Back ground and frontier on Matrix Converter (PWM Cyclo-Converter) for new drive system in next generation

Takashi Koga* Hyun-Woo, Lee

Kyungnam University
449, Wolyoung-dong, Masan, Korea 631-701

Abstract: *Today we have excellent motor drive system using high frequency carrier PWM control voltage source inverter with vector control strategy. In the other hand, we have met serious problems caused by high frequency switching. PWM Cyclo-converter called Matrix converter is expected as the new strategy possible to improve these problems and add some more convenient features suitable for new drive system with system integration. In this paper, we will introduce the background of this development and features of this converter from our research, additionally introduce remarkable active promotions for this converter as a survey.*

Keywords; Matrix converter, PWM Cyclo-converter, Motor drive, High frequency switching

1. Introduction

In these years, adjustable speed drive using AC motors and inverters has had remarkable expansion in industrial drive, Mechatronics and also appliances. And we have realized excellent control performance in inverter drive, using high frequency carrier PWM control voltage source inverter. However, we have met serious problems caused by high frequency switching, in the other hand. [21]

To improve these problems, there are many proposals as application of soft switching technology or protection system using some kind of filters. However, it is very difficult to apply soft switching technology for high performance inverter, using high frequency carrier consisted by sharp rise up pulse train. Obviously, protection filters give us additional cost.

For improvement those problems, there is proposal of PWM Cyclo-converter popularly called "Matrix converter" instead of high frequency switching PWM voltage source inverters.

In this paper, we will introduce the background of this proposal at first, next outline of Matrix converter as the expectable strategy for new drive system in next age, and finally remarkable promotions on the research and development of this converter mainly in Japan.

2. Back ground for new strategy

2.1 Progress of drive and its controllability

Today we have realized excellent performance in adjustable speed drive using inverter. For this field PWM controlled voltage source inverter has been used mainly in these years.

*) Takashi Koga Qualified Engineer
Koga Engineering Inc.
No. 3-2-8, Teraonaka, Ayase, 2521132 Japan
Tel & Fax: +81-467-78-0869
e-mail: koga-t@mue.biglobe.ne.jp
Now, Invited Professor of Kyungnam University

Major key technologies of these inverter drives are shown as follows:

1) Application of high frequency carrier, based on remarkable progress of switching performance in semi-conductor power devices.
2) PWM modulation technique.
3) Vector control method, possible to control output torque of AC motors like as DC motor.
4) Application of advanced control strategies, effective for improvement of control performance.

Today it is easy to use high frequency carrier over 10kHz with sinusoidal modulation or some other advance method on PWM modulation. And high frequency carrier is the most important for inverters, as beautiful waveform in motor current, reduction of acoustic noise from motor frame, improvement of parasitic resonance in mechanical system at some speed, and so on.

Especially, high frequency carrier had opened the door to the practical application of the vector control and also advanced control strategies. It is performed to control output torque of AC motor accurately like DC motor by this vector control strategy. And application of advance control technologies had made highly contributions for grade up on control function and its quality. These new technologies are very powerful weapon getting high performance in industrial drive and also in Mechatronics. [1]

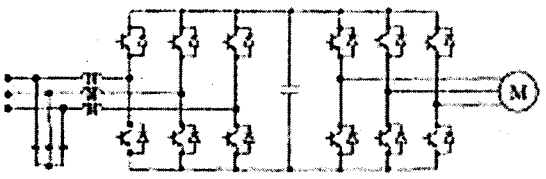


Fig. 2-2-1 AC/DC PWM converter applied for inverter drive

2.2 Requirement from power supply line

In practical inverter drive, it is popular to use simple rectifier with capacitor input low pass filter as AC/DC conversion. However, this gives us rich harmonics and wrong effective power factor in power supply line. These problems are growing up bigger and bigger in accordance with expansion of power electronics equipment in these years.

To improve this problem it is recommended to use AC/DC PWM converter as shown in fig.2-2-1. This topology gives us good power factor and fewer harmonics; however, it gives us very higher cost. Then, it is expected to get good power factor and beautiful waveform in power supply with lower cost.

2.3 Problems by high frequency switching

Although high frequency carrier contributes for inverter drive, high frequency switching accompanied with high frequency carrier gives us serious problems, based on high frequency component caused by high dv/dt of PWM pulses. Major problems are as follows.

1) Increasing of high frequency leakage current through loaded motor frame.
2) Insulation problems at the loaded motor coil.
3) Electric corrosion of bearing in loaded motor.

