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Direct Torque Control of Induction Motor with Matrix Converter

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Abstract

The matrix converter (MC) with direct torque control (DTC) combination is efficient way to get better performance specifications in the industry. The MC and the DTC advantages are combined together. The reduction of complexity and cost of DC link in the DTC since it has no capacitors in the circuit. However, the controlling torque is a big problem it in DTC because of high ripple torque production which results in vibrations response in the operation of the iductuction motor as it has no PID to control the torque directly. To overcome this, a combination of MC with DTC is applied to reduce the fluctuation in the output torque and minimize the steady state error. This paper presents the simulation analysis of induction machine drives using Maltlab/Simulink toolbox R2012a. Design of DTC induction motor drive, MC with constant switching frequency, speed controller and stability investigation as well as controllability and observabilty with minimum final prediction (FPE) steady state error and loss functionality has been carried out precisely.

Keywords: Induction Motor (IM), Direct torque control (DTC), Matrix converter (MC), Control drive, Speed control

1 Introduction

The induction motors (IM) plays an important role in the industry due to their low cost and operational reliability [1]. Adjustable speed drives (ASDs) are frequently used in many applications, such as air conditioning, elevators, electrical vehicles, ventilation, pumps, fans, heating, robotics [2].In 1984, I. Takahashi developed a new technique for the torque control of IM which is one kind of variable speed drives named as Direct Torque Control (DTC) [3]. New generation started with this technique characterized by current regulators, robustness, good performance, absence of PI regulators, and simplicity [4]. DTC methods of AC machines based on a PWM decoupling of both flux and torque as in the DC machines by the orientation control of the magnetic field. The DTC configuration for direct matrix converter has been presented in [5]. In a DTCIM drive, a decoupled control of torque and flux can be achieved by two independent control loops [6]. This configuration play vital role in the industry due many reasons like ability to adjust input power factor, no need to DC link capacitor, ensure sinusoidal waveforms for the input and output and power flow control in the forward and backward directions. Comprehensive researches studies on direct matrix converter with DTC [7]. The available literature on DTC drives too are mainly confined to performance enhancement in terms of torque ripples. Since the steady state as well as dynamic performance of a DTC drive is greatly affected by the flux control loop which in turn depends upon flux estimation algorithm [8]. Fuzzy logic controller of multilevel inverter, the space vector modulation presented in [9]. In [10] the inverter voltage vector selected from the switching table is applied for the time interval needed by the torque to reach the upper limit or lower limit of the band, where the time interval is calculated from a suitable modeling of the torque dynamics. AC-DC-AC sparse direct power converter introduced in [11]. Control of a Two Stage Direct Power Converter with a Single Voltage Sensor Mounted in the Intermediary Circuit presented in [12]. The DTC can be divided into two types, either direct self-control (DSC) or space vector modulation (SVM). DTC-SVM for Induction Motor Driven by Matrix Converter Using a Parameter Estimation Strategy done by [13]. The switching table has many drawbacks such as variable switching frequency due to hysteresis bands of both torque and flux as well as the change of speed motor. According to this variation in switching frequency, uncontrolled small region will be generated especially in the beginning of operation of induction motor. To obtain good solution for that, space vector modulation with DTC and matrix converter has been used. The stability is one of the most important demands in the control system after being subjected to a disturbance [14]. The MC can be used in the compressors, fans (blowers), mixers, general pumps or heat pumps and escalator drive system [15].

In this paper, a combination of fixed switching frequency DTC with MC scheme is presented, which developed to minimize the steady state error of input torque due highly torque noise in the DTC scheme that should be suppressed.

2 DTC Background

The DTC technique principle is shown in the Fig.1 can be interpreted as follow: At the first step, the phase currents and voltages of the system are measured. The outcome of forwarding such values to the flux and torque estimator will be the actual flux and torque of the system. The estimated torque is compared with their reference values in three levels torque

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hysteresis controller. At same time, the flux is compared with the reference flux values in two levels flux hysteresis controller. In order to construct the transistor control signal, the outputs of the stator flux and torque controllers further to the flux selector are used as inputs of the DTC switching look up table.

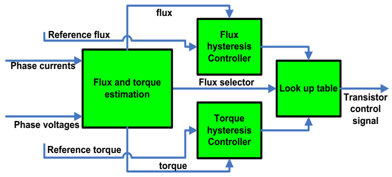

Fig.1. Principle of the DTC

The transistors control signals which are divided into nine different sections are used for controlling the three level matrix convertor, as can be shown in the Fig. 2.

The general selection table for the DTC, being (k) which is the sector number can be shown in table 1.

