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A Review on Performance Analysis of Matrix Converter Fed AC Motor Drive

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ABSTRACT

This paper presents a review on the analysis of characteristics that determines the performance of the Matrix Converter (MC) fed AC motor drive. Review is made based on the analysis of the different characteristics achieved in the literature. Different characteristic parameters considered in this paper are total harmonic distortion, common mode voltage, voltage transfer ratio and efficiency. Comparison and analysis of these characteristic parameters is done based on various semi conductor switches, topology, and control and modulation techniques.

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1. INTRODUCTION

Vital role of the variable speed ac motor drives is due to its enormous application in industrial and house hold applications such as lifts, pumps, compressor, textile mills and washing machines [1]. AC-AC converter system provides the variable speed drives with required voltage amplitude and frequency based on its system, load and environment conditions [2]. Among AC-AC converters Voltage Source Inverter (VSI) and Current Source Inverter (CSI) occupy the industry more than a decade [3]. The main drawback of VSI and CSI is its dc link component which makes it a bulky and limited operating lifetime [4]. In 1976, concept of the AC-AC converter without dc-link component was developed from the forced commutated cycloconverter by the authors Gyugi and Pelly [5]. Venturini and Alesina [6] introduced the Matrix Converter in 1980 and they provided the rigorous mathematical background.

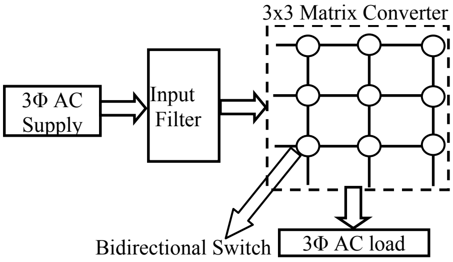

Figure 1. Basic Structure of Matrix Converter

VSI and CSI provide two stage conversion process. First stage is the rectifier that converts AC to DC. Second stage is the inverter that converts DC to AC. The Matrix Converter (MC) is a single-stage converter which has an array of m X n bi-directional power switches. The m phase voltage source is connected to n phase load. Figure 1 shows the structure of which represent the arrangement of bidirectional switches in matrix form. Matrix Converter directly converts AC to AC, thus avoiding two stage conversion processes.

Promising Characteristics of MC [7-13] makes it very popular among researchers and industrialist. The positive characteristics of MC are: 1) High power density 2) Bidirectional power flow 3) Sinusoidal input and output waveforms 4) Reduced volume and weight 5) Operation with unity power factor 6) Long lifetime and 7) Reliable in adverse conditions. Invention of new bidirectional power electronic switches, topologies and control methodologies opens up the area of research in the matrix converter to overcome its limitations. Limitations of MC are, 1) Maximum voltage transfer ratio is 0.86 2) Increased number of switches 3) Poor ride through capability 4) Complex control and modulation techniques 5) Complex protection circuits and 6) High common mode voltage.

An intensive review on the AC-AC converter topology was done by Kolar et al [14]. They provided the various circuits topologies of MCs and its fundamental modulation and commutation schemes. Authors [15] had analyzed the various control and modulation techniques such as scalar, carrier based pulse width modulation, space vector modulation, direct torque control and predictive control. A review on technological issues of MC its stand in the industry application along with the products in the markets has been presented by Empringham et al [16].

MC can be applied in variable speed drives, induction heating, aerospace, wind turbine system etc. The [17] and [18] had reviewed the application of MC to induction and permanent magnet synchronous motor drive. MCs are highly appropriate for sinusoidal load. Pulsating load degrades the performance of MC. MC is the best suitable for induction and permanent magnet synchronous motor drive which are operated in constant power region [19-21].

Performance analysis of every system estimates its value, ranking and application. Despite all the intensive reviews, performance comparison is needed to select the MC for its applications. Aim of all electrical motor drives is to achieve high performance along with miniaturization, high efficiency, low THD, fast response and fault tolerance. The aim of this paper is to review the performance of the MC fed to drives based on THD, CMV, voltage transfer ratio and efficiency. This paper provides the basic requirements of each parameters which are analyzed, compared and methods to improve the characteristics by the various author in the literature.

