Direct Grid Connection of Matrix Converter with Transition Control for Flywheel UPS

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Abstract— **This paper discusses an uninterrupted power supply (UPS) with a flywheel and a matrix converter using a direct grid connection. A flywheel type UPS has a problem where a standby power is bigger than that of the battery or EDLC type UPS. To solve this problem, an operation known as direct grid connection mode is proposed, where a matrix converter is the interface converter between the flywheel and grid. In the direct grid connection mode, the matrix converter has no switching operation. Thus, the converter loss is remarkably low in the standby mode due to no switching loss. However, a rush output current will occur in when the matrix converter is transited from PWM to direct grid connection mode. In order to solve this problem, in this paper, a transition control which treats the output voltage to correspond to the input voltage is proposed. Additionally, the validity of the proposed control is demonstrated in the simulation and experimental results.**

Keywords-component; Flywheel; Uninterrupted power supply; Matrix converter; Direct grid connection;

I. INTRODUCTION

Recently, batteries and EDLCs are usually used as the energy storage devices in the uninterrupted power supply (UPS). However, there are some problems such as short life time and environmental impact in the waste dispose [1][2]. On the other hand, studies on flywheel as energy storage have received significantly attentions recently. The flywheel has a good charging and discharging characteristics, and it has a longer life time because of no chemical objects. In addition, the flywheel can be used in hazard environments such as a desert and a cold area because the output characteristics do not change subjects to the ambient temperature [3] [4].

In general, a Back-to-Back (BTB) system, which is composed of a PWM rectifier and a PWM inverter, is used for flywheel system. However, the conventional BTB system has a problem where the power loss increases because the BTB system continues to perform switching during the idling condition, which is the standby mode. Some methods to improve the efficiency in a light load are to apply MOSFETs [5][6]. However, the reduction of the power loss during the standby mode is difficult because the BTB system needs to drive the AC motor at a constant speed.

On the other hand, a matrix converter has been studied actively recently [7-10]. The matrix converter does not required large electrolytic capacitor as an energy buffer and the size is small. The matrix converter is very suitable interface converter for the flywheel due to advantage of maintenance free for a long time. Besides, a direct grid connection which connects between power grid and matrix converter directly, can be used during the standby to reduce the switching loss. In the direct grid connection mode, the matrix converter has no switching operation. However, the voltage transfer ratio (v_{out}/v_{in}) of the matrix converter with PWM is limited up to 0.866 and as a result transition control is required for direct grid connection. Due to the above reason, the induction 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 located between the input side (power grid) and output side (induction motor).

In this paper, the flywheel with an induction motor driven by a matrix converter in the UPS is investigated. Additionally, the transition control from PWM to the direct grid connection mode is proposed. In the direct grid connection mode, the matrix converter has no switching operation, it is considered as a platform connected between the power grid and induction motor. Thus the induction motor is driven by direct supply power. Using this method, the converter loss is remarkably low due to no switching loss. Besides, a transition control is proposed, which the output voltage gradually corresponds to the input voltage in transiting to the direct grid connection. The rest of this paper is organized as follows. The system configuration is explained in Section II. The operating methodology of the proposed control is discussed in Section III. The performance of the proposed control is verified by detailed numerical simulation in Section IV. The experimental results are presented in Section V. The loss analysis in the standby mode is presented in Section VI. The summary in Section VII concludes this paper.

II. SYSTEM CONFIGURATION

Fig. 1 shows a UPS configuration with matrix converter. The power grid side and the flywheel side are defined as an input and an output of the matrix converter respectively.

The flywheel is driven by the induction motor that is connected to the power grid though a matrix converter. While an interruption occurs, the flywheel operates as a generator supplying the power to the load. In standby mode, the induction motor is driven by direct power from the gird via the matrix converter. During this mode, the matrix converter operates without switching, i.e. three legs are always turned on to serve as the U, V and W port for the induction motor.

III. Proposed Control

Fig. 2 shows a state transition diagram of the control mode. In the automatic speed regulation mode (Mode I, the induction motor is accelerated up to rating speed in starting up or after recovery from short interruption. When the motor speed reaches the rating, the mode state is changed to the transition control mode (Mode II). In the transition control mode, the output voltage corresponds to the input voltage gradually. After that the mode state is changed to the direct grid connection mode (Mode III). In the direct grid connection mode, the converter loss is reduced due to no switching operation. When the short interruption occurs in the power grid, the mode state is changed to UPS mode (Mode IV). In UPS mode, the load power is supplied from the flywheel. After the short interruption recovery, the mode state is changed to the automatic speed regulation mode.