In the voltage source 3-phase inverter, the output terminal voltage shows 4-step levels against to the earth in accordance with switching of power devices. In high frequency component, it is equivalent to the same situation adding common mode high frequency voltage to load terminal as shown in fig.2-3-1. When we use higher frequency switching in the inverter, this high frequency common mode voltage becomes bigger and bigger naturally.

These high frequency common mode pulses give us big leakage current through earth line of the motor and make sometimes miss-recognition of protection instruments for insulation failure. And this high dv/dt is terrible for motor insulator also.

More dangerous case, if the rotor connected directly to the load which has lower potential to the earth than the motor frame, the common mode current flows through the load and high peak voltage is supplied to bearing as shown in fig.2-3-2. This common mode voltage having high peak value is very serious for bearing. It is often the cause of electric collision in motor bearing. [2][3]

2.4 Additional requirement for new age

There are some more important requirements on power electronics for motor drive in next generation.

One is elimination of the chemical capacitor. In voltage source inverter, it is necessary to use big capacitor as low pass filter in DC stage, and chemical capacitor has been the most popular device in many years. However, chemical capacitor has finite life, then the reliability or workable life of inverter is depending on this chemical component.

Another is big size of chemical capacitor. There is new promotion for introduce of integrated motor, which has inverter over the motor frame. One of the

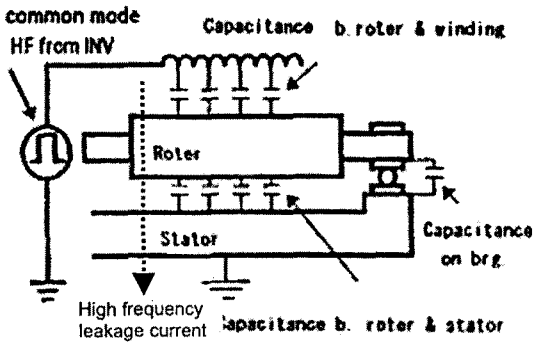


Fig.2-3-1 Common mode high frequency noise induced from inverter to motor

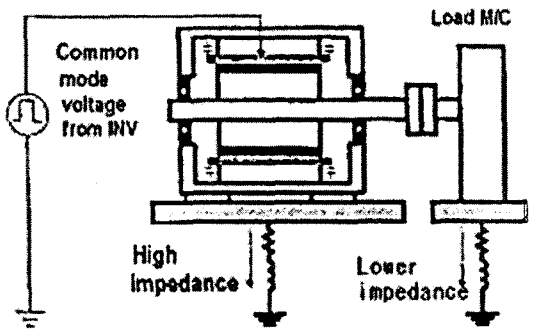


Fig.2-3-2 Effect of impedance to the earth

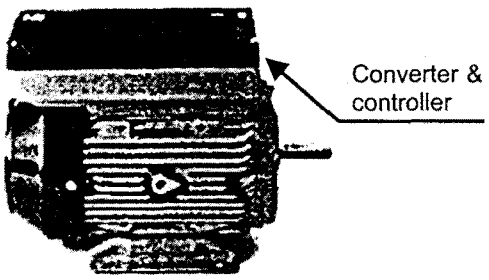


Fig. 2-4-1 Example of integrated motor developed by Danfos Co.

weak points in inverter drive is big size of chemical capacitor. Then there is strong requirement to make up inverter drive without chemical capacitor.

Integrated motor has another background in the field of system integration. In conventional industrial application, it is necessary to connect many devices each other by wiring. The higher integrated system gives us the more complex wiring as natural. As this wiring cost is one of the most serious problems in today's industry especially with higher revel system integration; the application of integrated motor is expected to be good solution for this problem.

In this integrated motor, inverter and control system are mounted over the motor frame as shown in fig.2-4-1. Then the wiring are reduced to only power

supply line and high speed LAN cable connecting between central controller and distributed computer integrated on each motor. In this integrated motor, the most important point is reduction of size of converter. Obviously, it is very important to eliminate chemical capacitor in DC filter, and to use smaller power devices in converter. [18][30]

2.5 Expected motor drive in new age

As mentioned above, the requirement to new drive system in next age is as follows;

1) Basically keeping good performance of today's inverter, as good ability for output waveform, control ability, and better efficiency in operation.
2) Free from problems caused by high frequency switching.
3) Easy applicable soft-switching technology for prevention of problems caused by high dv/dt.
4) Having good power factor and less harmonics in power supply line.
5) Without big chemical capacitor.
6) Expected to make up total system by simple circuit topology of AC/AC direct conversion, with higher efficiency, by economical devices, and smaller size applicable for integral motor.

