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A NEW DIRECT TORQUE CONTROL OF INDUCTION MACHINE FED BY INDIRECT MATRIX CONVERTER

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Key words: Indirect matrix converter (IMC), Direct torque control (DTC), Induction machine, Three levels neutral point clamped (NPC) inverter.

This paper proposes a new modified direct torque control for induction machine fed by three phase indirect matrix converter. The goal is to improve the performance of the control to reach three levels NPC inverter performances (flux, torque and speed) and to reduce the low frequency harmonics of the input current. The input power factor is fixed to one. Both the inversion stage and the rectification stage are controlled symmetrically to perform the same table as three levels NPC inverter. This method is simulated in Matlab/Simulink software with 1.5 kW induction machine. The results obtained are compared to the classical DTC. This method gives good performance in torque and flux in both transient and permanent mode and also it reduces the total harmonic distortion (THD) of the input filtered current.

1. INTRODUCTION

The indirect matrix converter (Fig. 1) is an ac-ac converter. It consists of an array of bidirectional switches, which are used to directly connect the power supply to the load without using any dc-link or large energy storage elements [1]. The absence of large energy storage elements in the dc bus such as the bulky and limited lifetime electrolytic capacitor is their major advantage over conventional rectifier inverter-based systems. It allows size and weight reduction of the converter and increases its reliability as well [1−3].

The indirect matrix converter (IMC) also provides the generation of load voltage with arbitrary amplitude and frequency, sinusoidal input and output currents, regeneration and unity power factor capability [1−3].

The intensive research on matrix converters (MC) starts with the work of Venturini and Alesina [4].

In the late 1980's and early 1990's space vector modulation (SVM) schemes were also introduced by several authors [5]. Then the ISVM modulation was introduced by L. Huber [5, 6]. In [1, 2] a review of MC research is proposed and in [3] the modulation strategies are reviewed.

The direct torque control (DTC) technique for induction motors was initially proposed as DTC or direct self-control [7, 8] in which cases the machine was fed by inverter. The main advantages of the DTC are: robust and fast torque response, no requirements for coordinate transformation, no requirements for PWM pulse generation and current regulators. The direct torque control was implemented to both direct and indirect MC [9, 10]. It was first introduced by D. Casadei *et al*. for direct matrix converter in [9]. In addition to the torque and the flux regulation, it permits the control of the input power factor. This method was extended to the indirect matrix converter in [10, 11].

A lot of research works in the improvement of the dynamics, the estimation of variables such as the flux and torque, the resolution of the drawbacks of the DTC in matrix converter are proposed by several authors [3, 12−15]. Other direct control methods (direct power control) using matrix converter in double fed induction generator (DFIG) with wind turbine are proposed in [16].

In this paper, a new DTC control for indirect matrix converter is proposed to perform the same table as the DTC for NPC inverter by controlling symmetrically both the rectification stage and the inversion stage.

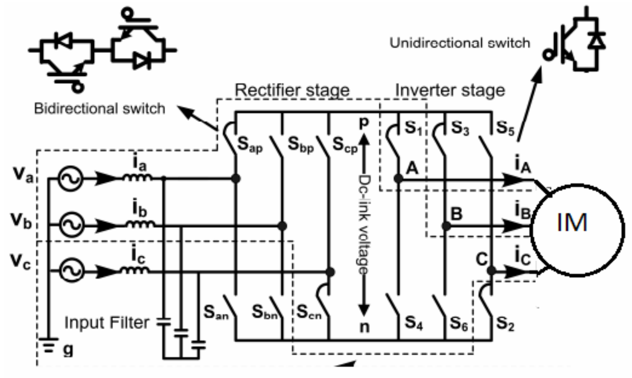

Fig. 1– 3×3 indirect matrix converter topology.

2. INDIRECT MATRIX CONVERTER THEORY

A circuit topology of the indirect matrix converter is illustrated in Fig. 1. The basic concept of the IMC is to separate the ac/ac conversion into two stages: the rectifier and the inverter stage with no dc-link capacitor [1, 17]. There are a lot of topologies of IMC such as the sparse, ultra-sparse and multilevel IMC [1, 2, 18].

