Direct Grid Connection of Permanent Magnet Synchronus Motor Using Auxiliary Inverter and Matrix Converter with Transition Control

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Abstract— **This paper discusses a direct grid connection system for the permanent magnet synchronous motor (PMSM). It is difficult to connect PMSM to the power grid directly due to the resonance between a synchronous reactance and the inertia moment. In order to solve this problem, the direct grid connection system which consists of an auxiliary inverter of small capacity and a matrix converter is proposed for PMSM. In the proposed system, a torque vibration caused by the resonance is suppressed by the auxiliary inverter and auxiliary windings in PMSM. Moreover, the matrix converter is used as a starter which accelerates PMSM up to synchronous speed of a power grid. In the direct grid connection mode, the matrix converter is matches voltage for PMSM with the grid voltage. Besides, the rush current is suppressed by the transition control which consists of an output voltage phase control mode and an output voltage amplitude control mode. In the direct grid connection mode, the matrix converter has no switching operation. Thus, the converter loss is remarkably low in a standby mode due to no switching loss. Additionally, the validity of the proposed system is demonstrated in the simulation and experimental results. From the results, the rush currents is suppressed to 2 A (18% of the rated current) by the transition control and the damping control when the PMSM is connected to the power grid.**

Keywords— Permanent Magnet Synchronous Motor; Auxiliary inverter; Matrix converter; Direct grid connection;

I. INTRODUCTION

Recently, the driving techniques for the permanent magnet synchronous motor (PMSM) have attracted a lot of attentions among the researchers in terms of the energy saving [1]-[3]. PMSM has high efficiency and high power density in comparison with an induction motor (IM) because PMSM does not have the excitation circuit. On the other hands, a direct grid connection for IM is widely utilized for fans and pumps [4]-[6].

The efficiency of the motor drive system is improved by replacing IM with PMSM. However, it is difficult to connect PMSM to the power grid directly because the torque vibration occurs due to the resonance between a synchronous reactance and the inertia moment. In order to solve this resonance, the damping (stabilization) control that uses the current feedback has been proposed as the motor drive technique [7-8]. This method suppresses the torque vibration with adding the vibrational component in the effective current to the output phase command of the voltage command. However, this method cannot be applied to the direct grid connection for PMSM because the inverter cannot control current corresponding to the pole position when the PMSM is directly connected to the power grid.

Matrix converters have been studied actively recently [9-13]. The matrix converter does not required large electrolytic capacitor as an energy buffer and its size is small. Besides, a direct grid connection which connects between the power grid and the motor directly can be used by the matrix converter to reduce the switching loss. In the direct grid connection mode, the matrix converter has no switching operation. However, the voltage transfer ratio, which is defined as output voltage/input voltage of the matrix converter with PWM is limited up to 0.866. As a result transition control is required for the direct grid connection. Due to the above reason, the motor current changes widely and over current will occur without the transition control. In addition, changing the output current will affect the power grid because the energy buffer is not connected between the input side (power grid) and output side. The transition control from PWM to the direct grid connection mode has been proposed as a control method for the matrix converter [13]. However, this technique can be applied to only IM.

In this paper, a direct grid connection system for PMSM using a small power capacity auxiliary inverter and the matrix converter is proposed. The aim of this paper is to achieve to connect PMSM to the power grid without the rush current. In the proposed methods, the torque vibration is suppressed by the auxiliary inverter and auxiliary windings in PMSM. A transition control is applied to the matrix converter used as a starter, which the output voltage gradually corresponds to the input voltage in transiting to the direct grid connected. For the above reason, this matrix converter is used only when PMSM is accelerated and shifted from the acceleration mode to the grid connection mode or vice versa. The power capacity of the auxiliary inverter is much smaller than that of the matrix converter because the output power of the auxiliary inverter is only used to suppress the vibration.

This paper is organized as follows; first, the configuration of the proposed system is introduced. Secondly, the control method of the starting inverter with V/f control and the transition control, and the auxiliary inverter with field-oriented control (FOC) is described. Thirdly, the performance of the proposed control is verified by detailed numerical simulation. Finally, the experimental results demonstrate that the proposed system drives the PMSM with suppressing the torque vibration and transiting the direct grid mode. The experimental results agree with the theoretical analysis results.