Table1. General selection table

Ψs in sector K		Torque	
Flux	Increase	Increase	Decrease
		Vk+1	V000
	Decrease	Vk+2	V111

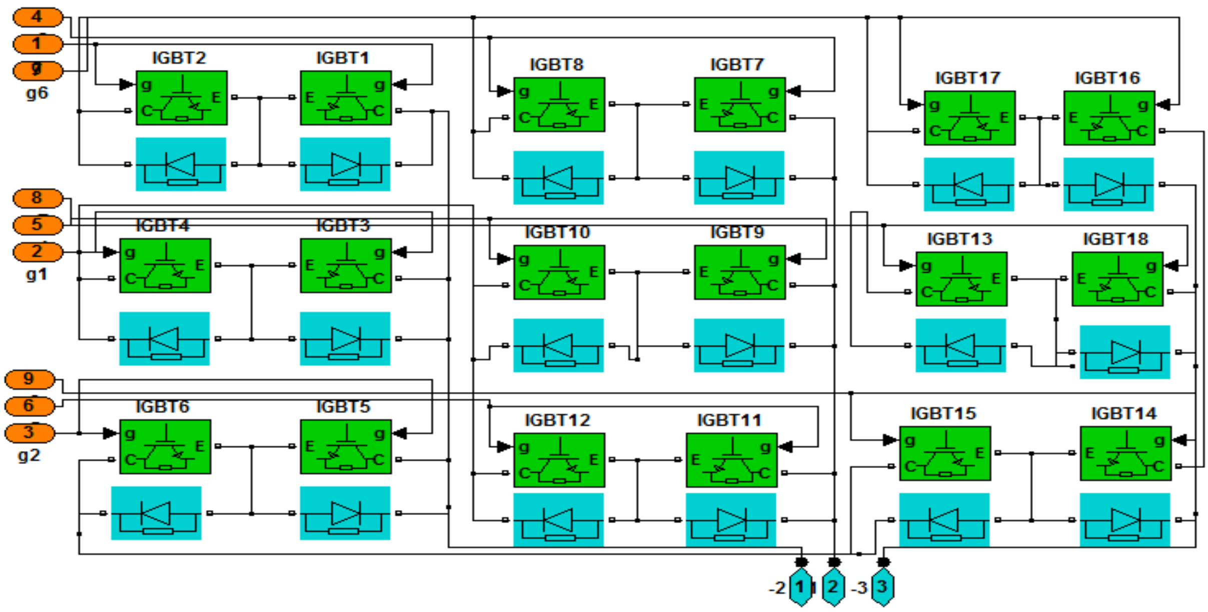

Fig.2. Simulink implementation of the three level matrix converter [23]

DTC zero sequence (V_{000} or V_{111}) vectors are used to maintain the torque constant and not including during the switching period.

The switching table in DTC allows selecting the vector position to apply to the MC according to the DC of the stator flux and the electromagnetic torque as can be shown in table 2. From table1, one can notice that the switching frequency of the IGBTs used in this scheme is not constant. If we control the tolerance bands, the average switching frequency can be kept at its reference value, hence the ripple current and torque will be minimized [16].

Table 2. DTC switching table

		sector					
		1	2	3	4	5	6
dφ=+1	dT= +1	V2	V3	V4	V5	V6	V1
	dT= 0	V0	V7	V0	V7	V0	V7
	dT= -1	V6	V1	V2	V3	V4	V5
dφ=+1	dT= +1	V3	V4	V5	V6	V1	V2
	dT= 0	V7	V0	V7	V0	V7	V0
	dT= -1	V5	V6	V1	V2	V3	V4

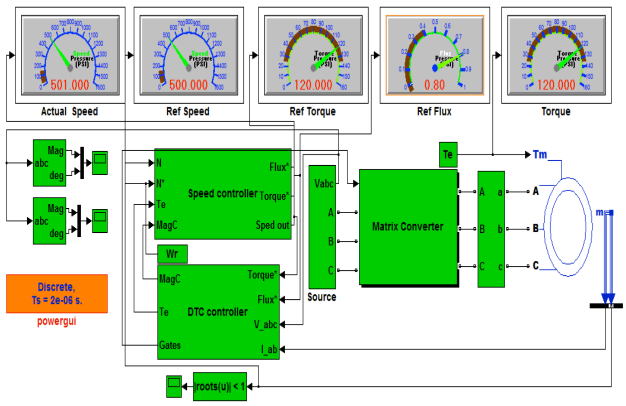

Fig.3. The proposed fixed frequency DTC scheme using matrix converter

The MCDTC proposed algorithm can be shown in Fig.3.

3. Matrix Converter

The advantages of the MC compared to conventional inverter types are as follows:

1. Waveforms of both Input and output are very clear [17, 18].
2. Minimal higher order harmonics are obtained

3. Capability of sub harmonics omitting
4. Capability of bi-directional energy flow
5. It has no DC link capacitors

The disadvantages of the matrix converter are as follows.

1. Maximum efficiency cannot be obtained in all cases.
2. The conventional AC-AC has less components compared to the MC
3. Each bi-directional switch should have its arrangement.
4. Sensitive to input voltage system.

The system consists of a 3-phase MC constructed from 9 back-to-back IGBT switches. The MC is supplied with three phase source and drives a static resistive load. The switching algorithm is based on space-vector modulation described in [1] which considers the MC as a rectifier and inverter connected via a DC link with no energy storage. Indirect space-vector modulation allows direct control of input current and output voltage and hence allows the power factor of the source to be controlled. The switching algorithm utilizes a symmetric switching sequence described in [2].

