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Back Ground and Expectation for Matrix Converter (PWM Cyclo-Converter) as New Drive System in Next Generation

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Abstract: *Today we have excellent motor drive system using high frequency carrier PWM control voltage source inverter. 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. In this paper, we will introduce the background, features and outline of this converter, and additionally introduce some remarkable activity on this converter.*

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

1. Introduction

In these years, adjustable speed drive using AC motor and inverter has had remarkable expansion in industrial drive, Mechatronics and also appliances. In this progress, the key component is high frequency carrier PWM control voltage source inverter using IGBT. However, we have met serious problems caused by high frequency switching, in the other hand.

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 such high performance inverter, using high frequency carrier consisted by sharp rise up pulse train. Obviously, filters give us additional cost.

As the fresh improvement those problems, there is proposal of PWM Cyclo-converter popularly called "Matrix converter" instead of voltage source inverter with high frequency carrier PWM control.

In this paper, we will introduce the background of at first, next outline and features of Matrix converter, and finally expectation as new drive system in next age, with important promotions on the development of this converter.

2. Back ground for new strategy

2.1 Progress of drive system

PWM controlled voltage source inverter has been used mainly for adjustable speed drive in these years.

Major key technologies of these excellent 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 popular 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 point for inverters, as beautiful waveform in motor current, reduction of acoustic noise from motor frame, 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]

2.2 Requirement from power supply line

In practical inverter drive, it is popular to use rectifier with capacitor as AC/DC converter. However, it gives us rich harmonics and low effective power factor in power supply current. This harmonics in power distribution system is growing up more and more serious accompany with the expansion of

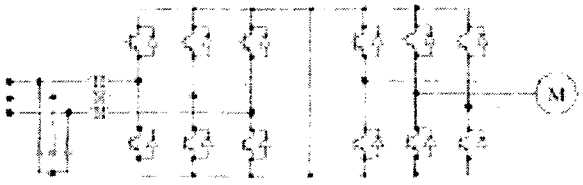

Fig. 2-2-1 AC/DC PWM converter applied for inverter drive

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power electronics equipment.

To improve this problem it is recommended to use AC/DC PWM converter as shown in fig.2-2-1. This topology has good power factor, fewer harmonics, and convenient function of re-generation and 4-quardant operation, however, it requires us naturally higher cost. Then, it is required to have better topology having good power factor and less harmonics in power supply current with lower cost.

2.3 Problems by high frequency switching

Application of high frequency carrier had made remarkable contribution for inverter drive, in the other hand, high frequency switching gives us serious problems. 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. High frequency component caused by high dv/dt of PWM pulses, 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 sometimes terrible for motor insulator.

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. At result, 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 more important requirements on motor drive applied for industry with system integration.

One is elimination of the chemical capacitor. In voltage source inverter, it is necessary to use big capacitor as low pass filter in AC/DC conversion stage. Chemical capacitor has been the most popular device in many years. However, chemical capacitor has finite life, then the reliability and/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 biggest problem is big size of chemical capacitor, in these application. Then there is strong requirement to make up inverter drive system without chemical capacitor.