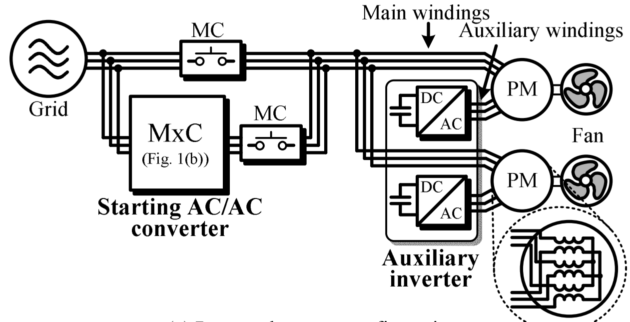
II. Proposed System

A. Configuration and control strategy of the proposed system

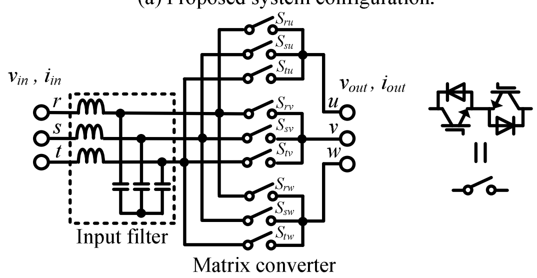
Fig. 1 shows the configuration of proposed system. In PMSMs, the auxiliary windings which are used in the damping control (with the auxiliary inverter) are placed in the slots together with the main windings. The proposed system uses two different power rating converters. The first one is the large power capacity matrix converter for the main windings to start to the acceleration. This matrix converter is used only when PMSM is accelerated and shifted from the acceleration mode to the grid connection mode or vice versa. The second one is a small power capacity inverter for the auxiliary windings to suppress the torque vibration caused by the resonance between the synchronous reactance and the inertia moment.

Fig. 2 shows a state transition diagram of the control mode in the proposed system. First, in the acceleration mode (Mode I), PMSM is accelerated up to the grid frequency in starting up by the matrix converter. When the motor frequency reaches the grid frequency, the mode state is changed to the transition control mode (Mode II & III). The transition control mode consists of the output voltage phase control mode (Mode II) and the output voltage amplitude control mode (Mode III). In the output voltage phase control mode, the phase of the output voltage corresponds to the phase of the input voltage gradually. In the output voltage amplitude control mode, the amplitude of the output voltage corresponds to the amplitude of the input voltage gradually with operating the matrix converter as an AC chopper. After that, the mode state is changed to the direct grid connection mode (Mode IV). In the direct grid connection mode, the converter loss is reduced due to no switching operation. In the end, PMSM is connected to the grid directly by the magnetic contactor. During all modes, the damping control suppresses the vibration of the speed. In terms of the effectiveness of the proposed system, it is very important that the power capacity of the auxiliary inverter is much smaller than that of the matrix converter. In other words, the damping power for the PMSM is much smaller than that of the main drive power.

Fig. 3 shows the relationship between the motor voltage and the motor speed. The rated voltage of PMSM is to the grid voltage for the direct grid connection. The voltage utilization of the matrix converter is 0.866 of the input voltage. For this reason, when the mode state is changed from the acceleration mode to the direct grid connection mode, the output voltage will increase in a sudden without a proper transition control. In addition, if the input voltage phase and the output voltage phase are different, large rush current or overcurrent might occur. Moreover, large transient variation of the output current will affect the power grid because energy buffer are not connected between the input side (power grid) and output side (PMSM). In order to solve these problems, the transition control that treats the output voltage to correspond to the input voltage is introduced between the acceleration mode and the direct grid connection mode.



(a) Proposed system configuration.



(b) Configuration of matrix converter.

Fig. 1 Proposed system configuration.

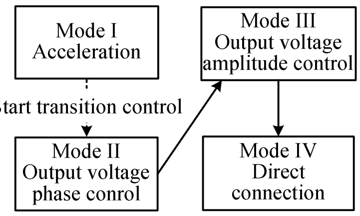


Fig. 2 State transition diagram of the control mode.

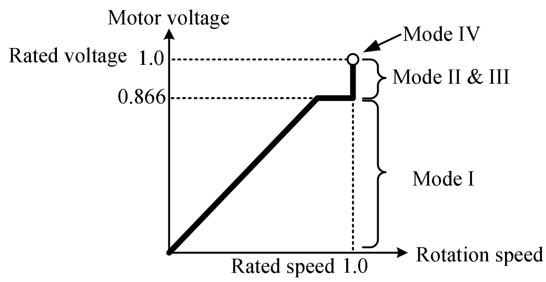


Fig.3 Relationship between motor voltage and rotation speed in each mode.