First of all the Simulink implementation of the matrix converter is carried out. MC consists of nine bi-directional sectors with reverse blocking capability, arranged as three sets of three so that any of the three input phases can be connected to any of the three output lines, as shown in Fig. 2. A bi-directional 18 diodes is used for blocking the voltage in MC [19]. The inversion matrix sequence of the SVM modulation when the voltage mod input to generate (v_1-v_2-v_7- v_8) with the switching pattern is constructed as in the Fig.4.

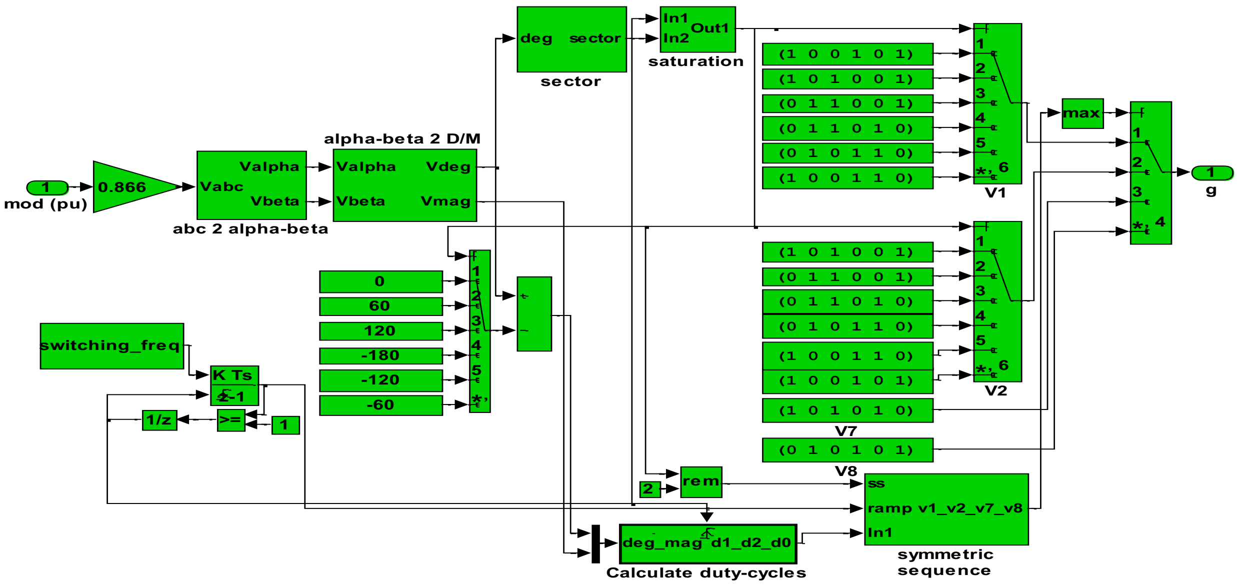

Fig.4. Matrix converter SVM symmetric switching in the voltage mod input

In the first position (0-60) degree, the torque will be decreased while the flux will be increased. In the positions (60-120) or (-120- (-60)) there is a flux ambiguity, in the position (-180- (-120)) the torque and the flux will be decreased and last position (180-120) the torque will be increase while the flux will be increased. There are two position between(30-(30)) are not used because the torque will increased or decreased in the same sector depending on the position if it's in the position of 30 or -30.

The symmetric sequence unit used the current mod as the input to generate (v_1-v_2-v_0) as shown in Fig.5