Fig. 3 shows the relationship between the motor voltage and the motor speed. The rated voltage of the induction motor is to the grid voltage for direct grid connection. Since the voltage utilization of the matrix converter is 0.866 or the input voltage, the induction motor is driven using flux weakening in high speed in order to consistent the output voltage command. Thus the output voltage is constant as flux weakening is implemented in high speed. For this reason, when the mode state is changed 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 located between the input side (power grid) and output side (induction motor). In order to solve these problems, the transition control that treats the output voltage to correspond to the input voltage is introduced between the automatic speed regulation mode and the direct grid connection mode. Besides, when the mode state is changed from the direct grid connection mode to the UPS mode, the output voltage will be decreased Nevertheless, the output current does not change widely due to an automatic current regulator (ACR) in motor controller.

Fig. 4 shows the control block diagram for the proposed system. The control method is based on a vector control of the induction motor. The q axis current command I_q^* into the ACR and the switching signal of the matrix converter are changed corresponding four control mode. 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.

A. Mode I – Automatic speed regulation mode

In the start-up of the induction motor, or after the UPS mode, the mode state is changed to the automatic speed regulation mode. In this mode, the induction motor is controlled to increase the motor speed up to rated speed by the

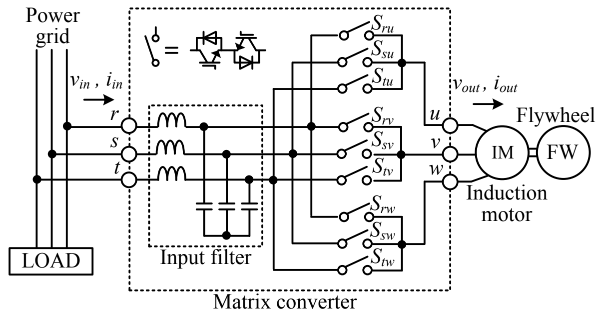


Figure 1. Proposed system using flywheel energy storage with matrix converter.

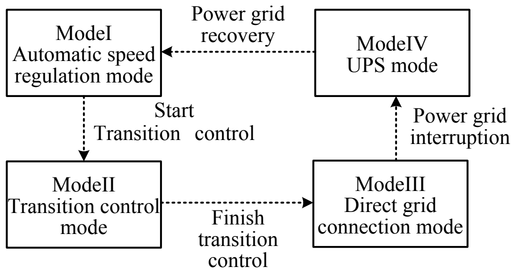


Figure 2. State transition diagram of the control mode.

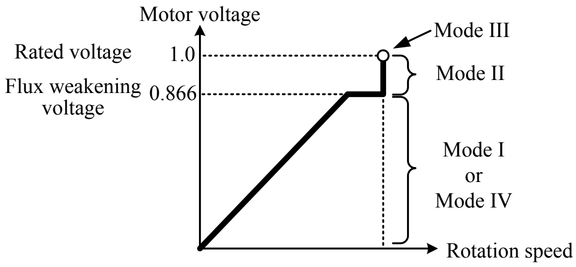


Figure 3. Relationship between motor voltage and rotation speed.

vector control as shown in Fig. 4. I_q^* is set to the output of an automatic speed regulator (ASR).

B. Mode II – Transition control mode

In transition control, the mode state is changed from the automatic speed regulation to the direct grid connection. In order to stabilize the output current, 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. Second, 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, I_q^* is set to zero. Second, 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. Finally, the final value is added with an electrical angular velocity. A transfer function from θ_{ref} to θ_{out} is represented by

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

Equation (1) is second order lag. Thus θ_{out} corresponds to $\theta_{ref.}$ Beside, K_θ and T_θ are designed by

$$K_\theta = 2\zeta\omega_n \qquad (2),$$

$$T_\theta = \frac{2\xi}{\omega_n} \qquad (3),$$

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

Fig. 5 shows the vector diagram on a d-q rotation frame when the output voltage phase corresponds to the input voltage phase. The input d_{in} axis is aligned with U phase of the input voltage vector v_{in}. In the output phase control, the output current vector i_{out} corresponds to the output d_{out} axis because I_q is controlled to zero. Additionally the output voltage vector v_{out} leads from i_{out} by load angle $\theta_{IM.}$

