CURRENT-CONTROLLED PWM-RECTIFIER WITH *di/dt* FEEDBACK /VOLTAGE-SOURCE INVERTER WITHOUT DC LINK COMPONENTS FOR INDUCTION MOTOR DRIVE

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Abstract— **The voltage-source inverters are normally equipped with an electrolytic capacitor in their DC link, however, the electrolytic capacitor has several disadvantages such as increasing size, limiting converter life and reliability. Therefore, several approaches for removing the DC link capacitor have been studied by the authors. This paper proposes a new voltage-source inverter without DC link components. To reduce waveform distortion of the AC source current, the current-controlled PWM-rectifier with *di/dt* feedback is introduced. The *di/dt* feedback gain and *LC* parameters are investigated by calculation for a 0.75kW induction motor driven by this inverter. The calculated AC source currents maintain nearly sinusoidal waveforms with a unity power factor.**

1. INTRODUCTION

The voltage-source inverter without DC link components have already been proposed and verified by the authors, that the inverter made possible the highly reliable four quadrant operation of the induction motor [1] - [3]. The rectifier section of this inverter requires the *LC* filter on the AC source side to improve AC source current. However, when the harmonic components of rectifier input current coincide with the resonance frequency of the *LC* filter, the AC source current is oscillated by resonance of this *LC* filter.

To improve the waveform distortion of the input current, control method based on state-feedback of the *LC* filter has been introduced and verified for the current-type PWM rectifier [4] [5]. However, this rectifier has a smoothing inductor on the DC side and is connected to resistive load.

This paper proposes a new current control method of the voltage-source inverter without DC link component for induction motor drive [6]. The current control strategy for the rectifier is based on hysteresis control that the difference of current errors between 2-phase is compared with the hysteresis band. Since the phase angle of *di/dt* feedback is leading $\pi/2$ than that of the AC source current, the phase angle of the difference of current errors which include *di/dt* as shown in eqn (3) is also leading. Therefore, the switching frequency of the rectifier is depend upon these leading phase angle. Consequently, the waveform distortion of the AC source current is restrained with increasing the PWM frequency of the rectifier. In this paper, the calculated characteristics are described for a 0.75kW induction motor driven by this inverter. As a result, it can be obtained that the AC source current maintain nearly sinusoidal waveforms with a unity power factor.

2. CIRCUIT CONFIGURATION

The overall system described in this paper is shown in Fig. 1. The main circuit consists of the inverter section, the rectifier section and the *LC* filter. There are no smoothing circuit such as electrolytic capacitors and reactors (or resistors) on the DC link. The inverter section employs the IGBT module as a switching device. The PWM-controlled signal, which is generated by comparing the sinusoidal modulating waves with the triangular carrier wave, are applied to each inverter gates. The rectifier section also employs twelve IGBT, and the current flow is possible in both direction when a IGBT is in on-state. The induction motor is loaded with a DC generator connected to resistors. The control circuit is composed of several detectors and logic operations to generate PWM signal for rectifier as the way of current closed loop.

3. CURRENT CONTROL LOOP FOR RECTIFIER

Fig. 2 shows the relationship between AC source phase voltage and gate signal of rectifier. There is no erectrolytic capacitor or reactor on the DC link in this inverter. Therefore, one of the switches in the upper arm of the rectifier and one in the lower arm must be on-state, in order to assure continuous current flow of the load, and without short-circuited between line-to-line. The gate signal of the rectifier is so generated during 60° period Ⓐ (in Fig. 2),

