Direct Torque Control with Improved Switching for Induction Motor Drive System Fed by Indirect Matrix Converter

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Abstract

The combination of indirect matrix converter with direct torque control is a way towards energy-saving of the world. This paper investigates the use of four-step switching in rectifier bridge of indirect matrix converters to reduce the electromagnetic torque ripple which appears when direct torque control technique is used in induction motors. By suitably selecting switching pattern, the electromagnetic torque ripple of the motor is effectively reduced. Indirect matrix converter has no electrolytic capacitors in the DC link, which results that volume and size of converter reduced and increased longevity. Using this switching strategy, the advantages of the DTC schemes and the benefits of the indirect matrix converters can be combined. The simulation results of DTC system based on IMC and the comparison of motor performance under the proposed control system with respect to those obtained under conventional DTC confirms its effectiveness and accuracy.

1. Introduction

Direct Torque Control (DTC) is an optimized AC drives control principle where inverter switching directly controls the motor variables: flux and torque. DTC of induction motor (IM) drives has been introduced in the 1980s by Depenbrock, Takahashi and Noguchi as an alternative to field orientation control (FOC), with the twofold objective of simplifying the control algorithms and achieving similar or even better performance [2]-[4].

The main advantage of DTC is the high performance achieved (decoupled control of torque and stator flux, Minimal torque response time and robustness) together with the simplicity of the scheme (no need for coordinate transformation, modulation block and current regulation), Although, some disadvantages are present such as non accuracy of torque and flux estimators, and an inherent torque and flux ripples because of non optimal switching [5]. Many articles have been published to solve problems of DTC. Some of this articles, have tried to improve flux and torque estimators [6],[7]. Some else have focused on optimized and novel switching techniques [8].

DTC is commonly used with a voltage source inverter (VSI), where electrolytic capacitor is used on the dc link of the AC/DC/AC converter in order to smooth the dc voltage and store the energy recovered from the machine during regeneration braking. Large electrolytic capacitors in dc link causes that size and weight of converter considerably increased and longevity decreased [9].

In recent years research on direct frequency conversion using Matrix Converters (MC) has become popular. Matrix converters have many desirable feature compared to the conventional voltage or current source inverter such as [10]-[14]: compact size, Regeneration capability, operation with unity power factor for any load and Good voltage transfer ratio, unitary power factor for any load.

Since the absence of a path for the inductive load current would result large overvoltages, so this converter require snubber circuit. But charge and discharge currents in snubber circuit result losses and disturb waveform of input currents [15]. Accordingly in this paper we use commutation strategy for snubberless matrix converter.

There have been typical two current commutation methods proposed which are not required snubber circuits for a PWM rectifier of AC-to-AC converters without DC link components. The first method named rectifier zero current commutation and second method named rectifier four-step commutation [15]. In this paper we use the rectifier four-step commutation method in the rectifier stage, therefore the mechanisms involved in the commutation process are firstly described.

The paper is organized as follows: in section II, a review of conventional DTC is presented; then, in section III, Indirect Matrix Converter (IMC) is introduced and its current commutation methods for rectifier stage (rectifier four-step commutation) is explained in section IV, in section V the DTC system based on IMC with optimum switching in rectifier bridge of IMC is modeled and explained, simulation results of proposed model and comparison by conventional DTC are available in section VI. Finally, the conclusions are exposed in section VII.

2. Direct Torque Control Principles

The main idea of the DTC is to choose the best vector of voltage, which keeps flux and torque in allowed bandwidth with minimum ripple. The block diagram of the DTC scheme is shown in Fig.1. The flux and torque estimations which are performed by means of mathematical model of induction motor are needed for DTC.