Fig. 6 shows a one single T-type equivalent circuit of the induction motor. R_s and R_r are the stator resistance and the rotor resistance, respectively, then, l_s, l_r and M the a stator leakage inductance, the rotor leakage inductance, and the mutual inductance, and s is the slip of the induction motor. Fig. 6 (a) is the equivalent circuit in acceleration or deceleration. Fig. 6 (b) is the equivalent circuit in constant speed. In the transition control, the motor speed is constant at rated speed. Fig. 6 (b) is applied in transition control. Thereby, the output phase command θ_{ref} which the output voltage phase corresponds to the input voltage phase is expressed by

$$\begin{aligned}\theta_{ref} &= \theta_{in} - \theta_{IM} \\ &= \theta_{in} - \tan^{-1}\frac{\omega_e(l_s+M)}{R_s}\end{aligned} \qquad (4),$$

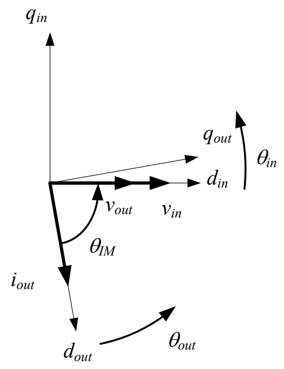
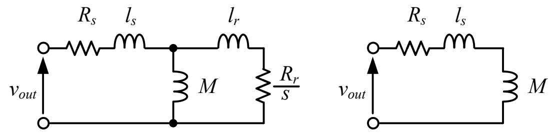


Figure 5. Vector diagram when the output voltage phase corresponds to the input voltage phase.



(a) In acceleration or deceleration (b) In constant speed

Figure 6. Equivalent circuit of an induction motor verified by the fundamental component.

where θ_{in} is the phase angle of input voltage, and ω_e is the electrical angular velocity. When the output voltage phase corresponds to the input voltage phase, matrix converter will be operated in an AC chopper switching mode.

Fig. 7 (a) shows a configuration of a V connection AC chopper, and Fig. 7 (b) shows a control block diagram [11-13]. 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. 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

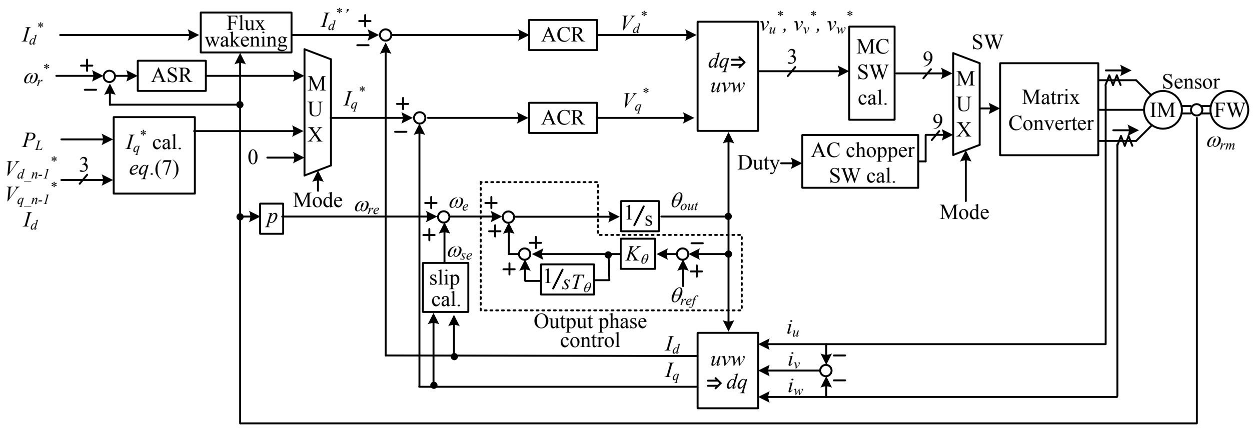


Figure 4. Control block diagram for the proposed system.

pulse of the matrix converter in the AC chopper mode. Duty ratio is increased from an initial value D_{int} to 1. D_{int} is expressed by

$$D_{int} = \frac{\sqrt{V_{d\_int}^{2} + V_{q\_int}^{2}}}{\sqrt{2}V_{in}} \quad (5),$$

where V_{in} is the RMS value of the input phase voltage, V_{d_int} and V_{q_int} are output voltage commands on d-q 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.