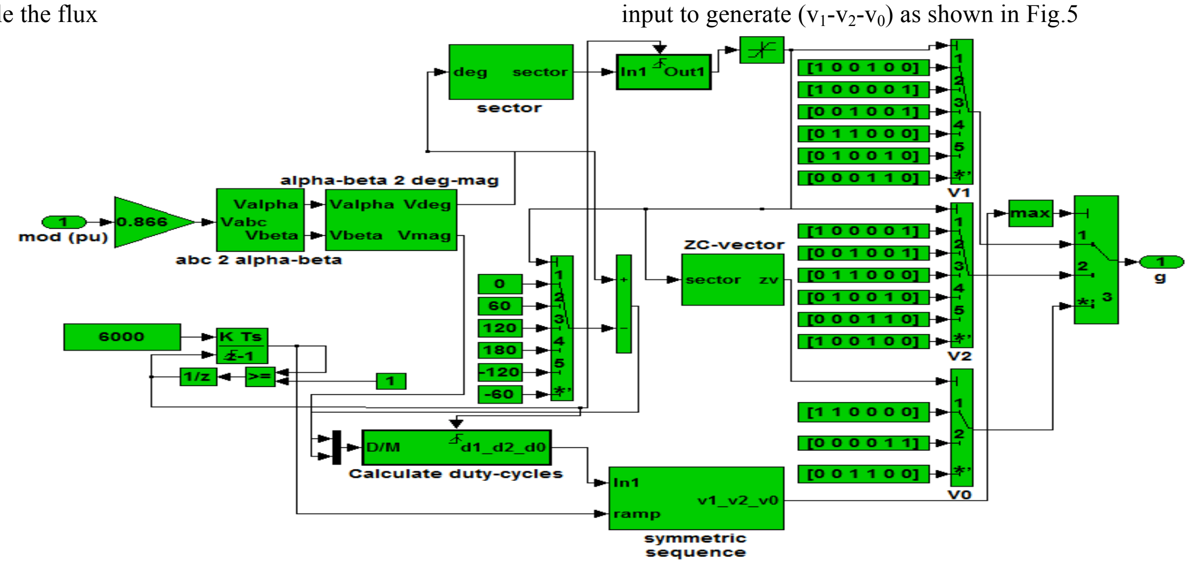

Fig.5. Matrix converter SVM symmetric switching in the current mod input

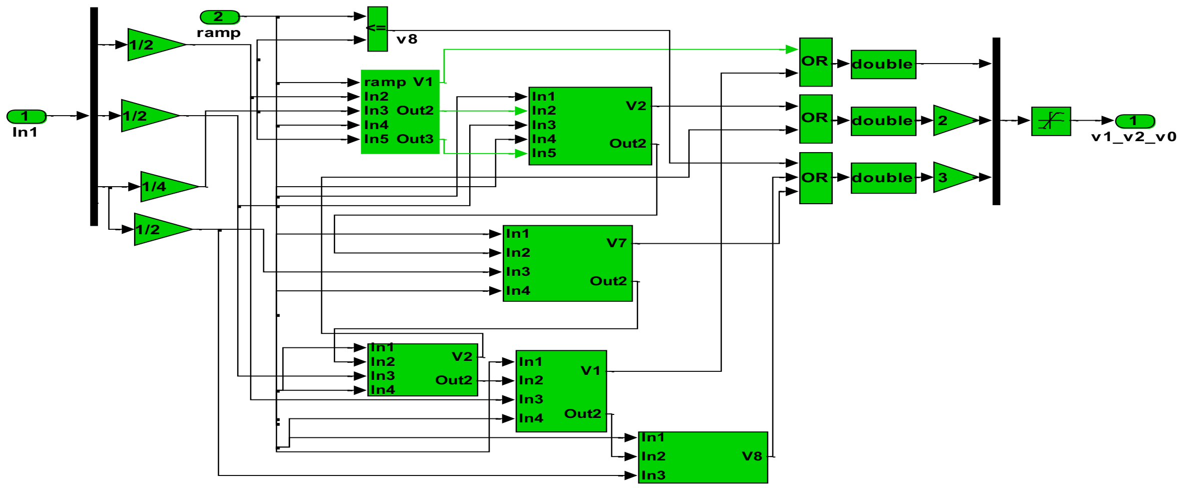

Fig.6. SVM symmetric sequence unit of the above figure

SVM symmetric sequence unit can be implemented using Matlab/Simulink as in Fig.6

An induction motor can be described in the stationary frame by the following flux and voltage equations.

$$\psi_s = L_s i_s + L_m i_r \quad (1)$$

$$\psi_r = L_m i_s + L_m i_r \quad (2)$$

$$v_s = R_s i_s + \frac{d\psi_s}{dt} \quad (3)$$

$$0 = R_r i_r + \frac{d\psi_r}{dt} - j\omega_r \psi_r \quad (4)$$

Where R_r, L_s, L_r, L_m, i_s, i_r, v_s, is rotor resistance, stator self-inductance, rotor self-inductance, mutual inductance, stator current vector, rotor current vector, stator voltage vector respectively. The stator flux variation can be expressed as:

$$\Delta\psi_s = (v_s - R_s i_s)t_{sp} = e_s t_{sp} \cong v_s t_{sp} \quad (5)$$

Where e_s is the electromotive force vector, and tsp is the sampling period. The control signal to generate the MC gates can be constructed from two lookup tables. First one when the magnitude of the flux equal one and the other one when the flux is equal to minus one as can be seen in the Fig.7 and Fig.8.

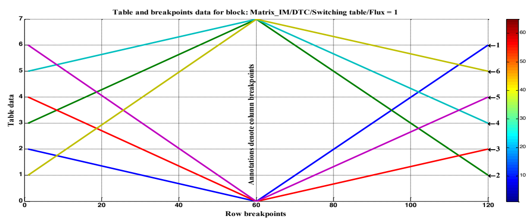

Fig.7. Lookup table data when the flux=-1

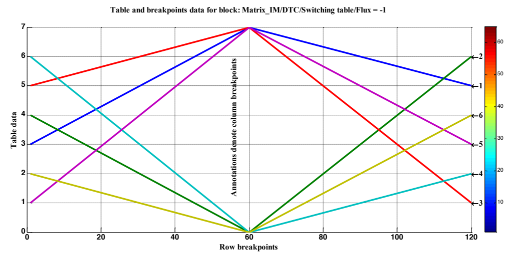

Fig.8. Lookup table data when the flux=1

The combinations from 1 to 9 which are the sectors (v_0-v_1-v_2-v_3-v_4-v_5-v_6-v_7-v_8) are used as a gate signal of the IGBT transistor as can be shown in the fig.9.

The first 6 states can be constructed from the current mode (qR) and the other 6 state as constructed from the voltage mode circuit (ql). The combinations of these 12 signals are used to construct the SVM used to control the MC.

Where in g is the output angle in the SVM rectification system to generate left (gl) and right (gR) axis of the sector when the voltage and current mode acts as the inputs to the circuits.