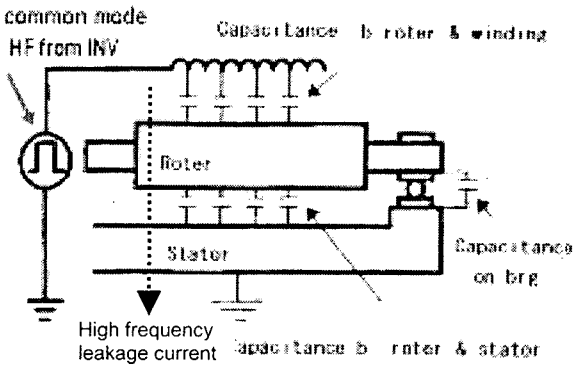


Fig.2-3-1 Common mode high frequency noise induced from inverter to motor

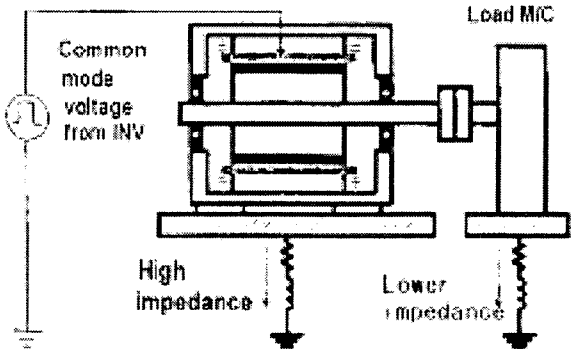


Fig.2-3-2 Effect of impedance to the earth

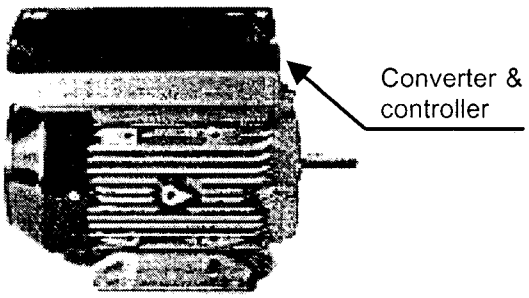


Fig. 2-4-1 Example of integrated motor developed by Danfos Co.

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 introduction of integrated motor is expected to be good solution for this subject.

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 mounted on each motor. In this integrated motor, the

most important point is reduction of size of converter and local controller. 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 beautiful waveform of input/output current, excellent control ability, and good efficiency in operation.
2) Free from problems caused by high frequency switching. And easy applicability of soft-switching technology for prevention of problems caused by high dv/dt.
3) Having good power factor and less harmonics in power supply line.
4) Without big chemical capacitor.
5) 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 above problems is application of soft switching. However, 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.

In today's motor drive, it is requested to have extremely high control performance and to apply wide range PWM. Then we should use high frequency pulse train and very wide control range in PWM system. In today's motor drive using vector control method, it is not special to use only a few microseconds as minimum pulse width. Thus there is big difficulty in the application of soft-switching for high performance drive system.

The cause of this difficulty is depending on the only one freedom in control concept of pulse width under fixed DC voltage. Then it is requested to get suitable circuit topology possible to use more wide pulse for high performance drive system.

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 convenient features, there are some difficulties to use reverse blocking device, to apply for multi-motor drive system, and to get reactor in suitable cost and size. [36]

3.3 Suggestion from "Thyristor Motor"

Before inverter drive, "Thyristor Motor" was appreciated from industrial drive widely as brush-less adjustable speed drive. The most famous topology is the combination of thyristor cyclo-converter as a load commutation inverter in high speed mode and synchronous motor with position sensor, as shown in fig. 3-3-1.

Cyclo-converter has good performance for variable frequency and variable voltage in low output frequency and has 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. [36]

Thyristor motor has excellent features, but the application is limited in these years, by the explosive expansion of inverter using IGBT.

