A Control Strategy for a Matrix Converter under a Large Impedance Power Supply

Junnosuke Haruna Jun-ichi Itoh
Nagaoka University of Technology
1603-1 Kamitomioka-cho Nagaoka City Niigata, Japan
itoh@vos.nagaokaut.ac.jp

Abstract - **This paper proposes a control strategy for a matrix converter with an input power supply such as generator. Currently, applications for grid connection have been considered such as micro-gas turbines, wind power systems, engine generators and so on. However, very large impedance power supply such as the generator has not been sufficiently examined. Especially the PM generator which is used in various applications has large synchronous reactance. Terminal voltage of the generator is not stable due to resonant phenomena between synchronous reactance and an input capacitor. Therefore, the induced electromotive force (e.m.f.) in the generator is estimated using a band pass filter (BPF). In addition, stabilization control on a rotating frame is also proposed for the input terminal voltage. In addition, this paper suggests an optimum input power factor control because the output voltage is smaller than the output voltage command when a conventional power factor control is used. By using the stabilization control, the input current THD of 4.2% is obtained through experimental results. Moreover, the validly of the optimum input power factor control is also confirmed by the experimental results.**

***Index Term*—**Matrix converter, Generator, Synchronous reactance, Stabilization control and Optimum input power factor control

I. INTRODUCTION

Recently, matrix converters, that can directly convert an AC power supply voltage into an AC voltage of variable amplitude and frequency without large energy storage, such as electrolytic capacitor, have been actively studied [1-14]. Matrix converters can contribute to the realization of down sized, light-weight, long-life and high efficiency power supplies, compared with the use of a PWM rectifier and inverter system.

However, matrix converters are mainly considered for motor drive system applications, such as elevators and air conditioners [11]. In addition, other recent applications for grid connection have been considered, such as micro-gas turbines, wind power systems, engine generators and so on. The behavior of matrix converters under the large line impedance of a power grid have been investigated [10]. However, very large impedance power supplies, such as generators have not been sufficiently examined.

For example, it has not been sufficiently discussed that the terminal voltage of the generator is not stable due to resonant phenomena between synchronous reactance and the input capacitor. For the conventional control, input current commands for the matrix converter are directly calculated by the input terminal phase voltages. As a result, the vibration of the input voltage influences the output voltage and the input current waveform. In order to suppress current distortion and over voltage of switching devices, a stabilization method for the matrix converter using the generator has been required.

The stabilization control method of the input current under considers the high line impedance has been already proposed in Ref. [9]. Even if the input voltage suddenly changes, the input current without the vibration can be kept because effective power and reactive power are controlled by instantaneous value. However, that effect has not been reported in case of large impedance, such as the generator input. In addition, the performance of the proposed method decreases when the power supply frequency widely changes because the stabilization control is achieved on a rest frame and uses a band pass filter.

Moreover the control method of the generator using the matrix converter has not been discussed, yet. The output voltage of the matrix converter depends on an input power factor because a voltage transfer ratio is limited by the input power factor. Therefore, the input power factor control has to consider from the point of view of the maximum voltage transfer ratio.

This paper proposes the control strategy for the matrix converter with the input power supply, such as generator. In this paper, the stabilization control on a rotating frame is proposed for the terminal voltage. In addition, optimum input power factor control is considered. This paper discusses the control characteristics of the matrix converter based on simulation and experimental results as follows; (1) fundamental operation with an R-L load and an induction motor load, (2) the acceleration characteristics of the generator (3) terminal voltage control with input current phase control, and (4) relation among the input current phase, induced electromotive force, the terminal voltage and the output voltage. The results of the simulation and the experiment confirmed the validity of the proposed system.

II. STABILIZATION CONTROL

A. *Problems of the generation system*

Fig.1 shows a circuit diagram of the matrix converter with the generator as the power supply. Input impedance of the generator is very large because synchronous reactance dominants the input impedance. The synchronous reactance of the generator is substituted by an input filter reactance.

Table 1. Simulation conditions.