4. Matrix Converter Switching Sequence

The control requirement of the switches of matrix converter through the duty cycle depends on the average output voltages to construct the required sinusoidal frequency and magnitude of the three phase voltage [20]. The matrix converter switching generation signal combination with the SVM rectification sequence can be shown in Fig.10.

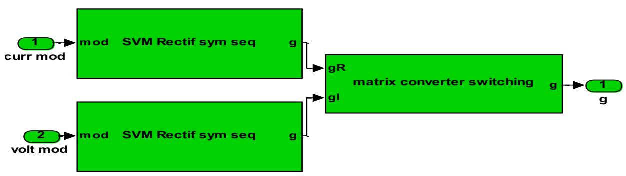

Fig.10. Matrix converter switching generation signal.

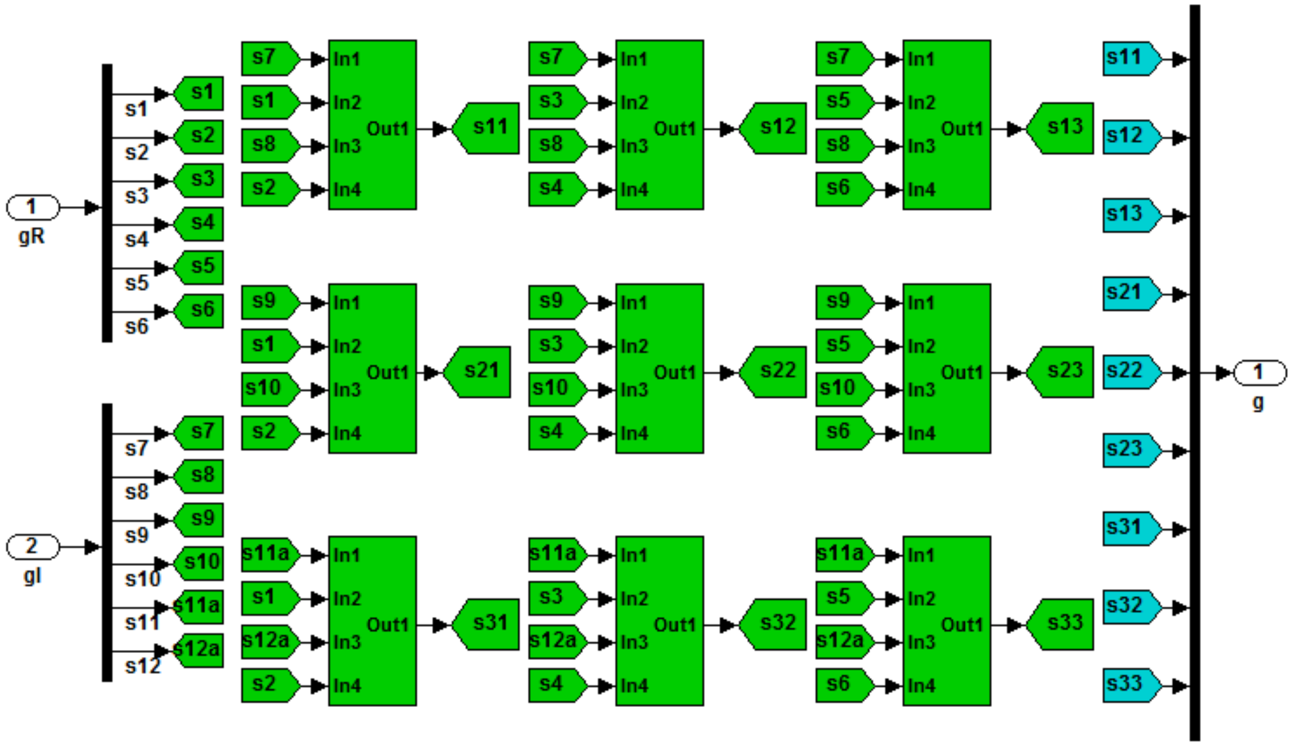

Fig.9. Switching signal construction

The reduction of harmonics in the input power supply can be obtained by MC compared with conventional inverter as well as there is cost reduction [21].

The SVM modulation of the proposed algorithm, required to measure any line voltages. Then, Vi/p and φ i/p are calculated as:

$$V^2_{i/p} = 4/9\,(V^2_{ab} + V^2_{bc} + V_{ab}V_{bc}) \tag{6}$$

$$\varphi_{i/p} = \tan^{-1}\left(\frac{-V_{bc}}{\sqrt{3}\ (2/3V_{ab} + 1/3V_{bc}}\right) \tag{7}$$

The ratio between input and the output voltages is calculated as

$$R_v = \sqrt{\frac{V^2_{o/p}}{V^2_{i/p}}} \tag{8}$$

The switching function of any IGBT switch can be expressed as in [22]

$$S_{KJ} = \begin{cases} 1 & switch\ S_{KJ} is\ closed \\ 0 & switch\ S_{KJ} is\ open \end{cases}$$

