Behavior of a Matrix Converter with a Feed Back Control in an Input Side

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***Abstract*--This paper discusses about characteristics of a matrix converter where a current feedback is applied to the input side. When the impedance of the power grid is high, such as a generator, the control stability of the matrix converter will be deteriorated. One of the solutions to this problem is to apply an input current stability control that is proposed. However, the efficiency of the generator will decrease at light load and heavy load. In this paper, the behavior of the input current control is analyzed, then the vector control is applied to the input side in order to obtain a stable operation and the maximum efficiency according to the pole position of the generator. This study confirms the validity of the vector control for the matrix converter input side with experimental results. The input current THD 2.8% is obtained under a RL load.**

***Index Terms*-- matrix converter, synchronous reactance, input current stability control, input current feed back control**

I. INTRODUCTION

Recently, matrix converters, that can directly convert AC power supply voltage into AC voltage of variable amplitude and frequency without large energy storages, such as electrolytic capacitors, have been actively studied [1-11]. Matrix converters have advantages in the following aspects; size reduction, light-weight, long-life and high efficiency power supplies, compared with the use of a PWM rectifier and an inverter system.

Matrix converters are mainly considered for motor drive system applications, such as elevators and air conditioners. Lately, applications for grid connection have been considered, such as micro-gas turbines, wind power systems, engine generators and so on. Moreover, a matrix converter for Hybrid EV is also considered. In these applications, the generator is connected to the input side of the matrix converter.

An impedance of the generators is higher than the commercial power grid. When the generator is connected to the matrix converter, a synchronous reactance is several dozen percent, the terminal voltage of the generator and the input current are unstable due to the resonance between the synchronous reactance and the input capacitor. Especially, when an output power is controlled to constant by the current regulator, negative resistance characteristic appears in the input side [1]. The stability control method of the input current, which is considering the high line impedance, has been already proposed in [3]. However, when under extremely high impedance power source, such as a generator, is used as the input, that effect has not been reported.

On the basis of these problems, the stability control method for the input current considering synchronous reactance of the generator has been already proposed by authors. The conventional method, which is proposed in [1], achieves suppression in the input current oscillation and the variable speed drive of a motor using a damping control on a rotating frame known a d-q frame.

On the other hand, the input current command of the conventional method consists of open loop control which is calculated from the terminal voltage of the generator. Open loop control is a simple construction. However, unity power factor control between an induced electro motive force (EMF) and the input current is difficult for light and heavy load because a filter capacitor current affects the input power factor for light load. In addition, the voltage drop due to the synchronous reactance also affects the input power factor under a heavy load.

This paper discusses the relationship among the input current, the filter capacitor current and the input power factor for induced EMF for a matrix converter in order to clarify the behavior of the input current. Next, this paper applies a vector control for the generator side using input current feedback. In this proposed method, the oscillation of the input filter is suppressed; and the input power factor between the induced EMF and the input current is controlled to unity regardless of the load amplitude. Lastly, the control characteristics of the matrix converter where the generator is connected as input, the experimental results are demonstrated as follows; (1) the fundamental operation with R-L load, (2) the input current distortion characteristics, (3) the relations among the load power, the input power factor and the amplitude of input current. The experimental results confirmed the validity of the proposed system.

II. INPUT POWER FACTOR FOR LIGHT AND HEAVY LOAD

Fig. 1 shows the circuit diagram of a matrix converter with the generator as an input. The bi-directional switches, which consist of reverse-blocking IGBTs (RB-IGBT), are connected between the input phase and output phase. The synchronous reactance of the generator is substituted by an input filter reactance. The input filter is constructed by only filter capacitor.

Generally, when a matrix converter is connected to a power grid, the input filter resonance is suppressed by a damping resistor. There are two types of connection pattern for the damping resistor. First, the damping resistor is connected in series to the filter capacitor. Second, the damping resistor is connected in parallel to the filter reactor. For the series connection, the power consumption of the resistor becomes larger because the capacitor current has large harmonics components at switching frequency. Therefore, the damping resistor is usually connected in parallel to the filter reactor. However, for the generator input, the damping resistor can not be inserted to the synchronous reactance in parallel practically.