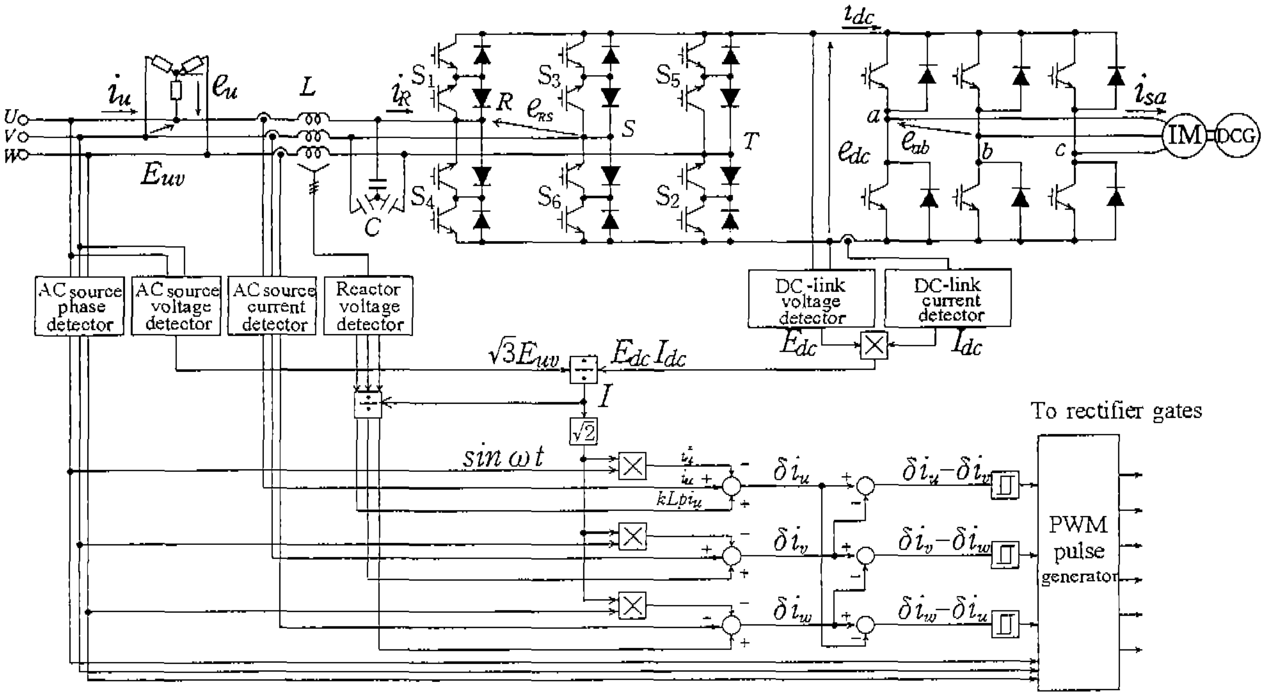


Fig.1. Circuit configuration.

that the upper arm of U−phase switch corresponding to the most highest AC source phase voltage keeps on−state, and the lower arm of V or W−phase switch is turned on each other by the command of the PWM pulse generator.

Generation of Reference Current

Based on power balance equation and assuming unity power factor operation, the reference current I is calculated as follows.

$$I=\frac{E_{dc}I_{dc}}{\sqrt{3}\,E_{uv}} \quad \cdots\cdots (1)$$

Where, E_{uv} and I are the rms values of the AC source input voltage and current; E_{dc} and I_{dc}, the average values of the DC link voltage and current. The averaging interval of E_{dc} and I_{dc} are each 60° period of the AC source. The three−phase reference current i_u^*, i_v^* and i_w^* are obtained by multiplying the AC source phase voltage waveforms.

$$\left.\begin{aligned} i_u^* &= \sqrt{2}\,I\sin\omega t \\ i_v^* &= \sqrt{2}\,I\sin(\omega t-\frac{2}{3}\pi) \\ i_w^* &= \sqrt{2}\,I\sin(\omega t+\frac{2}{3}\pi) \end{aligned}\right\} \quad \cdots\cdots (2)$$

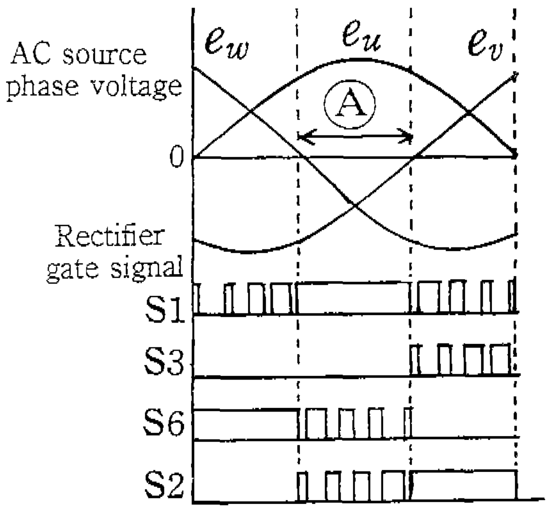


Fig.2. Relationship between AC source phase voltage and gate signal.