3. Approaches for improvement

3.1 Application of soft switching

The first approach for the problems mentioned above is application of soft switching technology. Although soft switching technology is very useful for switching regulators and some kind of power supply as UPS's, which have preferable narrow range in PWM control, there is big difficulty to apply this soft switching for motor drive.

When we apply soft switching technology, it is performed by moderation of dv/dt in each pulse constituent high frequency carrier PWM system. Then we add some resonance circuits to major devices reducing dv/dt of PWM pulses. It means that the pulses should have some suitable width possible to add moderation part. However, it is requested to have extremely high control performance in today's motor drive. At the results, we should use wide range control in PWM system for these systems. Then we should use high frequency pulse train in PWM system, and which pulse width has very wide control range. In today's motor drive using vector control method, it is not special to use only a few microseconds as minimum pulse width.

As mentioned above, the cause of this problem depends on the only one freedom in control concept of pulse width under fixed DC highest voltage. Then it is very difficult to get suitable compatibility between high control performance and soft switching in high frequency switching PWM voltage source inverter.

3.2 Current source inverter

Another approach is current source inverter (CSI). CSI is constructed by adjustable voltage DC source with reactor in DC stage, as shown in fig.3-2-1. In this topology, current of DC stage is kept constant, as a current source by the reactor. The voltage of output pulse is adjusted in accordance with motor speed. CSI has good output voltage waveform under preferable low carrier frequency.

Although this CSI has some features, there are some difficulties to get reverse blocking device, to apply for multi-motor drive, and to get reactor in suitable cost and size.

3.3 Suggestion from "Thyristor Motor"

Before inverter drive, "Thyristor Motor" was appreciated from industrial drive widely as brush-less adjustable speed drive. This motor is based on load commutation inverter; the most famous topology is the combination of thyristor cyclo-converter and synchronous motor with position sensor, as shown in fig. 3-3-1. [36]

Cyclo-converter has good performance for variable frequency and variable voltage power supply in low output frequency and no problem on shoot through. In this thyristor motor output voltage is adjusted by the conduction angle of thyristor, and commutation is conducted by pole position from the sensor. Using load commutation in high frequency area, this thyristor motor is applicable for wide speed range drive far over than synchronous speed.

Although thyristor motor has excellent features, this is limited to specific application today, by the higher cost of synchronous motor than induction motor and development of turn off device like as IGBT in cheep cost.

However, this cyclo-converter gets attention again as the excellent feasibility of AC/AC direct conversion with application of today's turn off devices. We shall discus in next chapter.

4. Expectation for Matrix converter

4.1 Inevitable way to Matrix converter

To fill the requirement on power conversion system applicable for motor drive mentioned above, there were many trials to get better conversion system. In this flow, there is attention to PWM Cyclo-converter having the attractive features in circuit topology. [4][28][29][31]

Off cause, there are many difficulties to clear up all requirements listed up in 2.5; Koga had aimed at this circuit topology from the experience about cyclo-converter type Thyristor-Motor, which were famous products of Toyo Electric Mfg. Co., Ltd. Japan, and had started the research on this converter with the guidance from Professor J.Oyama Nagasaki University Japan. The outline of this converter based

