Control Strategy for a Matrix Converter with a Generator and a Motor

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Abstract— **This paper proposes the stability control method for the input current of the matrix converter considering the synchronous reactance of a generator and a motor drive. When the stability control uses the input current feedback with a vector control for the generator side, the oscillation in the input filter can be suppressed. However, the output current oscillation occurs when the high response output current control at the same time due to no energy buffer in the matrix converter. The proposed stability control is the output current control including a damping factor for the input filter oscillation. This proposed method can achieve a stable operation for the generator side and the motor drive at the same time. In this paper, root placement is used to discuss the stability of the proposed controls. In addition, this paper confirms the validity of the proposed controls in a matrix converter with a generator and a motor by demonstrating the simulation and experimental results.**

I. INTRODUCTION

Recently, matrix converters, that can directly convert AC power supply voltage into AC voltage of variable amplitude and frequency without the large energy storages, such as electrolytic capacitors, have been actively studied [1-10]. Matrix converters have advantages in the following aspects; size reduction, light-weight, long-life and high efficiency power supplies, comparing with the PWM rectifier and an inverter system.

Matrix converters can be applied in motor drive systems, such as elevators and air conditioners. Lately, it also has been considered to apply for grid connection such as micro-gas turbines, wind power systems, and engine generators. Moreover, application of the matrix converter in the Hybrid EVs is also being considered. In these applications, the generator is commonly connected as the input side of the matrix converter.

Generally, the impedance of the generator 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 [5]. However, when an extremely high impedance power source, such as a generator, is used as the input, that effect was not reported. In addition, the voltage transfer ratio of the matrix converter decreases because the voltage drop by the synchronous reactance is not neglected. Moreover, the reactive current of the generator will increase which results the copper loss increased also.

In order to solve these problems, a stability control methods with the synchronous reactance of the generator have been proposed for the input current [2] by the authors. This control method has an input current feedback to suppress the oscillation between the synchronous reactance of the generator and the filter capacitor. The oscillation of the input filter could be suppressed; and the input power factor between the induced EMF and the input current is controlled to unity regardless of the load amplitude by using the input current feedback control method. As a result, distortion in the generator side could be suppressed. In addition, the voltage transfer ratio and reactive current of the generator are also compensated by the input power factor control. However, when an output current feedback control and the proposed method are applied at the same time to achieve the high performance motor control, the system becomes unstable. In order to prevent unstable situation, the output current control response is limited.

This paper achieves the high performance motor drive and stable operation of the generator side by using a proposed output current control including a damping factor. In this method, the stability control for the generator side is added to the output current control. The input current command is constructed on an open loop control as same as the conventional input current control of the matrix converter.

The reason of the input current feedback control ant the validity of the proposed method will be confirmed by demonstrating the simulation and the experimental results. In this paper, the characteristics of the input current feedback control where the generator is connected as the input, are demonstrated as follows; (1) the fundamental operation with R-L load, (2) the relations among the load power, the input power factor and the amplitude of input current at the light load. (3) Operation with a motor load. As for the proposed output current control method, the following results will be shown in sequence. (1) the fundamental operation with an induction motor load, (2) torque step response results.

II. MATRIX CONVERTER WITH THE GENERATOR

Figure 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 reactance is substituted by using the synchronous reactance of the generator. The input filter is constructed by only filter capacitor.

Generally, when the 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 damping resistor becomes larger because the capacitor current has large harmonics components. Therefore, the damping resistor is usually connected in parallel to the filter reactor. However, the damping resistor cannot be inserted to the synchronous reactance in parallel to a generator practically.

Figure 2 shows a configuration of the input filter of the matrix converter with the generator as the input. Figure 2 (a) shows the single equivalent circuit of the matrix converter where V_r and V_s are 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 Figure 2 (a), a block diagram of the input filter is introduced as shown in Figure 2 (b).