Generation of PWM Signal for Rectifier

From the control circuit of Fig. 1, the three−phase current errors δi_u, δi_v and δi_w are derived as follows.

$$\left.\begin{aligned} \delta i_u &= i_u - i_u^* + kLpi_u/I \\ \delta i_v &= i_v - i_v^* + kLpi_v/I \\ \delta i_w &= i_w - i_w^* + kLpi_w/I \end{aligned}\right\} \quad \cdots\cdots (3)$$

where i_u, i_v and i_w are the AC source current, k is the feedback gain, L is inductance of the LC filter and $p=d/dt$.

The third terms of right side of eqn(3) are feedback values which are derivative of the AC source current.

When the AC source current start to oscillate caused by resonansc of the LC filter, the feedback value of $kLpi$ increases rapidly with proportional to the resonance frequency. As the phase angle of $kLpi$ is leading $\pi/2$ than that of i, the phase angle of δi is leading than that of i-i^*. Therefore, the phase angle of difference between 2-phase current errors, such as $\delta i_v - \delta i_w$, is also leading, and crossing the hysteresis band earlier than the case of without feedback. Consequently, the waveform distortion of the AC source current is restrained with increasing the PWM frequency of rectifier. The average PWM frequency of rectifier is so defined as the number of switching pulse of the switch S_1 during 1 second.

The current i and $kLpi$ will increase with increasing the load, therefore, $kLpi$ is divided by the AC source rms current I in order to keep constant value of δi and the PWM frequency of rectifier with increasing the load.

Fig. 3 shows generating method of the PWM pulse for rectifier during period Ⓐ (in Fig.2). Fig. 3(a) shows the direction of current when the switch S_1 and S_6 are on-state, and solid line shows during motoring, and broken line shows during regenerating operation, respectively. The direction of the DC link current is assumed positive during motoring operation. Fig. 3(b) shows the generating method of the PWM pulse of rectifier during motoring operation. In this 60° period, the switch S_1 corresponding to most positive AC source phase voltage e_u keeps on-state, and the switch S_6 or S_2 is turn-on by command of the PWM pulse generator. In Fig. 3(b), the PWM pulse is so generated that the difference between V and W-phase current errors $\delta i_v - \delta i_w$ is compared with the hysteresis band h, In the case of,

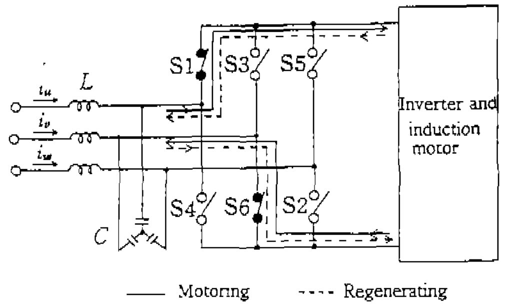
$$\delta i_v - \delta i_w > h \quad \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

then S_6 is turned on to reduce the V-phase current error δi_v. Another case of,

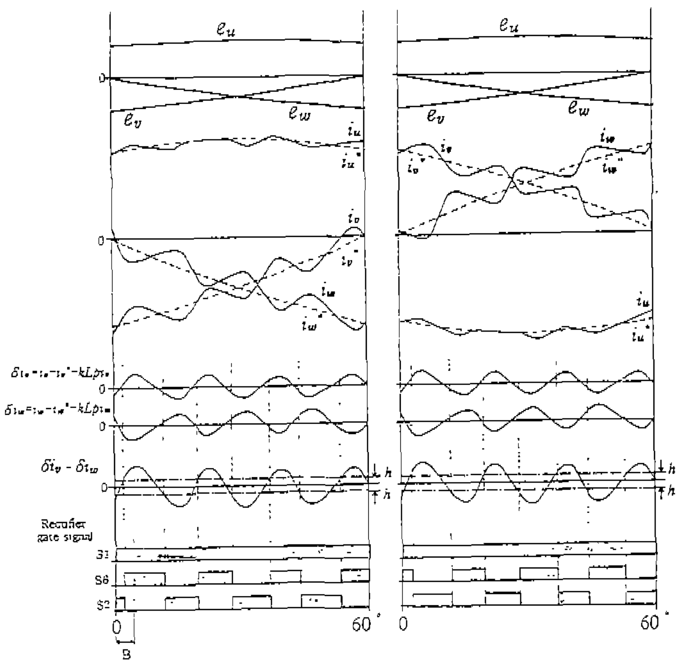
$$\delta i_v - \delta i_w < -h \quad \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

then S_2 is turned on to reduce the W-phase current error δi_w. Where, the hysteresis band h=0.015A is used in the calculation.

