APPROACHING DIFFERENT OF MINIMUM TORQUE RIPPLE FOR IMPROVING THE DIRECT TORQUE CONTROL OF INDUCTION MOTOR

Lotfi El M'barki, Moez Ayadi & Rafik Neji

Electric Vehicle and Power Electronics Group (VEEP), Laboratory of Electronics of Sfax, Tunisia
Department of Electrical Engineering, University of Sfax, Tunisia
Email: indtechtunisie@yahoo.fr

ABSTRACT

The induction motor (IM) is very well identified as the heart of electrical engineering of industry. The advance of changeable torque induction motor commands has a long history of improving direct torque control (DTC). Today's sophisticated industrial commands are the technique of the extensive research and the resulting ones from the system approach to obtain. The improvement method DTC (IMDTC) is employed on technique switching table, variation of the reference torque error and the judiciously selected of flux error. DTC employs a couple of hysteresis comparators to make together torque and flux dynamic control. The performance of this IMDTC has been confirmed by simulations represented using a versatile simulation, Matlab/Simulink.

Keywords: *Reduce torque ripple, IMDTC, THD, Thermal model.*

1. INTRODUCTION

For many years, induction machine have used the majority regular shape of electrical engineering command for industrial, in benefit reduction of torque ripple, improved quality of IM consumption, it ameliorates the lifespan of IM. In the DTC of IM is used by the selection of a switching vector from table. The ripples minimizations of torque and flux in IMDTC approach (a, b and c); are used on method switching vector from table, variation of the torque error and the judiciously selected flux error [1-7,10-14].

The IMDTC of the three-phase IM of figure 4 is subjected to values of the successive voltages, which realizes the protecting of its insulators and amelioration in its lifespan of motor. The critical model of IMDTC is to command directly together the stator flux relationship and electromagnetic torque of IM simultaneously by the selection of optimum inverter switching vector from table.

The switching logic control assist the creation of the stator voltage space vector, with a judiciously choice of ordering of IGBT of the inverter, on the foundation of the information of the sector in which the torque and the stator flux. The sector recognition relies on the precise estimation of stator flux location. The IMDTC controlled by the comparison between the estimated torque and the reference torque, also be controlled by the comparison of the estimated flux and the reference flux [8-11][17-20].

The remainder of this paper is organized as follows; System IMDTC of IM is presented in section 2, model IMDTC is discussed in section3, electrical model of IGBT is presented in section 4, the simulations results and discussions are dealt with in section 5 and overall conclusions are presented in section 6.

2. SYSTEM IMDTC OF IM

The parameters of IM are converted the equations of the three phases IM on the equivalent two-phase components, the equations of IM are given as follows [1-4][9-11][13-16][18].

$$V_{ds} = Rs.I_{ds} + \frac{d\phi_{ds}}{dt} \tag{1}$$

$$V_{qs} = Rs.I_{qs} + \frac{d\phi_{qs}}{dt} \tag{2}$$

$$V_{dr} = Rr.I_{dr} + \frac{d\phi_{dr}}{dt} + W_r \phi_{qr} \tag{3}$$

$$V_{qr} = Rr.I_{qr} + \frac{d\phi_{qr}}{dt} - W_r \phi_{dr} \quad (4)$$

For Vdr = Vqr = 0

$$\phi_{ds} = \int \left(V_{ds} - Rs.I_{ds}\right) dt \quad (5)$$

$$\phi_{qs} = \int \left(V_{qs} - Rs.I_{qs}\right) dt \quad (6)$$

$$\phi_{dr} = \int \left(V_{dr} - Rr.I_{dr} - W_r \phi_{qr}\right) dt \quad (7)$$

$$\phi_{qr} = \int \left(V_{qr} - Rr.I_{qr} + W_r \phi_{dr}\right) dt \quad (8)$$

The stator flux and phase angle are given by.