C. Mode III – Direct grid connection mode

In the direct grid connection mode, the induction motor is driven by the power from the power grid via the non-switching state of the 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. It is noted that the response time for UPS mode will be delay when the magnetic contactor is used.

D. Mode IV – UPS mode

When the short interruption occurs in the power grid, the mode state is changed to UPS mode. In this mode, the motor speed is decreased from rated speed. The power that use to compensating the short interruption is regenerated from the flywheel to the load. I_q^* is set to required value to supply the load power P_L. Beside, an active power P in rotating reference frame is expressed by

$$P = \frac{3}{2}\left(V_d I_d + V_q I_q\right) \quad (6),$$

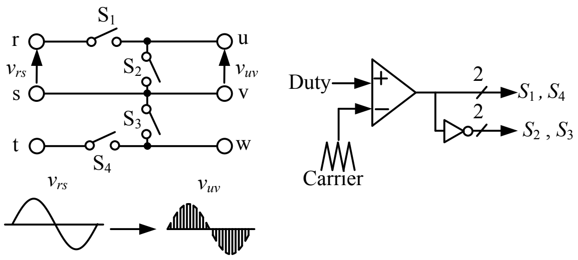
where 3/2 is the coefficient of a relative transformation to the rotating reference frame. Equation (6) is transformed about I_q, so that I_q^* required to supply P_L is expressed by

$$I_q^{*} = \frac{1}{V_{q\_n-1}^{*}}\left(\frac{2}{3}P_L - V_{d\_n-1}^{*} I_{d\_n-1}\right) \quad (7),$$

where $V_{d\_n-1}^*$ is a last value of a d axis voltage command, $V_{q\_n-1}^*$ is a last value of a q axis voltage command, and I_{d_n-1} is a last value of a d axis current. When the grid voltage returns to normal, the mode state is changed to the automatic speed regulation mode.

IV. Verification by Simulation

Table 1 shows parameters of the tested induction motor and the flywheel. Simulation condition is as follows; grid line voltage is 188 V and 50 Hz, as the grid voltage corresponds to the rated values of a tested induction motor. The switching frequency of the matrix converter is 10 kHz. Each PI controller of the vector control is designed, as the response of the ACR and the ASR are 4000 rad/sec and 400 rad/sec. Parameters of the output phase control are designed, as K_θ and T_θ are 14 and 140 msec. The response of the output phase control is 10 rad/sec. Besides, following results are standardized based on the rating of the induction motor.



(a) System configuration (b) Control block diagram

Figure 7. V connection AC chopper.

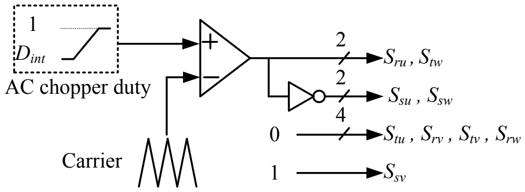


Figure 8. The control block diagram of the matrix converter in the AC chopper mode.

TABLE I. Induction motor and flywheel parameter

Motor rating		Motor and Flywheel parameter	
Rated power	3.7kW	Stator resistance	0.334Ω
Rated speed	1500r/sec	Rotor resistance	0.266Ω
Rated voltage	188V	Stator leakage inductance	0.998mH
Rated current	18A	Rotor leakage inductance	0.580mH
Rated frequency	51Hz	Mutual inductance	28.8mH
Pairs of poles	2	Excitation current	11.6A
		motor moment of inertia	0.0163kgm²
		Flywheel moment of inertia	0.608kgm²

Fig. 9 shows the simulation results including the transition control. The transition starts from the automatic speed regulation mode to direct grid connection mode. The mode state is changed from automatic speed regulation mode to direct grid connection 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 0.46 sec. At 0.46 sec, the voltage phase difference decreases to zero. Then the matrix converter is operated in the AC chopper mode. In the AC chopper mode, the amplitude of output voltage is increased gradually until it matches with the amplitude of input voltage amplitude. At 0.52 sec, the mode state is changed to the direct grid connection. As a result, the transition process is completed within 0.42 sec. Moreover it is confirmed that surge current does not occur during the transition period.

Fig. 10 shows the simulation result of the transition from the direct grid connection mode to the UPS mode. On the assumption that the short interruption occurs during 0.1 to 0.2 sec, the output q axis current command is set by - 0.3 p.u. As a result, the output d-q axis currents are conformed to agree with their commands. It is confirmed that the surge current does not occur during transition period.