PM Generator	E.m.f. (line-to-line)	135[V]	Load	5.184[Ω]
	Rated turns	1800[rpm]		6.785[mH]
	Rated frequency	90[Hz]	Output	90[V]
	Rated output	750[W]		90[Hz]
	Number of pole	6	Filter capacitor	1[μF]

Fig.2 shows the simulation results for the generator power supply with the parameters given by Table 1. The large oscillations in the input voltage and current occur. In addition, the terminal voltage (as same as capacitor voltage) rises over 400V. Because the input current distortion affects the terminal voltage, after that the terminal voltage distortion affects the input current of the matrix converter. As a result, the system approaches to unstable because a damping factor of the system decreases.

Fig.3 shows a block diagram showing the transfer function of the input filter. The transfer function shown in Fig.3 is described by Eq. (1). When the synchronous reactance of the generator is large, the ripple of the terminal voltage becomes large. Therefore, the control system becomes unstable as the damping term $(Y_0\text{-}K)/C_f$ in Eq. (1) decreases according to the increase in the ripple factor K.

$$\frac{V_c}{V_s}=\frac{1}{L_fC_f}\frac{1}{s^2+\frac{(Y_0-K)}{C_f}s+\frac{1}{L_fC_f}} \qquad (1)$$

where V_s is the input voltage, V_c is the terminal voltage, L_f is the synchronous inductance, C_f is the filter capacitor, Y_0 is the steady state values of the load power, and K is the ripple values of the load power.

B. Damping control of the input current

In order to obtain the input current command without the distortion factor, the phase information of the terminal voltage has to be detected exactly. The distortion factor of the terminal voltage can be removed using the band pass filter (BPF). In this case, a cut-off frequency of the BPF accords with the terminal voltage frequency. Therefore, the design of the BPF is difficult because the cut-off frequency of the BPF has to be adjusted by the output frequency of the generator. On the basis of these problems, this paper suggests the stabilization control method using an adaptive BPF on a rotating frame known a d-q frame.

Fig.4 shows a block diagram of the stabilization control with the adaptive BPF on the d-q frame. The fundamental frequency component on the d-q frame becomes a constant value, i.e. DC signal. In addition, harmonics components appear as a ripple on the AC component. Therefore, harmonics components can be completely removed by using a low pass filter (LPF) which has long time constant. One of the advantages of the proposed method is that the adjustment of cut-off frequency in LPF is not required depending on the generator speed because the fundamental frequency component of the input signal automatically is converted to a DC signal on the rotating frame.

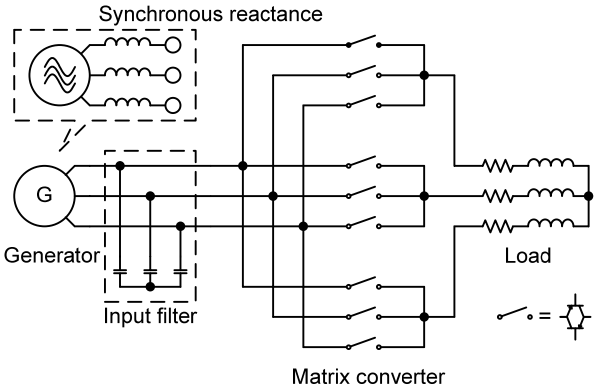


Fig.1 Circuit diagram of the matrix converter with the generator.

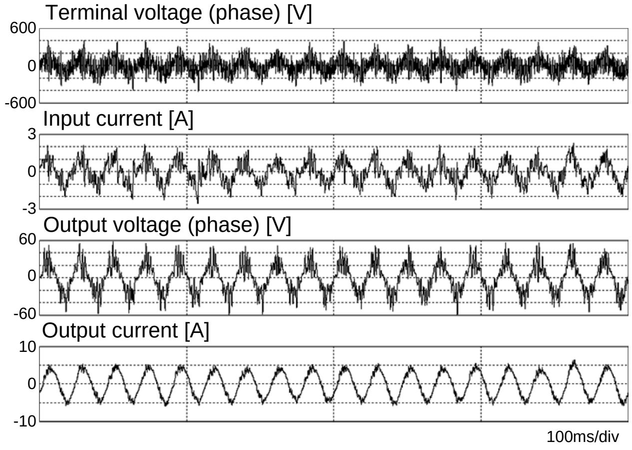


Fig.2. Input / output waveforms with the generator.