2.1 IMC modeling

The transfer function of IMC can be represented as

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = \begin{bmatrix} S_{Ap} & S_{An} \\ S_{Bp} & S_{Bn} \\ S_{Cp} & S_{Cn} \end{bmatrix} \times \begin{bmatrix} S_{pa} & S_{pb} & S_{pc} \\ S_{na} & S_{nb} & S_{nc} \end{bmatrix} \times \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (1)$$
$$= F_{inv} \times F_{red} \times V_i ,$$

where F_{inv} and F_{rec} are the transfer functions of inversion stage and rectification stage of IMC [18].

$$S_{Ki} = \begin{cases} 1 & if \text{ the switch } Ki \text{ is on} \\ 0 & if \text{ the switch } Ki \text{ is off} \end{cases} \quad (2)$$

S_{Ki} is the connection function of the switch Ki.

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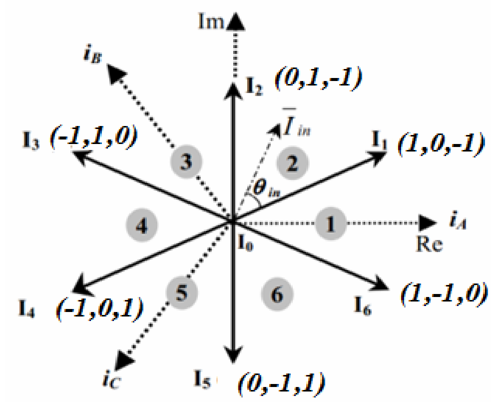
The input current space vector is defined as:

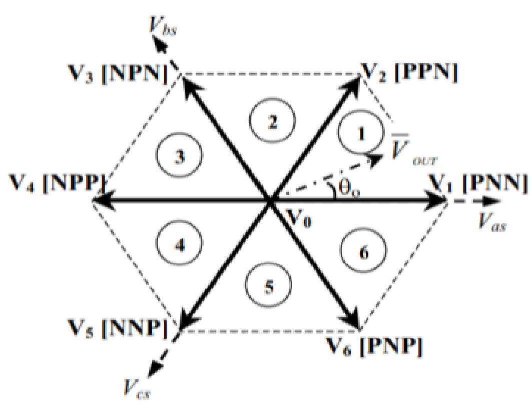
$$I_E = \frac{2}{3}\left(I_a + I_b \mathrm{e}^{2\pi i/3} + I_c \mathrm{e}^{-2\pi i/3}\right) . \qquad (3)$$

The output voltage vector is defined as

$$V_S = \frac{2}{3}\left(V_A + V_B \mathrm{e}^{2\Pi i/3} + V_C \mathrm{e}^{-2\Pi i/3}\right). \qquad (4)$$



(a)



(b)

Fig. 2 –Space vectors rectification stage and inversion stage: a) input current; b) output voltage.

Figure 2 shows the space vectors in both stages. V_{out} and I_{ref} are the reference space vector of respectively the output voltage and the input current.

3. CLASSIC DTC OF INDUCTION MACHINE FED BY IMC

The direct torque control (DTC) technique for induction motors was initially proposed for inverter [7]. In [12] a review of direct torque control methods is proposed. [9] is the first paper in which the principle of direct torque control is extended to the matrix converter fed induction machine. The principle of the DTC is to choose the best voltage vector, which keeps the flux and the torque in the allowed bandwidth with minimum ripple. The block diagram of the DTC scheme is shown in Fig. 3. The stator flux vector can be estimated using the measured output current and voltage.

$$\frac{\mathrm{d}\psi_S}{\mathrm{d}t} = U_s - R_s I_s , \qquad (5)$$

$$\begin{cases}\Psi_{ds} = \int (U_{ds} - R_s I_{ds})\mathrm{d}t \\ \Psi_{qs} = \int (U_{qs} - R_s I_{qs})\mathrm{d}t\end{cases}, \qquad (6)$$

where R_s is one stator winding resistance, for subscripts ds and qs stand for the d-axis and q-axis components of the voltages and currents of the stator windings of the motor.

The electromagnetic torque T_e is estimated as a cross product of estimated stator flux vector and measured motor current vector as presented in eq. (7).