Fig. 4 shows the control block diagram of the proposed system. In the proposed system, the control method of the matrix converter is based on a V/f control. On the other hand, the FOC and the damping controls are applied to the auxiliary inverter. The auxiliary inverter can control the current in auxiliary windings of the PMSM in order to suppress the torque and speed vibration. Since the torque and speed vibrations are caused by the phase difference between the rotational coordinates of the inverter and that of the PMSM, it can be suppressed by the damping control in the auxiliary

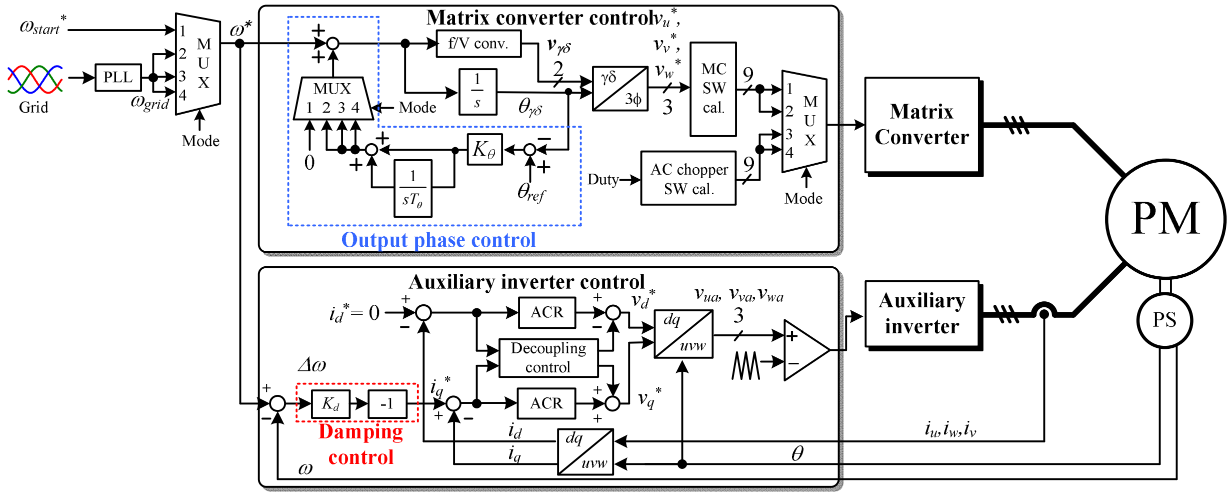


Fig. 4. Control block diagram for the proposed system.

inverter. Note that postion sesor less vector control can be applied to the auxiliary inverter when it is difficult to use position sesor.

Fig. 5 shows the relationship between a d-q rotating frame and a γ-δ rotating frame for a V/f control. In the control of the auxiliary invereter, the direction of the flux vector with permanent magnet is defined as d-axis as same as the conventional FOC. In the V/f control, the output voltage vector is defined as δ-axis, the axis which lags by $\pi/2$ rad from δ-axis can be defined as γ-axis. The lag of the load angle φ occurs between the d-q rotating frame and γ-δ rotating frame as shonwn in Fig. 5. Therefore, the load angle φ, rotational speed ω_{re} and the speed command ω^* can be expressed as

$$p\varphi = \omega_{re} - \omega^* \tag{1}$$

where p is differential operator.

When the vibration of the speed is caused by the resonance between the inertia moment and the synchronous reactance, the load angle φ also vibrates as shown (1). Then, the change of the load angle $p\varphi$ is the difference between the rotational speed and the speed command. In order to compensate the changes of the load angle $p\varphi$, the q-axis current command i_q^* is calculated from the damping controller as shown in Fig. 4. As a result, the vibration of the speed and torque caused by the resonance are suppressed by compensating the changes of the load angle $p\varphi$ with the current controlled by the FOC and the damping control.

The switching signal of the matrix converter is changed corresponding four control modes. Besides, θ_{ref} is the output phase command for the output phase control used in the transition control. Other than the transition control, the output phase control is not used. Therefore, θ_{ref} is set to θ_{out}. Control methods of each control modes are explained in follows.