From figure2, voltage vectors can be expressed by:

$$U_i = V_{dc} e^{J(i-1)\frac{\pi}{3}} \qquad i = (1, 2, ..., 6) \qquad (1)$$

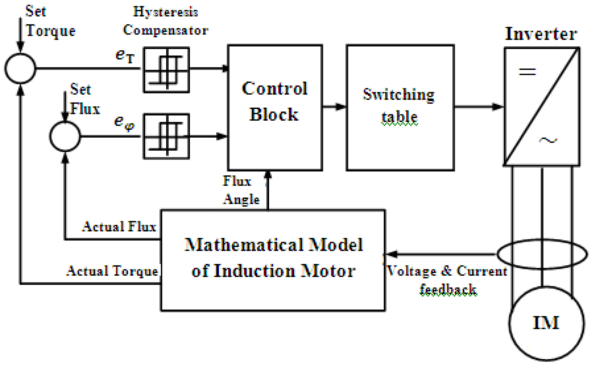


Fig. 1. Block diagram of DTC

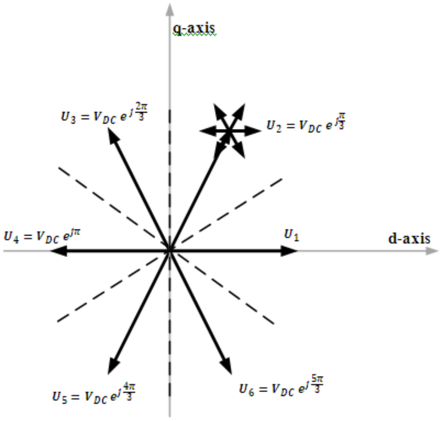


Fig. 2. Stator voltage vectors and flux position

Where J is the square root of -1. As shown in Fig.2, the position of the stator flux is divided into six sectors, highlighted by dashed line and the flux position is determined with this sectors.

The stator flux vector can be calculated using the measured current and voltage vectors.

$$\frac{d\psi_s}{dt} = U_s - R_s I_s \tag{2}$$

$$\psi_{ds} = \int (U_{ds} - R_s I_{ds})dt \tag{3}$$

$$\psi_{qs} = \int (U_{qs} - R_s I_{qs})dt \tag{4}$$

Where R_s is the stator resistance and subscripts ds and qs stand for the d -axis and q -axis components of the voltages and currents of the stator windings of the motor.

Torque is estimated as a cross product of estimated stator flux linkage vector and measured motor current vector.

$$\begin{aligned} T_{em} &= \frac{3}{2} p \left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds} \right) \\ &= \frac{3}{2} p \frac{L_m}{\sigma L_r L_s} \left| \overline{\psi_s} \right| \left| \overline{\psi_r} \right| \sin\theta \end{aligned} \tag{5}$$

Where p is the number of pole pairs, $\overline{\psi_s}$ and $\overline{\psi_r}$ are stator and rotor flux respectively and Θ is the angle between $\overline{\psi_s}$ and $\overline{\psi_r}$.

The estimated flux magnitude and torque are then compared with their respective desired values and the resulting value are fed into the two-level and three-level hysteresis comparators respectively. the outputs of both stator flux and torque comparators together with the position of the stator flux are used as inputs of the switching table (see table 1) [16].

This is noteworthy that Because of that rotor time constant is larger than the stator one, the rotor flux changes slowly compared to the stator flux; in fact, the rotor flux can be assumed constant. If it happens that there is a deviation from the reference more than allowed tolerance, the hysteresis controller and switching table help DTC to choose appropriate inverter state to make flux and torque return in their tolerance band as quickly as possible.

Table 1. Optimum switching Table

H_φ		1			0		
H_{Te}		1	0	-1	1	0	-1
Flux sector	1	U_2	U_7	U_6	U_3	U_0	U_6
	2	U_3	U_0	U_1	U_4	U_7	U_1
	3	U_4	U_7	U_2	U_5	U_0	U_2
	4	U_5	U_0	U_3	U_6	U_7	U_3
	5	U_6	U_7	U_4	U_1	U_0	U_4
	6	U_1	U_0	U_5	U_2	U_7	U_5

3. Indirect Matrix Converter

Indirect Matrix Converter (IMC) is an AC/DC/AC converter, but bulky DC link capacitor is eliminated in it and a filter in entrance is used instead. Also, bi-directional switch in rectifier stage are used (see fig.3).

