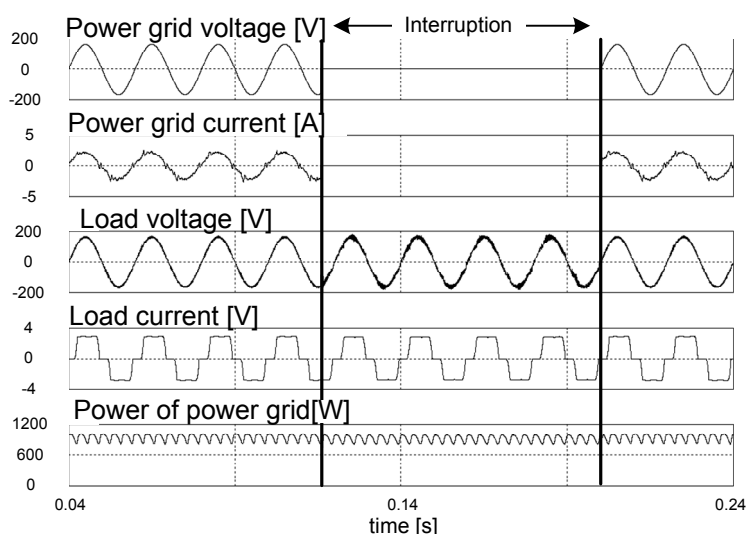Fig. 9. Simulation results for active filter operation.

Fig. 10. Simulation results for UPS operation.

VI. Experimental results

Figure 11 shows the experimental results for reactive power compensation using the proposed system and RL load. The experimental conditions are almost the same as the simulation, except for the direction of the power flow, the LC filter design of the matrix converter, and the commutation method according to the polarity of the input voltage [3]. The experimental setup constrains the operation mode, which is motoring. The input current of the matrix converter controlled as lead phase for the power grid voltage. As a result, the power factor of the power grid current was corrected as unity.

Figure 12 shows the experimental results for active filter operation for a diode rectifier load. In figure 12(a), a good sinusoidal waveform is obtained for the input current of the matrix converter. However, the power grid current contain the distortion due to the input current generates the harmonics components. On the other hands, in Figure 12(b), the power grid current is compensated by the matrix converter. As a result, the power grid current becomes a sinusoidal waveform. However, a few distortion remains in the load current. One of the reasons for the distortion is the influence of voltage error by commutation.
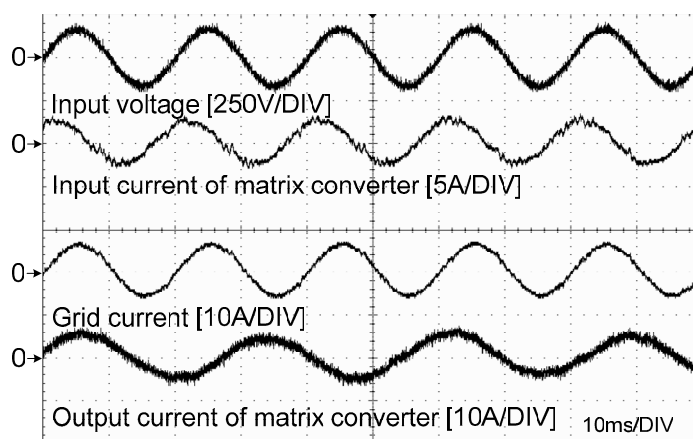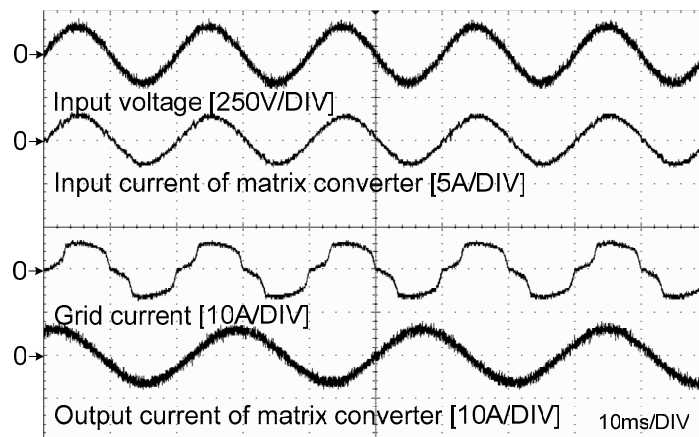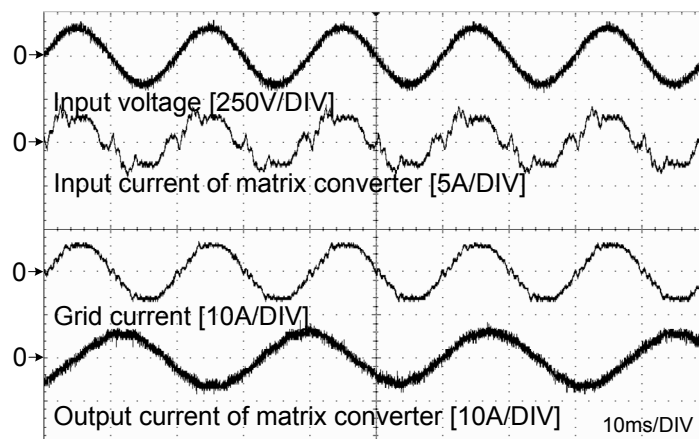