B. *Mode I – Acceleration mode*

In the start-up of PMSM, the mode state is changed to the acceleration mode. In this mode, PMSM is controlled in order

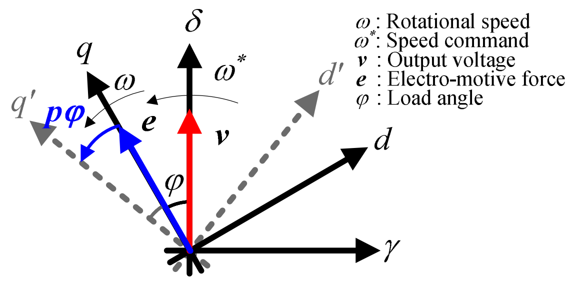


Fig. 5. Relationship between the d-q rotating frame and the γ-δ rotating frame. The γ-δ rotating frame lags by the load angle φ from the d-q rotating frame.

to increase the motor speed up to rated speed by the V/f control as shown in Fig. 4. In general, when PMSM is driven with only V/f control, the resonance between the synchronous reactance and the inertia moment of the motor causes the torque vibration. However, PMSM can be driven stably in the proposed system by applying the damping control to the auxiliary inverter.

C. *Mode II – Output phase control mode*

In transition control [11], the mode state is changed from the acceleration mode to the direct grid connection mode. In order to stabilize the output current caused by a transition from the acceleration mode to the direct grid connection mode, it is necessary that the output voltage corresponds to the input voltage gradually. Thereby, first, the output voltage phase must be corresponding to the input voltage phase using the output phase control. Secondly, the amplitude of output voltage needs to be corresponding to the amplitude of input voltage using an AC chopper switching mode.

Using the output phase control, the output phase θ_{out} can correspond to the output phase command θ_{ref}. First, the difference between θ_{out} and θ_{ref} is equaled to zero through a PI controller which is defined by a phase gain K_θ and a phase integral time T_θ. Next, the final value is added with an electrical angular velocity. A transfer function from θ_{ref} to θ_{out} is represented by

$$G_\theta(s) = \frac{\frac{K_\theta}{T_\theta}(1 + T_\theta s)}{s^2 + K_\theta s + \frac{K_\theta}{T_\theta}} \quad (2)$$

Equation (2) is second order transfer function. Thus θ_{out} corresponds to θ_{ref}. Beside, K_θ and T_θ are designed by

$$K_\theta = 2\zeta\omega_n \quad (3)$$

$$T_\theta = \frac{2\xi}{\omega_n} \quad (4)$$

where ξ is damping coefficient, and ω_n is response speed of the output phase control.

Fig. 6 shows the vector diagram on a d-q and γ-δ rotation frame before and after the output voltage phase corresponds to the input voltage phase. In the proposed system, the output voltage vector is defined as δ-axis, the axis which lags by π/2 rad from δ-axis can be defined as γ-axis because V/f control is applied to the matrix converter. The input d_{in} axis is aligned with U phase of the input voltage vector v_{in}. In the output phase control, the output voltage vector v_{out} corresponds to the input voltage vector v_{in} on the input d_{in} axis.

D. Mode III – Output voltage amplitude control mode

Fig. 7 (a) shows a configuration of a V connection AC chopper, and Fig. 7 (b) shows a control block diagram [12-14]. The output voltage is PWM waveform that the envelope curve is sinusoidal. The output frequency is same as the input frequency. Moreover the voltage transfer ratio of the V connection AC chopper is from 0 to 1. Thus, switching operation of the matrix converter is fixed to correspond to the switching operation of the V connection AC chopper, so that the maximum transfer ratio of the matrix converter is improved up to 1.

Fig. 8 shows the control block diagram of the switching pulse of the matrix converter in the AC chopper mode. Duty ratio is increased from an initial value D_{int} to 1 in the AC chopper mode. D_{int} is expressed by

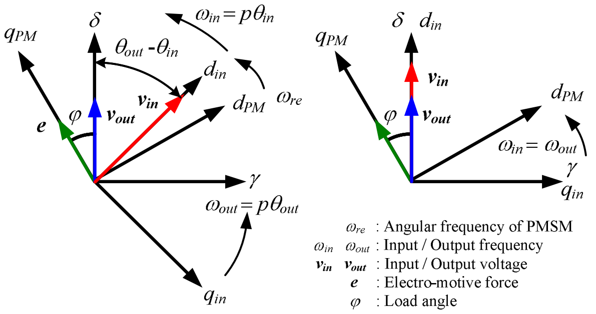
$$D_{int} = \frac{\sqrt{V_{\gamma\_int}^2 + V_{\delta\_int}^2}}{\sqrt{2}V_{in}} \quad (5)$$

where V_{in} is the RMS value of the input phase voltage, V_{γ_int} and V_{δ_int} are output voltage commands on γ-δ axis at the moment of the operation mode changing to the AC chopper mode.