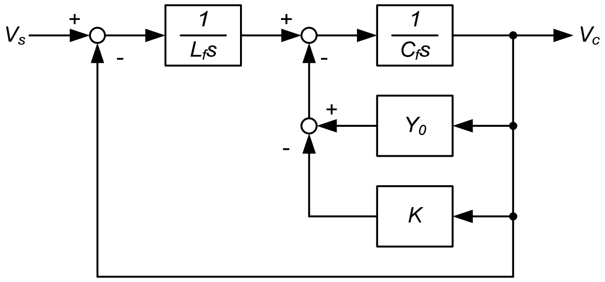


Fig.3. Block diagram with transfer function of the mission input filter.

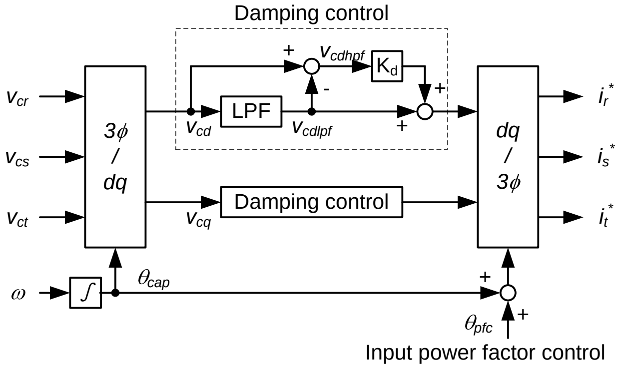


Fig.4. Block diagram of the stabilization control.

The proposed damping control is realized as shown in Eq. (2). The input current commands are then obtained by the inverse transformation of the rotating frame as shown in Fig.4.

$$I_c^{**} = \frac{1}{1+sT}V_c - K_d(V_c - \frac{1}{1+sT}V_c) = \frac{1-sTK_d}{1+sT}V_c \quad (2)$$

where, T is the time constant, K_d is the damping factor, $I_c^{**}$is the input current command of the matrix converter, and V_c is the terminal voltage.

Fig.5 shows a block diagram with the transfer function of the input filter after the proposed stabilization control. The transfer function from V_c to V_s shown in Fig.5 is described by Eq. (3). As a result, the stability of the system increases as the damping term of Eq. (3) becomes Y_o/C_f

$$\frac{V_c}{V_s} = \frac{1}{L_f C_f}\frac{1+KL_f s}{s^2+\frac{Y_o}{C_f}s+\frac{1}{L_f C_f}} \quad (3)$$

C. Stabilization control for the output voltage

Fig.6 shows a control diagram of the output voltage command with ripple compensation where v_{cdlpf}, v_{cqlpf}, v_{cd} and v_{cq} are taken from Fig.4. The output voltage of the matrix converter is also influenced by the input voltage. When the ripple of the input voltage remains, the oscillation appears in the output voltage. Therefore, the output voltage command in the matrix converter is compensated by the magnitude of the terminal voltage. A mean value v_{cns} and the instantaneous value v_{ins} of the magnitude of the terminal voltage are calculated using Eq. (4) and (5). The compensation gain v_{ripple} is obtained from v_{cns} divided by v_{ins}. For example, if v_{cns} is greater than v_{ins}, then v_{ripple} is over 1.0, and the output voltage command is decreased.

$$v_{cns} = \sqrt{v_{cdlpf}{}^2 + v_{cqlpf}{}^2} \quad (4)$$

$$v_{ins} = \sqrt{v_{cd}{}^2 + v_{cq}{}^2} \quad (5)$$

III. OPTIMUM CONTROL OF THE INPUT POWER FACTOR

In this chapter, we discuss the relation among the input power factor control, the input terminal voltage, and the output voltage. First, the relation between the terminal voltage and induced e.m.f. is considered. The input terminal voltage is influenced by the input power factor in case of the large impedance power supply, such as the generator.