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

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

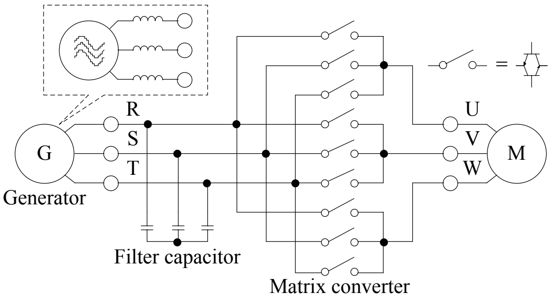
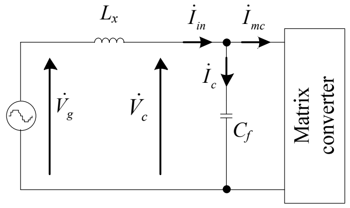
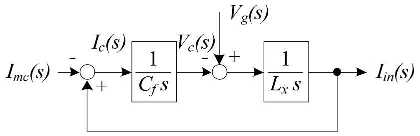


Figure 1. System configuration diagram of the matrix converter with the generator and the motor.



(a) Equivalent circuit of the input filter.



(b) Block diagram of the input filter.

Figure 2. Configulation of the input filter.

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

III. PROBLEM OF INPUT FEEDBACK CONTROL

In the stabilization method, which use an input current feedback [2], 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. However, when this control is applied with an output current control, the system becomes unstable. In this chapter, the stability of the system is discussed when the input current control and the output current control are used at the same time.

Figure 3 shows the block diagram of the input filter and input current control. The input current I_{in} is directly 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}. In order to suppress the resonance of the input filter, a PID controller is required.

Figure 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 load. Figure 4 (a) shows the phasor diagram without the proposed control and Figure 4 (b) shows the phasor diagram applies with the proposed control. In the light load, the ratio of I_c to I_{in} is larger than the heavy load. Then, the phase angle between I_{mc} and I_{in} becomes larger. Therefore, the phase angle of I_{in} cannot control to the same phase of V_g. On the other hand, In Figure 4 (b), I_{in} can be controlled directly by using the current feedback. As a result, the efficiency of the generator is optimized in the light load.

From Figure 3, the transfer function from the input current command I_{in}^* to the input current I_{in} is described by

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

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

Figure 5 shows the root placement of the input current feedback control with the PI control and the PID control. In the PI control, a real component of the root placement 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 can be suppressed by the PID control.

Figure 6 shows the experimental results where the generator as an input with a R-L load. Figure 6 (a) shows the input and output waveforms without any stability control method. Figure 6 (b) shows the waveforms using the input current feedback control. In Figure 6 (a), the large oscillation occurs in the input terminal voltage and the input current. As for Figure 6 (b), the oscillation of the input side is drastically suppressed in comparison with Figure 6 (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%. These results lead to the conclusion that the proposed control is extremely effective for a generator.

Figure 7 shows the relationship between the load power and the input power factor between the generator terminal voltage and the input current. As for the conventional, the input power factor is smaller in compared to the input current feedback control. This is because the input power factor cannot be controlled due to the current influence at filter. The amplitude of the input current with the input current feedback control is smaller than that of the conventional control. The proposed control can reduce the copper loss.

Figure 8 shows the simulation results of the motor load with input current feedback control and an output current vector control. Each waveform has very large distortion and the input current and the output current cannot be controlled according to the references. As a result, the system becomes unstable.

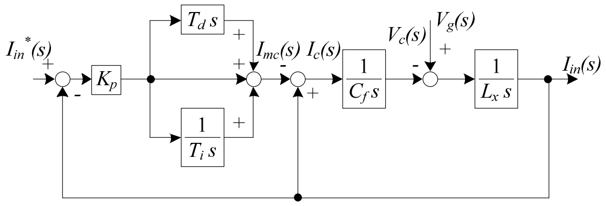
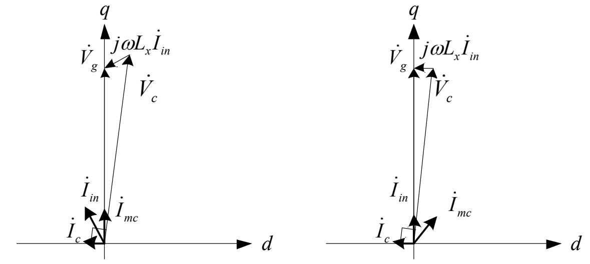


Figure 3. Input current feedback control for the generator side.



(a) Without any control.

(b) Input current feedback control.