The duty ratio is increased up to 1, in other words, Switches turn on constantly. After that, the mode state is changed to the direct grid connection mode.

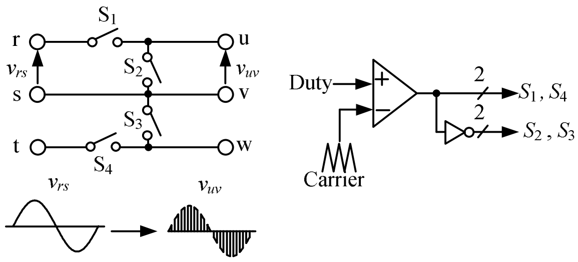
E. Mode IV – Direct grid connection mode

In the direct grid connection mode, PMSM is driven by the power from the power grid via the non-switching state of the



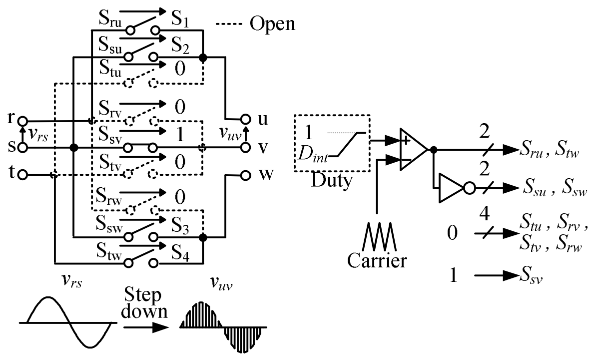
(a) Mode I. (b) Mode II.

Fig. 6. Vector diagram when the output voltage phase corresponds to the input voltage phase.



(a) System configuration. (b) Control block diagram.

Fig. 7. V connection AC chopper. The output voltage is PWM waveform that the envelope curve is sinusoidal. The output frequency is same as the input frequency. Moreover the voltage transfer ratio of the V connection AC chopper is zero to 1.



(a) Correspondence of switching pattern. (b) Control block diagram.

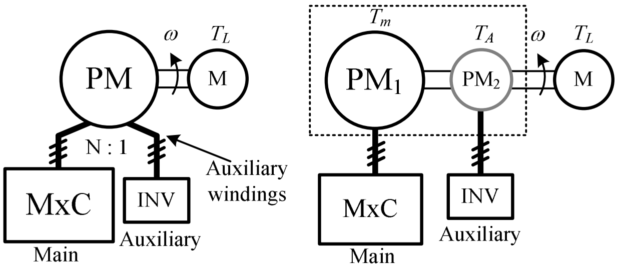
Fig. 8. Control block diagram of the matrix converter in the AC chopper mode. The duty ratio is increased up to 1 with operating the matrix converter as the AC chopper, in other words, switches turn on constantly.

matrix converter. Switches S_{ru}, S_{sv}, and S_{tw} are turned on and the remaining switches are turned off. Moreover, if a magnetic contactor shunting the input and output of the matrix converter are added, the conduction loss is reduced drastically.

III. Simulation Results

A. Mode I- Acceleration test with damping control

Fig. 9 (a) and (b) show the simulation and experimental models that are used to verify the operation of the proposed



(a) Connection diagram. (b) Simplification model.

Figs. 9. Simulation and experimental model of the PMSM in addition auxiliary windings for damping control. In order to neglect the magnetic coupling in the simulation and the experiment, the proposed system is validated using (b).

system. Due to the reason that the mutual magnetic interference occurs between the main and the auxiliary windings, the control for the auxiliary inverter becomes complicated. Therefore, the proposed system is validated using a model where two PMSMs are connected in series via single shaft. Then, the rear end of the main PMSM is connected to the load machine. It means that the magnetic coupling is neglected in the simulation and the experiment. Table 1 shows the details of the tested PMSM. Simulation conditions are as follows; grid line voltage is 200 V and grid frequency is 50 Hz in the simulation. The rated value of the tested PMSM corresponds to the grid voltage in the simulation. The switching frequency of the matrix converter is 10 kHz. Parameters of the output phase control are designed, as K_θ and T_θ are 8 and 80 msec. The response of the output phase control is 10 rad/sec. Besides, following results are standardized based on the rating of PMSM in Table 1.