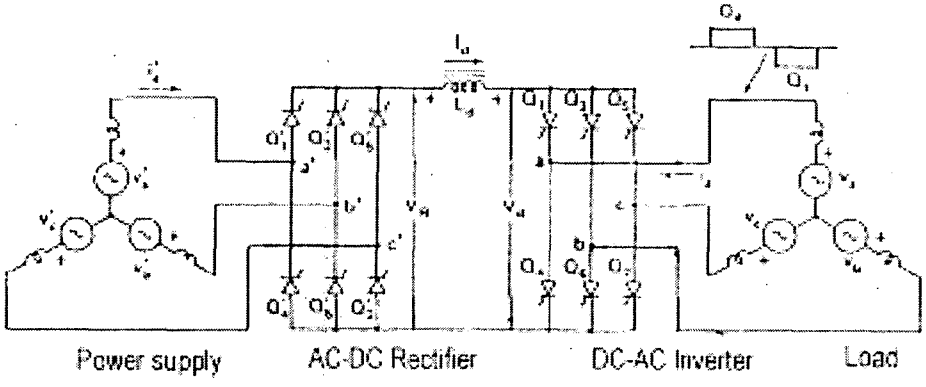


fig.3-2-1 Configuration of current source inverter and its idealized waveform

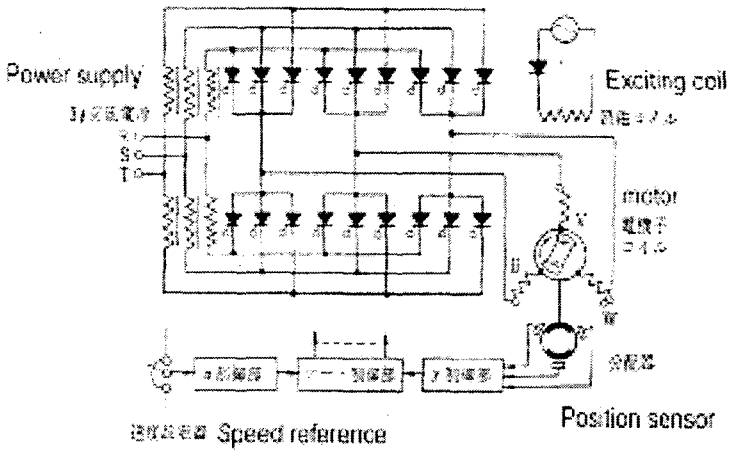


Fig.3-3-1 Configuration of Thyristor motor using cyclo-converter

However, this cyclo-converter gets attention again by the excellent feasibility of AC/AC direct conversion with the application of turn off devices.

4. Outline of Matrix Converter

4.1 introduction

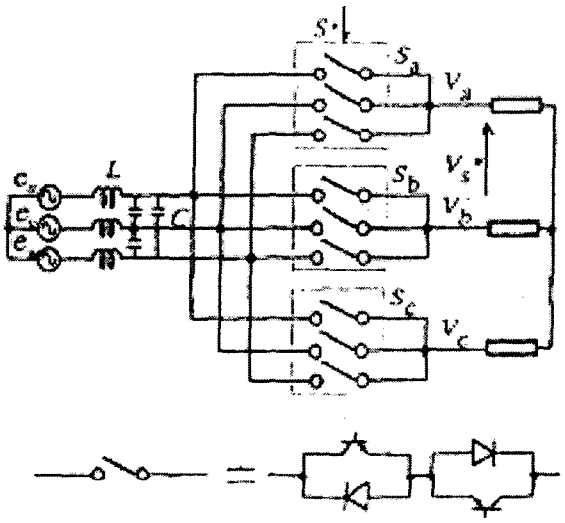
Off cause, there are many difficulties to clear up all requirements listed up in 2.5, Koga had aimed at this Matrix Converter from the experience of Thyristor-Motor which were famous products of Toyo Electric Mfg. Co., Ltd. Japan, and had started the research on this converter under the guidance from Professor J.Oyama Nagasaki University Japan.

As the circuit operation of this converter is a little complicate than conventional converters, the outline of this converter based on fundamental research is shown in following section. [4]-[12]

4.2 Configuration of Matrix converter

4.2.1 Circuit and switches

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 bi-directional device today. Then they are constructed often by anti-parallel connection of reveres blocking device or the combination of active switches and diodes as shown in this figure.



(a) Combination switch with diodes

(b) Anti-parallel switch

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

4.2.2 Switching sequence

In this converter there are important limitation on the switching operation as follows:

a) Do not short power supply lines.

b) Do not open inductive load.

If the switch opens the load circuits including some inductance normally, the devices should have serious serge voltage. Then it is necessary to apply some suitable switching sequence for each device.