Fig. 2 shows a configuration of the input filter of the matrix converter with the generator as the input. Fig. 2 (a) shows the single equivalent circuit of the matrix converter where V_r and V_s is the input phase voltage, V_g is the induced EMF of the generator, V_c is the terminal voltage of the generator, I_{in} is the input current, I_{mc} is the PWM current of the matrix converter, I_c is the filter capacitor current, V_{mc} is the output voltage, L_x is synchronous reactance of the generator and C_f is the filter capacitor. From Fig. 2 (a), a block diagram of the input filter is introduced as shown Fig. 2 (b).

A transfer function from the PWM current to the input current in Fig. 2 (b) is calculated by

$$\frac{I_{in}}{I_{mc}} = \frac{\frac{1}{L_x C_f}}{s^2 + \frac{1}{L_x C_f}} \qquad (1).$$

A damping factor does not appears in (1) because the denominator does not contains the fist order of Laplacian s, so the filter resonance between the synchronous reactance L_x and the filter capacitor C_f will continue then the system becomes unstable. Therefore, a control scheme to suppress the resonance is required for the input side control.

Fig. 3 shows a block diagram of the conventional stability control on the d-q frame [1]. V_{cr}, V_{cs}, V_{ct} are the three phase terminal voltage of the generator, θ_{vc} is phase angle of the terminal voltage of the generator, θ_{pfc} is input power factor control command, K_d is the damping gain of conventional stability control and I_r^*, I_s^*, I_t^* are the input current command. In the conventional stability control, the fundamental frequency component of the terminal voltage on the d-q frame becomes a constant value, i.e. DC signal. In addition, harmonics components appear as a ripple. Therefore, the distortion component of the terminal voltage can be removed by using a low pass filter (LPF) which has a long time constant. After that, the distortion component is subtracted to the input current command I_{in}^*.

On the other hand, the input current command of conventional method is constructed on an open loop control. The input current I_{in} is not controlled directly by the input current command I_{in}^*. Therefore, it becomes difficult since the PWM current of the matrix converter I_{mc} is decided by the filter current I_c and the disturbances, which is generated by commutation error.

The relationship among the input current I_{in}, the PWM

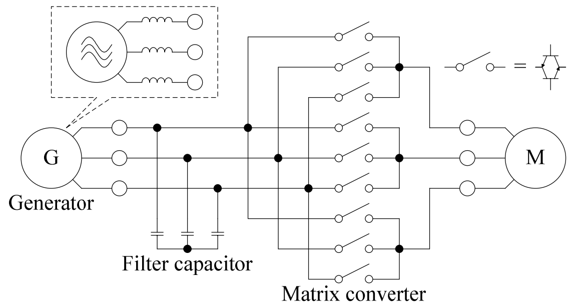
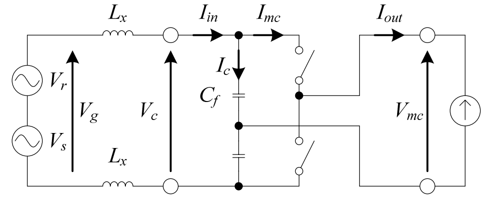
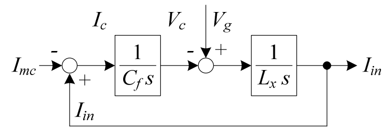


Fig. 1. System configuration diagram of the matrix converter with the generator as input.



(a) Single phase equivalent circuit.



(b) Block diagram of input filter.

Fig. 2. Configuration of input filter.

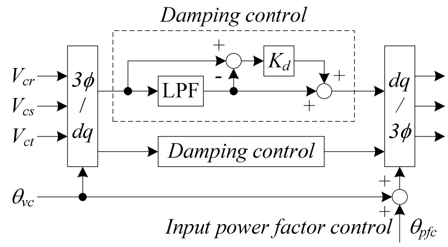


Fig. 3. Conventional input current stability control.

