Voltage Vectors of Matrix Converters For Torque Ripple Reduction in Direct Torque Control of Induction Machines

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Abstract--The matrix converter is an array of controlled semiconductor switches that connects directly the three-phase source to the three-phase load. This converter has several attractive features that have been investigated in the last two decades. In the last few years, an increase in research work has been observed, bringing this topology closer to the industrial application. This paper presents the state-of-the-art view in the development of this converter, starting with a brief historical review. An important part of the paper is dedicated to a discussion of the most important modulation and control strategies developed recently. Special attention is given to present modern methods developed to solve the commutation problem. Some new arrays of power bidirectional switches integrated in a single module are also presented. Finally, this paper includes some practical issues related to the practical application of this technology, like overvoltage protection, use of filters, and ride-through capability.

Index Terms-- **Direct Torque Control (DTC), Matrix Converter (MC).**

I. INTRODUCTION

Among the most desirable features in power frequency changers are the following:

1) Simple and compact power circuit.
2) Generation of load voltage with arbitrary amplitude and frequency.
3) Sinusoidal input and output currents.
4) Operation with unity power factor for any load.
5) Regeneration capability.

These ideal characteristics can be fulfilled by matrix converters, and this is the reason for the tremendous interest in the topology. The matrix converter is a forced commutated converter which uses an array of controlled bidirectional switches as the main power elements to create a variable output voltage system with switch [1]–[4]. With this solution, the power circuit was bulky and the performance was poor unrestricted frequency. It does not have any dc-link circuit and does not need any large energy storage elements. The key element in a matrix converter is the fully controlled four-quadrant bidirectional switch, which allows high-frequency operation. The early work dedicated to unrestricted frequency changers used thyristors with external forced commutation circuits to implement the bidirectional controlled Direct torque control (DTC) is a high-dynamic and high performance control technique for induction motor drives which has been developed in the last two decades as possible alternative to DC servo drives. In direct torque controlled adjustable speed drives, the motor flux and the electromagnetic torque are the reference quantities which are directly controlled by the applied inverter voltage vector. The main advantages of DTC are: fast torque and flux responses, no need for speed or position sensors and no requirements for coordinate transformation. In fact, it only needs to know the stator resistance and terminal quantities (v and i) in order to perform the stator flux and torque estimations. Therefore, the DTC schemes have attracted many researchers to study and investigate for a long time. DTC has also some disadvantages: the difficulty to control the torque and the flux at very low

speed, the higher current and torque ripple which imply higher machine losses and noise, the inherent variable switching frequency and the lack of direct current control [1]. Recently, three phase matrix converters (MC) have emerged to become a good alternative to the well known voltage source inverters (VSI). Matrix converter is a direct ac/ac converter that allows each output phase to be connected to each input phase. A 3x3 matrix converter can be usefully implemented for connecting a 3 phase voltage source to a 3 phase load or machine. The matrix converter is an advanced circuit topology capable of converting AC-AC, providing generation of load voltage with arbitrary amplitude and frequency, bidirectional power flow, sinusoidal input/output waveforms, and operation with unity input power factor. Furthermore, since no inductive or capacitive elements are required, matrix converter allows a very compact design [2], [3].

Eupec Company has developed a new technology for integrating the whole matrix converter power devices in a single package and the integrated power modules are now available commercially. This type of packaging can minimize the stray inductance and the size of the power devices [4]. Yaskawa Company has implemented a commercial matrix converter and has shown it has many advantages. For example, it requires small mounting place because the braking resistance or regeneration converter is unnecessary. It has less total current harmonic distortion and higher power factor at the input side when compared with the rectifier/dc-link/inverter. Moreover, it has longer life because no capacitor is used. The cost of matrix converters will be reduced and will compete with the traditional VSI. As a result, one can predict that the applications of matrix converters will become more and more popular in the near future [5].

The DTC using a multi-level inverter can produce more sets of space vectors to control torque and flux of a motor and gain smoother electromagnetic torque of the motor. However, the multi-level inverters need more power switch elements and cause more cost and complication to the whole system [6].