Because it has converter configuration with two separate stages (rectifier and inverter stages), it has been considered more flexible to modify its topology. Pulse width modulation algorithms of conventional inverters can be utilized, which can greatly simplifies its control circuit. Furthermore commutation problem of DMC are considerably reduced by utilize specific current commutation methods [5],[6].

Regarding commutation strategies of MC, two main rules should be taken into account: 1) The incoming and outgoing switches should not be switched on together at any point in time 2) Also these switches should not both be switched off at the same timeestroy the switches [8].

Typically two types of commutations methods have been proposed which don't require snubber circuits for a PWM rectifier of AC-to-AC converters without DC link components. The first method named rectifier zero current commutation and the second method named rectifier four-step commutation.

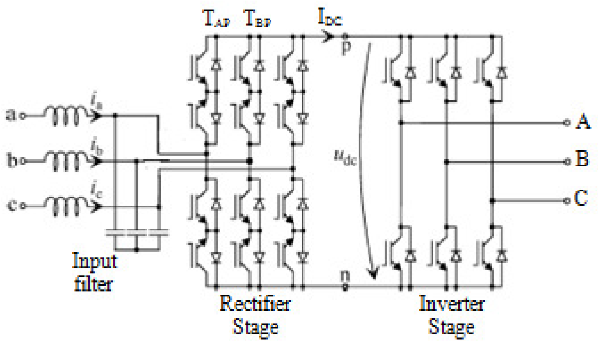


Fig. 3. Indirect Matrix Converter

In these methods, although the losses in snubber circuits and the switching losses in the PWM rectifier can be reduced, a complicated control circuit must be added to synchronize the switching of both the PWM rectifier and the PWM inverter [3].

In this paper we use the four-step commutation method in the rectifier stage, therefore the mechanisms involved in the commutation process are firstly described.

4. Four-Step Commutation Strategy

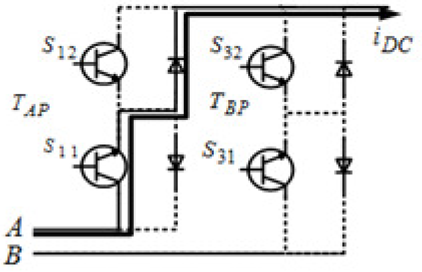
The commutation process of matrix converter is more complicated compared with traditional AC-DC-AC converter due to having no natural free-wheeling paths, so the commutation problem is one of the main reasons for hindering practical applications [22].

Regarding commutation strategies of MC, two main rules should be taken into account: 1) The incoming and outgoing switches should not be switched on together at any point in time since this will result in an input line to line short circuit leading to switch over current; 2) Also these switches should not both be switched off at the same time since there is no path for the inductive load current and large over-voltage would destroy the switches [12].

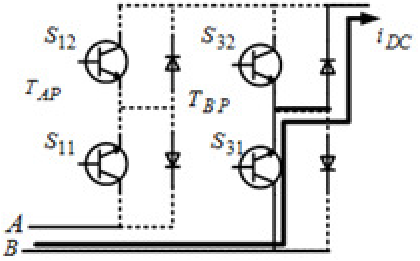
Nandor Burany firstly presented the four-step commutation strategy to solve commutation problem according to rigorous logic control [22],[23]. And the optimized methods based on four-step commutation were presented one after another to improve the waveform of input and output and enhance the commutation reliability [22].

Direction of output current and value of input voltage determine the sequence of switches that using four-step commutation strategy. When output current or the two input phase-voltage difference is very small, it's possible to commutate unsuccessfully. Therefore commutation reliability depends on accuracy in detecting the direction of output current and two input-phase voltage differences.