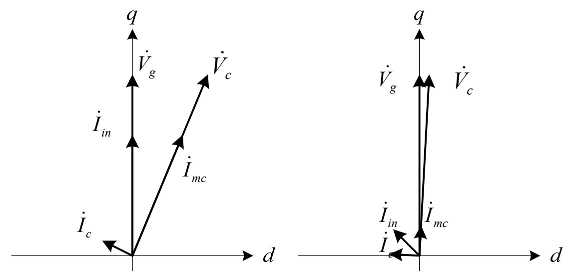


Fig. 4. Relationship among the input current, the input PWM current and the input filter current of the matrix converter.

current of the matrix converter I_{mc} and the filter current I_c is calculated by

$$I_{in} = I_{mc} + I_c \qquad (2).$$

Fig. 4 shows the phasor diagram of the relationship among the input current I_{in}, the PWM current of the matrix converter I_{mc} and the filter current I_c in case of the light and heavy load. In this paper, an EMF power factor is defined as the power factor between the induced EMF V_g and the input current I_{in}. When the EMF power factor is controlled to unity, the d-axis component of the input current I_{in} does not occur. Then, the amplitude of the input current I_{in} becomes the minimum value. Therefore, the maximum efficiency of the generator can be obtained.

In the heavy load in Fig. 4, the filter current I_c can be neglected because the amplitude of the input current I_{in} is much larger than the filter current I_c. Therefore, the EMF power factor can be controlled to unity nearly. However, in the light load, the filter current I_c can not be neglected because the ratio of the I_c to I_{in} is larger. Then, the phase angle between the PWM current of the matrix converter I_{mc} and the input current I_{in} becomes larger. That is, the EMF power factor can not be controlled to unity.

On the other hand, the output voltage of the matrix converter V_{out} is described by

$$V_{out} = \lambda V_g \cos\theta \quad (3),$$

where λ is the modulation index and $\cos\theta$ is the EMF power factor. Therefore, voltage transfer ratio, which is defined as the ratio between the induced EMF V_g and the output voltage V_{out}, depends on the EMF power factor. Consequently, the voltage transfer ratio decreases and the generator loss increases due to the increase of the input current.

For example, in the view of applications, that the efficiency at light load is important, such as HEV, an improvement of the EMF power factor at light load is required.

III. Feed Back Control of Input Current

This chapter describes the proposed input current vector control for the generator side using an input current feedback. In this proposed method, the oscillation of the input filter is suppressed by the current regulator; and the EMF power factor is controlled to unity regardless of the load amplitude.

Fig. 5 shows a block diagram of the input filter and current control. The input current I_{in} is controlled to a stable condition by the feedback control that is calculating the error between the input current command I_{in}^* and input current I_{in}. The input current command I_{in}^* is given to obtain the unity EMF power factor; i.e. $i_d^*=0$.

Fig. 6 shows the phasor diagram of the relationship among the input current I_{in}, the PWM current of the matrix converter I_{mc} and the filter current I_c using the unity EMF power factor control in the light load. The input current I_{in} can be controlled directly by using the current feedback. As a result, the amplitude of the input current is optimized. It should be noted that the input current command I_{in}^* is considered like a reluctance torque in non-salient-pole-type synchronous generator.

In order to suppress the resonance of the input filter, the control parameter in the automatic current regulator (ACR) needs to be designed. An input side of a matrix converter is same as a current source type rectifier. Then, the filter voltage feedback is corresponding to the reactor current feedback on a voltage source type converter. However, the input current feedback on the matrix converter requires a differential component to express an equivalent component for the filter voltage dimension.

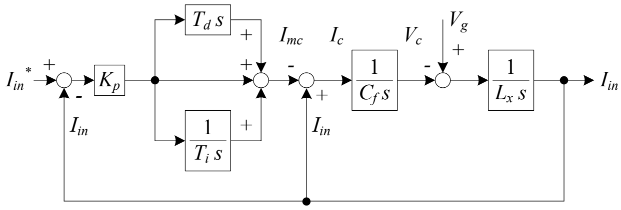


Fig. 5. Block diagram of input current feed back control.

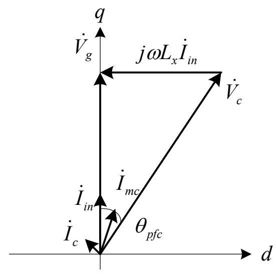


Fig. 6. Relationship among input current, input PWM current and input filter current of input filter with proposed input current feed back control.

That is, a PID controller is needed. Next, the stabilization of the input current with a PID control is considered.