By combining the advantages of matrix converters with the advantages of DTC schemes, it is possible to achieve fast torque and flux responses in a wide speed range. But the main drawback of the conventional DTC will make more serious electromagnetic torque ripple [7].

As a result, the drive system fed by the matrix converter doesn't need any additional power switch elements and can attain the same performance as the multi-level inverter. According to the properties of a matrix converter, there are three different voltage vectors on each space vector location. By suitably selecting the space vector, the current deviations and the torque ripple of the motor can be effectively reduced.

This paper proposes to select the most appropriate voltage vector with respect to the error of the torque. The standard look-up table for direct torque control by matrix converters is improved in order to include the small, medium and large voltage vectors of Matrix Converters. With the new look-up table and new hysteresis comparator with seven levels output the system will differentiate between small, medium and large torque errors and consequently reduce the electromagnetic torque ripple and output current THD. Simulation results demonstrate the effectiveness of the proposed scheme.

II. MATRIX CONVERTER THEORY

The three-phase to three-phase matrix converter consists of nine bidirectional switches that allow any output phase to be connected to any input phase. The circuit scheme is shown in Fig. 1. The input terminals of the converter are connected to a three phase voltage-fed system, usually the grid, while the output terminals are connected to a three phase current-fed system, like an induction motor might be. With nine bidirectional switches, the matrix converter can theoretically assume 512 (2^9) different switching state combinations, but not all of them

can be usefully employed. Regardless of the control method used, the choice of useful matrix converter switching state combinations must comply with two basic rules: Taking into account that the converter is supplied by a voltage source and usually feeds an inductive load, the input phases should never be short circuited and the output currents should not be interrupted. From a practical point of view, these rules imply that one and only one bidirectional switch per output phase must be switched on at any instant.
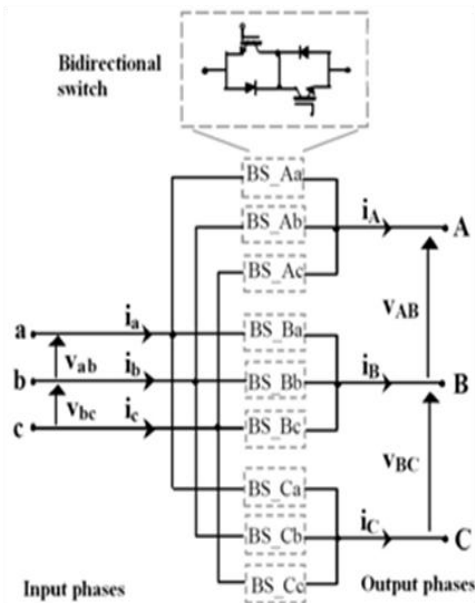

Fig. 1. Three-phase to three-phase matrix converter

Under these constraints, it can be verified that in a three-phase to three-phase matrix converter only 27 different switch configurations are permitted. These 27 switch configurations are listed in Table I. Each configuration is identified by a number and by a three letter code. The three letters describe which output phase is connected to which input phase according to the schematic representation of Fig. 1. For instance, the configuration named "baa" refers to the matrix state where output phase A is connected to input phase b, output phase B is connected to input phase a and output phase C is connected to input phase a.

According to the corresponding output voltage and input current space vectors, these matrix converter configurations are classified as "active", "zero" and "synchronous" configurations.