V. EXPERIMENTAL RESULTS

In this section, the proposed control is confirmed by experimental setup. Note that RL load (R is 10.3Ω, L is 10mH) is used instead of the induction motor because the flywheel system is constructing now. The parameters of each controller are same as the simulation.

Fig. 11 shows the experimental results of the output phase control. The input voltage v_{rs} and the output voltage v_{uv} are passed through the low pass filter (LPF), so that the phase difference between the input voltage and the output voltage can be identified. As a result, the output voltage phase corresponds to the input voltage phase within 0.6sec. Moreover there is no rush current in the process.

Fig. 12 shows the experimental results of the transition control. At first, the current commands is set as, I_d* is 0A, and I_q* is 5A. Additionally 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.

Fig. 13 shows the experimental results of the transition process from the direct grid connection mode to the UPS mode. In UPS mode, I_q* is set to 5A. As a result, the output q axis currents are confirmed well agreed to the commands. Also, the surge current is not occurred during transition period.

VI. LOSS ANALYSIS

Fig. 14 shows the converter loss analysis in standby mode, as the matrix converter operates in the vector control mode or the direct grid connection mode. The Switching power device is FGW30N60VD (600V 30A, Fuji electric). In the vector control mode, the exciting current in the induction motor is decreased due to the flux weakening. Hence, the conduction loss in the vector control is smaller than the direct grid connection mode. Besides, the matrix converter has no switching operation in direct grid connection mode, so that the switching loss does not occur. As a result, the converter loss in the direct grid connection mode is reduced by 16.5%, compared to the vector control mode.

VII. CONCLUSION

This paper discusses the transition control method for the matrix converter with flywheel for an UPS. Using the direct grid connection mode, the power loss of the matrix converter is reduced remarkably due to no switching operation. By loss analysis, the converter loss in the direct grid connection mode is reduced by 16.5%, compared to the vector control mode. However, the voltage transfer ratio of the matrix converter is limited up to 0.866, so that the rush output current will occur in transition from PWM to direct grid connection mode. To solve this problem, the transition control which treats the output voltage to correspond to the input voltage in term of phase angle is proposed. From the simulation results, it was confirmed that the mode state is changed from the automatic speed regulation mode to the direct grid connection mode within 0.42 sec, moreover the output current is shown stable controllable. Besides, the experimental results also confirmed that the surge current does not occur in transition.

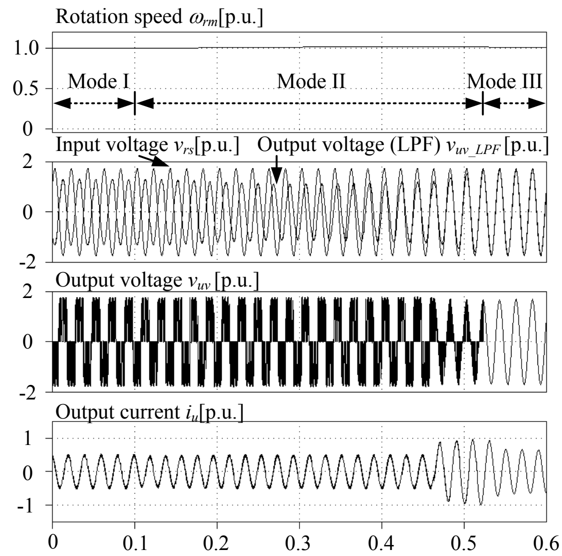


Figure 9. Simulation result of transition from automatic speed regulation mode to direct grid connection mode.

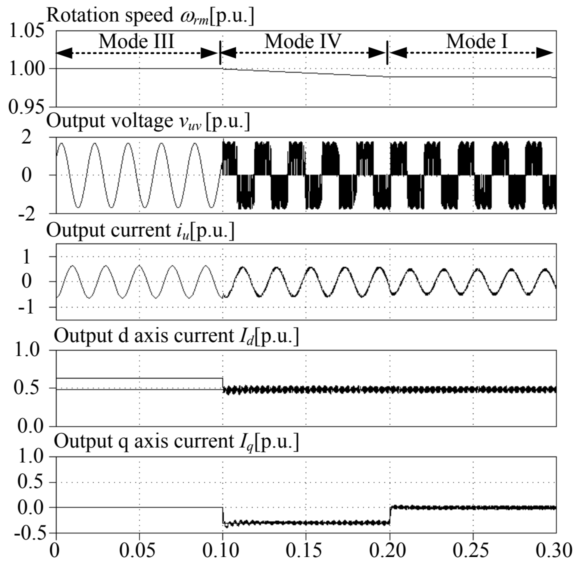


Figure 10. Simulation result of transition from direct grid connection mode to automatic speed rebulation mode.