The organization of the paper is: Section II introduces the fundamental of MC along with its classification and control methods, Section III provides the intensive study on harmonic distortion, Section IV deals with the Common mode voltage, Section V illustrates the voltage transfer ratio, Section VI presents the efficiency of MC, and finally, conclusions are made in Section VII

2. CLASSIFICATIONS OF MC

Origin of the MC has started with the improvement made in the frequency converters with DC energy storage. Elimination of the DC energy storage resulted in MC. Classification of MC was shown in the Figure 2.

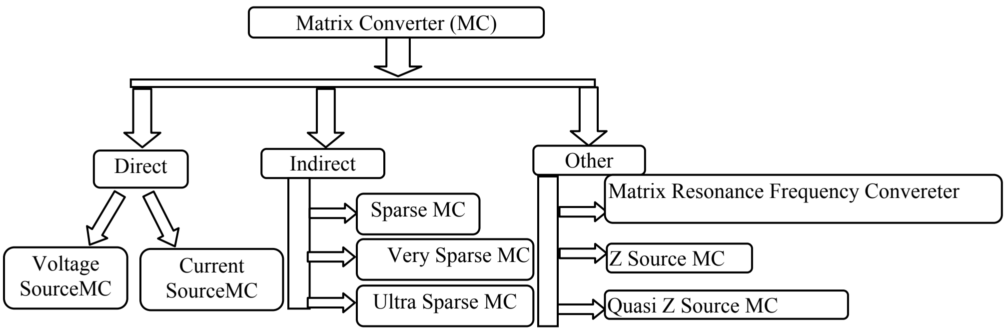

Figure 2. Classification of MC

MC is mainly classified as direct MC and indirect MC.Direct MC is classified as voltage sources MC and current sources MC.Direct MC as shown in Figure 3 doesnot need any two stage conversion from AC to DC and DC to AC. It directly converts AC to AC, thus eliminating the unnecessary conversion process .Bidirectional semiconductor switches are symbolized as S_{11} to S_{33}. Indirect MC as shown in Figure 4 has rectification (AC to DC) and inversion (DC to AC) process similar to VSI with replacement of dc-link capacitor with clamp circuit. Indirect MC as shown in Figure 4 has both rectifier and inverter stage but does not have the DC energy storage. Indirect MC is classified based on the topology and number of devices used. Intermediate category between with and without DC energy storage is given as hybrid MC. 18 active devices are used in indirect MC. Reducing the number of active device to 15, 12 and 9 is introduced as sparse MC [22], verysparse MC [23] and ultra sparse MC [24] respectively. New arrival in the converter family is the Z-source MC. Z-source MC uses 21 active devices but has the advantage of simultaneous buck boost capability [25].