$$\phi_s = \sqrt{\phi^2{}_{ds} + \phi^2{}_{qs}} \text{ and } \theta_s = \text{arctg}\left(\frac{\phi_{qs}}{\phi_{ds}}\right) \quad (9)$$

The torque, stator flux and rotor flux are given by the following equations.

$$T_e = \frac{3}{2} P \phi_s I_s \sin\theta \quad (10)$$

$$\phi_s = L_s I_s + M I_r \quad (11)$$

$$\phi_r = L_r I_r + M I_s \quad (12)$$

The voltage V_{dc} is the DC bus voltage and the commands (S_1, S_2 … S_6) are the inputs signals of IGBTs with they are relevant to the inverter strategy.

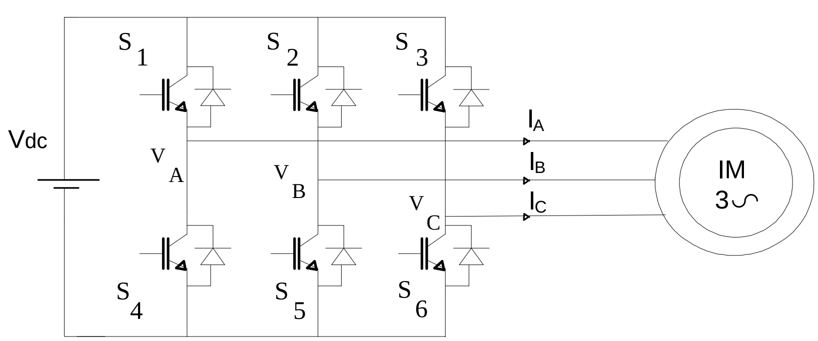


Figure 1. Three- phase voltage inverter

The voltages (V_A,V_B and V_C) are given by the following matrix.

$$\begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} = -\frac{2V_{dc}}{3} \begin{bmatrix} -1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & -1 & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & -1 \end{bmatrix} \begin{bmatrix} S_1 \\ S_2 \\ S_3 \end{bmatrix} \quad (13)$$

The commands (S_1, S_2, or S_3) of inverter are given by the following equations.

$$V_{ds} = \frac{1}{3} V_{dc} \left(2S_1 - S_2 - S_3\right) \quad (14)$$

$$V_{qs} = \frac{1}{\sqrt{3}} V_{dc} \left(S_2 - S_3\right) \quad (15)$$

The three-phase inverter of eight output states is given by the following equations.

$$V_{di} = \sqrt{\frac{2}{3}} V_{dc} \cos[(i-1)\frac{\pi}{3}] \quad , \quad V_{qi} = \sqrt{\frac{2}{3}} V_{dc} \sin[(i-1)\frac{\pi}{3}] \quad (16)$$

$$V_i = V_{di} + jV_{qi} \quad (17)$$

For $i = 1,2,\ldots 6$; are six non-zero active voltage space vectors

and $V_0 = V_7 = 0$; are tow zero voltage space vectors.

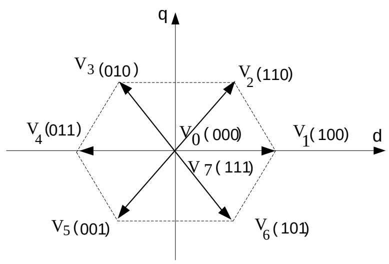


Figure 2. The effect of voltage vectors.

The electromagnetic torque can be rewritten in d-q coordinates as.

$$T = \frac{3.P}{2} \left(\phi_{ds} I_{qs} - \phi_{qs} I_{ds}\right) \quad (18)$$

3. MODEL IMDTC

Generally in the figure3 system of IM, the comparators torque and stator flux are carried out below an approach IMDTC with the optimal switching logic [1-4,13-15,18]. The three-phase inverter is subjected to values of the successive voltages, can be used via Vdc and by the switches (S_1, S_2 and $S_{3)}$. This method uses a new approach control of torque and flux to minimize the flux and torque ripple. The flux control (ε_φ) is carried out by the two following equations.