From Fig. 5, the transfer function from the input current command I_{in}^* to the input current I_{in} is described by

$$\frac{I_{in}}{I_{in}^*} = \frac{\frac{K_d}{L_x C_f}s^2 + \frac{K_p}{L_x C_f}s + \frac{K_i}{L_x C_f}}{s^3 + \frac{K_d}{L_x C_f}s^2 + \frac{1+K_p}{L_x C_f}s + \frac{K_i}{L_x C_f}} \quad (4),$$

where s is Laplacian, K_p is a proportional gain, K_i is an integral gain and K_d is differential gain.

When K_i and K_d equal to zero (i.e. P control), the first order s term becomes zero. Therefore, the damping factor is zero. In addition, when the K_i does not equal to zero (PI control), second order s term disappears. Therefore, the system is still unstable by PI control. However, when the K_d is added even if the K_i equals to zero (PD control), the damping factor can be set. Therefore, in the input current control system on the rotating frame, the stabilization is secured by K_d and steady state error is eliminated by K_i.

From (4), the sate equation of the current control is given by

$$p\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ \frac{K_i}{L_x C_f} & \frac{1+K_p}{L_x C_f} & \frac{K_d}{L_x C_f} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} i_{in}^* \quad (5),$$

$$i_{in} = \begin{bmatrix} -\frac{K_i}{L_x C_f} & -\frac{K_p}{L_x C_f} & -\frac{K_d}{L_x C_f} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \quad (6),$$

where x_1, x_2 and x_3 is state variable. In order to evaluate the damping factor quantitatively, root locus of the PI control and the PID control is obtained from (5).

Fig. 7 shows the root locus of the PI control and the PID control when K_p equals 0.1 pu, T_i equals 1 ms and T_d equals 1 ms. Proportional gain K_p is normalized by the amplitude of the output current. In PI control, a real component of the root locus is positive. In addition, an imaginary component is large. Therefore, the system that uses PI control is oscillating and unstable. On the other hand, in the PID control, all imaginary component moves to the negative side and is smaller than the PI control. Therefore, the oscillation of the input side is suppressed by using the PID control.

The proportional gain K_p, the integral action time T_i and the derivative action time T_d can be designed from Fig. 7. In this paper, the stabilization of the proposed input vector control is discussed by the roots placed near the real axis. The damping factor can be calculated in comparison with the roots and the second order standard form equation. When an angle between the root and the origin is 45 degree, the damping factor becomes 0.7 in the second order. In this paper, the damping factor is adjusted to 0.7 from Fig. 7. As a result, the derivative action time T_d is set to 1ms.

Fig. 8 shows a details configuration of input current feedback control. The phase information of induced EMF is required to control the input power factor between the induced EMF and the input current. This induced EMF information is detected from a pole position sensor. It should be noted that the phase information of induced EMF can be estimated from the input current i_{in}, the terminal voltage of the generator v_c, the synchronous reactance L_x and a generator frequency f_{in}. The induced EMF phase and generator frequency are calculated from the pole position sensor and digital Phase Locked Loop (PLL). The integral block to calculate the phase angle θ_{in} is reset to zero by rising the u-phase pulse of the pole position sensor. The input current command i_d^* equals to 0 pu and i_q^* equals to 1 pu respectively. A coordinate transformation of the input current is used as θ_{in}, which is calculated by PLL. Then the input current phase is controlled to the same phase as the induced EMF of the generator regardless of the load amplitude.

The q-axis command i_q^* is always set to 1 in the matrix converter because the amplitude of the input current is dominant by the output active power and the input power factor. Therefore, the amplitude of the input current is required to normalize the input current. The amplitude of the input current can be introduced from the input power and the output power to neglect the converter losses. The input power and output power are described by (7) and (8) respectively;

$$p_{out} = v_u^* i_u + v_v^* i_v + v_w^* i_w \quad (7),$$

$$p_{in} = I_{amp}\left(v_{gr} i_r^* + v_{gs} i_s^* + v_{gt} i_t^*\right) \quad (8),$$

where v_u^*, v_v^*, v_w^* are three phase output voltage commands, i_u, i_v, i_w are the three phase output current, v_{gr}, v_{gs}, v_{gt} are the three phase induced EMF of the generator, i_r, i_s, i_t are the input current and I_{amp} is the amplitude of the input current. The induced EMF v_{gr}, v_{gs}, v_{gt} of the generator can be calculated by the frequency and the induced EMF constant in generator parameters. From (7) and (8), the amplitude of the input current is calculated by

$$I_{amp} = \frac{v_u^* i_u + v_v^* i_v + v_w^* i_w}{v_{gr} i_r^* + v_{gs} i_s^* + v_{gt} i_t^*} \quad (9).$$