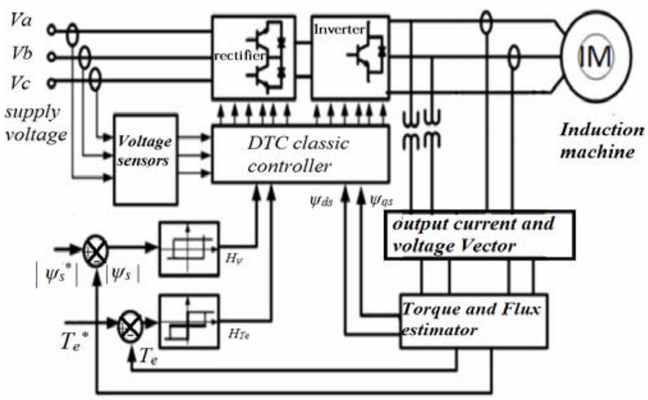
$$T_e = \frac{3}{2} p(\Psi_{ds} I_{qs} - \Psi_{qs} I_{ds}) = = \frac{3}{2} p \frac{L_m}{\sigma L_s L_r} \left|\overline{\psi_s}\right| \left|\overline{\psi_r}\right| \sin(\theta), \qquad (7)$$

where $2p$ is the pole number. ψ_s, ψ_r and θ are the stator flux vector, the rotor flux vector and the angle between them respectively.

Table 1

Classical DTC table

Flux sector		1	2	3	4	5	6
H_ψ=1	H_{Te}=1	V_2	V_3	V_4	V_5	V_6	V_1
	H_{Te}=0	V_7	V_0	V_7	V_0	V_7	V_0
	H_{Te}=−1	V_6	V_1	V_2	V_3	V_4	V_5
H_ψ=0	H_{Te}=1	V_3	V_4	V_5	V_6	V_1	V_2
	H_{Te}=0	V_0	V_7	V_0	V_7	V_0	V_7
	H_{Te}=−1	V_5	V_6	V_1	V_2	V_3	V_4



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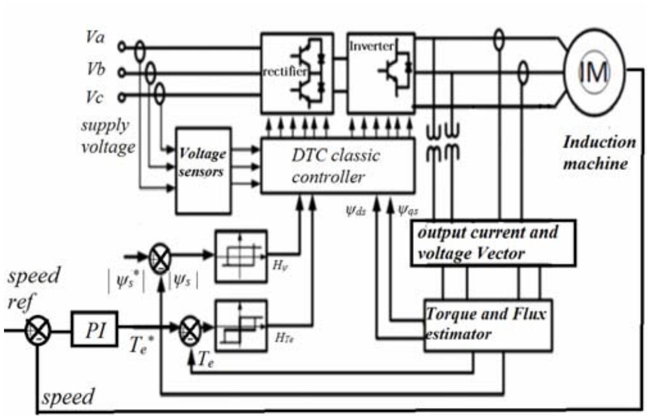


(b)

Fig. 3 – Classic DTC scheme: a) without speed regulation; b) with speed regulation.

The outputs of both stator flux and torque comparators (H_ψ, H_{Te}) respectively together with the position of the stator flux are used as inputs of the basic DTC switching look up table (Table 1).The position of the stator flux is divided into six different sectors (S (i)) as shown in Fig. 4a.

In the indirect matrix converter, the table of classic DTC is applied in the inversion stage. For the rectification stage a simple SVM is applied to maintain a set of input currents with controllable displacement angle. The input currents have to be synchronized with the input voltages [6, 17]. To maximize the power transfer, the input current ratio has to be taken unitary and the zero vector has to be cancelled [17].

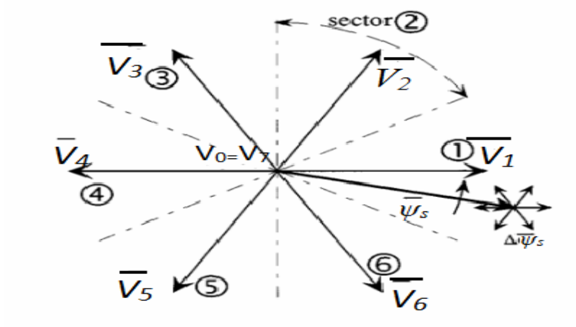
4. NEW DTC OF INDUCTION MACHINE FED BY IMC

This new algorithm is based on the three level NPC inverter DTC algorithm [19] which is adapted to the classical IMC. The main idea is the ability to construct the entire three level NPC inverter vectors as in Fig. 4.b (mean) by controlling both the rectification stage ratio based on the eq. (8) and the inversion stage using two vectors with the same duration

$$V_{pn} = \frac{3}{2}\overline{V_{in}} r_i \cos(\varphi_i)\,, \tag{8}$$

where $\overline{V_{in}}$ is the peak value of the input voltage, r_i is the input rectification ratio, φ_i is the displacement angle.