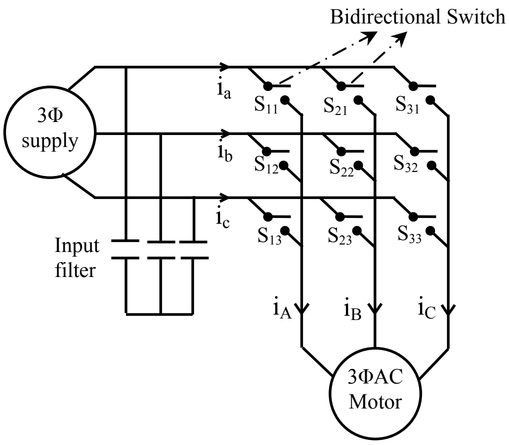

Figure 3. Three Phase 3 X 3 Direct MC

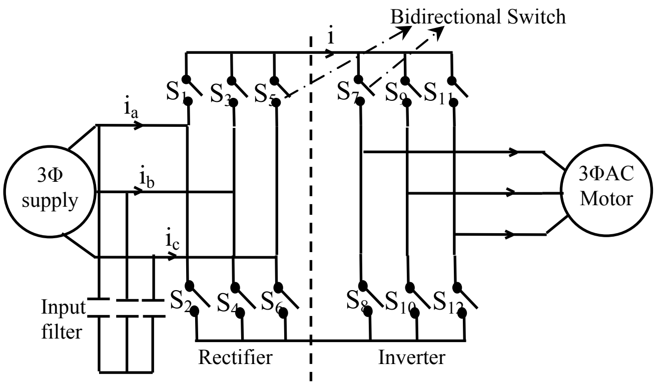

Figure 4. Classical Indirect Three Phase MC

3. HARMONIC ANALYSIS

Harmonics is an anxiety because they can cause excessive heating and pulsating, and reduces torque in motors and generators; increased heating and voltage stress in capacitors; and disoperation in electronics, switchgear and relaying. In short, harmonics can lead to reduced equipment life, if a system is designed without consideration for harmonics and if equipment is not properly rated and applied. It is, therefore, useful to measure and limit harmonics in electric power systems. A standard for limitation of harmonics is provided by IEEE STD 519-1992 and it is now updated as IEEE STD 519-2014.Harmonics is distinguished as voltage and current harmonics. Predominantly Voltage harmonic distortions are always less than current harmonic distortions [24].

3.1. Voltage Harmonics

Total harmonic distortion for voltage is specified in the (1)

$$THD_V = \sqrt{\sum_{n=2}^{n_{max}} \left(\frac{V_n}{V_1}\right)^2} \times 100 \tag{1}$$

Where V_n = harmonic Voltage, n = harmonic order (3, 5, 7…), V_1 = fundamental harmonic order

Table 1, specifies the voltage harmonic limits declared by IEEE STD 519.Most of the application uses the voltage limit below 69kV. According to the IEEE, STD 519 for bus voltage below 69kV the individual voltage distortion limit and total harmonic distortion limit should be within 3% and 5% respectively.

Table 1. Voltage Distortion Limits from IEEE 519
(For conditions lasting more than one hour. Shorter periods increase limits b 50%)

Bus Voltage at Point of Common Coupling	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
1.0 kV and below	5.0	8.0
Below 69 kV	3.0	5.0
69 kV ≤ V_{rms} ≤161 kV	1.5	2.5
V_{rms} >161 kV and above	1.0	1.5

Note: High Voltage systems can have up to 2.0% THD where the cause is a High Voltage DC terminal which will attenuate by the time it is tapped for a user.

3.2. Current Harmonics

There is a contradiction in the current harmonics specified by the most of the authors and the IEEE 519.Authors specify their current harmonics in THD while the IEEE 519 specify it in total demand distortion (TDD). The equation (2) and (3) represent the formula for THD and TDD of current respectively [24].

$$THD_I = \sqrt{\sum_{n=2}^{n_{max}} \left(\frac{I_n}{I_1}\right)^2} \times 100 \tag{2}$$

$$TDD_I = \sqrt{\sum_{n=2}^{n_{max}} \left(\frac{I_n}{I_L}\right)^2} \times 100 \tag{3}$$

I_n= harmonic current, I_1= fundamental current and I_L= maximum demand load current

The difference between THD and TDD is the denominator I_1 and I_L. For harmonic measuring purpose the I_1 measured will always be less than I_L measured. Therefore, THD calculated will always greater than TDD calculated. Table 2 specifies the current distortion limits according to the IEEE STD 519.This shows the current harmonic limits for individual harmonics and its TDD. For current limit within 20A and voltage below 69kV, the allowed TDD is 5%. Table 3 specifies the current and voltage THD of different methodolgies of MC. Lowest current THD was recorded in this study various authors.