TABLE I
MATRIX CONVERTERS SPACE VECTORS

Vector	ABC	e_o	α_o	i_i	β_i
+1	a b b	$2/3V_{ab}$	0	$2/\sqrt{3i}\ A$	$-\pi/6$
-1	b a a	$-2/3V_{ab}$	0	$-2/\sqrt{3i}\ A$	$-\pi/6$
2	b c c	$2/3V_{ab}$	0	$2/\sqrt{3i}\ A$	$\pi/2$
-2	c b b	$-2/3V_{ab}$	0	$-2/\sqrt{3i}\ A$	$\pi/2$
3	c a a	$2/3V_{ab}$	0	$2/\sqrt{3i}\ A$	$7\pi/6$
-3	a c c	$-2/3V_{ab}$	0	$-2/\sqrt{3i}\ A$	$7\pi/6$
4	b a b	$2/3V_{ab}$	$2\pi/3$	$2/\sqrt{3i}\ B$	$-\pi/6$
-4	a b a	$-2/3V_{ab}$	$2\pi/3$	$-2/\sqrt{3i}\ B$	$-\pi/6$
5	c b c	$2/3V_{ab}$	$2\pi/3$	$2/\sqrt{3i}\ B$	$\pi/2$
-5	b c b	$-2/3V_{ab}$	$2\pi/3$	$-2/\sqrt{3i}\ B$	$\pi/2$
6	a c a	$2/3V_{ab}$	$2\pi/3$	$2/\sqrt{3i}\ B$	$7\pi/6$
-6	c a c	$-2/3V_{ab}$	$2\pi/3$	$-2/\sqrt{3i}\ B$	$7\pi/6$
7	b b a	$2/3V_{ab}$	$4\pi/3$	$2/\sqrt{3i}\ C$	$-\pi/6$
-7	a a b	$-2/3V_{ab}$	$4\pi/3$	$-2/\sqrt{3i}\ C$	$-\pi/6$
8	c c b	$2/3V_{ab}$	$4\pi/3$	$2/\sqrt{3i}\ C$	$\pi/2$
-8	b b c	$-2/3V_{ab}$	$4\pi/3$	$-2/\sqrt{3i}\ C$	$\pi/2$
9	a a c	$2/3V_{ab}$	$4\pi/3$	$2/\sqrt{3i}\ C$	$7\pi/6$
-9	c c a	$-2/3V_{ab}$	$4\pi/3$	$-2/\sqrt{3i}\ C$	$7\pi/6$
0	a a a	0	..	0	..
0	b b b	0	..	0	..
0	c c c	0	..	0	..
…	a b c	e_i	X	i_o	X
…	a c b	e_i	X	i_o	X
…	b a c	e_i	X	i_o	X
…	b c a	e_i	X	i_o	X
…	c a b	e_i	X	i_o	X
…	c b a	e_i	X	i_o	X

As it can be seen in the second column of Table I, the active configurations have the common feature of two output phases connected to the same input phase. There are 18 active configurations numbered by ±1, ±2,…,±9 in

Table I. They determine six fixed positions of the output voltage space vector $\bar{e}_o$ which are not dependent on the input voltage space vector phase angle and six prefixed positions of the input current space vector $\bar{l}_i$ which are not dependent on the output current space vector phase angle. The magnitude of the space vectors $\bar{e}_o$ and $\bar{l}_i$ is variable and depends on the instantaneous values of the input line voltages and output line currents respectively. The representation of the output voltage space vectors and input current space vectors is shown in Fig. 2.

There are 3 zero configurations which are numbered 0 in Table I. In zero configurations, the three output lines are connected to the same input phase, so that they determine zero output voltage and input current space vectors.

There are 6 synchronous configurations not numbered in Table I. These configurations determine those output space vectors which have a phase angle that is dependent on the input voltage space vector phase angle. Likewise, the input current space vector has a phase angle which is related to the output current space vector phase angle. The magnitude of the space vectors $\bar{e}_o$ and $\bar{l}_i$ is constant and equal to the magnitude of the input phase voltage and output line current space vectors respectively.
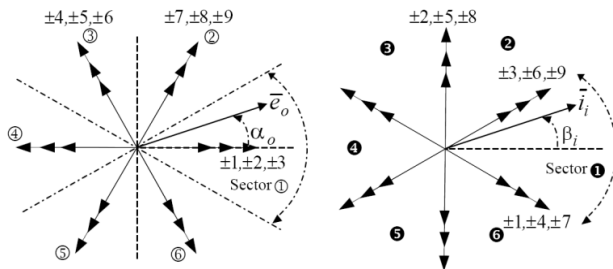