$$\phi_{s\min} - \phi_{ref} = \varepsilon_{\varphi_{\min}} \quad , \quad \varepsilon_\varphi \geq \varepsilon_{\varphi_{\min}} \quad (19)$$

$$\phi_{s\max} - \phi_{ref} = \varepsilon_{\varphi_{\max}} \quad , \quad \varepsilon_\varphi \leq \varepsilon_{\varphi_{\max}} \quad (20)$$

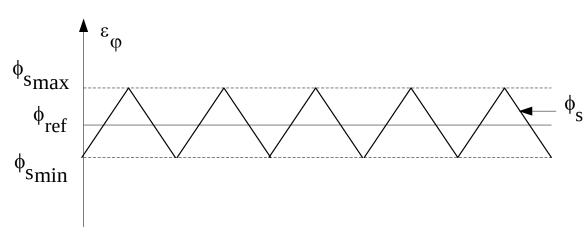


Figure 3. Hysteresis control of flux.

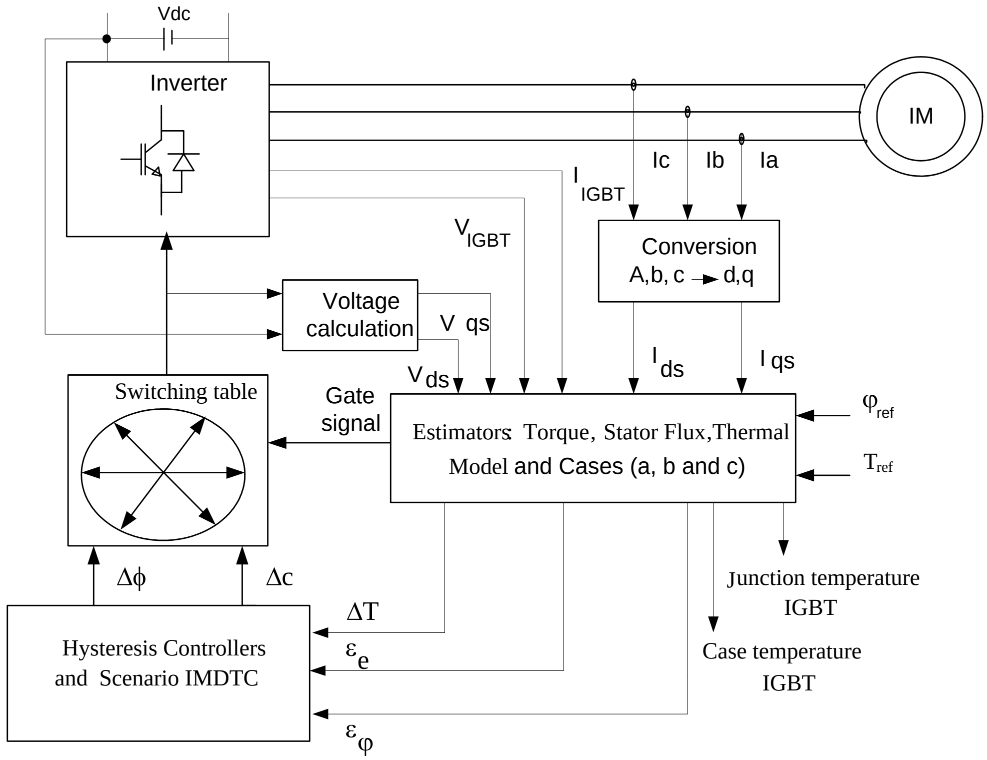


Figure 4. IMDTC principle

The stator flux and rotor flux of the IM are determined by the following equations.

$$\begin{bmatrix} \frac{d\phi_S}{dt} \\ \frac{d\phi_r}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R_S}{H_S} & \frac{mr.R_S}{H_S} \\ \frac{mr.R_r}{H_S} & jWr - \frac{R_r}{\sigma L_r} \end{bmatrix} \begin{bmatrix} \phi_s \\ \phi_r \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} V_s \tag{21}$$

$$I_s = \frac{\phi_S - m_r \phi_r}{H_s} \quad \text{with } H_s = L_s.\sigma \text{ and } m_r = \frac{M}{L_r} \tag{22}$$

The torque is given by the following equation.

$$T_e = \frac{3}{2}\frac{p.M}{L_r L_s.\sigma}\phi_s \phi_r \sin(\theta_s - \theta_r) \tag{23}$$

The angle between the stator flux and rotor flux; is critical role in scheming output torque.