In future work, the verification of the proposed control by experiment with the induction motor will be shown.

ACKNOWLEDGMENT

A part of this study was supported by Industrial Technology Grant Program in 2009 from New Energy and Industrial Technology Development Organization (NEDO) of Japan.

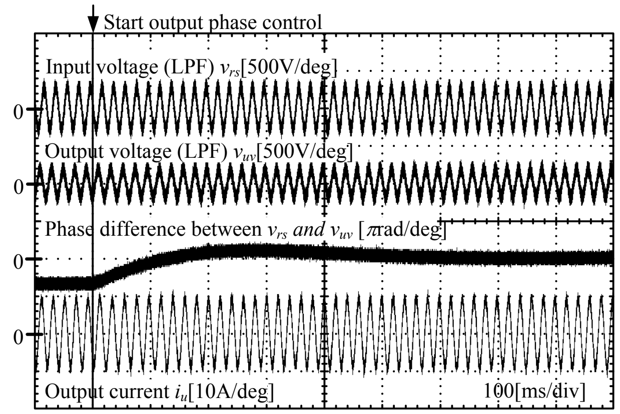


Figure 11. Experimental result of the output phase control.

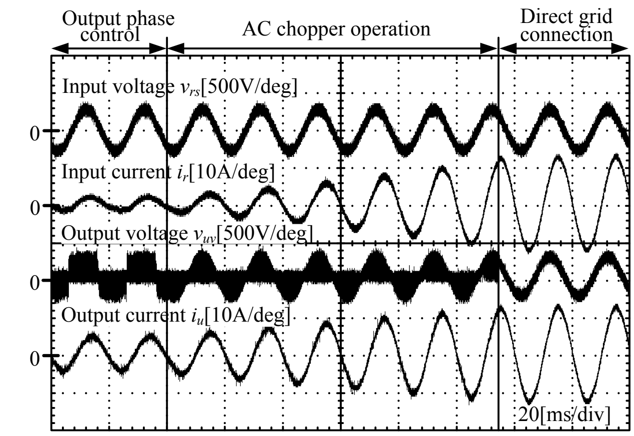


Figure 12. Experimental result of the transition from the automatic speed regulation mode to the direct grid connection mode.

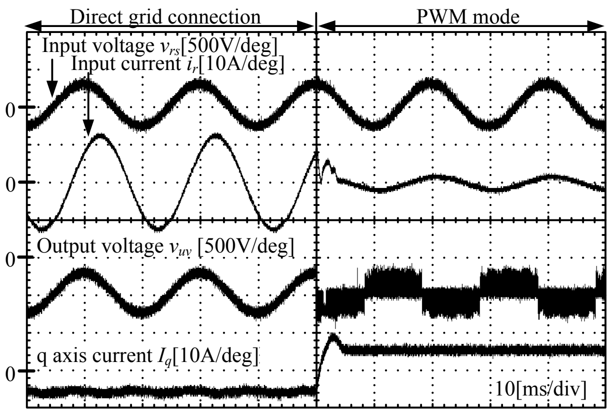


Figure 13. Experimental result of the transition from the direct grid connection mode to the UPS mode.

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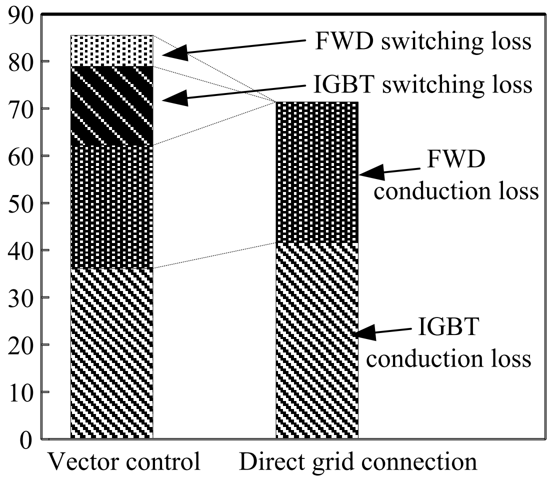

Figure 14. Converter loss analysis in the vector control mode and the direct grid connection mnode.