Fig. 10 shows the simulation results when the acceleration mode is applied (a) without and (b) with damping control. In Fig. 10(a), the vibration occurs in the torque and the rotational speed during the acceleration. After the acceleration, the vibration is maintained. On the other hand, in Fig. 10(b), the vibrations in the torque and the rotational speed and the load angle are suppressed by the auxiliary inverter which causes the auxiliary torque to neutralize the vibration of the rotational speed. Besides, it can be confirmed that the rotational speed is well following to the rotational speed command. However, the largest power produced from the auxiliary inverter is only 0.5 p.u. From the results, the power capacity of the auxiliary inverter is shown smaller than that of the main inverter. Moreover, the auxiliary inverter only operates when the torque vibration occurs. Note that the power capacity of the auxiliary inverter is dominated by the response time of the torque vibration suppression.

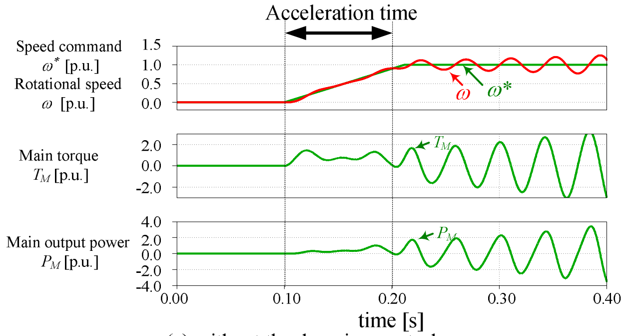
B. Direct grid connection with transient control

Fig. 11 shows the simulation results from the acceleration mode to the output phase control mode. The mode state is changed from the acceleration mode to the output phase control mode at 0.1 sec, after that, the phase angle of the output voltage phase is gradually corresponding to the phase angle of input voltage phase, which is completed at 0.6 sec. At 0.6 sec, the voltage phase difference decreases to zero. After that, the matrix converter is operated as the AC chopper mode.

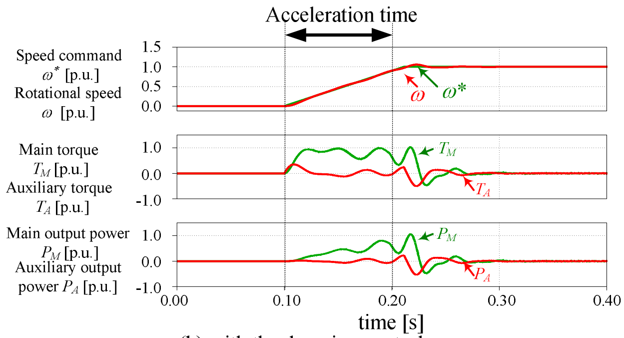
Fig. 12 shows the simulation results including the transition control. At 0.1 sec, the mode state is changed to the output amplitude control mode. In the output amplitude control mode using the AC chopper, the amplitude of output voltage is increased gradually until it matches with the amplitude of input voltage at 0.17 sec. It takes 0.07 sec to finish the output amplitude control. At 0.17 sec, the mode state is changed to the direct grid connection mode. As a result, the transition process is completed within 0.57 sec. Moreover it is confirmed that surge current does not occur during the transition period.

Table 1. Simulation condition

	PM_M	PM_A
Rated power [W]	1500	750
Rated speed [min^{-1}]	1800	
Rated current [A]	8.2	4
Number of pole pairs	3	3
Armature resistance [Ω]	1.55	1.98
d-axis inductance [mH]	11.5	15.2
q-axis inductance [mH]	23	33.2
Electro-motive force constant [Vs/rad]	2.46	0.338
Inertia moment [kgm^2]	0.0051	0.0026



(a) without the damping control.



(b) with the damping control.

Figs. 10. Simulation results for a single motor drive without and with damping control. (a) The vibration of torque and rotational speed occur during the acceleration. (b) It can be confirmed that the rotational speed is well following to the rotational speed command owing to the damping control. The vibrations in the torque and the rotational speed are suppressed by the auxiliary inverter.

IV. Experimental Results

In this section, the proposed control is confirmed by experimental setup. Table 2 shows the experimental condition. The parameters of each controller in the experiment are same as in the simulation.