Fig. 2. (a) Output Phase Voltage Space Vectors (b) Input Current Space Vectors

III.   PRINCIPLE OF DIRECT TORQUE CONTROL BY VSI

In direct torque controlled adjustable speed drives, the motor flux and the electromagnetic torque are the reference quantities which are directly controlled by the applied inverter voltage vector.
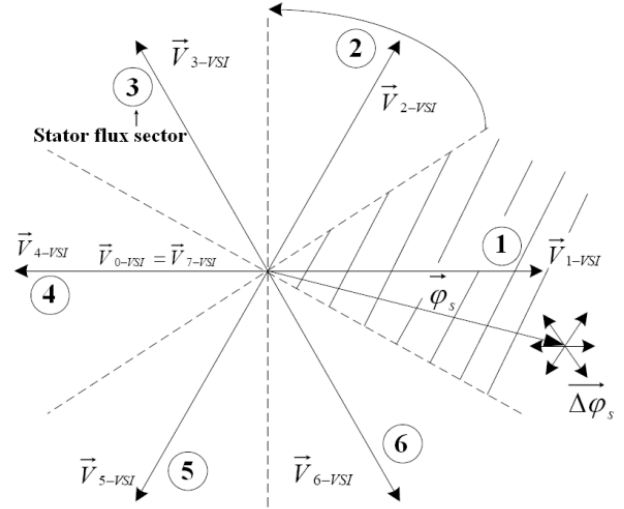
At each cycle period, the proper inverter voltage vector is selected according to the switching table given in Table II, in order to maintain the estimated torque and stator flux within the limits of two hysteresis bands. More precisely, the vector is chosen according to the position of the stator flux vector and the instantaneous errors in torque and stator flux magnitude.

Looking at Fig. 3, it is worth noting that due to the fixed direction of the inverter voltage vectors and also the rotating motion of the stator flux vector in the d-q stator frame, for each inverter voltage vector, the amplitude of its radial and tangential components will be variable within a sector.

IV.   THE USE OF MATRIX CONVERTER IN DTC

Among the 27 voltage and current vectors, only the active and null vectors will be considered in DTC. As it can be seen in Fig. 2, the direction of the active voltage vectors is constant. However, their magnitude depends on the input voltages. It should be noted that the direction of the active voltage vectors of a MC is similar to the direction of the active voltage

vectors generated by a conventional VSI.

Fig. 3. VSI output line-to-neutral voltage vectors and corresponding stator flux variations

Once the classical DTC control scheme has selected the optimum vector to be applied to the machine, it is a matter of determining the corresponding matrix converter switching configuration. For example, if the VSI output vector $\bar{V}_{1-vsi}$ has been chosen, looking at Table

I and Fig. 2(a) and Fig. 3, it can be seen that matrix converter can generate the same vector by means of the switching configurations $\pm1,\pm2,\pm3$. But not all of them can be usefully employed to provide vector $\overline{V}_{1-vsi}$. In fact, at any instant, the magnitude and the direction of their corresponding output voltage vectors depends on the position of the input phase voltage vector $\bar{e}_i$.

TABLE II
BASIC DTC BY VSI CONFIGURATION
SELECTION

Stator flux sector		1	2	3	4	5	6
$C\varphi_{=+1}$	$C_T=1$	V 2-vsi	V 3-vsi	V 4-vsi	V 5-vsi	V 6-vsi	V 1-vsi
	$C_T=0$	V 7-vsi	V 0-vsi	V 7-vsi	V 0-vsi	V 7-vsi	V 0-vsi
	$C_T=-1$	V 6-vsi	V 1-vsi	V 2-vsi	V 3-vsi	V 4-vsi	V 5-vsi
$C\varphi_{=-1}$	$C_T=1$	V 3-vsi	V 4-vsi	V 5-vsi	V 6-vsi	V 1-vsi	V 2-vsi
	$C_T=0$	V 0-vsi	V 7-vsi	V 0-vsi	V 7-vsi	V 0-vsi	V 7-vsi
	$C_T=-1$	V 5-vsi	V 6-vsi	V 1-vsi	V 2-vsi	V 3-vsi	V 4-vsi

Among the 6 vectors, only those having the same direction of $\overline{V}_{1-vsi}$ and the maximum magnitude are considered. For example, looking at Fig. 4 and Table I it can be seen that, if vector $\bar{e}_i$ is in sector 1 or 2, the switching configurations to be used are +1 and –3. It has been verified that, whatever is the sector which the vector $\bar{e}_i$ is in, the matrix converter has always two switching configurations for each VSI output vector chosen by the classical DTC scheme.