Table 2. Harmonic Current Distortion Limits in percent of I_L from IEEE STD 519

Line No.	I_{SC}/I_L	h<11	$11 \le h \le 17$	$17 \le h \le 23$	$23 \le h \le 35$	$35 \le h$	TDD
				V_{rms}≤69kV			
1	<20*	4.0	2.0	1.5	0.6	0.3	5.0
2	20-50	7.0	3.5	2.5	1.0	0.5	8.0
3	50-100	10.0	4.5	4.0	1.5	0.7	12.0
4	100-1000	12.0	5.5	5.0	2.0	1.0	15.0
5	>1000	15.0	7.0	6.0	2.5	1.4	20.0
				69kV≤V_{rms}≤161kV			
6	<20*	2.0	1.0	0.75	0.3	0.15	2.5
7	20-50	3.5	1.75	1.25	0.5	0.25	4.0
8	50-100	5.0	2.25	2.0	0.75	0.35	6.0
9	100-1000	6.0	2.75	2.5	1.0	0.5	7.5
10	>1000	7.5	3.5	3.0	1.25	0.7	10.0
				V_{rms}>161kV			
11	<25*	1.0	0.5	0.38	0.15	0.1	1.5
12	25<50	2.0	1.0	0.75	0.3	0.15	2.5
13	>50	3.0	1.5	1.15	0.45	0.22	3.75

Table 3. Current and Voltage Harmonics

Sl.NO	Methodology	Lowest Current THD reported in the paper	Lowest Voltage THD reported in the Paper
1.	Direct Torque Control [25]	7.33%	-
2.	Direct Torque Control [26]	7.74%	46.23%
3.	Predictive control direct MC [27]	17.8%(input)	-
4.	Indirect MC [28]	2%(input)0.52% (output)	-
5.	Venturini [29]	9.8%(output)	-
6.	Indirect converter with boost function [30]	4%(input)3.7%(output)	-
7.	Vector controlled direct MC [31]	5%(max)(input)	5%(max)
8.	Predictive control [32]	23.8%(input)	-
9.	Space vector modulation [33]	17.6%(input)	64.8%

4. COMMON MODE VOLTAGE

Common Mode Voltage (CMV) is one of the main causes for the early motor winding insulation damage failure and bearing deterioration which in turn reduces the machine operational life. High performance is achieved with lower value of CMV which in turns also reduces dv/dt. CMV at the motor's neutral point V_{CM} is defined as (4) by the authors [34].

$$V_{CM} = \frac{(V_{aN} + V_{bN} + V_{cN})}{3} \tag{4}$$

Prediction of V_{cm} is done by knowing the output voltage per phase that each switching state under evaluation would produce. There are different methods to reduce CMV, namely:
1) Rotating vector applied in double sided space vector modulation [35]
2) Correct zero vector which presents smallest amplitude at all output phases [36].
3) Two opposite active vector [37]
4) Only rotating vector [38, 39]
First method records 42.3% CMV. The last method achieves 40% CMV.Even though rotating vector applied in double sided space vector modulation reduces CMV than rotating vector, the THD was increased from 6% to 21 %. Proposed method has better THD only when the modulation index is greater than 0.5. Space Vector Modulation pattern reduces the unwanted leakage current that flows through stators windings and bearings, without changing the fundamental output voltages and input currents. Simulation results show a potential Common mode derivative voltage reduction range from 11% to 33.34%, depending of the input vector's position. This reduction is not enough to solve the problem with machine lifetime reduction but it is a good outset to solve it [40].

5. VOLTAGE TRANSFER RATIO

Ratio between output voltage and input voltage is called as Voltage Transfer Ratio. The maximum theoretically proven voltage transfer ratio for a MC is 0.866 provided by venturini. Figure 5 illustrates the fitting of output target voltage within the input voltage [13]. Main hinder of MC when applied to industry is its limited voltage transfer ratio. Limitation in voltage transfer ratio increase the output current for constant power applications. Increase in the output current causes higher losses both in load side as well as converter side [41, 42]. Voltage sag at input power line causes two to four times reduction in the electromagnetic torque. Thus, voltage transfer ratio greater than will help the MC fed drive system full torque at heavy load conditions [43].