Fig.7 illustrates an equivalent circuit of a single phase for the input side. The generator is expressed by using the induced e.m.f. E_0, the terminal voltage V_c, the stator resistor R and the synchronous inductance X_L. The matrix converter MC can control the input power factor freely.

Fig.8 shows a vector diagram when the input power factor is controlled at a phase lag and a phase lead when the values of R, which is much smaller than the synchronous reactance, can be neglected. It should be noted that the input power factor is decided by the θ_{pfc} as shown in Fig.4.

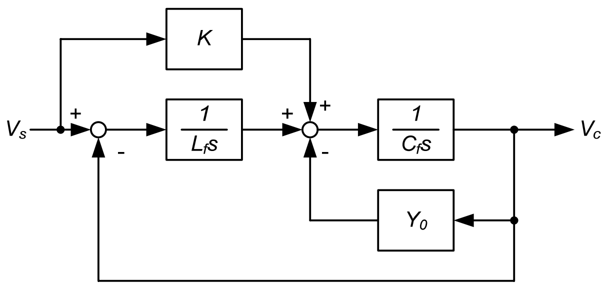


Fig.5. Block diagram of input filter in the proposed method.

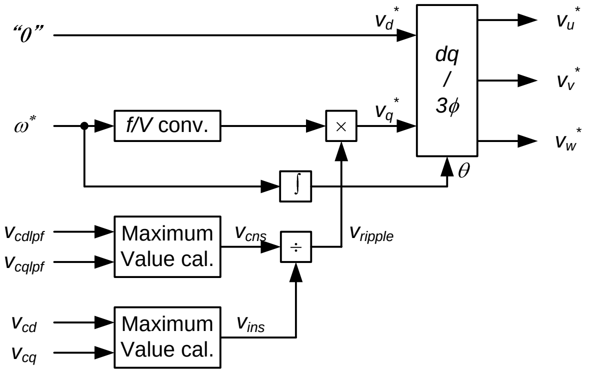


Fig.6. Control diagram of the output voltage command compensation.

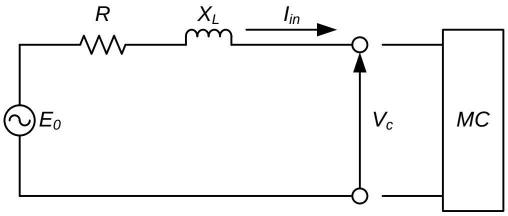
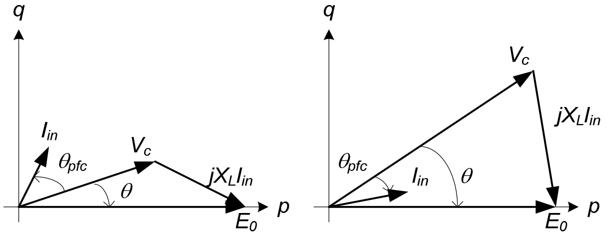


Fig.7. An equivalent circuit at single phase of the generator.



(a) $\theta_{pfc}<0$ (Lag control) (b) $\theta_{pfc}<0$ (Lead control)

Fig.8. Relationship among the power factor, the terminal voltage and e.m.f.