The process of commutation is explained with Fig.4. T_{AP} and T_{BP} are shown in Fiq.3. For example in this case the purpose is to show switching between phase A and B . phase A connects to rectifier output through IGBT of switch S_{11} and diode of switch S_{12} . At this point, as it is shown (dotted lines in figure 4.a) current does not pass from other transistors and diodes. It has been supposed that commutation begins from phase A to phase B . When $i_{DC} > 0$ the following four-step switching sequence is: 1) turn off S_{12} ; 2) turn on S_{31} ; 3) turn off S_{11} ; 4) turn on S_{32} . When $i_{DC} < 0$, the following four-step switching sequence is: 1)turn off S_{11}; 2)turn on S_{32}; 3)turn off S_{12}; 4)turn on S_{31}.



a: path of current flow (t=t$_1$)



b: path of current flow (t=t$_2$)

Fig. 4. Commutation from T_{AP} to T_{BP}

5. Modeling Novel DTC for IM Based on IMC with Optimum Switching

In this section the suggested model of Direct Torque Control based on Indirect Matrix Converter with optimum switching in rectifier bridge is presented and analyzed. The figure 6 shows the related diagram block.

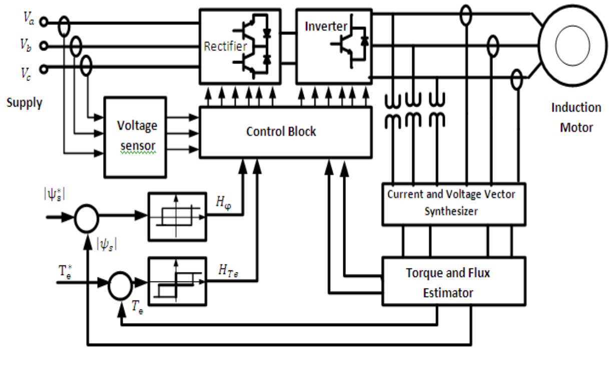


Fig. 6. Schematic diagram DTC based on IMC

As its shown, input voltages are sensed and along with torque and flux error, produced six command for bi-directional switch of rectifier bridge. According to switching of rectifier bridge and with regard to the lack of DC capacitor, the output of rectifier bridge is approached like fig.7. This figure is divided into three parts: low voltage, medium voltage and high voltage [24].

If torque error is within allowed band, there is no necessity for drastic changes. So, with appropriate switching in rectifier bridge the low voltage is produced in DC link. If this error is a little outside of allowed band, the medium voltage is produced in DC link, and finally if this error so much, the high DC voltage is produced with switching in the rectifier section. This method helps a lot to optimized Direct Torque Control of induction motor.

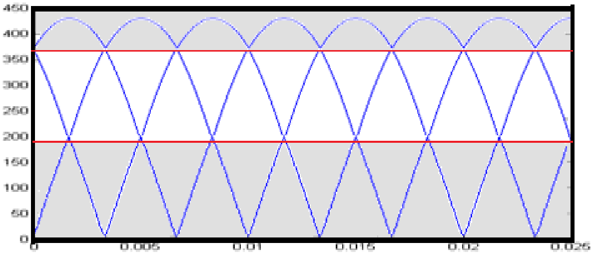


Fig. 7. Output voltage of rectifier bridge

5. Simulation results

Figs. 8-15 illustrate the simulation results obtained using SIMULINK/MATLAB software under the following conditions: Line-to-line input voltage $430V$ and input frequency $50Hz$. The load torque is $10N.m$. The parameters of induction machine are listed in table 2.

The parameters of the Ac filter in entrance of converter for the MATLAB simulation are:

Filter inductor: 10 mH Filter capacitor: 100 µF

Table 2. The parameter of Induction motor

Parameter name	value
Rated output power	2.25kW
Number of poles	4
Resistance	
Stator	0.435Ω
Rotor	0.816Ω
Inductance	
Stator	2mH
Rotor	2mH
Mutual inductance	69.3mH

The time variations of flux and torque are described in Table 3.

Table 3. Time variation of torque and flux

period	Torque (N.m)	Flux (Wb)
0<t<0.2s	20	0.6
0.2<t<0.3s	10	0.6
0.3<t<0.4s	10	0.7

A. *Torque*

The result of torque control for both classical DTC and the proposed method is presented in Figs.8 and 9. As can be seen, the proposed method leads to less deviation from the set value of torque (desired torque) rather than the conventional DTC. Speed of motor is shown in fig. 10.