V_{pn} or U_{rec} is the dc link voltage. The basic of this algorithm is presented in the Fig. 5.



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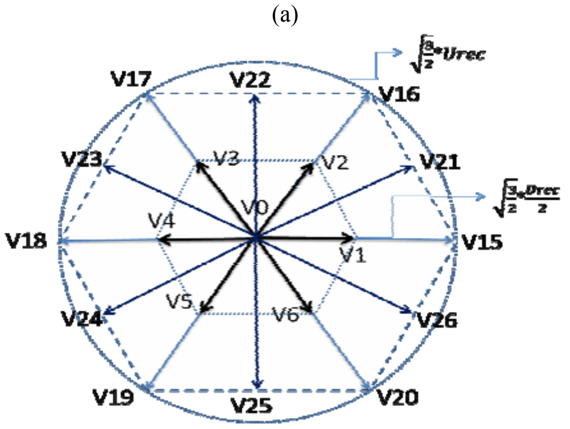
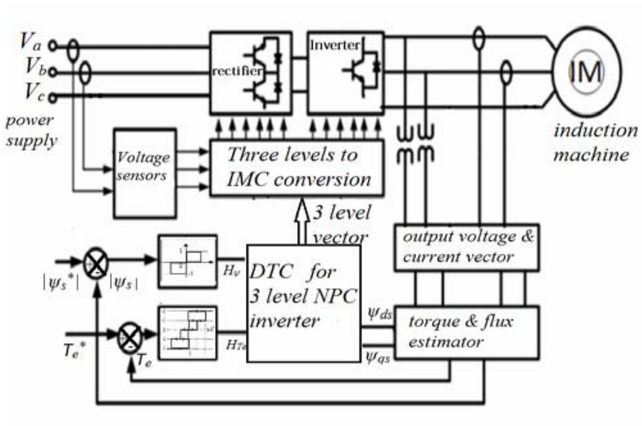


(b)

Fig. 4 – Space vectors: a) flux vector and its sectors; b) three level NPC inverter vectors.



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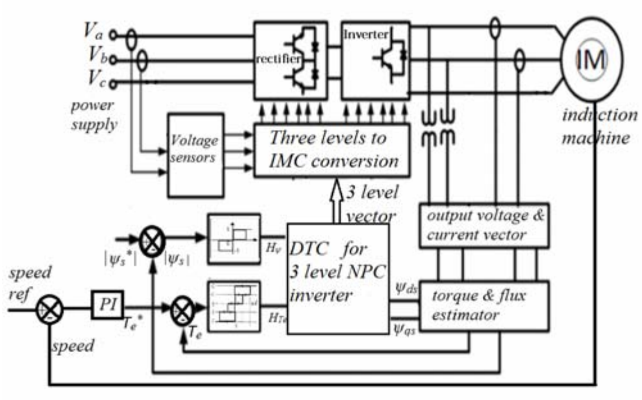
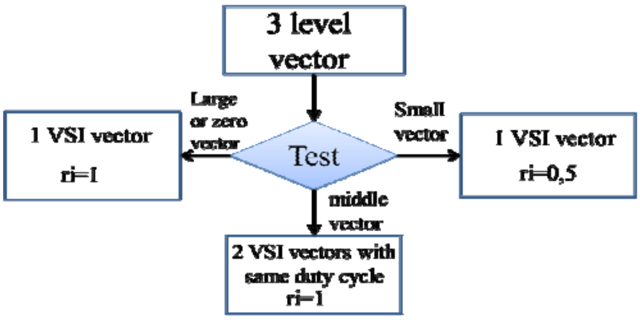


(b)

Fig. 5 – New DTC basic scheme:
a) without speed regulation; b) with speed regulation.