The input terminal voltage V_c that is smaller than the e.m.f. E_0 is obtained in case of a lag power factor as shown in Fig.8 (a). In contrast, the input terminal voltage becomes larger than e.m.f. in case of a lead power factor as shown in Fig.8 (b). In these cases, an effective power P and a reactive power S are obtained by Eq. (6) and (7)

$$S = v_c\left(i_p + ji_q\right) \quad (6)$$

$$P = E_0 i_p \quad (7).$$

From the Eq. (6) and (7), the input power factor $cos\ \theta$ is calculated as shown in Eq. (8).

$$cos\,\theta = \frac{P}{S} = \frac{E_0 i_p}{v_c\sqrt{i_d^2 + i_q^2}} \quad (8)$$

Next, the relation between the terminal voltage, e.m.f. and the output voltage is considered. A maximum voltage transfer ratio of the matrix converter is limited to 0.866 of the input terminal voltage because the minimum envelop with a full-wave rectification of the line voltage of the input terminal is $\sqrt{3}/2$. In addition, the voltage transfer ratio depends on the input power factor. AS a result, the maximum voltage V_{out} is constrained as shown in Eq. (9)

$$V_{out} = 0.866 V_{in} \lambda \cos\theta \qquad (0 \le \lambda \le 1) \quad (9)$$

where V_{out} is the output voltage, V_{in} is the input voltage, λ is the modulation index, and $\cos\theta$ is the input power factor.

Finally, the maximum output voltage of the matrix converter is obtained by Eq. (10) using Eq. (8) and (9).

$$V_{max} = 0.866 v_c \cos\theta = 0.866 \frac{i_p}{\sqrt{i_d^2 + i_q^2}} E_0 \qquad (10)$$

Therefore In Eq. (10), when i_d=0, the voltage transfer ratio becomes the maximum value. In other words, in order to obtain the maximize voltage transfer ratio of the matrix converter, the e.m.f. phase agrees with the terminal voltage phase.

IV. SIMULATION RESULTS

Simulations using PSIM (*Power Sim Inc.*) is introduced in order to confirm the validly of the proposed stabilization control. Table 1 shows the simulation conditions. A commutation time is neglected in these simulations.

A. *Generator power supply with a R-L Load*

Fig.9 shows the simulation results for a generator power supply with a R-L load. The generator speed is constant. Good sinusoidal waveforms are obtained for the output voltage, input and output current. The total harmonic distortion (THD) of 2.9% and 4.9 % are obtained for the input and output currents, respectively.

B. *Acceleration characteristics with motor load under constant generator speed*

Fig.10 shows the acceleration characteristics with an induction motor load. The output frequency command increases from 0 to 25Hz. It was confirmed that the motor speed follows the acceleration. The input current distortion factor in the stationary state is 9.9%, and the output is 2.8%. It should be noted that the input current distortion factor is high because the induction motor has no-load.

C. *Generator acceleration results with a R-L load*

Fig.11 shows the acceleration characteristics of the generator with damping control. After the generator is started, the terminal voltage increases slowly. The output voltage and input current follow the speed of the generator. If the generator accelerates without damping control, the terminal voltage rises to 600V and control becomes unstable. However, the maximum terminal voltage has reached over 300V although the damping control is applied. This course is that the input filter ripple remains in the transient state. In order to suppress the terminal voltage, the design of the input filter and damping control will be optimized.

It should be noted that the simulation results agree well with the experimental results. Therefore the experimental results using the generator can be estimated by the simulation results.

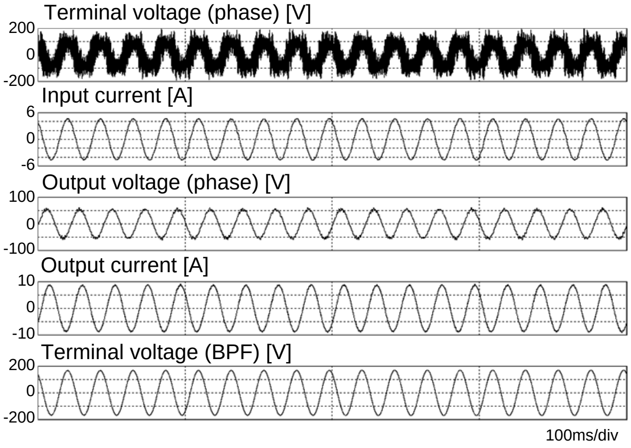


Fig.9. Simulation results of generator power supply with R-L load.