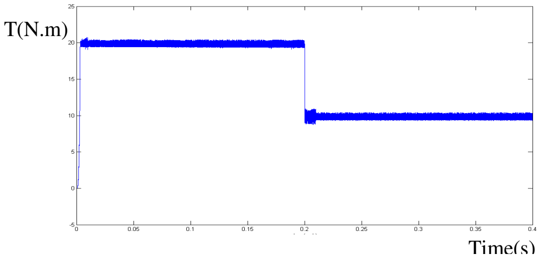


Fig. 9. Output torque of DTC based on IMC with optimum switching

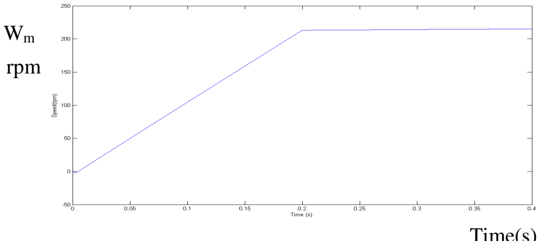


Fig. 10. Speed of the motor

A. *Flux*

Fig. 11 shows the flux response to a sudden change at time $t = 0.3s$. Figs. 12 and 13 show the flux circular trajectory for both classical DTC and the proposed method. It is obvious that this way can improve steady and dynamic performance of the system and decrease unreasonable flux ripple.

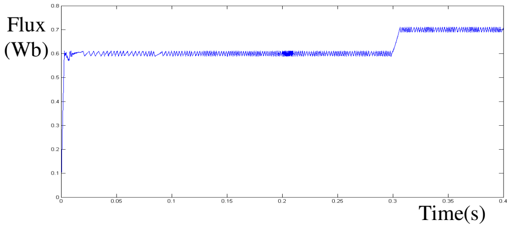


Fig.11. Flux response

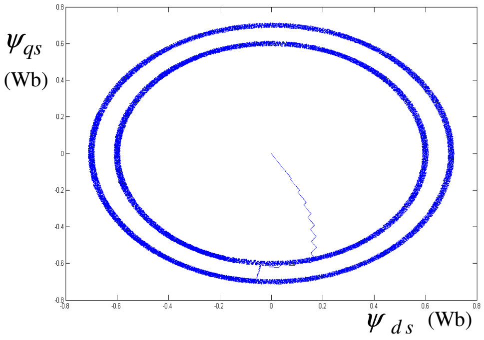


Fig. 12. Flux circular trajectory of conventional DTC

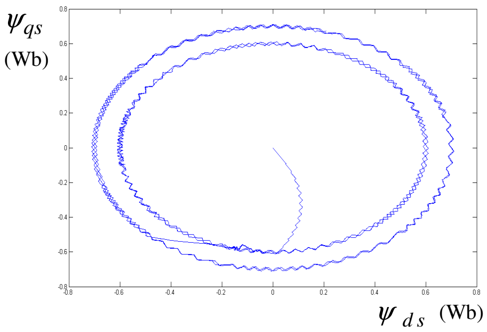


Fig. 12. Flux circular trajectory of DTC based on IMC with optimum switching

B. *DC voltage*

Fig. 13 shows the high DC link voltage of IMC that is shown for example.

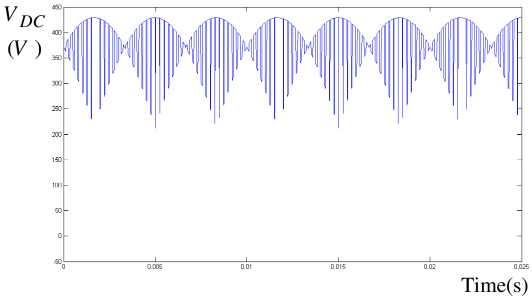


Fig. 13. DC voltage of IMC

C. *Input phase voltage and phase current*

Fig. 14 shows the waveforms of input phase voltage and phase current. From this figure, it can be observed that the input phase current is also sinusoidal. It can be found in this figure that, the phase angle of current is leading the voltage. This result is caused by choice of the parameters of input filter.