Figure 4. Relationship among the input current, the input PWM current and the inut filter current.

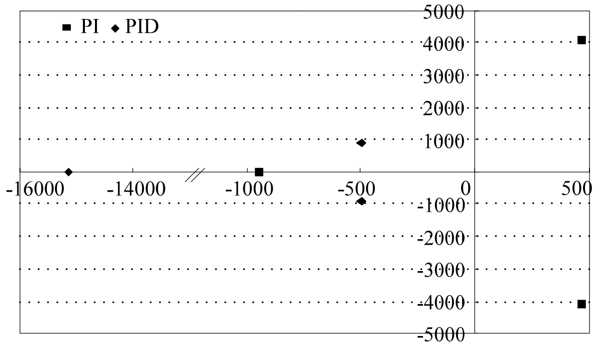
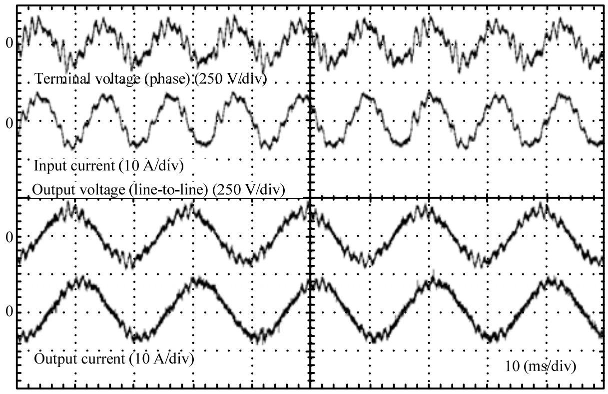
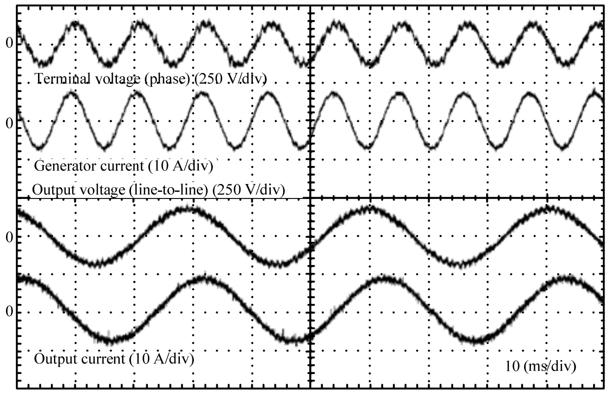


Figure 5. Root placement of the proposed input current feedback control with PI control and PID control.

In this case, the system has two current controllers at the both of the input and the output side. Each current controller tries to control the active power independently. However, the matrix converter cannot control the active power of the input and the output side independently because the matrix converter is a direct AC/AC power converter that does not has any energy storages. Therefore, a power supply directly proves the active power to the output side. In this case, the active power is decided by the motor load torque and speed. However, in the generator side, the input current feedback control required to control the active power to suppress the distortion component of the input side. Consequently, the instantaneous active power between the input and the output



(a) Experimental results without proposed control.



(b) Experimental results with proposed control

Figure 6. Experimental results with RL load using proposed input current feedback control.

current control is different. Therefore, operation of each controller interferes. As a result, the system becomes unstable.

IV. PROPOSED OUTPUT CURRENT CONTROL INCLUDING DAMPING FACTOR

This chapter describes the proposed output current control including the damping factor. In this proposed method, the output current and oscillation of the input filter are controlled at the same time.

The output voltage of the matrix converter is directly converted from the input voltage. When the input voltage has distortion, consequently the output voltage will be affected and distorted. Thereby, the output current will be distorted too. Thus, the input current is distorted and the distortion of the terminal voltage will be increased. Therefore, the distortion of the input side is affecting the output side similarly. In the proposed system, the current controller must be applied to only one side of the matrix converter to avoid interferes of the controller. Generally, high performance controller is required for adjustable speed drive. Therefore, in this paper, the stability control for the input side is integrated o the output current control. The input current stability control constructed by the open loop control is already proposed by the authors [1]. In order to achieve the stable operation and output current control, the input current stability control is combined to the output current control.

TABLE I. IPM GENERATOR PARAMETERS.