Where K= {A, B, C} is labeled input phase and j= {a, b, c} is labeled the output phase. The condition of the switching function can be expressed by the following relationship:

$$S_{AJ} + S_{BJ} + S_{CJ} = 1 \tag{9}$$

Under these constrains, a 3×3 MC has been implemented with 27possible switching states. Let d_{Kj} (t) be the duty cycle of switch S_{Kj}, defined as:

$$d_{KJ}(t) = t_{KJ} / t_{sampling} \quad \& \, 0 < d_{KJ} < 1 \tag{10}$$

The low frequency of MC can be obtained by:

$$D(t) = \begin{bmatrix} d_{Aa}(t) & d_{Ba}(t) & d_{Ca}(t) \\ d_{Ab}(t) & d_{Bb}(t) & d_{Cb}(t) \\ d_{Ac}(t) & d_{Bc}(t) & d_{Cc}(t) \end{bmatrix} \tag{11}$$

The Simulink implementation of duty cycle unit can be shown in fig.11.

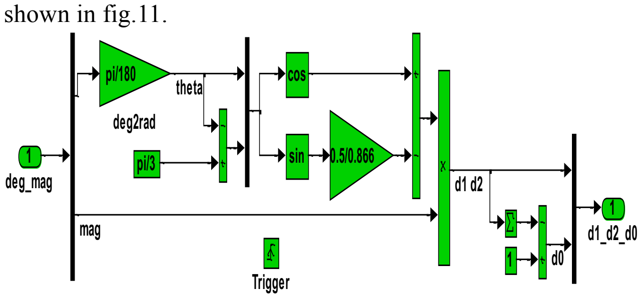

Fig.11. Simulink implementation of duty cycle calculation

$$d_1\_d_2 = (\cos(\vartheta) - (\pi/3 - \vartheta)\sin(0.5/0.866)) * |v| \tag{12}$$

$$d_0 = 1 - \sum d_1\_d_2 \tag{13}$$

The low-frequency component of the output phase voltage as in (14)

$$V_{op}(t) = D(t).V_{i/p}(t) \tag{14}$$

Where Vop is the output voltage vector and Vi/p is the input voltage vector.

The low-frequency component of the input current as in (15)

$$I_{ip}(t) = D^{T}(t).I_{op}(t) \tag{15}$$

The torque can be affected directly by the stator current as well as number of poles, mutual inductance and rotor inductance [23] as in (16)

$$T_e = p\left(\frac{L_m}{L_r}\right)(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}) \tag{16}$$

The space vector modulation (SVM) technique is one of the most important modulations used for the DMC due to the advantages of this technique like the reduction of total harmonic distortion and the controlling the duty cycle 100%. The SVM rectifier system switching sequence can be implemented using two states current and voltage stages to yield the matrix converter switching and hence the gates signals of the IGBTs of the MC as can be seen in the Fig. (2).

The input current modulator and the voltage modulator are used for controlling of gates signals in efficient way. The DTC with matrix converter proposed technique depends completely on the best choice of the switching mechanism to get better steady state error of both torque and flux compared to their references. The matric configuration switching technique used in this method can be illustrated in table. 2.

Simulink implementation of hysteresis controllers of the torque and flux can be shown in Fig.12

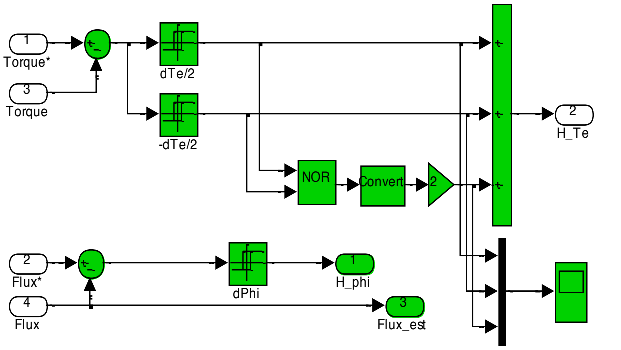

Fig.12. Simulink implementation of the torque and flux hysteresis controllers

The Simulink implementation of voltage in alpha and beta coordinate can be shown in Fig.13.

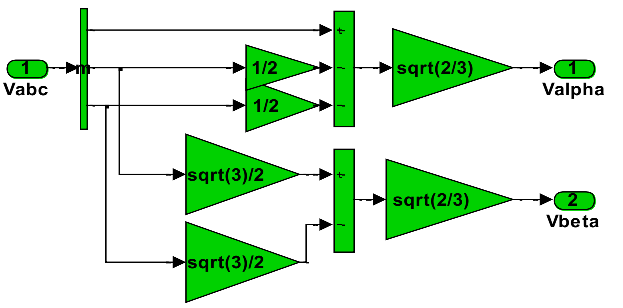

Fig.13. Simulink implementation of alpha and beta voltage components.

5. Simulation Results

To investigate the proposed algorithm, the Simulink program has been used first to model the induction motor, matrix converter, DTC and speed controller. The simulation has been carried out assuming that the sampling period is 20e-6 sec and ideal switching devices, 0.8 Wb flux reference. The results of the DTC control simulation are shown in the following figures. The MCDTC technique is simulated with Simulink to investigate the performance of the proposed control scheme. Fig. 14 shows the speed command and the speed tracking which is completely coincided when the speed command is changed to 500 RPM and increased to 2000 RPM.