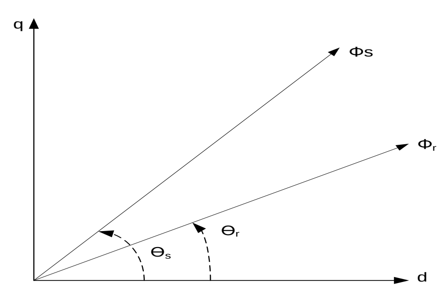


Figure 5. The principle of angle between the stator flux and rotor flux

The rotor and stator fluxes of equation 21 are expressed in the discrete form as.

$$\phi_{s(k+1)} = \left(1 - \frac{R_S}{H_S}.t_{cp}\right)\phi_{sk} + \frac{mr.R_S}{H_S}\phi_{rk}.t_{cp}. + V_{sk}.t_{cp} \tag{24}$$

$$\phi_{r(k+1)} = \frac{mr.R_r}{H_S}\phi_{sk}t_{cp} + \left(\left(jWr - \frac{R_r}{\sigma.L_r}\right)t_{cp} + 1\right)\phi_{rk} \tag{25}$$

The use application of method IMDTC, introduce the improvement torque ripple with t_{cp} controlling period of a small value and k+1 is sampled instant. The torque and flux errors ($\varepsilon_{e,}$ ε_{φ}) are realized by tow hysteresis controllers and alters their outputs at the cycling period. The torque control (ε_e) is carried out by the two following equations.

$$T_{e.max} - T_{ref} = \varepsilon_{e_{max}} \quad , \quad \varepsilon_e \le \varepsilon_{e_{max}} \tag{26}$$

$$T_{e.min} - T_{ref} = \varepsilon_{e_{min}} \quad , \quad \varepsilon_e \ge \varepsilon_{e_{min}} \tag{27}$$

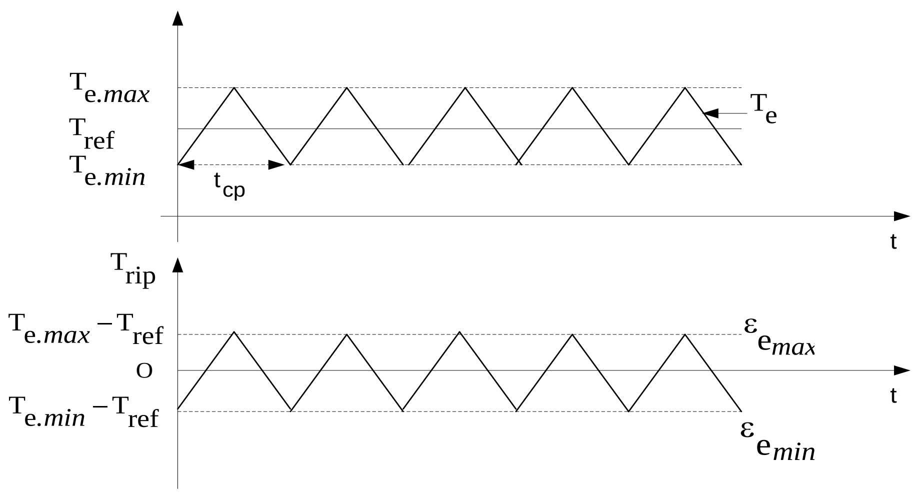


Figure 6. Hysteresis control of torque and torque ripple (T_{rip}).