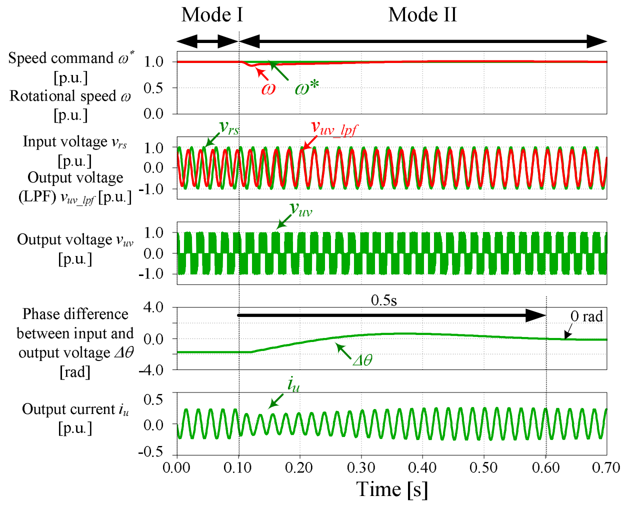


Fig. 11. Simulation result of transition from acceleration mode to output phase control mode.

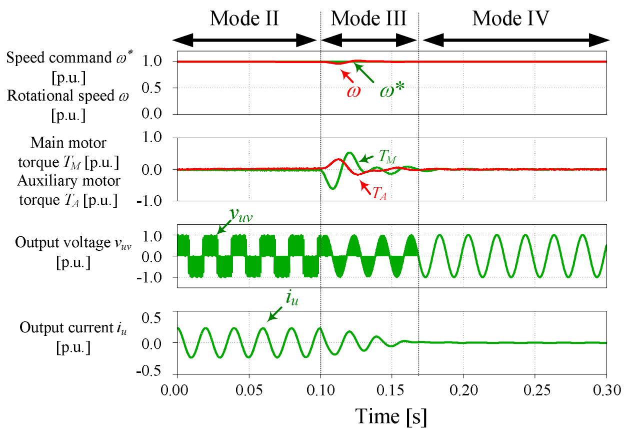


Fig. 12. Simulation result of transition from output phase control to direct grid connection mode.

Fig. 13 shows the experimental results that illustrate the motor speed vibration when the proposed system is applied (a) without the damping control and (b) with the damping control (ζ = 0.3) in an acceleration test. In this experiment, it is difficult to measure the torque response directly. Therefore, the speed vibration is evaluated instead of the torque response. In Fig. 13(a), the proposed system is implemented without the damping control. The speed vibration occurs during the acceleration. After the acceleration, a 400 r/min of speed vibration and the 10 $A_{p\text{-}p}$ of current vibration in q-axis of the main inverter are maintained. On the other hand, Fig. 13(b) demonstrates the experimental results, where the proposed system is implemented with the damping control (ζ = 0.3). The effectiveness of the auxiliary inverter from the results confirms that the speed vibration is reduced from 400 r/min to nearly 0 r/min in compared with the acceleration test of Fig. 13(a). The 10 $A_{p\text{-}p}$ of the current vibration in the q-axis of the main inverter is suppressed as well. Nevertheless, it is confirmed that the q-axis current of the auxiliary inverter flows only during acceleration and deceleration. Moreover, the maximum q-axis current of the auxiliary inverter is 20% of the q-axis current of the main inverter when the damping factor is designed at 0.3. Therefore, it is confirmed that the auxiliary inverter can suppress the speed vibration via auxiliary windings with a small q-axis current of the auxiliary inverter even if in the acceleration test.

Fig. 14 shows the experimental results of the output phase control. Note that the grid line voltage is 100V and grid frequency is 50Hz in the experiment because the tested PMSM is general PMSM. As a result, the output voltage phase

Table 2. Experimental condition

	PM_M	PM_A
Rated power [W]	1500	750
Rated speed [min^{-1}]	1800	
Rated current [A]	8.2	4
Number of pole pairs	3	3
Armature resistance [Ω]	1.55	1.98
d-axis inductance [mH]	11.5	15.2
q-axis inductance [mH]	23	33.2
Electro-motive force constant [Vs/rad]	0.368	0.338
Inertia moment [kgm^2]	0.0051	0.0026
Rotational speed in stationary state [rad/s]	900	