Such redundancy can be benefited to control a third variable in addition to the stator flux and the electromagnetic torque. The average value of the sine of the displacement angle ψ_i between the input current vector and the corresponding input phase voltage vector has been chosen as the third variable. This variable will be indicated by sin ψ_i . If the constraint to comply with is a unity input power factor, such aim can be achieved by keeping the value of sin ψ_i equal to zero. The variable sin ψ_i is directly controlled by the hysteresis comparator.

The switching table based on these principles is shown in Table III [7]. In the first column, the voltage vectors selected by the conventional DTC are present. The top row contains the sector in which the input phase

voltage vector lies. Depending on whether the power factor control needs $C\psi$, one of the two columns +1,-1 is selected.

TABLE III
MATRIX CONVERTER SWITCHING TABLE FOR DTC

	Sector of input phase voltage vector											
	❶		❷		❸		❹		❺		❻	
C_ψ	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1	+1	-1
$V_{1\text{-vsi}}$	-3	1	2	-3	-1	2	3	-1	-2	3	1	-2
$V_{2\text{-vsi}}$	9	-7	-8	9	7	-8	-9	7	8	-9	-7	8
$V_{3\text{-vsi}}$	-6	4	5	-6	-4	5	6	-4	-5	6	4	-5
$V_{4\text{-vsi}}$	3	-1	-2	3	1	-2	-3	1	2	-3	-1	2
$V_{5\text{-vsi}}$	-9	7	8	-9	-7	8	9	-7	-8	9	7	-8
$V_{6\text{-vsi}}$	6	-4	-5	6	4	-5	-6	4	5	-6	-4	5

V. IMPROVEMENT OF DTC USING ALL VECTORS OF MATRIX CONVERTER

By dividing the input voltage vector path into twelve sectors, according to Fig. 4 and using the new MC switching table for DTC presented in Table IV, the DTC algorithm will be able to distinguish between small, medium and large vectors. In order to reduce the torque ripple, in addition to the large vectors of MC, the medium and small vectors can also be used. Thus the DTC scheme must be modified resulting in a new torque hysteresis comparator that will provide seven different levels instead of three levels to distinguish between small, medium and large positive and negative torque errors. The new seven- level hysteresis comparator is shown in Fig. 5. If the ideal value of $C\psi$ for power factor hysteresis comparator, can't be found in one input voltage sector, then the other vector in the same sector can be selected from Table IV to control the unit input power factor.

As it is shown in Fig. 5, when the absolute value of torque error E_{Te} is equal to or greater than 0.2, and less than 0.6, the value of the is ±1, the small voltage vector table is selected and E_{Te} will decrease until the absolute value of E_{Te} is equal to 0.1.

When the absolute value of torque error E_{Te} is equal to or greater than 0.6, and less than 1, the value of H_{Te} is ±2, the medium voltage

vector table is selected and E_{Te} will decrease until the absolute value of E_{Te} is equal to 0.2 When the absolute value of torque error E_{Te} is equal or greater than 1, the value of H_{Te} is ±3, the large voltage vector table is selected and E_{Te} will decrease until the absolute value of E_{Te} is equal to 0.6.