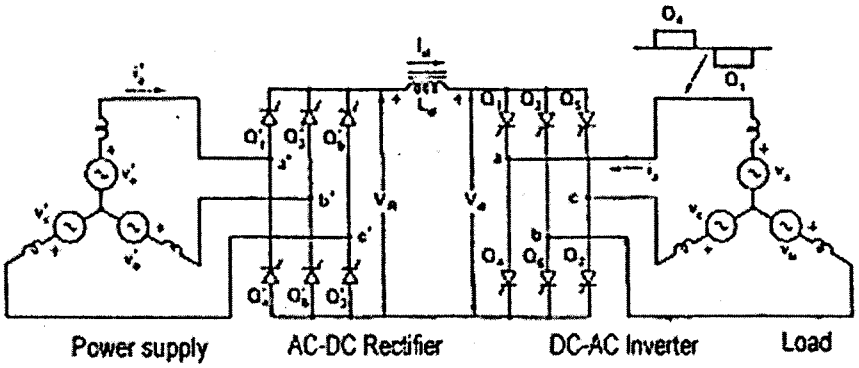


fig.3-2-1 Configuration of current source inverter and its idealized waveform

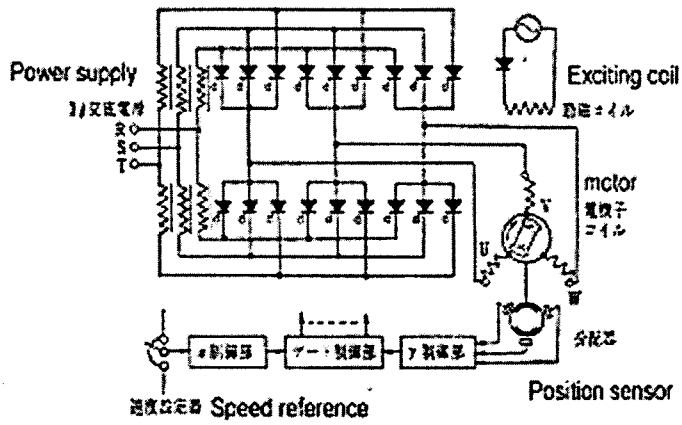


Fig.3-3-1 Configuration of Thyristor motor using cyclo-converter

on our fundamental research is shown in following section. [4]-[12]

As this concept has got highly attention from many specialists today, major activities will be introduced in following chapter.

4.2 Configuration of Matrix converter

Fig. 4-2-1 shows the main circuit configuration of Matrix converter. As the switching devices are requested to switch AC current, however, it is difficult to get suitable device in the market today. Then they are constructed often by the combination of active switches and diodes as shown in this figure.

As the circuit operation of this converter is a little complicate than conventional converters, showing only features and some important points in following part, detail explanation will be presented in another chance.

4.3 Features of Matrix converter

In this Matrix converter there are very attractive performances as follows: [6]-[10][29]

1) Possible to make direct conversion AC to AC in variable frequency and variable voltage output.
2) Possible to adjust power factor of input power supply line.
3) Obviously available to perform 4-qudant power conversion, with reversible power flow.
4) Possible to make waveform control for input and output current, like as conventional AC/DC/AC conversion system shown in fig.2-2-1.
5) Need not to use big capacitor or reactor for energy storage.
6) 18-devices are needed, more than 12-devices of conventional AC/AC conversion system shown in