Table1, the technique-switching vectors indicate the output signal gate of the voltage switches of the inverter; realized by Stator flux ($\Delta\phi$) and torque (Δc) hysteresis controllers in IMDTC

Table 1. Switching table for conventional DTC

sector		1	2	3	4	5	6
Flux	Torque						
$\Delta\phi = 1$	$\Delta c = 1$	V_2	V_3	V_4	V_5	V_6	V_1
	$\Delta c = 0$	V_0	V_7	V_0	V_7	V_0	V_7
	$\Delta c = -1$	V_6	V_1	V_2	V_3	V_4	V_5
$\Delta\phi = 0$	$\Delta c = 1$	V_3	V_4	V_5	V_6	V_1	V_2
	$\Delta c = 0$	V_7	V_0	V_7	V_0	V_7	V_0
	$\Delta c = -1$	V_5	V_6	V_1	V_2	V_3	V_4

The total harmonic distortion (THD) is defined as the RMS value of the fundamental current (I_{1RMS}) and RMS value of the harmonic (I_{nRMS}). The quality IMDTC of IM is measured with the total harmonic distortion (THD_I) for the phase current.

$$THD_I\% = 100 \frac{\sqrt{\sum_{n=2}^{\infty} I_{nRMS}^2}}{I_{1RMS}} \tag{28}$$

The uncertainty torque (ΔT) is ordered by reference torque (T_{ref}).

$$\text{Case (a); } \Delta T = \frac{20.T_{ref}}{100} \tag{29}$$

$$\text{Case (b); } \Delta T = \frac{10.T_{ref}}{100} \tag{30}$$

$$\text{Case (c); } \Delta T = \frac{0.1.T_{ref}}{100} \tag{31}$$

$$\text{With } \Delta T \in \left[\varepsilon_{e_{min}}, \varepsilon_{e_{max}} \right] \tag{32}$$

The IMDTC to return the instantaneous torque equal with the reference torque at the end of the cycle and the technique is given by the following equation.

$$Te(k+1) \cong T_{ref} \tag{33}$$

The electromagnetic torque (T) and torque estimation (Te) of IM are given by the following equation.

$$\frac{Te}{T} = 1 \tag{34}$$

4. ELECTRICAL MODEL OF IGBT

The thermal model of IGBT is used in IMDTC with a temperature without cooling. The electric model used for the Semikron module SKM 75GB 123D of IGBT at various temperatures; the voltage drop at the boundaries ($V_{CEsat(t)}$), with power dissipated (P_{dis}) and internal resistance ($R_{CE(Tj)}$). The technique investigation that was performed with the Semikron module SKM 75GB 123D (75A/1200V) is presented by the following equations [21].

$$P_{dis(t)} = V_{CE(Tj)}.I_{c(t)} + R_{CE(Tj)}.I^2{}_{C(t)} \tag{35}$$

$$V_{CE(Tj)} \le 1{,}5 + 0{,}002.(T_j - 25) \tag{36}$$

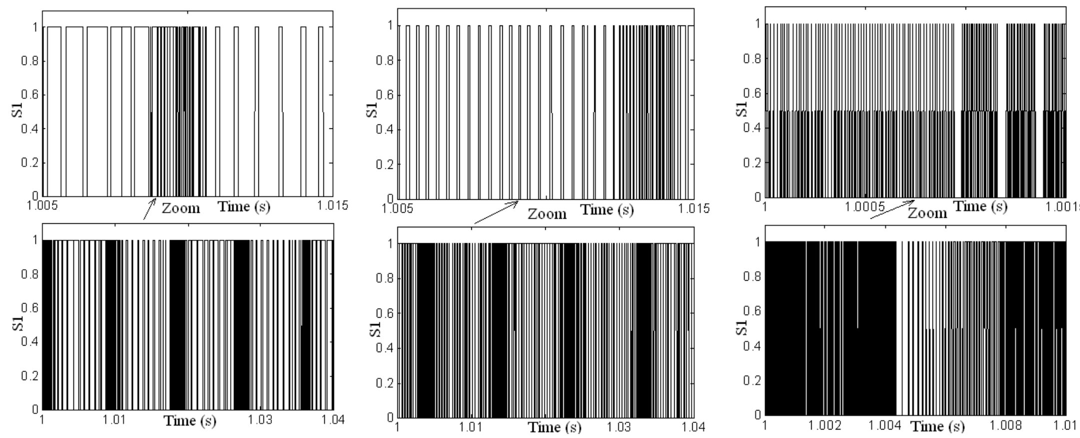
$$0{,}00008.(T_j - 25) + 0{,}020 \le R_{CE(Tj)} \le 0{,}030 + 0{,}00010.(T_j - 25) \tag{37}$$