In the case of anti-parallel connection of reverse blocking thyristors shown in fig.4.2.1 (b), the suitable switching sequences are shown as follows: [20]

[1] when $e_u > e_v$

Step1. Tr_V on (no current by reverse bias of Tr_V)

Step2. Tr_u on (Current commutates to Tr_V, when Tr_u has current)

Step3. Tr_v' on (Current commutates to Tr_V', when Tr_u' has current, and Tr_u' is biased reverse direction)

Step4. Tr_u' off

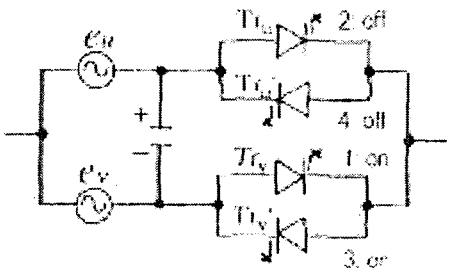


fig. 4-2-2 Gate drive sequence at $e_u > e_v$

[2] when $e_u < e_v$

Step1. Tr_V' on (no current by reverse bias of Tr_V')

Step2. Tr_u' on (Current commutates to Tr_V', when Tr_u' has current)

Step3. Tr_v on (Current commutates to Tr_V, when Tr_u has current, and Tr_u is biased reverse direction)

Step4. Tr_u off

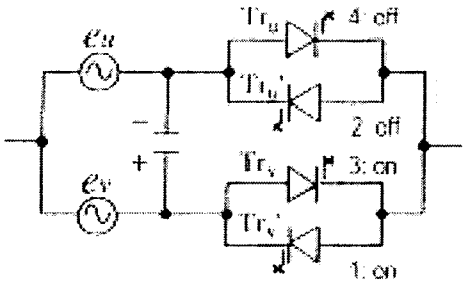


fig.4-2-3 Gate drive sequence at $e_u < e_v$

4.2.3 Conversion control

The fundamental control of Matrix converter is output voltage control. In conventional control maximum output voltage was only 66% of input voltage. Fig.4-2-4 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]

Although it is possible to get higher output voltage by above 2-lines selection method of fig. 4-2-4, the power factor of input current is low, because the active control is performed by 2-lines only.

To improve power factor and waveform of input current, 3-lines control method using medium voltage line is proposed as shown in fig.4-2-5. [9]

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.4-2-4.