VI.   SIMULATION RESULTS

In order to validate the proposed method and compare it with the classical DTC using MC, some simulations have been carried out. The test machine is a standard 7.5 kW four-pole 400V 50Hz cage induction motor and has the following parameters:

Rs=0.7384 Ω Rr=0.742 Ω
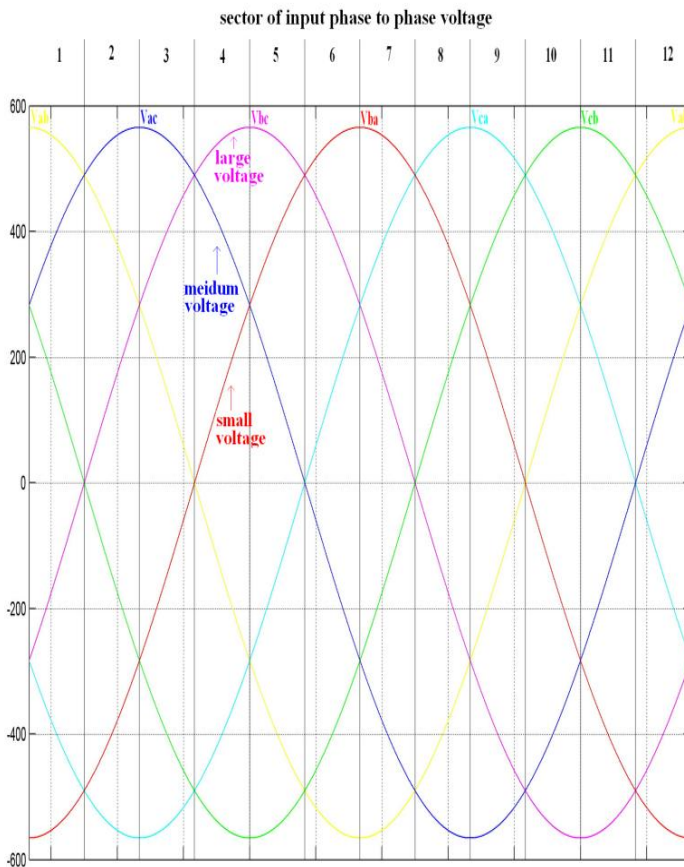Lm=0.1241 H Lls=3.045 mH Llr=3.045 mH

Fig. 4. Small, medium and large voltage vectors of matrix converter and 12 sector of input line voltage

TABLE IV
LOOK UP TABLE FOR THE USE OF ALL MC
VOLTAGE VECTORS

SMALL VECTORS

Sector	1	2	3	4	5	6	7	8	9	10	11	12
H_ψ	-	+	-	+	-	+	-	+	-	+	-	+
$V_{1\text{-vsi}}$	-2	2	1	-1	-3	3	2	-2	-1	1	3	-3
$V_{2\text{-vsi}}$	8	-8	-7	7	9	-9	-8	8	7	-7	-9	9
$V_{3\text{-vsi}}$	-5	5	4	-4	-6	6	5	-5	-4	4	6	-6
$V_{4\text{-vsi}}$	2	-2	-1	1	3	-3	-2	2	1	-1	-3	3
$V_{5\text{-vsi}}$	-8	8	7	-7	-9	9	8	-8	-7	7	9	-9
$V_{6\text{-vsi}}$	5	-5	-4	4	6	-6	-5	5	4	-4	-6	6

MEDIUM VECTORS

Sector	1	2	3	4	5	6	7	8	9	10	11	12
H_ψ	-	+	-	+	-	+	-	+	-	+	-	+
$V_{1\text{-vsi}}$	-3	1	2	-3	-1	2	3	-1	-2	3	1	-2
$V_{2\text{-vsi}}$	9	-7	-8	9	7	-8	-9	7	8	-9	-7	8
$V_{3\text{-vsi}}$	-6	4	5	-6	-4	5	6	-4	-5	6	4	-5
$V_{4\text{-vsi}}$	3	-1	-2	3	1	-2	-3	1	2	-3	-1	2
$V_{5\text{-vsi}}$	-9	7	8	-9	-7	8	9	-7	-8	9	7	-8
$V_{6\text{-vsi}}$	6	-4	-5	6	4	-5	-6	4	5	-6	-4	5