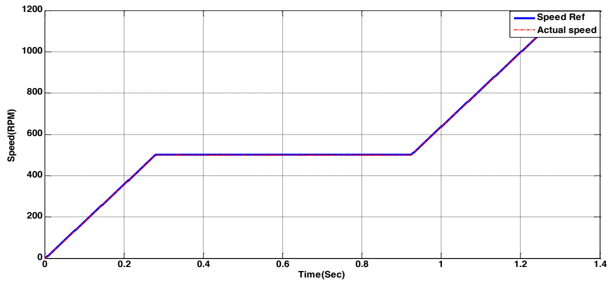

Fig.14. Speed reference and actual speed response

The triangular reference torque compared to the actual torque to investigate the error that will be high frequency triangular waveform as can be shown in red in Fig.15 with the fundamental and 5th harmonics of the command torque.

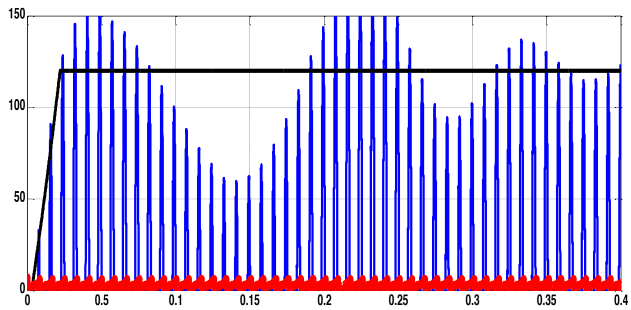

Fig.15. Reference, fundamental and 5th harmonics of the command torque

Fig. 16 shows the actual torque without constant switching frequency. The variable switching frequency in the basic DTC is due to the variation of the time taken for the torque error to achieve the upper and lower hysteresis bands. The dynamic performances of the proposed MCDTC control method are tested for a step torque command 120 N.m. The waveform and the steady state error slopes are highly dependent on operating conditions. Consequently, the torque ripple will remain high, even with small hysteresis band.

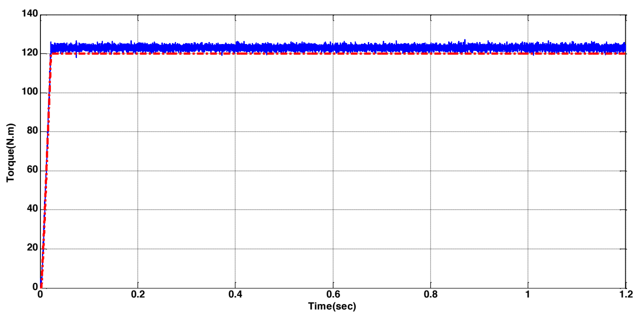

Fig.16. Actual (blue) and reference torque dynamic without constant

frequency DTC

The torque ripples which are generated due to the operation of hysteresis controller are reduced by using the proposed control method as can be shown in Fig.17.

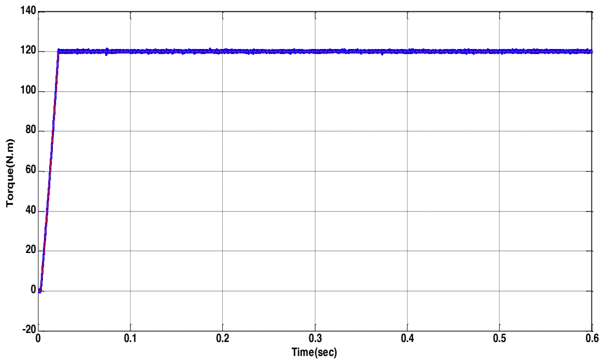

Fig.17. Actual and reference torques with proposed DTC

Stator current with proposed method can be shown in Fig.18.

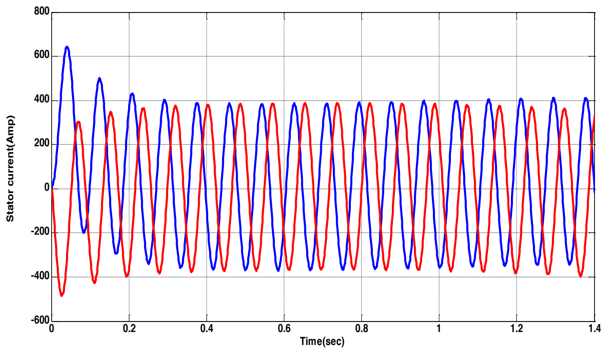

Fig.18. Stator current with the proposed DTC scheme

The stator current in the Fig. 18 shows acceptable results of the proposed strategy. The switching frequency of the IGBTs is 6 kHz and can be released up to 20 kHz.

To ensure better design of the proposed algorithm, 20 samples residues autocorrelation and cross correlation for both input and input combinations proves good results as can be shown in Fig.19.