Fig.3(c) shows the generating method of the PWM pulse of rectifier during regenerating operation. The DC link current flows negative direction. In this 60° period, the switch S_1 keeps on-state as the same manner as motoring operation. In the case of $\delta i_v - \delta i_w > h$, then S_2 is turned on to reduce the W-phase current error δi_w. On the other hand, $\delta i_v - \delta i_w < -h$, then S_6 is turned on to reduce the V-phase current error δi_v.



(a) Direction of current in rectifier and DC link.



(b) Motoring operation. (c) Regenerating operation.
Fig.3. Generating method of PWM pulse of rectifier.

4. STEADY STATE ANALYSIS

Fig. 4 shows part Ⓑ (in Fig. 3(b)) of the switching waveforms formed by combining the inverter with rectifier. For the interval t-t' in Fig. 4, S_1 and S_6 of the rectifier are on-state, and the voltage vector of the inverter is V_6. Then the equivalent circuit from the AC source to induction motor is shown in Fig.5.

From the equivalent circuit in Fig. 5, the voltage and current equation for variable $x(t)$ are shown as follows,

$$px = A_6 x \quad \cdots\cdots\cdots\cdots\cdots\cdots (6)$$

where $x(t) = [e_1, e_2, i_u, i_v, e_{CR}, e_{CS}, i_{s\alpha}, i_{s\beta}, \Psi_{r\alpha}, \Psi_{r\beta}]^T$, e_1 and e_2 are assumed the AC source voltage; $i_{s\alpha}, i_{s\beta}$ the primary currents; $\Psi_{r\alpha}, \Psi_{r\beta}$ the secondary flux linkages of an induction motor in the α - β stationary coordinate. A_6 is 10×10 matrix which is determined by the equivalent circuit in Fig. 5. The turn-on switches are determined by solutions of (6) and current error conditions of eqns(4) and (5). Equation (6) is computed by mean of Runge-Kutta method with the time step Δt. These calculations are continued for the analysis period 360° using matrices A_m ; and A_m is determined by the switching waveforms combined with the inverter and rectifier.

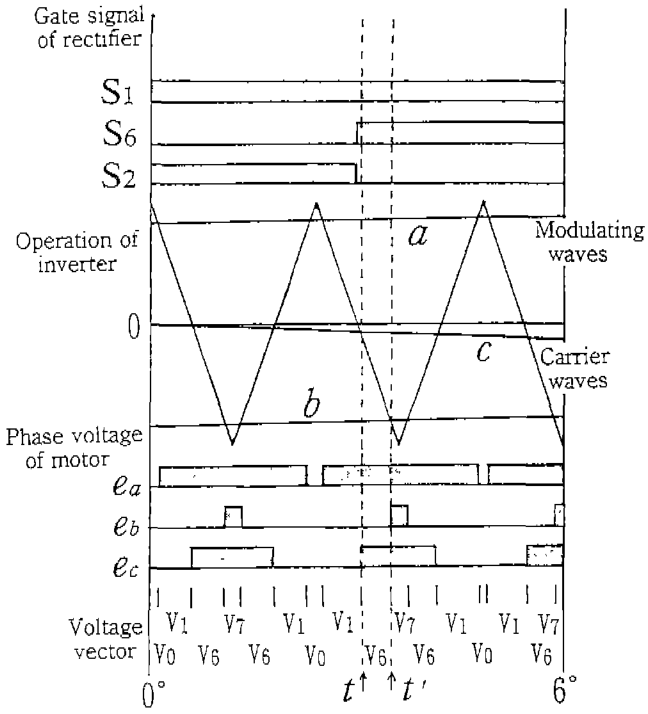


Fig.4. Waveforms of rectifier and inverter.