3.7 kW IPMSM Generator			
Rated rotational frequency	1800 rpm	Stator resistance	0.693 Ω
Rated Voltage (line-to-line)	180 Vrms	d-axis inductance	6.2 mH
Back e.m.f. (line-to-line)	150 Vrms	q-axis inductance	15.3 mH
Rated current	14 Arms	Number of pole	6

TABLE II. EXPERIMENTAL CONDITION OF INPUT CURRENT FEEDBACK CONTROL.

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	

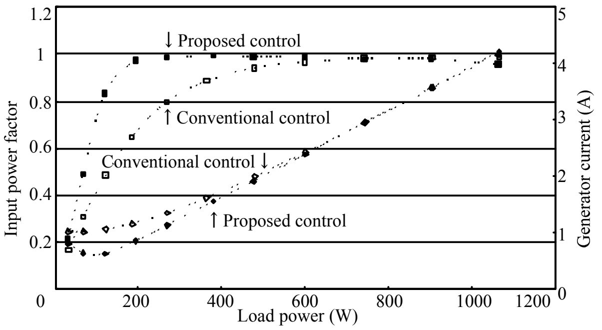


Figure 7. Experimental results of input power factor characteristics with proposed input current control.

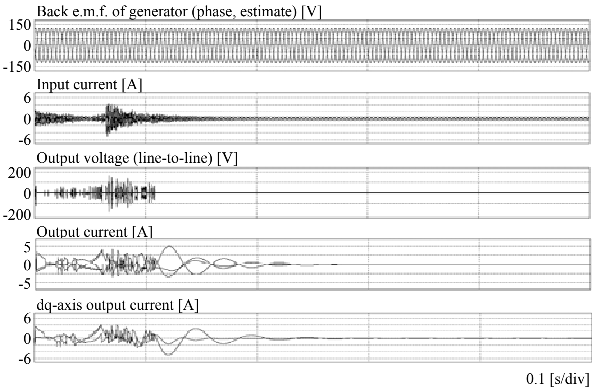


Figure 8. Simulation results of with the motor load using the input current feedback control and the vector control.

Figure 9 shows a block diagram of the conventional stability control on the d-q frame. V_{cr}, V_{cs}, V_{ct} are the three phase terminal voltage of the generator, θ_{vc} is the phase angle of the terminal voltage of the generator, θ_{pfc} is the 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 are appearing 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}^*.

Figure 10 shows the block diagram of the proposed output current control where T_{lpf} is the time constant of the LPF, K_d is the damping gain, K_p is the proportional gain of the output current control and T_i is the integral action time. Proposed control is the combination of input current stability control and the output current control. The proposed control is applied on the d-q frame. First of all, the error between output current command and output current will be calculated. Next, the ripple of the output current error due to the oscillation in the input filter is completely removed by the low pass filter. After that, the fundamental component of the output current is controlled by the PI controller. The ripple component is controlled by the damping gain K_d. Finally, the damping factor is added to output of PI controller. As a result, the output current control and damping control for the input side can be achieved at the same time.

Figure 11 shows the root placement of the output current between the PI control and proposed control. In the PI control, a real component of the root placement is positive. Therefore, the system that uses PI control is oscillating and unstable. On the other hand, in the proposed control, all imaginary component moves to the negative side. Therefore, the oscillation of the input side is successfully suppressed by using the proposed control.

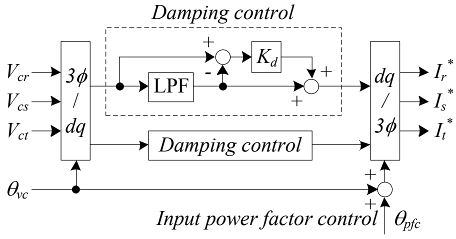


Figure 9. Block diagram of the input current stability control.

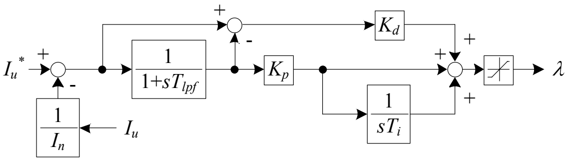


Figure 10. Block diagram of the proposed output current control.