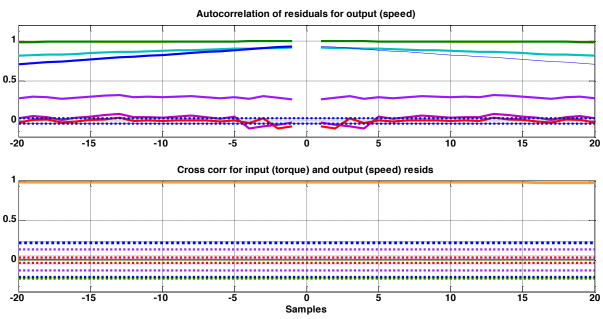

Fig.19. Autocorrelation and crosscorrelation residuals

The transfer function of system from torque to the speed as in (17):

$$G = \frac{0.00024s^{-3} + 2.744e - 6s^{-2} + 5.49e - 9s + 5.901e - 12}{s^{-4} + 0.0055s^{-3} + 1.3e - 5s^{-2} + 2.74s + 2.34e - 11} \quad (17)$$

The speed controller PI controller transfer function with zero delay time designed as in (18)

$$G_{PID} = \frac{K_p}{1 + T_p s} * \exp(-T_d s),\ K_p = -0.233, \quad (18)$$

$$T_d = 0,\ T_p = 87.677$$

The nonlinearly generated in the output has been tested to ensure better performance in the induction motor in two regions of operation can be shown in Fig.20.

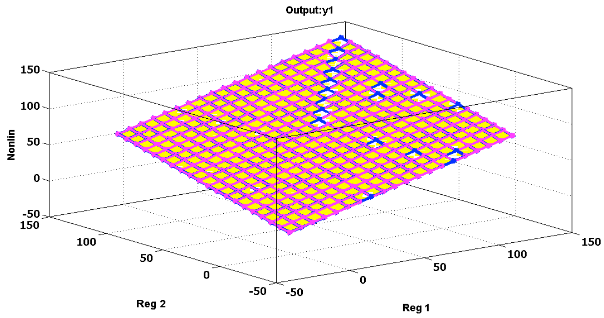

Fig.20. Nonlineary test of the output regions

Estimation of the nonlinearity of the output before and after applying the proposed algorithm will be listed in table3 as using identification Matlab tools.

Table3. Nonlinearity information with and without proposed algorithm

Without constant switching Frequency			**With constant switching frequency**		
Fit (%)	FPE	Loss Function	Fit (%)	FPE	Loss Function
90.21	1.303	1.086	99.9	0.0001918	0.0001872

Where FPE is the final predicted error

The state space model of the system will be 4th order, Matlab instruction is used to find whether the system is controllable, observable or not as in (19) & (20).

$$Co = cntrb(A, B) \quad (19)$$

$$Co = \begin{bmatrix} 0.0028 & -0.0676 & 0.1175 & -0.0507 \\ -0.2133 & 5.3307 & -7.4653 & -1.7762 \\ 0.2165 & -5.4898 & 1.5892 & 3.8917 \\ -0.8181 & -0.0344 & 0.6350 & -0.8818 \end{bmatrix}$$

$$O_{bsv} = obsv(A, C) \quad (20)$$

$$O_{bsv} = \begin{bmatrix} 1.0e+03* & & & \\ 1.6710 & -0.0439 & 0.0875 & -0.4993 \\ 0.0000 & -0.0450 & -0.1128 & 0.9720 \\ -0.0004 & 0.1190 & -0.0226 & -0.4595 \\ -0.0000 & -0.0520 & 0.1766 & -0.8859 \end{bmatrix}$$

With rank of 4, the system is completely controllable and observable. The stability test determines if all roots of the input polynomial lie inside the unit circle. Implemented using the Schur-Cohn algorithm can be shown in Fig.21. The output is containing the value 1 or 0. The value 1 indicates that the system is stable while the value 0 indicates that the system is unstable [23].

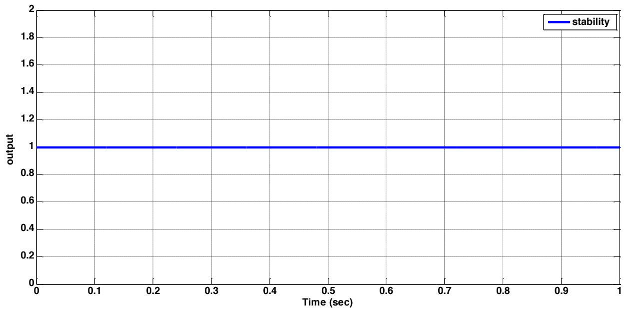

Fig.21. Stability test according to Schur-Cohn algorithm

There are no sensitive parameters during the IM running with higher speeds, but at low speeds the stator flux estimation becomes so important and critical due to error in stator resistance property [24].

6. Conclusions

Direct torque and Matrix converter modeling and simulation has been carried out. The proposed algorithm tested to ensure better performance specifications. DTCMC converter is used for supplying the IM. Minimizations of the steady state error of the torque with lowest final predicted error are obtained. Stability has been tested according to Schur-Cohn algorithm. The proposed algorithm with the constant switching frequency helped to design controllable, observable states of the given system. State space transfer function and design of the PI controller investigated with identification facilities of the Matlab/Simulink as well as the torque, the speed and current waveforms proves the effectiveness of the control scheme.

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