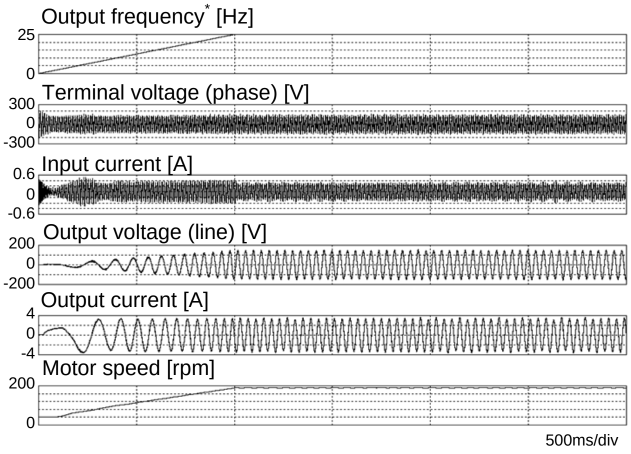


Fig.10. Simulation results of acceleration with motor load.

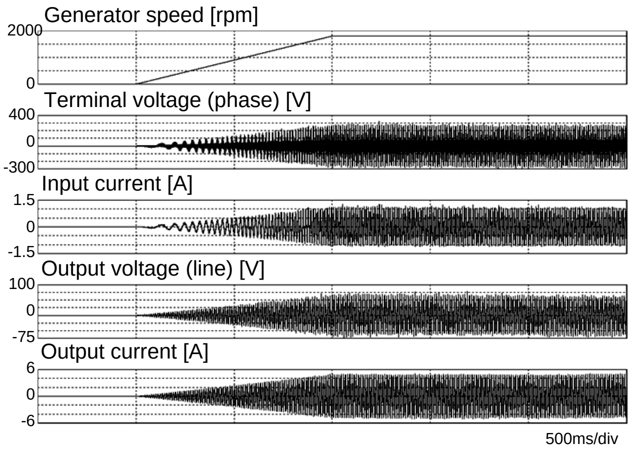
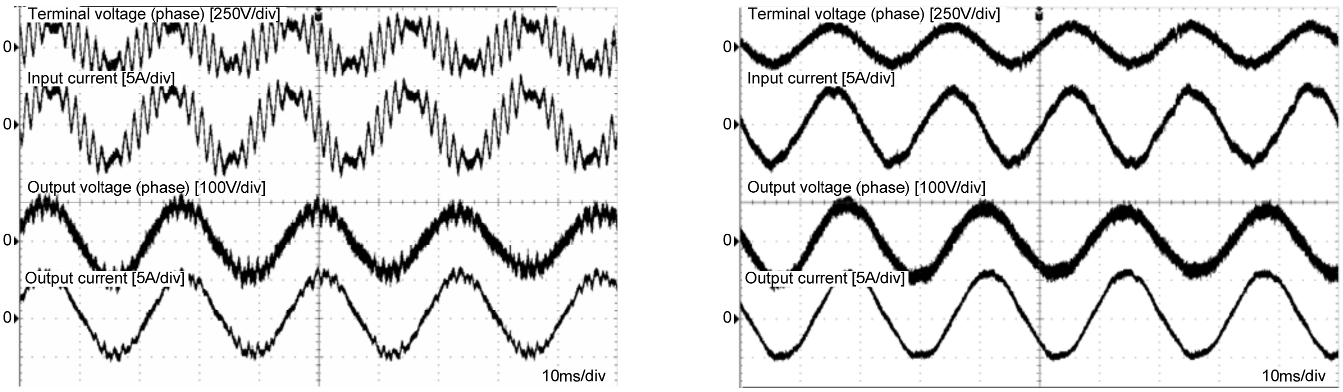
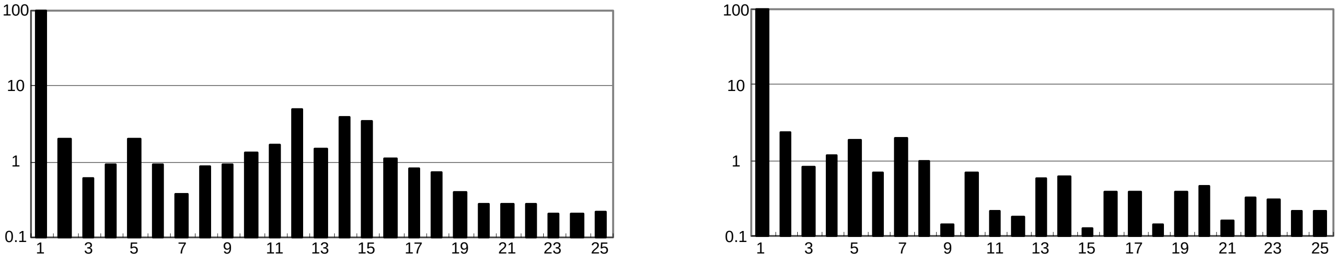