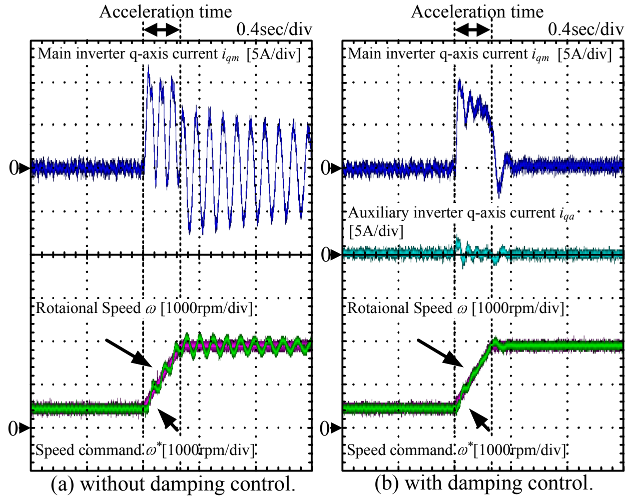


Fig. 13. Acceleration and deceleration test without/with damping control in motor-generator set. (a) After the acceleration, the 400 r/min - speed vibration is maintained. (b) The speed vibration is reduced from 400 r/min to nearly 0 r/min in compared with (a).

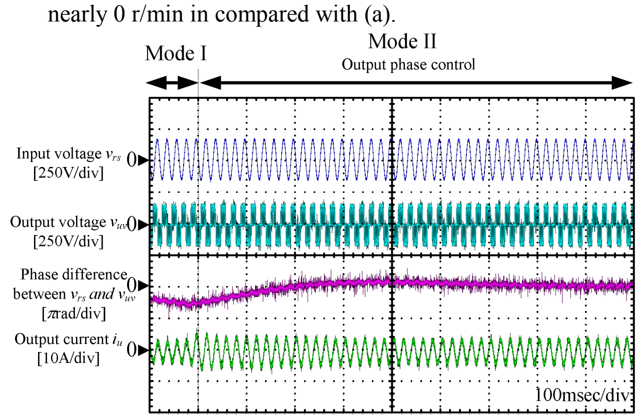


Fig. 14. Experimental result of the output phase control in motor-generator set. There is no rush current in this process.

corresponds to the input voltage phase within 0.6sec. Moreover there is no rush current in this process.

Fig. 15 shows the experimental results of the transition control. The input voltage phase already corresponds to the output voltage phase due to the output phase control. During AC chopper operation mode, it is confirmed that the output voltage waveform is similar to the output voltage of V connection AC chopper. Moreover, the AC chopper duty is increased gradually, so that the output current is increased. After that the mode state is changed to the direct grid connection mode. Therefore the output voltage waveform corresponds to the input voltage waveform. As a result it is confirmed that the surge current does not occur during the transition period to direct grid connection mode.

V. CONCLUSION

This paper discusses the direct grid connection for PMSM using the small power capacity auxiliary inverter and the matrix converter used as the starter. The proposed system solves the problem that PMSM cannot be directly connected the power grid. The features of the proposed system are following;

i) The proposed system is composed by two different converter, which are the matrix converter to start up and the small power capacity auxiliary inverter to suppress the torque and speed vibration caused by the resonance between the synchronous reactance and the inertia moment.

ii) PMSM can be stabilized by the damping control applied to the auxiliary inverter even when the PMSM is directly connected to the power grid.

iii) A transition control is applied to the matrix converter, which the output voltage gradually corresponds to the input voltage in transiting to the direct grid connection.

From the simulation and experimental results, it was confirmed that the speed vibration is suppressed by the damping control applied to the auxiliary inverter. Moreover, the rush current does not occur when the mode state is changed from the acceleration mode to the direct grid connection mode.

In future work, the verification of the proposed control by experiment with PMSM adding the auxiliary windings will be shown.

ACKNOWLEDFMENT

A part of this study was supported by industrial technology grant program in 2011 from new energy and industrial technology development organization (NEDO) of Japan.

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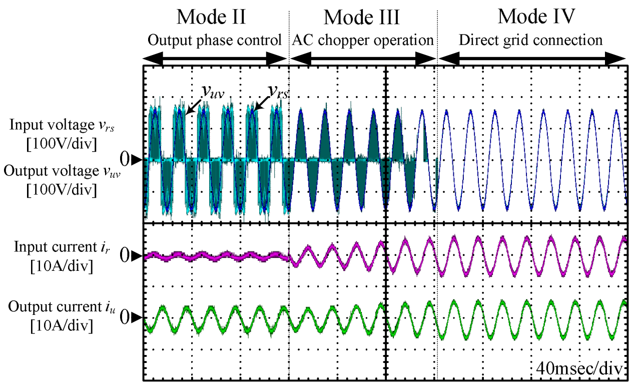

Fig. 15. Experimental result of the transition from the output phase control mode to the direct grid connection mode in motor-generator set.

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