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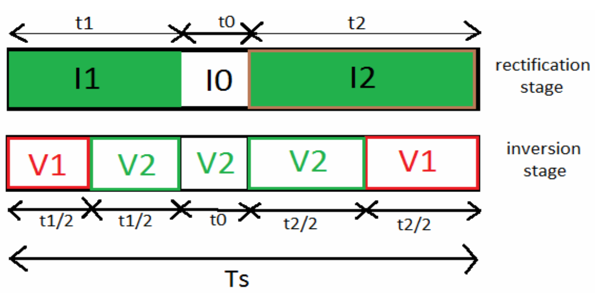


(b)

Fig. 6 – Conversion principle:
a) three level to IMC conversion; b) switching pattern.

The first step is to choose the three level vector based on the output of the flux and torque hysteresis comparator (three level for the flux , five level for the torque) and the position of flux vector (table of three level NPC inverter DTC [19]).

After that, any of these vectors can be constructed by using two voltage source inverter (VSI) vectors with the same duration and by changing the ratio of the rectification stage according to the algorithm presented in Fig. 6.a.

For example the vector $V15$ can be represented by using $V1$ in the VSI stage and $r_i = 1$ in rectification stage. $V1$ of three level inverter can be represented by using $V1$ in VSI stage and $r_i = 0.5$ in rectification stage. $V21$ of three level inverter can be represented by using $V1$ and $V2$ with the same duty cycle in the inversion stage and $r_i = 1$ in rectification stage.

The third step is to synchronize the inversion and the rectification stage control in order to minimize the low frequency harmonics and the THD. An example of synchronization is presented in Fig. 6b.

During each switching period, two active and one zero vector are applied to synthesize the input current and to control also the dc link voltage.

During the application of each input vector, the two output VSI vectors chosen by the controller are applied with the same duration.

During the application of the zero vector in rectification stage, the inversion stage cannot be controlled, so the same output vector is kept to minimize the number of commutations in order to decrease losses in the switches.

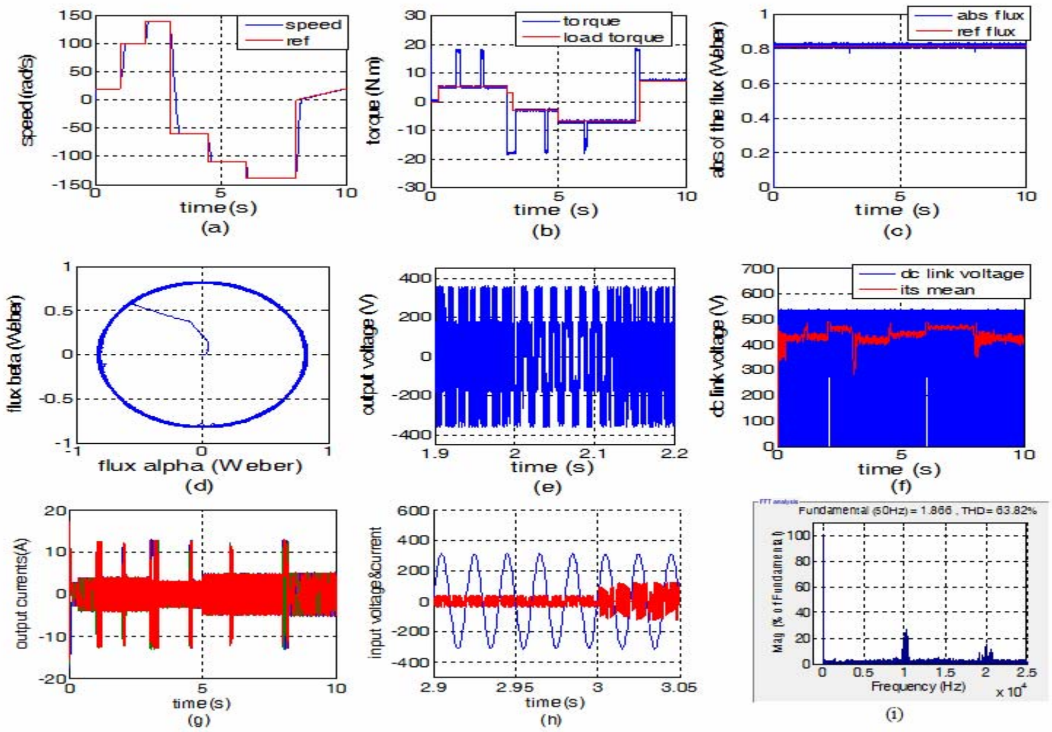


Fig. 7– New DTC control with regulation; a) speed and its ref; b) electromagnetic torque and load torque; c) stator flux magnitude and reference; d) stator flux vector; e) output IMC voltage; f) dc link voltage with its mean; g) output currents; h) input current and input voltage; i) input current harmonics spectrum.