Fig.11. Simulation results of generator acceleration with R-L load.



(a) Experimental result without damping control

(c) Experimental result with damping control



(b) FFT result of input current of (a).

(d) FFT result of input current of (d).

Fig.12. Experimental results with large impedance power supply.

Table 2. Experimental conditions.

Large impedance power supply	V_{in} (line-to-line)	151[V]	Load	7.5[Ω]
	Reactance	12[mH]		5[mH]
	Frequency	50[Hz]	Output	100[V]
	Damping gain	0.5		50[Hz]
	Number of pole	6	Filter capacitor	6.6[μF]

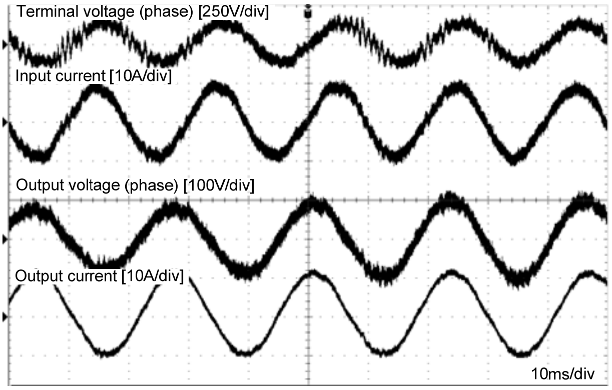
V. EXPERIMENTAL RESULTS

A. Stabilization control

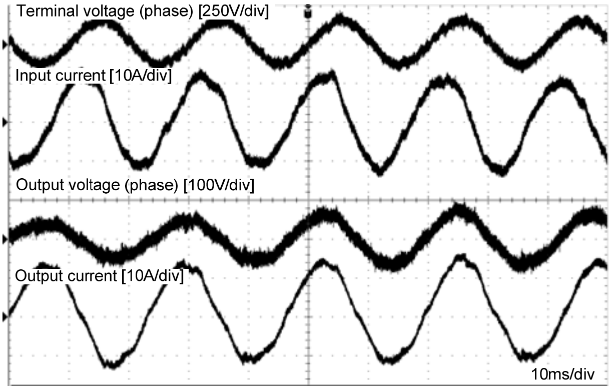
Fig.12 shows the experimental results of a large impedance power supply with a R-L load. The experimental parameters of Table 2 were used. Fig.12 (a) and Fig.12 (c) shows waveforms of the input and output voltage and current, Fig.12 (b) and Fig.12 (d) are the harmonics analysis results using fast Fourier transform (FFT) of the input current. A large reactance was connected between the power supply and the matrix converter in order to simulate a generator.

In case of Fig.12 (a) and (b), the stabilization control is not applied. Therefore, each waveform has large oscillation. 12.2% of the input current THD is obtained. The frequency components of 12th and 14th are especially large. This reason is that the resonant frequency of the input filter, which consists of the filter capacitor and the synchronous reactance, is 565Hz to which the 11th and 14th frequency is close.