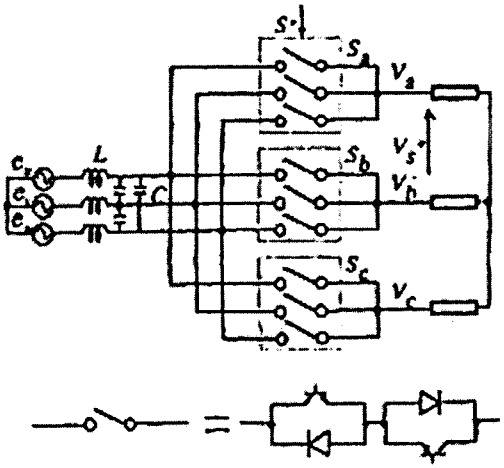


Fig. 4-2-1 Circuit configuration of Matrix Converter

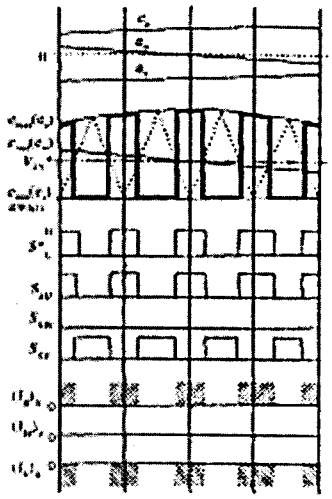


Fig.5-1-1 PWM control for max. output voltage

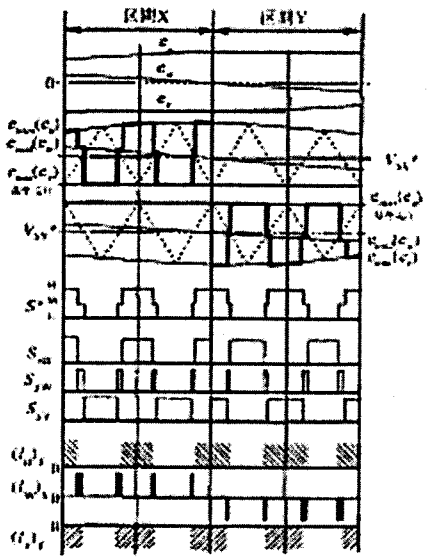


fig.5-1-2 PWM control for improved power factor

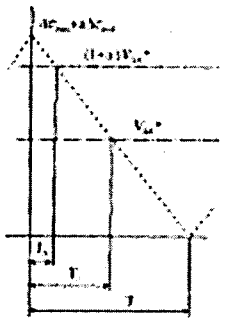


Fig.5-1-3 Timing estimation
for medium voltage line

fig 2-1-1, but the current capacity of each device is 1/3 of conventional system, then total device capacity is only 0.57 of conventional system.

7) Possible to get high conversion efficiency, based on conducting devices in the same time is only 2 when we use suitable reverse blocking device, theoretically better efficiency than conventional conversion circuit topology conducting 4-devices.
8) Expectable to get good waveform by lower switching frequency.

In the other hand there are drawbacks as follows:

a) Necessary to use reverse blocking device to get better performance.
(Expecting to get reveres blocking IGBT prepared for this application from Infinicon Co. Germany, Fuji Electric Co. Japan [34], or others. [32][33])
b) Necessary take cares for switching procedure for prevention of serge voltage or short circuit current, in the combination of reverse conductive devices and diodes shown in fig.4-2-1.
(Dr. Oyama and Koga recommended suitable gate control sequence in the application of reverse conductive device.) [20]
c) Maximum output voltage is low, (Normally 0.577, possible 0.866 using patent of Koga.[12] And Fuji Electric Co. propose over modulation method for getting higher output voltage equal to power supply in the application for motor drive [26])
d) Necessary to apply suitable on-line control system having quick operation, as there is no energy storage component of capacitor or reactor.

5. State of the art of Matrix converter

5.1 Basic development

In this chapter some results from our basic research are introduced as assistance for understanding of Matrix converter.

a) Conversion control

The fundamental control of Matrix converter is output voltage control. Fig.5-1-1 shows the idealized waveforms getting highest output voltage of 0.866 of supply voltage by the selection method of highest and lowest voltage line. [12]

b) Improvement of power factor and harmonics

It is possible to get highest output voltage 0.866 of supply voltage, however, by this basic method the power factor is low, because the active control is performed by 2-lines only.

To improve power factor and waveform of input current, some improvement is proposed, as shown in fig.5-1-2, the output voltage is controlled using medium voltage line also.

In this method the switching chance of devices is increased, but the loss of the devices are not so much difference with 2-line switching system, because the device switching voltage is lower than the case of fig.5-1-1.

To get suitable output voltage the switching point for

this medium voltage is generated by the voltage equivalent method shown in fig.5-1-3 and equation (5-1-1) and (5-1-2).

$$\frac{T_0}{T} = 1 - \frac{(1+a)V_{Sr}^*}{\Delta e_{max} + a\Delta e_{mid}} \qquad (5\text{-}1\text{-}1)$$

$$\frac{T_1}{T} = 1 - \frac{V_{Sr}^*}{\Delta e_{max} + a\Delta e_{mid}} \qquad (5\text{-}1\text{-}2)$$

c) On-line control

In matrix converter there is no energy storage equipment different from conventional converter as shown in fig.2-1-1, so the output is influenced by the condition of power supply line directly. Then it is necessary to apply quick workable on line control. Fig 5-1-4 shows the concept of control system, including gate control, carrier pattern generator, gate drive sequence and some sensing circuit needed for conversion control. [6][7][10]

Fig.5-1-5 shows experimental results of input and output waveforms at inductive load, and fig.5-1-6 (a) and (b) show also experimental results about the distortion of input and output current in the relation with carrier frequency.

Through these results of the fundamental research, it is confirmed that this Matrix converter has good waveform even if lower carrier frequency.