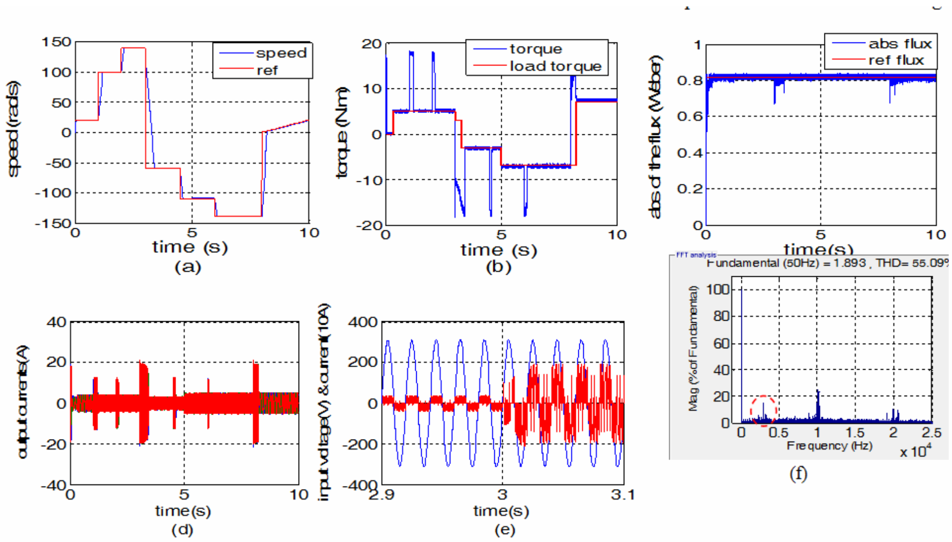
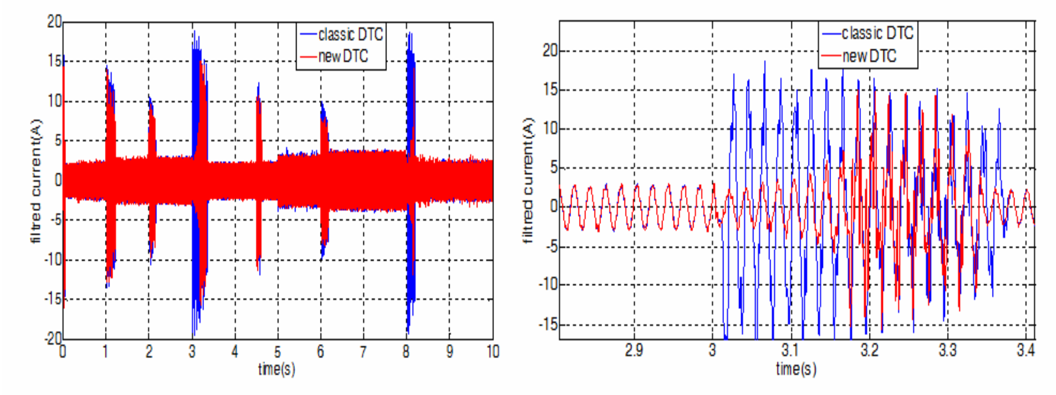


Fig. 8 – DTC classic with regulation simulation results; a) speed and its ref; b) electromagnetic torque resistant torque; c) stator flux magnitude and its reference; d) output currents; e) input current with the input voltage; f) input current harmonics spectrum.



(a) (b)

Fig. 9 – Input filtered currents in the two methods; a) without zoom; b) with zoom.

5. SIMULATION RESULTS AND DISCUSION

In order to analyze the performance of the proposed schema, the new and the classical DTC are both simulated with induction machine−which the parameters are presented in Appendix 1 − in Matlab/Simulink.

Figure 7 shows some simulation results of the new DTC with speed regulation. Figure 8 shows some simulation results of classical DTC with speed regulation. Figure 9 shows input filtered current with the two methods.