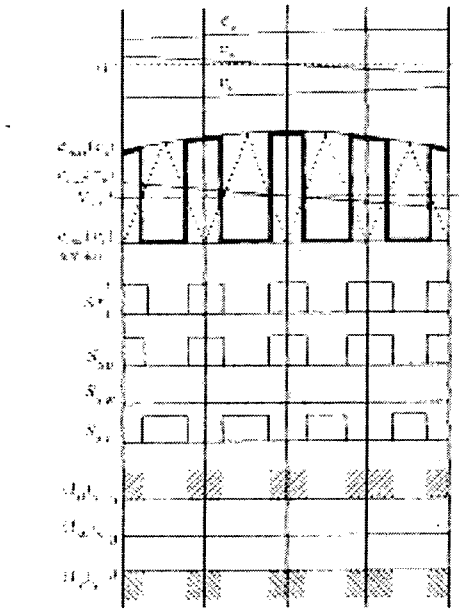


fig. 4-2-4 PWM control for maximum output voltage 0.866 of supply voltage

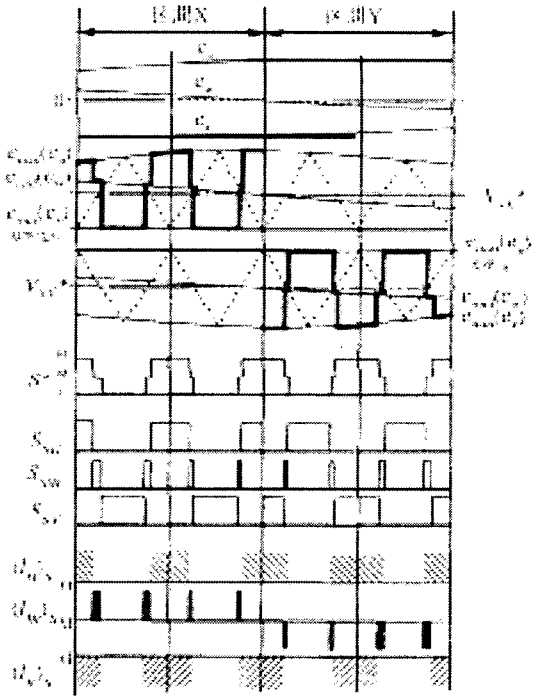


fig.4-2-5 PWM control for improved power factor

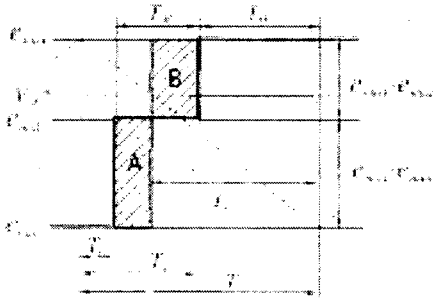


fig. 4-2-6 Timing estimation for selection of medium voltage line

To get suitable output voltage the switching point for this medium voltage is generated by the voltage equivalent method shown in fig.4-2-6 and equation (4-2-1) and (4-2-2).

$$\frac{T_0}{T} = 1 - \frac{(1+a)V_{Sx}^*}{\Delta e_{\max} + a\Delta e_{mid}} \qquad (4\text{-}2\text{-}1)$$

$$\frac{T_1}{T} = 1 - \frac{V_{Sx}^*}{\Delta e_{\max} + a\Delta e_{mid}} \qquad (4\text{-}2\text{-}2)$$

4.2.4 On line control

In matrix converter there is no energy storage equipment different from conventional converter as shown in fig.2-1-1 and fig.4-2-1, 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 4-2-7 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]

4.3 Features of Matrix converter

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

1) Direct conversion AC to AC in variable frequency and variable voltage output.
2) Good power factor of input power supply line. [19]
3) 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 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) 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. [27][35]
8) Expectable to get good waveform by preferable low switching frequency.

Fig.4-3-1 shows experimental results of input and output waveforms at inductive load, and fig.4-3-2 shows experimental results of the relation between distortion factor and carrier frequency. By these results, distortion factor is better than the case of voltage source inverter, even if in lower carrier frequency.