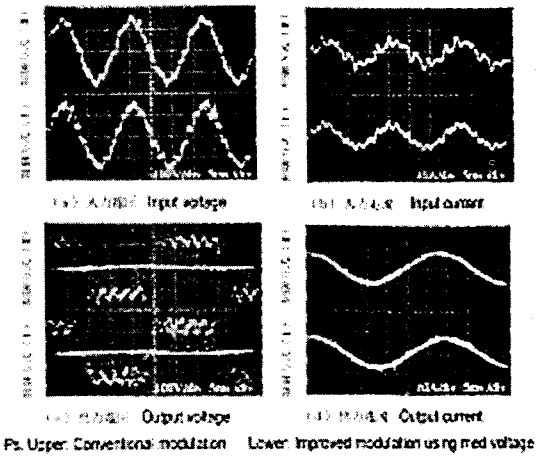


Fig.5-1-5 Waveforms of voltage and current in the case of inductive load, at carrier frequency 2.16kHz

5.2 Trend of Matrix converter

There are some more steps to make clear before practical application of Matrix converter, because of the complex control, which is necessary to control AC/DC conversion and DC/AC conversion within one control scheme. Fortunately it is expectable to have splendid progress of microcomputer year and year, then it is not so difficult to make up suitable control

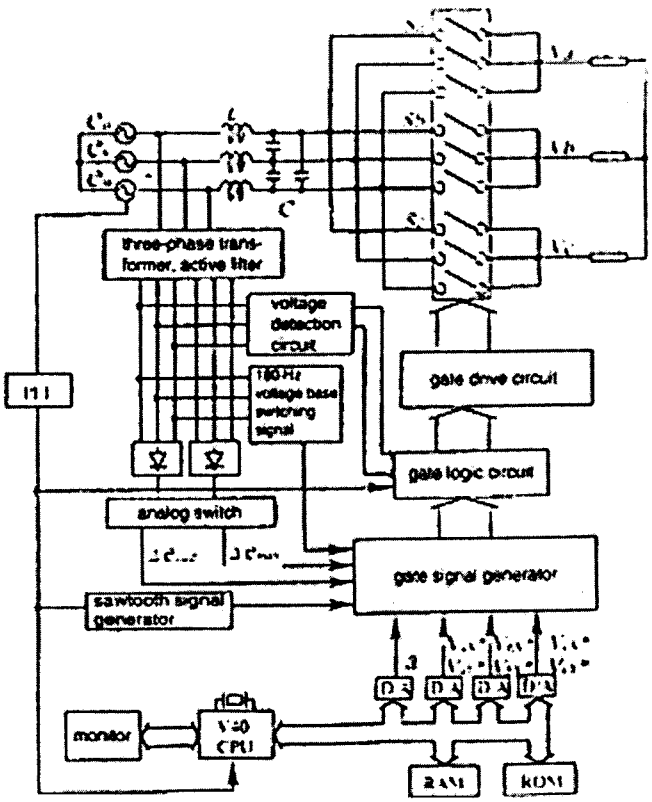
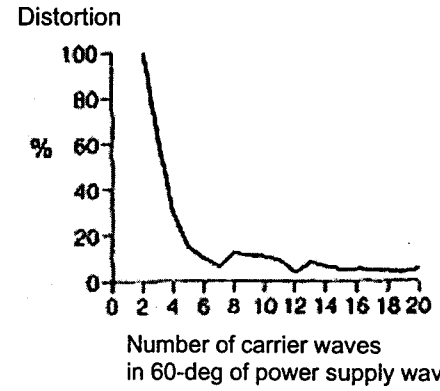
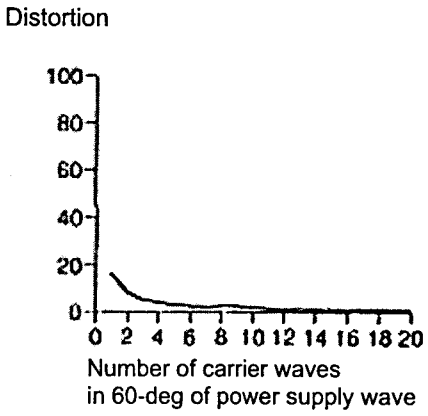


Fig.5-1-4 Configuration of on line control



(a) Input Current



(b) Output Current

fig.5-1-6 Distortion in the influence of carrier frequency in inductive load

system by simple way in near future.

Then today's research and development of Matrix converter is seemed shifting to development of practical product or application. It is expected this Matrix converter will enter into industrial drive market as major drive system in near future.