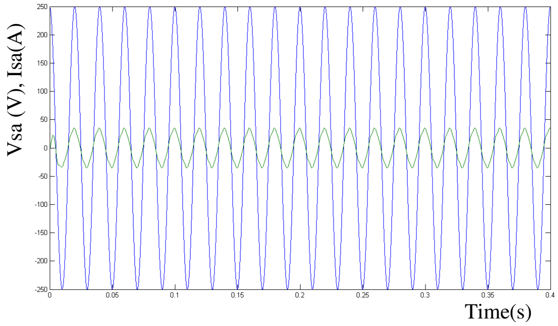


Fig. 14. Input phase voltage & current

D. *Output currents*

From Fig. 15, it can be noted that the waveforms of three phase output currents are essentially sinusoidal. This result, in turn, demonstrates that there are no low order harmonics in the output voltage.

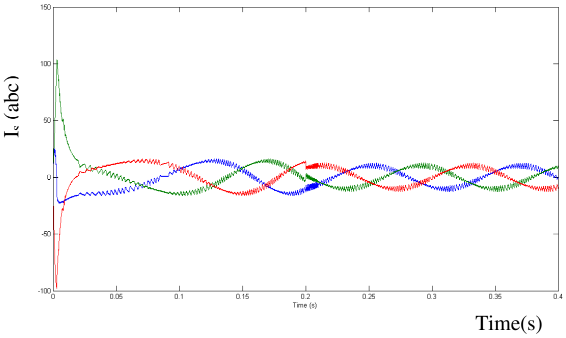


Fig. 15. Three phase output current

6. Conclusions

In this paper for enjoyment of the benefits of matrix converters and direct torque control (which was explained in detail) simultaneously with direct torque control based on indirect matrix converter is proposed. The advantages of this combination are: small size, fast response in torque control, near sinusoidal input current, adjustable input displacement power factor, regeneration capability and long life-time. To reduce problems, snubbers were excluded from the converter and Four-step commutation strategy was used instead. This method increased the complexity of switching but also reduces problems of snubbers such as increasing losses and volume of converter. Simulation results obtained from SIMULINK/MATLAB simulation software verify the effectiveness of the strategy proposed in this paper.

7. References

[1] E. Ozkop, H.I. Okumus, “Direct torque control of induction motor using space vector modulation (SVM-DTC), ’’ Power System Conference. MEPCON 2008. pp: 368 – 372.

[2] M. Depenbrok, “Direct self-control (DSC) of inverter-fed induction machine,” IEEE Trans. Power Electron., vol. 3, no. 4, pp. 420–429, Oct. 1988.

[3] I. Takahashi and T. Noguchi, “A new quick-response and high efficiency control strategy of an induction motor,” IEEE Trans. Ind. Appl., vol. IA-22, no. 5, pp. 820–827, Sep./Oct. 1986.

[4] G. Buja, R. Menis, “Steady-State Performance Degradation of a DTC IM Drive Under Parameter and Transduction Errors’’, IEEE Trans. Ind. Appl., Vol.55, Issue:4 , pp: 1749 – 1760, 2008.

[5] M. J. Ghorbani; M. Akhbari; H. Mokhtari; “Direct torque control of induction motor by Active Learning Method,’’ 1st Conference on Power Electronic & Drive Systems & Technologies (PEDSTC), pp: 267 – 272, 2010.

[6] L. Yongdong; H. Hu; J. Chen; W. Jixiong; “Predictive control of torque and flux of induction motor with an improved stator flux estimator,’’ Power Electronics Specialists Conference, 2001. PESC.Vol.3, pp: 1464 – 1469.

[7] L. Tang, “Investigation of an improved flux estimator of a direct torque controlled interior permanent magnet synchronous machine drive,’’ Power Electronics Specialists Conference, 2004. Vol.1, pp: 451 – 457.

[8] Gharakhani, A. Radan, “A Novel Strategy for Minimizing the Variation of Neutral Point Voltage and Switching Frequency in DTC Controlled, NPC Driven Induction Motors,’’ Electric Machines & Drives Conference, 2007. Vol.1, pp: 748 – 753.