When we analyse the simulation results of the two control methods with speed regulation, we can notice the following points

- The two algorithms follow the speed reference Fig. 7a and Fig. 8a, but the new DTC takes less time than the classical DTC.
- The torque using the new DTC is more regular, the hysteresis bound is respected Fig. 7b, especially when changing the speed reference, but with the classical DTC it is not the case Fig. 8b.
- The flux using the new algorithm respects its reference and its bound Fig. 7(c, d). However, in the classical DTC, the hysteresis bound of the flux is not totally respected when changing the speed direction and in low speed Fig. 8c.
- The input current in the two cases are in phase with input voltage Fig. 7h and Fig. 8e. For the harmonic spectrum, low frequency harmonics in classical DTC are present Fig. 8f, but with the new DTC we don't have these rays (Fig. 7i).
- The THD of the input current with the two strategies is practically the same, but in classical DTC the signal is slightly better Fig. 8e (THD1 = 48.25 %) and Fig. 7h (THD1 = 53.8 %). This difference is due to the harmonics coming from the rectification stage when applying a ratio of 0.5. We can see that in the dc link voltage Fig. 7h which is not regular compared to the classical DTC where it is constant.
- The current when changing the speed reference (transient mode) in classical DTC is bigger than the new DTC. For example, in second 3 the current with classical DTC is about 20 A (Fig. 8d), however for the new DTC it is about 13 A (Fig. 7g). The duration of this peak is more important in classical method, because of the destabilization of the flux during the transitory mode.
- The dc link voltage changes with the speed reference variations and with load torque in the new DTC (Fig. 7f).
- When we take account of the input filter, which is sized using the algorithm presented in [20], the filtered input current using the new DTC is more proper, especially in transient mode (Fig. 9).

6. CONCLUSION

A new fixed switching DTC of the IMC based on the DTC table of three level NPC inverter is proposed, simulated with speed regulation and compared with the classical IMC DTC.

The new DTC algorithm gives better flux and torque performance, harmonics spectrum (no low frequency harmonics) compared to the classical method.

The new algorithm gives good performance in transient mode and low speed, practically the same as using NPC three level inverter.

The drawback of variable switching frequency in the inversion stage in classical DTC is solved with this new algorithm.

The THD of the input current is slightly bigger using the new method because of the control of the rectification stage with low ratio in some sequences. This problem is solved using the input filter.

The implementation of this method is a little more complex compared to the classical method.

One of the benefits of this method is the size reduction of the input filter because there is no low frequency harmonics, and also the simplicity of the sizing of its components (L_f, C_f) based on the switching frequency F_s.

This method can be generalized to other multilevel converters and to be applied with the space vector modulation. Also an experimental implementation will be done.

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APPENDIX 1

Table 2

Machine and simulation parameters

Output power 1.5 kW	Input voltage 220/380 V
Rated voltage 220/380 V	*Ts* the switching period = 0.0001 s
Rated current 6.7/3.7 A	PI regulator parameters $P = 12$ $I = 0.09$
Speed Ω = 1 420 rpm $f = 50$ Hz	Input filter $C_f = 21$ µF, $L_f = 17.5$ mH
Stator and rotor resistance $R_s = 4.85$ Ω, $Rr = 6.3$ Ω	Classical DTC Δψ = 0.01 Wb, $\Delta Te = 0.2$ N.m
Stator and rotor inductance $L_s = 0.274$ H, $Lr = 0.274$ H	New DTC Δψ = 0.01 Wb, $\Delta T_{emax} = 0.2$ N.m $\Delta T_{emin} = 0.04$ N.m
Mutual inductance $L_m = 0.2580$ H load torque C_r	Inertia and friction coefficient $J = 0.031$kg.m2, $K_f = 0.001136$ Nms/rad

APPENDIX 2

THD definition according to CIGRE

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots.. + V_n^2}}{V_1}. \quad (9)$$

THD definition according to CEI

$$\mathrm{THD1} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \ldots.. + V_n^2}}{\sqrt{V_1^2 + V_2^2 + V_3^2 + V_4^2 + \ldots.. + V_n^2}}. \quad (10)$$

Mechanic equation:

$$\frac{\mathrm{d}\Omega}{\mathrm{d}t} = \frac{1}{J}(T_e - C_r - K_f\Omega). \quad (11)$$