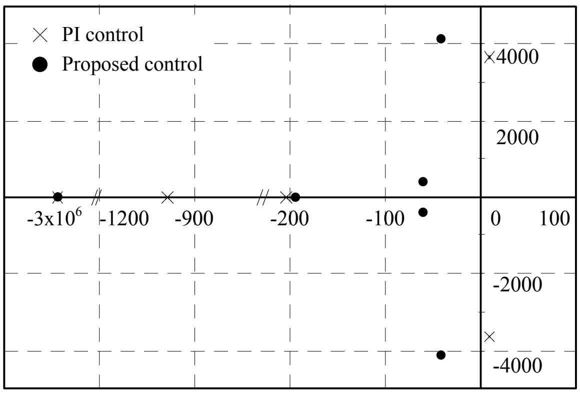


Figure 11. Root placement of the proposed input current feedback control with PI control and proposed control.

Figure 12 shows a details configuration of output current control including the damping factor. As well as the proposed input feedback control, the phase of the induced EMF is detected by the pole position sensor for controlling the input power factor to unity. The phase angle of the input current command is calculated from the digital PLL. The input current command i_{din}^* is always fixed to 0 pu and i_{qin}^* equals to 1 pu respectively. Phase angle of an output side motor is calculated from motor encoder. Output current command and phase angle of the output side are used for the proposed output control. In this control, Automatic Speed Control (ASR) and Automatic Flux Control (AFR) can be applied to decide the d-q axis output current command. In addition, the ASR, AFR and ACR PI gain can be designed

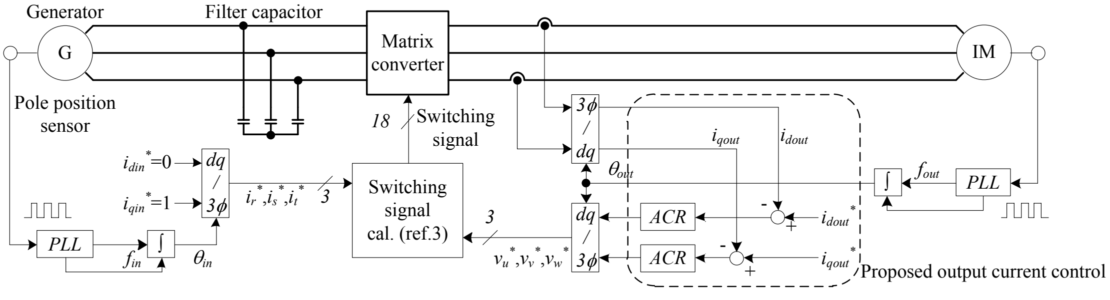


Figure 12. Control block diagrams of the proposed stability control

TABLE III. INDUCTION MOTOR PARAMETER

3.7 kW Induction motor			
Rated rotational frequency	1500 rpm	Stator resistance	0.414 Ω
Rated Voltage (line-to-line)	188 Vrms	Stator inductance	1.24 mH
Back e.m.f. (line-to-line)	146 Vrms	Rotor resistance	0.423 Ω
Rated d-axis current	8.11 Arms	Rotor inductance	1.24 mH
Rated q-axis current	15.69 Arms	Mutual inductance	34.3 mH
Rated current	18 Arms	Number of pole	4

TABLE IV. SIMULATION PARAMETERS

Other simulation conditions			
Filter capacitor	6.6 μF	Carrier frequency	10 kHz
Generator frequency		1800rpm (rated)	
Modulation method		Virtual AC/DC/AC conversion(3)	
Commutation		Ideal commutation	
Kp	2.42 [pu]	Ti	5.9 [ms]
I_{dout}^*	0.45 [pu] (constant)	Kd	0.3 [pu]
I_{qout}^*	0.2 to 0.4 (0.1s step) [pu]	Constant speed load	1000 [rpm]