LARGE VECTORS

Sector	1	2	3	4	5	6	7	8	9	10	11	12
H_ψ	-	+	-	+	-	+	-	+	-	+	-	+
$V_{1\text{-vsi}}$	1	-3	-3	2	2	-1	-1	3	3	-2	-2	1
$V_{2\text{-vsi}}$	-7	9	9	-8	-8	7	7	-9	-9	8	8	-7
$V_{3\text{-vsi}}$	4	-6	-6	5	5	-4	-4	6	6	-5	-5	4
$V_{4\text{-vsi}}$	-1	3	3	-2	-2	1	1	-3	-3	2	2	-1
$V_{5\text{-vsi}}$	7	-9	-9	8	8	-7	-7	9	9	-8	-8	7
$V_{6\text{-vsi}}$	-4	6	6	-5	-5	4	4	-6	-6	5	5	-4

The simulation model of this novel DTC-MC adjustable speed system is set up with MATLAB/SIMULINK power system toolbox. The sampling period used is 20μs and the matrix converter model has been developed using IGBT switches.
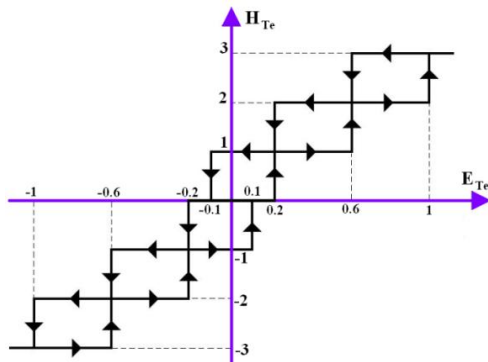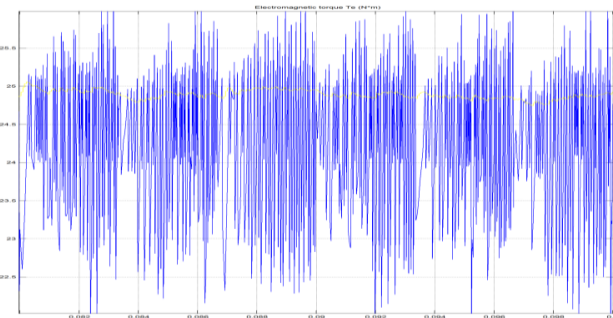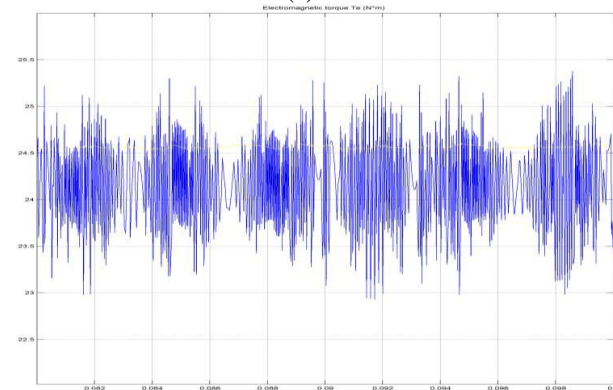
Fig. 6. Electromagnetic torque at 1000 rpm in
(a) Classical method (b) Proposed method

Fig. 5. New torque hysteresis comparator with seven output levels

A. High-Speed Results:

These results are obtained with both the classical method and the proposed method at speed 1000 rpm and torque 25 N.m. The electromagnetic torque, and the output current THD, are shown in Fig. 6 and Fig. 7 respectively. It can be seen that in the proposed method, torque ripple and output current THD are significantly reduced.

(a)

(b)

(a)

(b)

Fig. 7. Output Current THD at 25 N.m and 1000 rpm
in (a) Classical method (b) Proposed method

B. Low-Speed Results:

The performance of the proposed drive system has also been tested at low speed. The torque reference is 6.5 N.m and the rotor speed is 500 rpm. Fig. 8 and 9 show the obtained results. As can be seen, even at low speed, the toque ripple and output current THD are significantly reduced. This confirms validity of the proposed scheme.