5.3 Attractive promotion for Matrix converter

Today we have many presentations about Matrix converter. Here are introduced some active promotions and remarkable reports presented mainly in Japan, as follows:

1) Nagasaki University has been making the most important contribution on this research and sending many papers. [4]-[12][27] In combination with Dresden University, they had presented on the trial application of ARCP (Auxiliary resonant commutation pole, important soft switching technology suitable for high power application) method for Matrix converter, showing the possibility of soft switching application for Matrix converter. [15]
2) Tokyo Institute of Technology had made excellent researches and reported about current control [16] and about prevention of resonance in input filter, important in practical application. [17]

   Farther more they presented new papers of matrix converter regarding control strategy at the research meeting of IEE-Japan held February 2003 [19] and detail analysis about input power factor of Matrix converter at the annual conference of IEE-Japan held March 2003 [22].
3) Yaskawa Electric Company of Japan has active promotion on this Matrix converter and presented many reports on improvement of performance and about improvement on the control strategy suitable for instantaneous power line failure, very important in practical application. [13][14][28][31]
4) Fuji Electric Company of Japan has also high activity about AC/AC direct power conversion and presented good idea of AC/AC conversion circuit using conventional IGBT modules with soft switching function [23].

   In these years, they have reported about the development of reveres blocking IGBT applicable for Matrix converter [24], and presented attractive papers about Matrix converter in the annual conference of IEE-Japan held in March 2003.

   They had presented paper about the control strategy using virtual AC/DC/AC conversion concept useful for Matrix converter and very important idea about expansion of the maximum output voltage up to 100% of supply voltage by using over modulation method, in the application for motor drive. [25] [26]

   In normal application this over modulation gives us wrong waveform in output voltage and torque ripple of loaded motor. However, they propose to apply reverse modulation for virtual DC voltage mentioned above paper, in accordance with torque ripple. Although the waveform is not beautiful, it is possible to prevent torque ripple in loaded motor, by using this proposal.
5) Aarborg University of Denmark has high activity on the research of Matrix converter. By the guidance of this University, Danfoss Company of Denmark had opened their development plan on Matrix converter for their regular products as integrated drive. [18][30]
6) IEEE Industrial Electronics Society had made special transaction on Matrix converter April 2002, including 15 papers. From this special edition, we can see many active promotions.

   As the commencement, professor P.Wheeler and their research group presented general view of matrix converter technologies, and pointed out the major subjects to be solved at the practical application.[29]

   And there are many important papers from Technical University of Berlin, University of Dresden, [35] and so on.
7) IEE-Japan had started research committee on direct AC/AC conversion in January 2003.

6. Conclusion

It is realized to have excellent motor drive system today, based on high frequency switching and with the application of vector control method,[1] and many other advanced control technologies. In the other hand, we have met serious problems caused by high frequency switching and some new requirements in accordance with new circumstance.

As shown above, there are many active promotions for the research and development on Matrix converter in the field of power conversion, and it seems now accelerating in the world.

Matrix converter is expected as the most expectable new power conversion system possible to meet the requirement on motor drive.

As the infrastructure for Matrix converter is now completing, it is expected that the Matrix converter will enter into the major line up of industrial drive in near future.

이 논문은 경남대 전기에너지 절약 연구센터의 지원으로 수행되었음.