[9] X. Chen, M. Kazerani; “A New Direct Torque Control Strategy for Induction Machine Based on Indirect Matrix Converter,’’ IEEE International Symposium on Industrial Electronics, Vol.3, pp: 2479 - 2484 July 9-12, 2006

[10] M. Jussila, H. Tuusa, “Space-Vector Modulated Indirect Matrix Converter under Distorted Supply Voltage - Effect on Load Current,’’ Power Electronics Specialists Conference, 2005. pp: 2396 – 2402.

[11] L. Wei, T. A. Lipo, “A novel matrix converter topology with simple commutation,’’ Industry Applications Conference, 2001. Vol.3, pp: 1749 – 1754.

[12] P.W. Wheeler, J. Rodriguez, J.C. Clare, L. Empringham, A. Weinstein; “Matrix converters: a technology review,” IEEE Transactions on Industrial Electronics, Vol. 49, Issue 2, Apr 2002 pp. 276 – 288.

[13] Y. Minari, K. Shinohara, R. Ueda, “PWM-rectifier/voltage-source inverter without DC link components for induction motor drive,” IEE Proc. On Electric Power App., Vol. 140, No. 6, pp. 363 –368, 1993.

[14] D. Casadei, G. Grandi, G. Sera, A. Tani, “Space vector control of matrix converters with unity input power factor and sinusoidal input/output waveforms,” IEEE Industrial Electronics, IECON 1993, pp. 171-175

[15] K. Iimori; K. Shinohara; K. Yamamoto; “A study of dead-time of PWM rectifier of voltage- source inverter without DC link components and its operating characteristics of induction motor,’’ Industry Applications Conference, 2004. vol.3, pp: 1638 – 1645.

[16] G. S. Buja and M. P. Kazmierkowski, “Direct torque control of a PWM inverter-fed AC motors—A survey,” IEEE Trans. Ind. Electron.,vol. IE-51, no. 4, pp. 744–757, Aug. 2004.

[17] Sangshin Kwak, “Indirect matrix converter drives for unity displacement factor and minimum switching losses,’’ Electric Power Systems Research, Volume 77, Issues 5-6, April 2007, pp 447-454.

[18] L.Wei, T.A.Lipo, H.Chan:” Matrix Converter Topologies with Reduced Number of Switches”, PESC2002, No.2-3-1(2002)

[19] M.Muroya Iimori,K.Shinohara,K.Yamamoto :”A Zero Current Switching Strategy of PWM Rectifier of Converter without DC Link Components for Induction Motor Drive”, Trans. Inst. Elector. Engng. Jpn., Vol.122-D,No.6,

[20] M. Mwoya; K. Shinohara; K. limori and H. S&o; “Four-step commutation strategy of PWM rectifier of converter circuit without dc link components for induction motor drives,” proc. Conf. Rec IEEE IEMDC. 2001. pp. 770-772.

[21] K. Shinohara, K. Iimori, M.Muroya, Y. Matsusita, “Commutation Strategy for PWM Rectifier of Converter without DC Link Components for Induction Motor Drive”, Proc. of EPE-PEMC2002

[22] M. X. he; T. G. jun; W. X. Ian; F. Y. li; Z. Xiao; H. Y. fei; “Research on Improved Four-step Commutation Strategy of Matrix Converter Based on Two Line Voltage Synthesis’’ Second International Conference on Innovative Computing, Information and Control, ICICIC '07 , pp: 503 – 503, 2007.

[23] Wheeler P, Clare J, Empringham L. “Enhancement of matrix converter output waveform quality using minimized commutation times,’’ IEEE Trans. On Industrial Electronics, 2004, 51(1): 240-244.

[24] Y. Li, W. Liu; “A Novel Direct Torque Control Method for Induction Motor Drive System Fed by Two-stage Matrix Converter with Strong Robustness for Input Voltage,’’ Industrial Electronics and Applications, 2007. pp: 698 -702

[25] D. Casadei, G. Serra and A. Tani, “The Use of Matrix Converters in Direct Torque Control of Induction Machines,’’ IEEE Transactions on Industrial Electronics, vol. 48, no. 6, Dec. 2001.