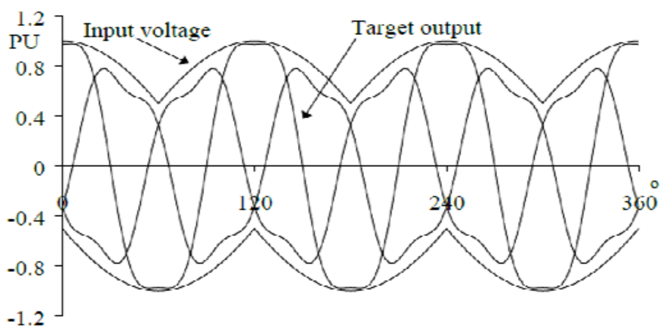

Figure. 5. Illustrating Voltage Transfer Ratio as 0.866

Methods to improve the voltage transfer ratio are listed below:
1) Feeding converter from the power supply through transformer [44]
2) Operating MC in over modulation region [45, 46]
3) Matrix Resonant Frequency Converter (MRFC) [47]
4) Z source MC [48, 49] and Quasi Z source MC [50]

First and simple method to improve the voltage transfer ratio is to boost by transformer but it is bulky, expensive and affects the system efficiency. Second method is to operate the MC in over modulated region. The voltage transfer ratio is 0.92 for the square wave modulation and 0.88 for the trapezoidal wave modulation. Thus, this method does not allow voltage transfer ratio greater than one. Next possibility is to use a MRFC, which consists of a MC added with a resonant component, and will provide voltage transfer ratio greater than one. The MRFC has to synchronize the MC and the resonant component operation. Thus control becomes complex. The MRFC has less input power factor.

The last but the latest method is to use Z-source network.Z-source Direct MC, is developed by adding three inductor, capacitor, switches and diodes. As ZSDMC permits the short circuit, the commutation process becomes simple and easy. This also reduces the voltage and current stress on the switch. The ZSDMC can reach voltage gain up to 1.15 but its inherited phase shift makes the control inaccurate. With Quasi Z-source Direct MC, the voltage gain can be raised to four or five times higher.

6. EFFICIENCY

Energy consumed by the ac motor drive during life time is 60-100 times more than initial cost of the motor [51]. Efficiency is defined as the ratio of output power to input power. Efficiency depends on the switching loss, conduction loss and drive loss. A comprehension comparison is made in paper [52, 53] between the classical converter (VSI/CSI) and MC (with IGBT and RB-IGBT).The significant efficiency achievement of 97.5% was proven.

Primary switching devices used in MCs include, MOSFET, the gate turnoff thyristor (GTO), integrated gate commutated thyristor (IGCT), MOS turnoff thyristor (MTO) and the MOS controlled thyristor (MCT) [55, 56]. The entire above specified device has less reverse blocking capability and has lower switching frequency. Bidirectional gate insulated transistor (IGBT) and reverse blocking IGBT (RB-IGBT) semi conductor switch is primarily used in MC to have high switching frequency and increased reverse blocking capability [57]. Even when the IGBT and RB-IGBT reduces the power/volume ratio, the classical IGBTs are considered as the higher switching losses will lead to the reduced output power in a given design. The silicon carbide (SiC) switches [58-60] can be used to increase the switching frequency without sacrificing too much of the thermal budget to switching losses.

Table 4. Comparison of Si IGBT and SiC Devices

Sl.No	Devices	Efficiency
1	SiC JFET	97.5%
2	SiC BJT	97%
3	SiC MOSFET	96.5%
4	SiC IGBT	96%
5	RB-IGBT	97.5%
6	IGBT	91.5%

With the SiC JFET efficiency of the MC is maintained above 96% for all frequency. Selection modulation techniques significantly affect the loss. Table 4 shows the comparision of different swithching devices used in the MC and its efficiency. Among all switching devices SiC JFET and RB-IGBT acchives the highest efficiency of 97.5%. The efficency of the MC depends on the device, topology, control and modulation technichies used.

7. CONCLUSION

In this paper, a comprehensive review on the characteristics of the MC is made. This review has compared diverse literature available in area of MC. The review showed the existence of continuous development of the MC in terms of topology, devices, control method and application to improve the performance in terms of total harmonic distortion, common mode voltage, voltage transfer ratio and efficiency. This opens the scope of improvement in the MC for industrial and house hold applications. With the results reported in this paper, the several options for specific application which needed specific characters in MC can be selected. However, the best option needs deeper research.

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