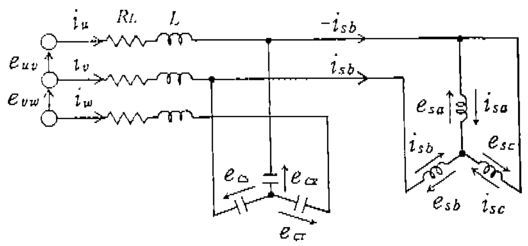


Fig.5. Equivalent circuit in V6 mode. (Interval t~t' in Fig.4.)

TABLE I.
SPECIFICATION OF THE SYSTEM

Induction motor	Rectifier	Inverter
P_0=0.75kW	E_{uv}=240V	Sinc-triangle PWM
4poles	L=3mH	Carrier frequency:8820Hz
f=60Hz	C=2 μF	Modulation index:0.95
r_s=3.45 Ω	R_L=2.5 Ω	
r_r=2.09 Ω	h=0.015A	
L_s= L_r=0.192H	k=0.003	
M=0.184H		

5. SIMULATION

Fig. 6 shows the voltage and current waveforms with changing the input capacitance and inductance for 20kHz of the PWM frequency. Trace from top to bottom, i_u is the AC source current; i_{CR} the capacitance current; i_R the rectifier input current; e_{RS} the rectifier input line-to-line voltage. Small deviation of the AC source current i_u is observed during each 60° period corresponding to the U-phase voltage is the most highest and lowest period. This is caused by the resonance of the LC filter. Total harmonic distortion (THD) of the AC source current i_u shows the minimum value of 12.5% at the condition of C=2uF, L=3mH, and the LC filter capacity is about 50VA. The LC filter capacity is so calculated as the total reactive power of L and C with including harmonic components.

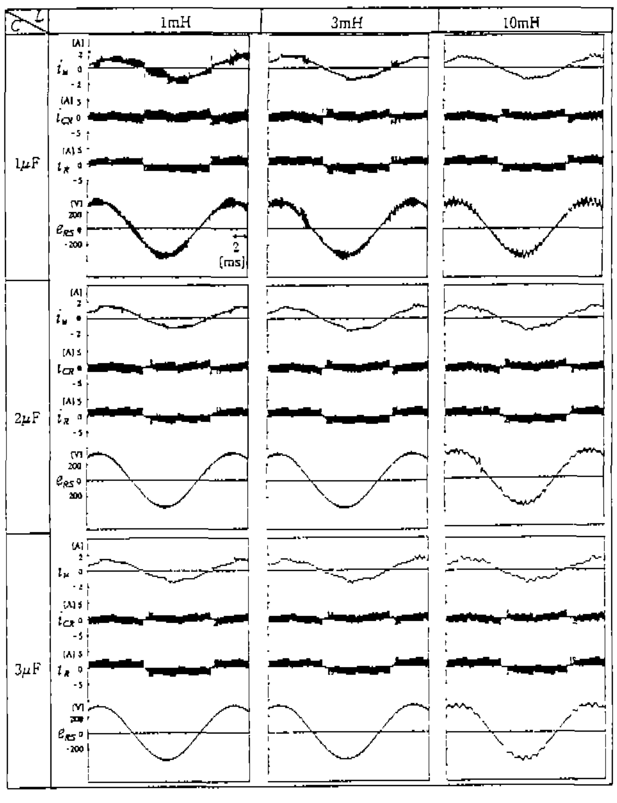


Fig.6. Voltage and current waveforms with changing input capacitance and inductance.
(Average PWM frequency of rectifier is 20kHz and s=3%.)

6. CONCLUSION

In this paper, the calculated characteristics have been described for a 0.75kW induction motor driven by this new inverter, which rectifier is controlled by the current closed loop with *di/dt* feedback. The results obtained in this paper are summarized as follows.

(1)The relationship between parameter of the *LC* filter and *di/dt* feedback gain *k* is clarified for the required PWM frequency of rectifier. The calculated THD of the AC source current is obtained the minimum value of 12.5% for L=3mH, C=2uF when the PWM frequency of rectifier is set around 20kHz.

(2) From the calculated investigations, it is shown that the proposed control method is effective in reducing the waveform distortion of the AC source current. As a result, the *LC* filter capacity is about 50VA when motor slip is 3%.

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