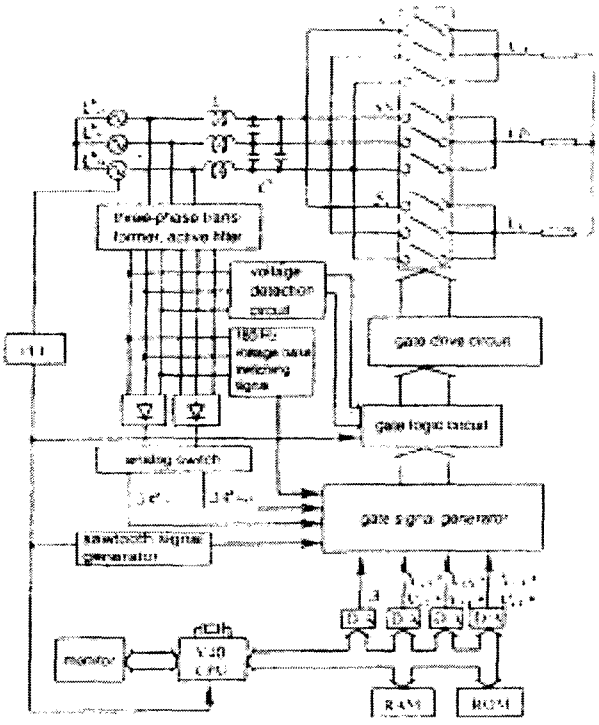


fig.4-2-7 Configuration of on line control

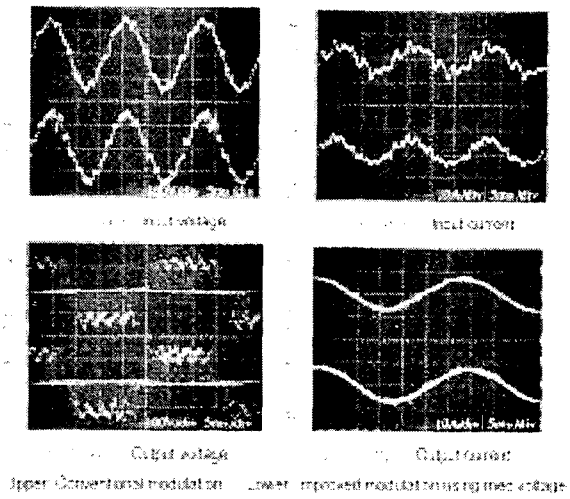


fig.4-3-1 Waveforms of voltage and current in case of inductive load at carrier frequency of 2.16kHz

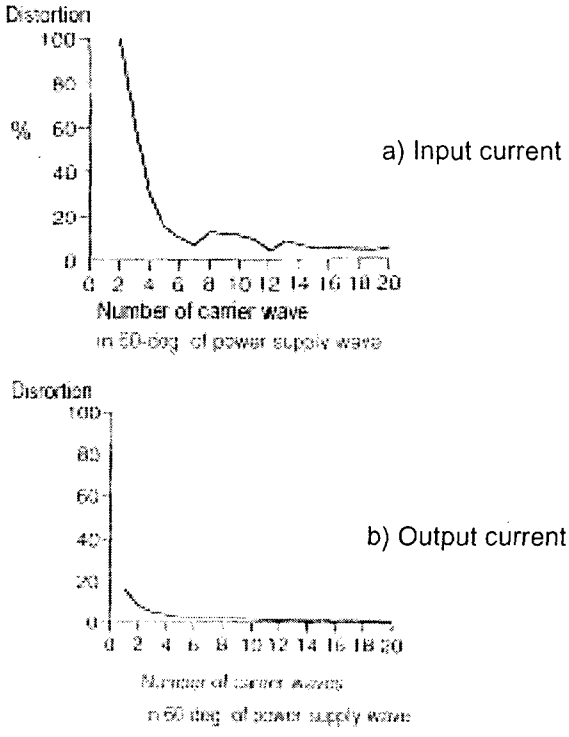


fig.4-3-2 Relation between distortion and carrier frequency in inductive load

5 State of the art on Matrix Converter

5.1 Attractive promotions

Very long way on Matrix converter, today we have many active promotions, as shown in references. IEEE Industrial Electronics Society had made special transaction on Matrix converter April 2002. [29]

5.2 Devices

Ii is desired to have suitable reverse blocking device
in Matrix converter. Today we have expectable news for reveres blocking IGBT from Infinicon Germany, and Fuji Electric Japan. [24][34][32][33]

5.3 Output voltage expansion

Maximum output voltage is available 0.866 of input voltage by patent of Koga. [12] Fuji Electric Japan proposed new idea getting higher output voltage up to 100% of supply voltage, by using over modulation method in the application for motor drive. [25] [26]

5.4 Waveform improvement

There is some possibility to have unbalance power supply voltage. In this case, we have met big distortion in input current at matrix converter. Danfos A/S denmark and Yaskawa Electric Japan proposed improvement of this distortion. [13][19][31][37]

5.5 Input filter

There is necessity to use small L-C filters in input lines of Matrix converter as shown in fig. 4-2-1. Optimum design of these filters is important. Tokyo Institute of Technology had reported on prevention of resonance in this input filter. [16] [17] [22]

5.6 Application of soft-switching

Matrix converter is convenient for application of soft-switching. Nagasaki University had reported the application of ARCP (Auxiliary resonant commutation pole) soft-switching method. [15]

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, and many other advanced control technologies. In the other hand, we have met serious problems caused by high frequency switching and requirements in accordance with new circumstance.

There are some more steps to make clear before practical application of Matrix converter. 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.

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