In case of Fig.12 (c) and Fig.12 (d), the stabilization control is applied. The large oscillation components are decreased in comparison with Fig.12(a). The input current THD of 4.2% is obtained. The input current THD is decreased by approximately 30% by using the stabilization control. The frequency components from 9th to 19th are drastically eliminated. Therefore, the stabilization control can greatly suppress the filter resonance. The upper limit of the



(a) θ_{pfc} equals 20 [deg] (optimum value).



(b) θ_{pfc} equals 60 [deg] (over).

Fig.13. Input / output waveform at input power factor.

suppressed frequency components is decided by the response of the damping control.

These results lead to the conclusion that the stabilization control is extremely effective for a large impedance power supply such as a generator.

B. Optimum input power factor control

Fig.13 shows experimental results for a large power supply with a R-L load using the stabilization control and the optimum input power factor control. This case also uses large reactor instead of the synchronous reactance of the generator. The output voltage command was set to 65V.

When the input power factor angle θ_{pfc} equals 0deg, which means unity power factor for the input terminal, the output voltage of 60V is obtained. Although the output command is 65V, the output voltage according to the command is not provided because the terminal voltage decreases under the lag phase.

When θ_{pfc} equals 20deg, the output voltage of 64.8 V is obtained as shown in Fig.13 (a). In this case, the phase of the input current agrees with the phase of the induced e.m.f. which is simulated by the power supply. As a result, the output voltage rises by 4.8V and equals the voltage command.

Fig.13 (b) shows the result of the over power factor control. When θ_{pfc} is controlled beyond the optimum point, the output voltage is remarkably drops. In addition, the input current THD becomes worse because the over modulation occur due to the low input power factor.

Fig.14 shows the relation between the phase angle θ_{pfc} and the ratio of the terminal voltage and the induced e.m.f., the ratio of the output voltage and the induced e.m.f. The maximum value of the V_u/E_0 is obtained at θ_{pfc}=20deg as shown in Fig.14. Therefore, when a generator is used as the power supply, the input current phase should be controlled at the same phase as the induced e.m.f. in order to obtain the maximum voltage transfer ratio.

On the other hand, the quantity of the terminal voltage rises over the optimum point of θ_{pfc}. In addition, V_{cr}/E_0 becomes over 1.0. As a result, the maximum value of the V_{cr}/E_0 of 1.21 is obtained. The terminal voltage decreases in large lead phase because the input current can not be controlled due to the over modulation.

VI. CONCLUSION

This paper proposes a new control strategy for the matrix converter with the input power supply such as a generator. The problem of the large impedance power supply is low stability because the damping resistor in the input filter can not be used. To solve this problem, this paper proposed the stabilization control on the rotating frame. In addition, the relation among the input power factor, the terminal voltage, output voltage and the induced e.m.f. was analyzed, and the optimum power factor control is also proposed.

The experimental and simulation results lead to the conclusion that the matrix converter is valid for the large input impedance power supply such as the generator using the proposed stabilization control and the optimum power factor control.

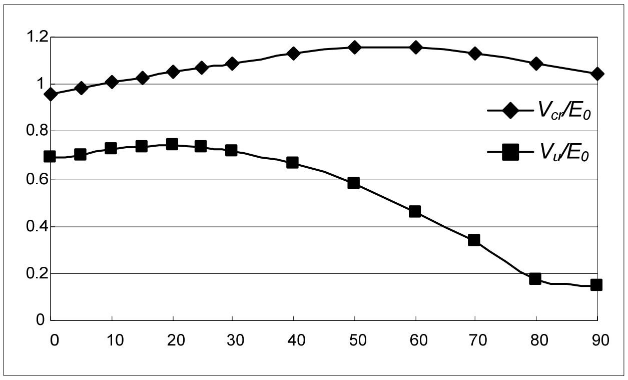


Fig.14. Relationship among terminal voltage, output voltage and back electromotive force.

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