VII. CONCLUSION

This paper introduces a novel Direct Torque Control with matrix converters which uses not only the largest output voltage vectors, but also the medium and small ones to reduce the electromagnetic torque ripple and output current THD. The new look up table for DTC-MC is

designed for the small, medium and large matrix converter output voltage vectors. Furthermore, the torque error hysteresis comparator is modified in order to distinguish between small, medium and large positive and negative torque errors. Simulation results show that by using all the voltage space vectors of the matrix converter, the torque ripple and output current THD are significantly reduced.
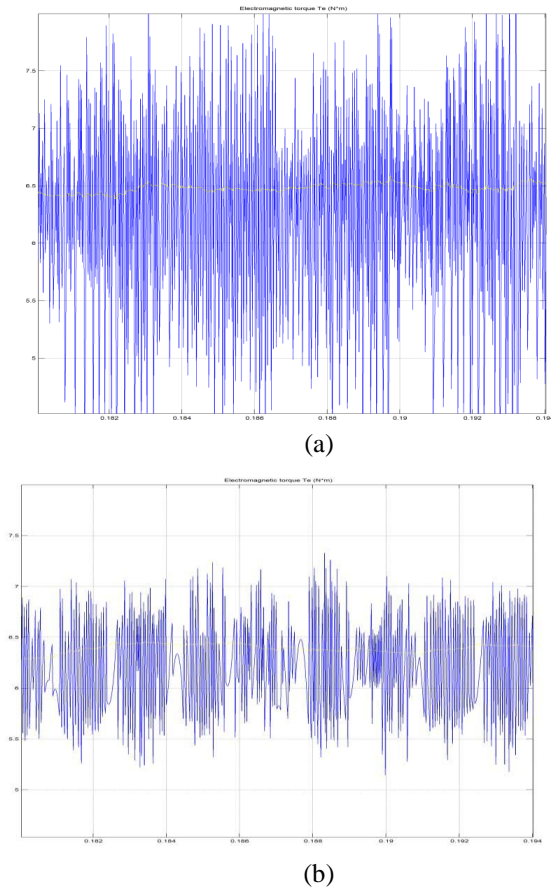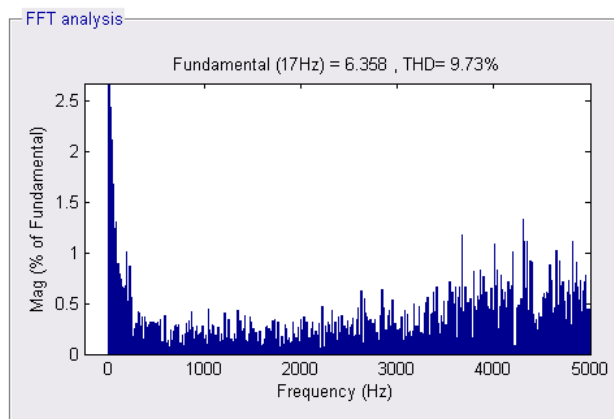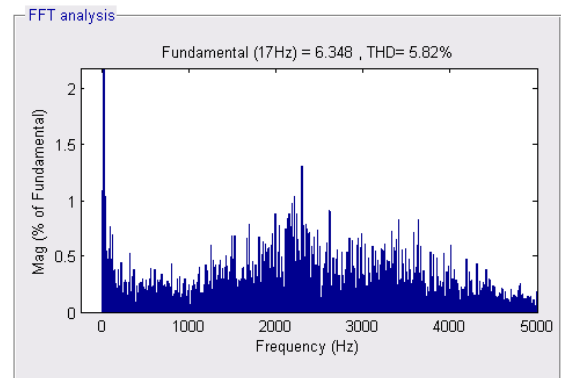
(a)

(a)

(b)

Fig. 8. Electromagnetic torque at 500 rpm in (a) Classical method (b) Proposed method

(b)

Fig. 9. Output Current THD at 6.5 N.m and 500 rpm in (a) Classical method (b) Proposed method

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