5. SIMULATIONS RESULTS AND DISCUSSIONS

The technique model of IMDTC is to command directly together the stator flux relationship and electromagnetic torque of IM simultaneously by the selection of a switching vector via table1 and table 2 from optimum inverter switching vector. With IMDTC is determined enters the two basic variables (Δc and $\Delta\phi$) and table 2 to realize the results of three approaches (case (a), case (b) and case (c)).

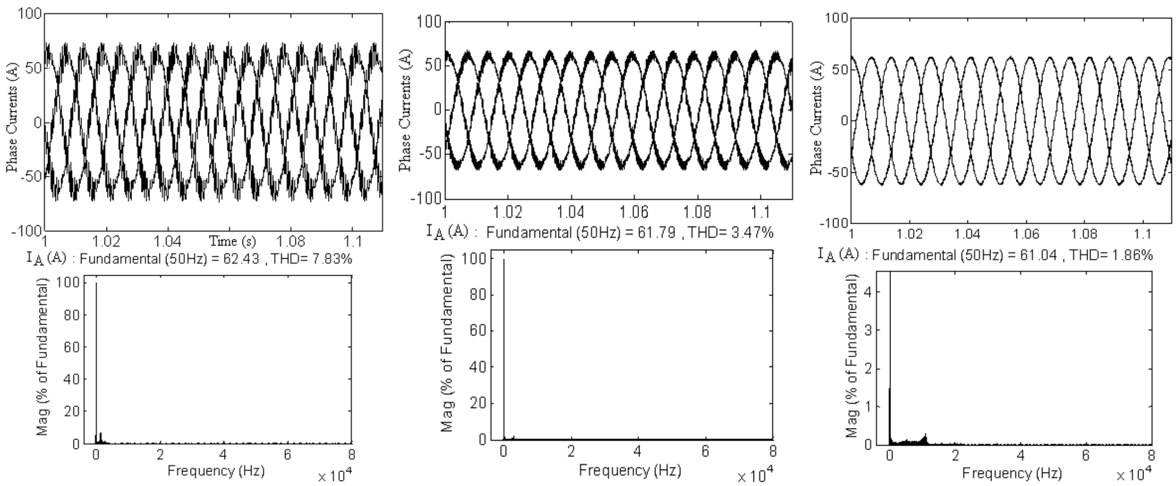
Table 2. Improving the torque ripple by approaches

Cases	a	b	c
X	20	10	0.1
ΔT (N.m)	8	4	0.04



(a) (b) (c)

Figure 7 .Signals generated from the comparison of hysteresis controllers (torque with the flux) in IMDTC of IGBT1.

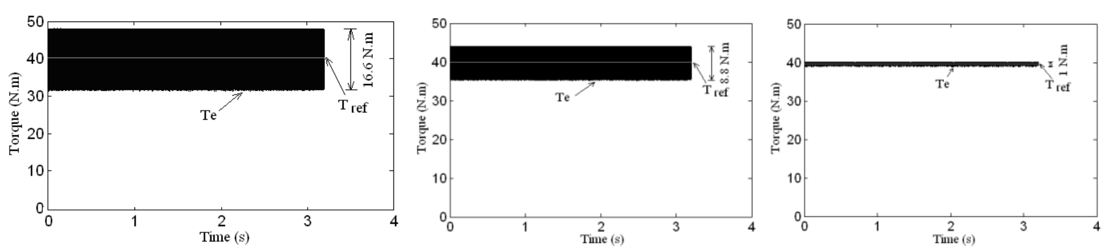


(a) (b) (c)

Figure 8. Phase currents and THD_I of IMDTC (case (a), case (b) and case (c)).