In this system, when the resonance frequency of the input filter is set high enough than the operation frequency of the generator, the filter capacitance becomes smaller due to large synchronous reactance under same resonance frequency. Then the ripple of the terminal

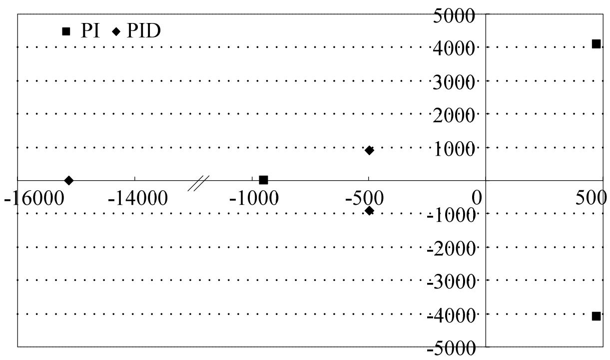


Fig. 7. Block diagram of input current feed back control.

Table 1. Parameters of the synchronous generator.

Rated power	3.7 kW	Stator resistance	0.695 Ω
Rated rotational frequency	1800 rpm	d-axis inductance	6.2 mH
Rated Voltage (line-to-line)	180 Vrms	q-axis inductance	15.3 mH
Back e.m.f. (line-to-line)	150 Vrms	Number of pole	6

Table 2. Experimental conditions.

Filter capacitor	6.6 μF	Output frequency	30 Hz
Modulation index	0.866	Carrier frequency	10 kHz
Generator frequency		1800rpm (rated)	
Output control		V/f control (Open-loop)	
Modulation method		Virtual AC/DC/AC conversion[2]	
Commutation		Voltage commutation	
Commutation time		2.5μs	
RL load		12.5 Ω, 5 mH	

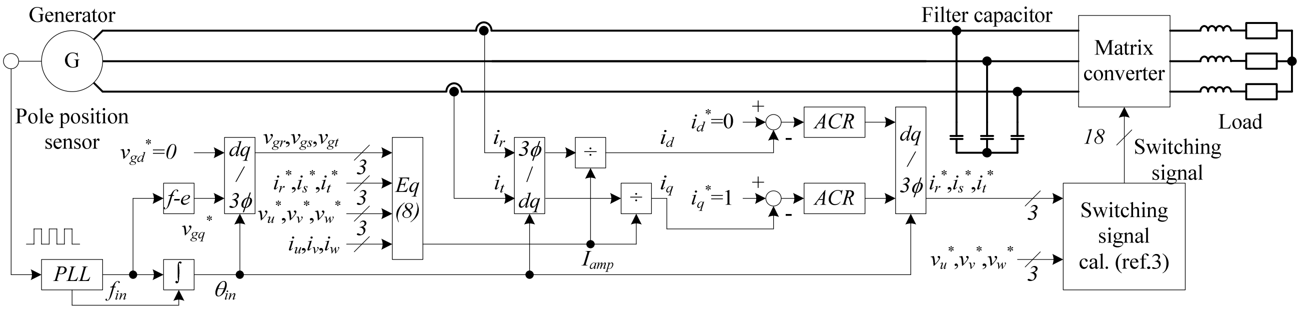


Fig. 8. Configuration diagram of input current feed back control.

voltage becomes larger. Consequently, the switching devises might break down due to the problem of over voltage. Therefore, in this system, the filter capacitance is set to a large value to reduce the ripple of the terminal voltage of the generator and resonance frequency.