Reference

1) T.H.Chin, I.Miyasita, T.Koga [Sensor-less Induction motor drive --An Innovative Component for Advanced Motion Control--] IFAC World Congress Id-022, pp445-450, July 1996
2) A.Imayanagida, M.Nakamura [Bearing corrosion of induction motor in adjustable drive] IEEJ SPC9860, 1998
3) Don Macdonald, et al. [PWM drive related bearing failure] IEEE IAS-Magazine 6/7, 1999
4) J.Oyama, T.Koga, et al. [Performance of PWM cyclo-converter] Trans. IEEJ Vol.113-D, No.9, pp1086-1093, 1993
5) J.Oyama, T.Koga, et al. [Distortion characteristics of PWM cyclo-converter] Trans. IEEJ Vol.116-D, No.4, p404-410, 1996
6) J.Oyama, T.Koga, et al. [VVVF On-line Control of Matrix Converters] Trans. IEEJ Vol.116-D, No.6, p664-651, 1996
7) J.Oyama, T.Koga, et al. [VVVF On-line Control of Matrix Converters] Trans. IEEJ Vol.119, No.2, June 1997
8) J.Oyama, T.Koga, T.A Lipo, et al. [New Control Strategy for Matrix Converter] IEEE PESC-89, pp360-367, June.1989.
9) J.Oyama, T.Koga, T.A Lipo. et al. [Power Factor Improvement of PWM Matrix Converter using Intermediate Voltage] PCC93-Yokohama, p284-289, Aprl.1993
10) J.Oyama, T.Koga, et al. [A New On-line Gate Circuit for Matrix Converter] IPEC-95 p754-759, Aprl.1995
11) J.Oyama, T.Koga, et al. [Effect of the Filter on Matrix Converter Characteristics under a New Control Method] SPEEDAM-96, June, 1996, 636, 1991
12) J.Oyama, T.Koga, et al. [Control method for PWM controlled power converter] Japanese patent No.2022413, Registerd 1996
13) H.Hara, E.Watanabe, et al. [The Matrix converter drive performance under input voltage conditions] IEEE PESC2001, pp.1089-1095, 2001
14) H.Hara, E.Watanabe, et al. [Performance improvement of matrix converter drive] JIASC No.214 2002
15) J.Oyama, R.Teichman, et al. [Application of ARCP matrix converter to AC/DC conversion] JIASC 2001
16) K.M.Song, Y.Sato, et al. [A, new PWM method for instantaneous output current control of Matrix converter with sinusoidal input current] ICPE 2001 pp.179-183, 2001
17) K.M. Song, Y.Sato, et al.[An investigation of control method for matrix converter to reduce input current distortion caused by resonant in input filter] JIASC No.215 2002
18) U.Jaeger, et al. [Line-fed motor drive based system integration -- A technology on the verge of a break through-] CIPS 2000, pp.182-189, Bremen, June 2001
19) K.M.Song, Y.Sato, et al. [A new control method with sinusoidal input and output current waveforms for Matrix converters] SPC03-36 pp61-66, IEEJ Tech. Meeting on Semiconductor Power Conversion, Feb.2003
20) J.Oyama, T.Koga, et al. [Gate control sequence for PWM cyclo-converter using SI-Thyrisors] No.246, Kyushu Annual Conference of IEEJ, May 1995.
21) T.Koga [Development of Matrix Converter (PWM Cyclo-Converter) suitable for New Age] Korea-Japan Joint Symposium, October 2002
22) K.M.Song, Y.Sato, et al. [Investigation of input displacement factor of Matrix converters with PWM control] No.4-065, Annual conference of IEEJ, March.2003
23) K.Kuroki, H.Ohkuma. et al. [Basic performance of direct AC/AC conversion circuit using bi-directional switch] Trans. IEE-J, No.2, Vol.118-D pp236-242, Feb. 1998
24) M.Takei, et al. [Application technique for reveres blocking IGBT] Fuji Electric Journal Vol.75, No.8, p.445-448, Aug. 2002
25) J.Itoh, N.Eguchi, et al. [PWM method for Matrix converter based on virtual AC/DC/AC conversion] No.4-066, Annual conference of IEEJ, March.2003
26) I.Satoh, J.Itoh, et al. [Inproved method of available voltage areas for Matrix converter] No.4-067, Annual conference of IEEJ, March.2003
27) J.Oyama, E.Watanabe, et al. [Switch loss and and current distribution analysis of matrix converter] No.20, JIASC Aug. 2001
28) H.Hara, E.Watanabe, et al. [Motor drive using Matrix converter] Yaskawa Electric Journal Vol.64, No.2 Feb. 2002
29) P.W.Wheeler,.odrigueez, et al. [Matrix converter: A technology review] Trans.IEEE-IE pp276-288 Vol.49. No.2. April 2002
30) C.Kiumpner, F.Blaabjerg, et al. [A new matrix converter motor (MCN) for industry applications] Trans. IEEE-IE pp325-335 Vol.49 No.2. April 2002
31) Jim-Koo,Kang, E.Watanabe, et al. [The Matrix converter drive performance under abnormal input voltage conditions] IEEE PESC-2001 pp1089-1095 June 2002
32) M.Bruckmann, et al. [Application of a new IGBT module for matrix converter] L1a-3 EPE2001, August 2001
33) A.Lindermann [A new IGBT with reverse blocking capacity] L3a-7 EPE2001, August 2001
34) M.Takei, et al. [600V IGBT with reverse blocking capacity] pp413-416, ISPSD2001
35) S.Bernet, et al. [Design and loss comparison of matrix converter] Trans.IEEE-IE pp304-314 Vol.49 No.2. April 2002
36) T.Koga [Power Electronics and Motor Drive] 3.6 pp87-96, Book published by Publication Dept. of Tokyo Denki Univ. Jan.1977