Generally, the switching frequency minimizes ripples torque; like the passage of case (a) to the state of case (c), however, when changing cases, the switching frequency augment of IGBT in figure 7.

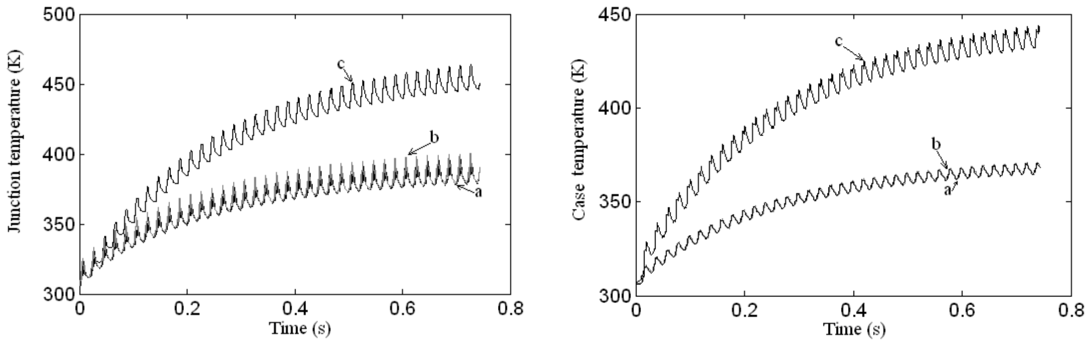
Concerning figure 8, the IMDTC realize reduce the total harmonic distortion (THD) in the IM. Moreover, the cases improve output current, reduces output total harmonic distortion and current stress on IGBT. By improving DTC of figure 8.(c), the current equal 61.04 A with THD equal to 1.86% and the THD_I is reduced to 5.97%.The THD_I is showed in figure 8.(C), which is better harmonic distortion comparing to the currents in figures 8(a) and 8(b).



(a) (b) (c)

Fig.9.IMDTC of approaches (case (a), case (b) and case (c)) results for a load of 40 Nm and improvement of the torque ripple

The figures 9, a voltage inverter feeds the motor is designed using an IMDTC, shows respectively, the reference torque proposed by DTC and the electromagnetic torque of IM presented in the same condition; one finds a modification of improvement of torque undulation with case (a) equal ±8.3 N.m, case (b) equal ±4.4 N.m and case (c) equal ±0.5.



a1 a2

Figure 10 .a1. Evolution of the junction temperature (in the IGBT1), a2. Evolution of the case temperature (in the IGBT1).

In order to estimate the junction temperature of the IGBT1, figure 10.a1 shows the evolution of the maximal junction temperature in the IGBT1. In the thermal model, three different approaches of inverter have been used; the IMDTC have used the majority regular improvement of command for IM, in benefit torque ripple reduction, improved quality of IM consumption, it ameliorates the lifespan of IM. On the contrary, the junction temperature of IGBT1 obtained by case (a), otherwise like the case (b), lower of the junction temperature obtained by the case (c) and even remark for the junction temperature, like the case temperature (figure 10.a2).