IV. Experimental Results

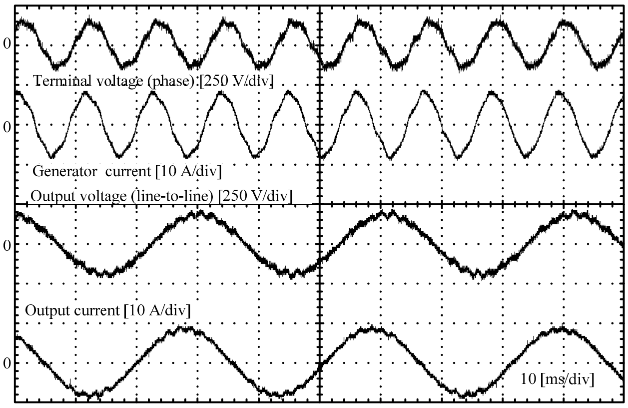
This chapter discusses the validity of the proposed input current feed back control by the experiments. Table 1 shows the parameters of the synchronous generator. The experiment set-up uses an interior permanent magnet (IPM) generator. The IPM generator has harmonics distortion in the induced EMF of the generator. It should be noted that the harmonics distortion of the induced EMF is neglected. The generator speed is constant of rated speed. The output voltage control is an open loop V/f control in [12]. Other experimental parameters are shown in Table 2.

Fig. 9 shows the experimental results where the generator as an input with a R-L load. Fig. 9 (a) shows the input and output waveforms with the conventional control method. Fig. 9 (b) shows the waveforms using the proposed input current control.

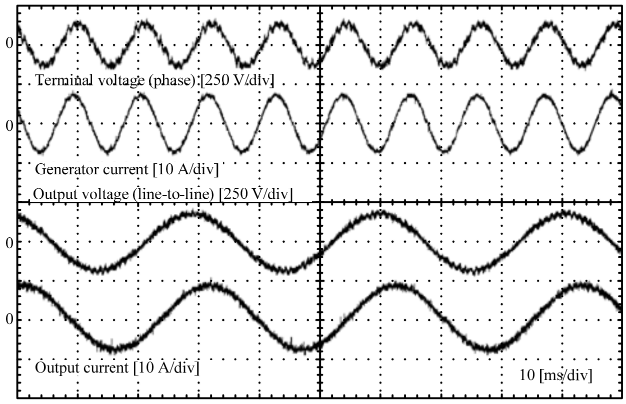
In Fig. 9 (a), the large oscillation occurs in the input terminal voltage and the input current. Additionally, the output waveforms have a distortion due to the resonance between the input filter capacitor and the synchronous reactance. The total harmonic distortion (THD) of the input current is 10.7% and the THD of the output current is 4.2%.

As for Fig. 9 (b), the oscillation of the input side is drastically suppressed in comparison with Fig. 9 (a). Moreover, the distortion of the output side is eliminated. The THD of the input current is 2.8% and the THD of output current is 1.7%. The THD of the input current reduced by quarter and the THD of the output current reduced by half with the proposed input current feed back control. These results lead to the conclusion that the proposed control is extremely effective for a generator.

Fig. 10 shows the plot diagram based on the experimental results that contain the input current THD characteristic of the following controls; the conventional control, the proposed control, and the non-stability control. In non-stability control, as the load increases, the influence of the input filter resonance becomes larger because the damping factor is only a winding resistance. Therefore, the input current distortion will increase. In addition, the input current distortion of the conventional control is improved. However, the input current distortion of the conventional method becomes larger in heavy load regions. That is, in the heavy region of conventional control, the voltage drop due to the synchronous reactance becomes larger. Therefore, the output voltage command becomes over modulation. On the other hand, in the proposed method, the input current distortion is drastically improved at all load regions because the EMF power factor is controlled to unity and q-axis input



(a) Without stability control.



(b) Proposed input current vector control.

Fig. 9. Experimental results with RL load.

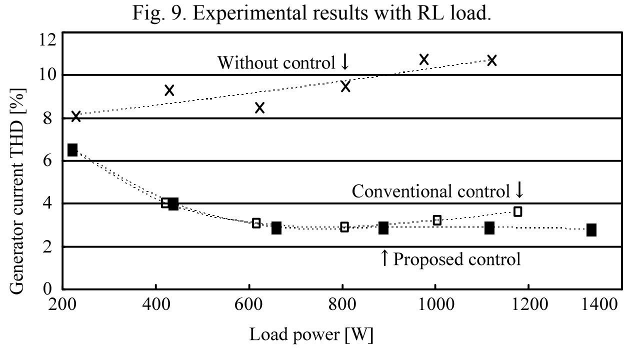


Fig. 10. Generator current THD characteristic by conventional method and proposed method.

current is always zero. Therefore, the maximum voltage transfer ratio can be obtained. As a result, the input current does not distorted.