TABLE V. EXPERIMENTAL PARAMETERS

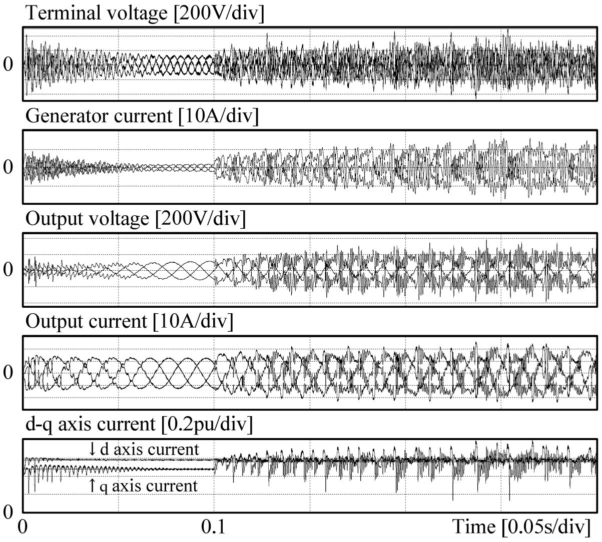
Input voltage (line-to-line)	200V50Hz	Input inductance	12mH
Filter capacitor	6.6 μF	Carrier frequency	10 kHz
Modulation method		Virtual AC/DC/AC conversion	
Commutation		Input voltage commutation	
K_p (ASR)	20.0 pu	T_i (ASR)	12.5 ms
K_p (ACR)	1.59 pu	T_i (ACR)	5.9 ms
I_{dout}^*	0.45 pu	K_d	0.6 pu

based on the specification of the motor. The damping gain K_d and Time constant of LPF T_{lpf} can be designed by the root placement as shown in Figure 11.

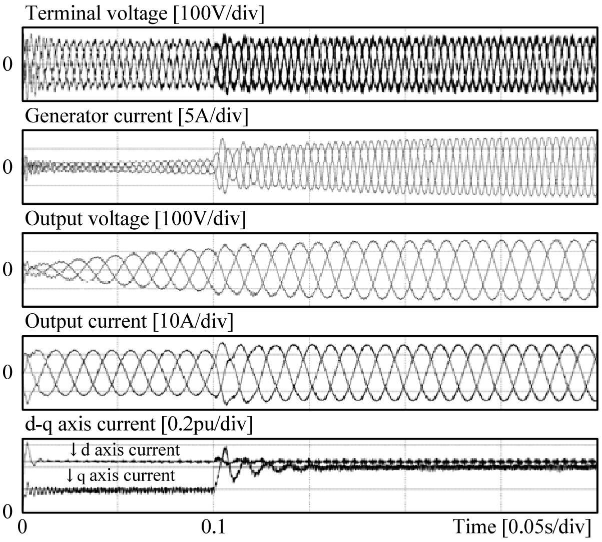
V. SIMULATION AND EXPERIMENTAL RESULTS WITH PROPOSED OUTPUT CURRENT CONTROL INCLUDING DAMPING FACTOR

This chapter demonstrates the simulation and experimental results by using two proposed control methods. Table III and IV are used for the simulation with the proposed output current control including the damping factor. In addition, Table III and V are used for the experimental results with the proposed output current control.

Figure 13 shows the simulation results of the matrix converter with the generator and the motor. Figure 13 (a) shows the input and output waveforms without the proposed output current control method. Figure 13 (b) shows the waveforms using the proposed output current control. In Figure 13 (a), the large oscillation occurs in the input terminal voltage and the input current. d axis and q axis current also contains of the large distortion. On the other hand, in Figure 13 (b), the oscillation of the input side is drastically suppressed in comparison with Figure 13 (a). Moreover, the distortion of the output side is eliminated. The THD of the input current is 3.4%. These results lead to the conclusion that the proposed control is extremely effective for the generator and the motor.



(a) Without proposed output current control.



(b) With proposed output current control.

Figure 13. Simulation results with the generator and the motor using proposed output current control.

Figure 14 shows the experimental results of the matrix converter with a large inductance grid power supply and the induction motor. Figure 14 (a) shows the input and output waveforms without the proposed output current control method. Figure 14 (b) shows the waveforms using the proposed output current control. In this experimental result, the commercial grid and large inductance are used in the input side to simulate an operation of the generator because of the limitation of experimental condition. In addition, the ASR is added to the input of the q-axis current command of

Figure 12. The parameter of ACR and ASR is shown in Table V.