Fig. 11. Experimental result of reactive power compensation with RL load.

(a) Without harmonics compensation.

(b) With harmonics compensation.

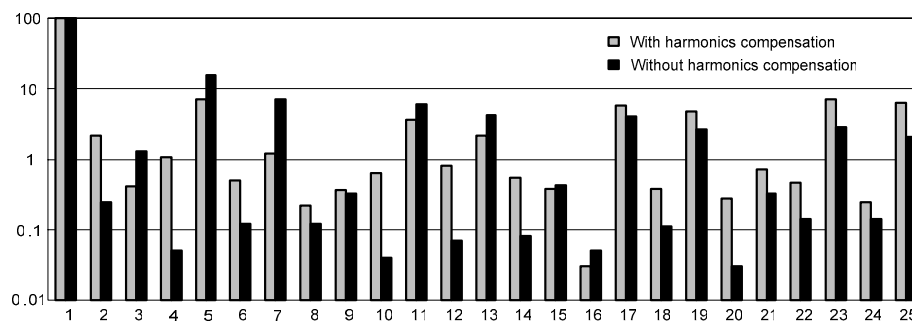Fig. 12. Experimental result of active filter operation.

Fig. 13. Harmonics analysis results of the power grid current.

Figure 13 shows the analysis results of harmonics under the diode rectifier load as shown in Figure 12. The frequency components of 3rd, 5th, 7th and 11th are decreased by applying the proposed harmonics compensation. However the frequency components of even numbers are higher because the oscillation of the input current depends on the LC filter causes the current distortion.
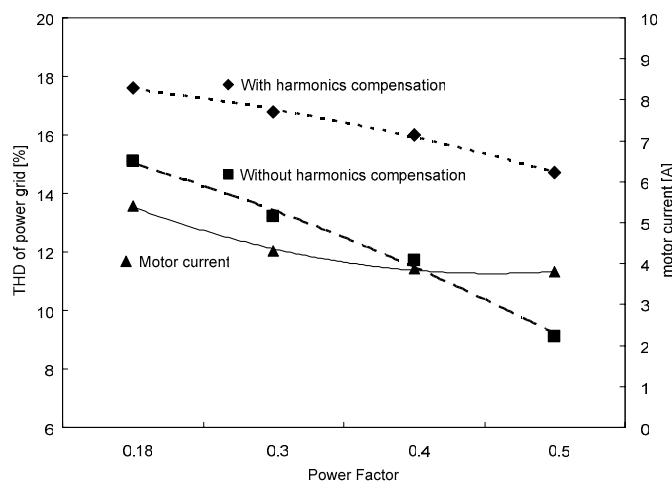
Fig. 14. Relation between power factor and THD.

Figure 14 shows the relation between the power factor of the PM motor connected side and the total harmonics distortion (THD) of the power grid. When the power factor of the PM motor increase, THD of the power grid becomes low. This means that the compensation is effective according to increasing the power factor of the PM motor. This reason can be explained as follows. The large power factor increases the virtual DC link current. As a consequence the input current control range is widened as discussed in chapter IV. The validity of the analysis is proved because this experimental result agrees with equation (6).

Conclusion

This paper proposes a new application of the AC/AC direct converter. Reactive power, harmonic current and power interruption can be compensated by the proposed input current control method of matrix converter. In addition, this paper described the range of the reactive power compensation, clearly. The proposed compensation strategy is not only applicable to conventional matrix converters, but it can also be used for an indirect matrix converter with a dc link.

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