Fig. 11 shows the relationship between the load power and the input power factor (not the EMF power factor) between the generator terminal voltage and the input current. Figs. 11 (a) and 11 (b) show the power factor characteristic at the light load and the heavy load respectively.

In the light load region, the EMF power factor is closed to the input power factor because the phase angle θ_{pfc} between the induced EMF and the terminal voltage of the generator is near to zero from Fig.4 (b).

From Fig. 11 (a), the proposed method shows that the EMF power is closed to the unity power factor in the light load region. As for the conventional, the input power factor is smaller in compared to the proposed method. This is because the input power factor can not be controlled due to the current influence at filter. The input current of the proposed control is smaller than that of the conventional control. The proposed control can reduce the copper loss to one-third of the conventional method at maximum point of the light load.

On the other hand, in the heavy load region, the input power factor will decrease because θ_{pfc} increases at the heavy load. Then the input power factor should be controlled to a lead phase.

As for Fig. 11(b), the input power factor of the conventional method can be controlled to unity. However, the amplitude of the input current also increased. In the case for proposed method, the input current is also increase but the increment ratio is lower than the conventional method. This is because the reactive current in the proposed method can be always controlled to zero and the EMF power factor is controlled to unity. But for conventional control, the reactive current (d-axis current) increases at heavy load because the input power factor is controlled to unity. The proposed control can reduce the copper loss by 26% of the conventional method at maximum point of the heavy load.

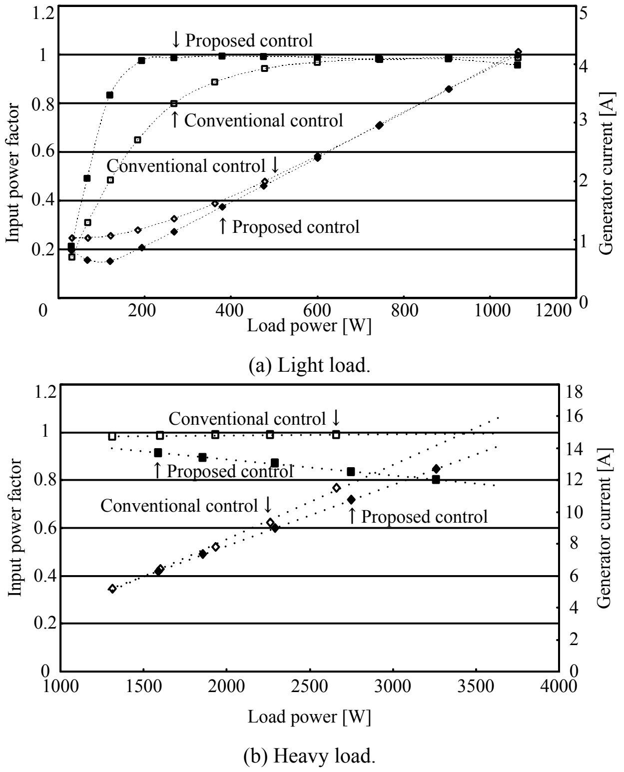


Fig. 11. Relationship between load power and input power factor by proposed method and conventional method.

V. CONCLUSIONS

In this paper, the problem of the power factor between the induced EMF and the input current where the load is light or heavy has been clarified. In order to solve this problem, this paper applies the input current feedback control into the input side of the matrix converter with the generator as an input. In addition, a state equation is introduced from the transfer function in order to analyze the stability of derivative element of proposed input current control.

This paper confirms the operation of the proposed control by the experiment. The results show as follow;

(1) The THD of the input current reduce to a quarter.

(2) Proposed control can correct the EMF power factor at light load and heavy load.

(3) Proposed control can reduce the copper loss by one of the third of the conventional method at the maximum point.

The experimental results lead to a conclusion that the input current feedback control for the matrix converter where the generator performs as an input is a valid control.

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