In Figure 14 (a), the large oscillation occurs in the input terminal current. The THD of the input current is over 35%. As a result, the system becomes unstable without the stability control as shown in Figure 13 (a). On the other hand, in Figure 14 (b), the input and output waveforms can be controlled to the sinusoidal by the proposed output current control. Especially, the large oscillation of the input current can be suppressed. The THD of the output current is 13.8%. As a result, the system becomes stable by using the proposed output current control. It should be noted that the input waveform happens with some distortion due to the commutation error. This problem can be solved by the commutation error compensation method [11].

Figure 15 shows a torque step response result. In the center of this result, the load torque changes from 0% to 100%. Spike voltage and current did not happen on these waveforms after the torque steps up. So, the system can be kept to the stable condition even if the load torque changes suddenly. These results lead to the conclusion that the proposed output current control including the damping factor for the input filter oscillation control can suppress the oscillation in the input current and also drive the induction motor under a variable speed.

VI. CONCLUSION

This paper discusses about the control strategy for a matrix converter with a generator and a motor. By using the input current feedback control, the stable operation of the generator was confirmed. However, the output current control is applied to control the motor, thus the system becomes unstable due to the interference of the controller. In order to solve this problem, this paper proposed the output current control including the damping factor can control the motor current. The proposed control can achieve the stable operation of the generator and the high performance motor drive at the same time. The validity of the proposed method is confirmed with simulation and experimental results. These results lead to the conclusion that the proposed output current control including the damping factor is extremely effective for the motor drive application with the generator as input.

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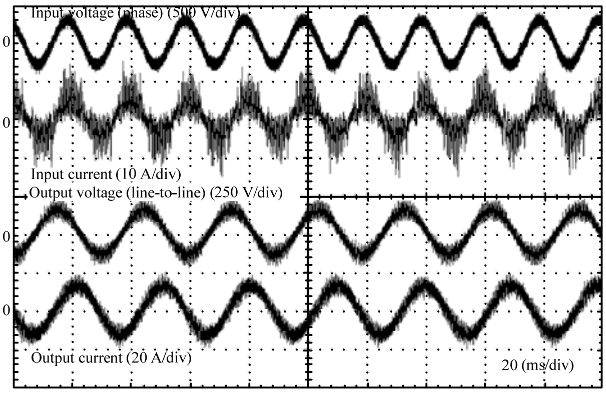
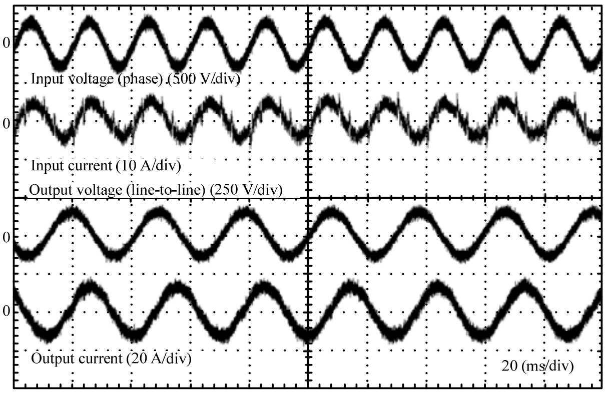


(a) Without proposed output current control.



(b) With proposed output current control.

Figure 14. Experimental results with the generator and the motor using proposed output current control.

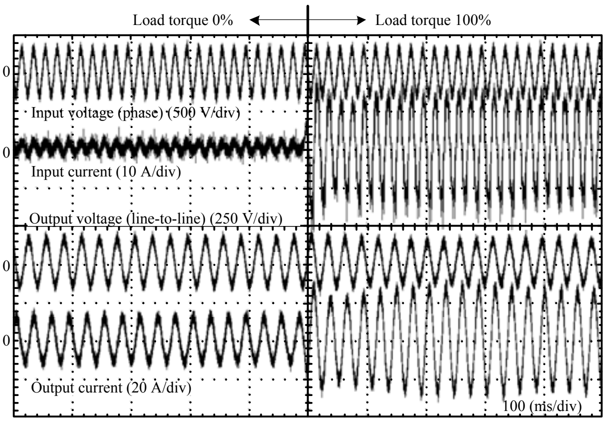


Figure 15. Torque step response result with the proposed output control.

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