Table 3. List of Symbols

R_s: Stator resistance (1.4534 Ω), R_r: Rotor resistance (1.4160 Ω), L_r: Rotor inductance (0.0143H), L_s: Stator inductance (0.0144H), M: Mutual inductance (0.0132H), V_{ds}, V_{qs}: d-axis and q-axis stator voltages, I_{ds}, I_{qs} : d-axis and q-axis stator currents, $\sigma = 1 - \frac{M^2}{Lr.Ls}$: Blondel coefficien t, Φ_r: Rotor Flux, Φ_s : Stator flux,	T_r: Load of torque (40 N.m), T: Electromagnetic torque, Te: Torque estimator, T_{ref} : Reference torque, F: Friction coefficient (0.015 kg.m² /S), J: Moment of inertia (0.150 kg.m²), p : Number of pole pairs in the motor (2), f : Fundamental frequency (50 Hz), V_{dc}: Continuous tension (460V), tsp: Small control period, ωr : Rotor pulsation, (k +1) : Sample instant.

6. OVERALL CONCLUSIONS

The aim of the paper was to give a fair comparison between cases (a, b and c), to allow IMDTC, improved quality of IM consumption and it ameliorates the lifespan of IM with development of temperature switching IGBT. The improvement of the corresponding IMDTC has strictly followed an appropriate methodology, which offers extensive advantages and allows the foundation of a DTC of optimized reusable IM. The application IMDTC of induction motor, allows by using hysteresis controllers to regulate torque and flux with the information of the angular location, is used to address the switching table. The IMDTC allows minimizations in output current total harmonic distortion and the torque ripple. It has been summarized that the IMDTC is a better choice for this kind application.

7. ACKNOWLEDGEMENTS

The authors would thank my colleagues in ENIS-Tunisia, in FSG-Tunisia, and in ESSTT-Tunisia for the helpful support in the work.

8. REFERENCES

[1] Gabriel Cimuca, Stefan Breban, Mircea M. Radulescu,Christophe Saudemont, and Benoit Robyns," Design and Control Strategies of an Induction-Machine-Based Flywheel Energy Storage System Associated to a Variable-Speed Wind Generator", IEEE Trans.on Ener.Conv.,Vol .25,No.2,June2010,pp 526-534.

[2] Kuo-Kai Shyu, , Juu-Kuh Lin, Van-Truong Pham, Ming-Ji Yang, and Te-Wei Wang, "Global Minimum Torque Ripple Design for Direct Torque Control of Induction Motor Drives", IEEE Transact. Ind. Elec, VOL. 57, No.9, September 2010,pp3148-3156.

[3] Yongchang Zhang, Jianguo Zhu," Direct Torque Control of Permanent Magnet Synchronous Motor with Reduced Torque Ripple and Commutation Frequency", Copyright (c) 2010 IEEE, This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication,pp 1-14.

[4] Auzani Jidin, Nik Rumzi Nik Idris, Abdul Halim Mohamed Yatim, , Tole Sutikno, Malik E. Elbuluk, "An Optimized Switching Strategy for Quick Dynamic Torque Control in DTC Hysteresis-Based Induction Machines", 2010 IEEE, This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication,p 9.

[5] Bekheira Tabbache, Abdelaziz Kheloui and Mohamed Benbouzid," An Adaptive Electric Differential for Electric Vehicles Motion Stabilization", This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication,p8.

[6] I. Takahashi and Y.Ohmori, "High performance Torque Control of year Induction Motor", IEEE Transactions one Industry Applications, vol. 25, pp. 257-264, March/April 1989.

[7] M. Depenbrock, "Direct self-control (DSC) of inverter-fed induction machine", IEEE Trans. Power Electron., vol.3, pp. 420-429, Oct. 1988.

[8] Zhifeng Zhang, Renyuan Tang, Baodong Bai, and Dexin Xie," Novel Direct Torque Control Based on Space Vector Modulation With Adaptive Stator Flux Observer for Induction Motors", IEEE Transactions one Magnetics, Vol. 46, No. 8, August 2010,pp 3133- 3136.

[9] Kyo-Beum Lee, Member, IEEE, Sung-Hoe Huh, Ji-Yoon Yoo, Member, IEEE, and Frede Blaabjerg, Fellow, IEEE," Performance Improvement of DTC for Induction Motor-Fed by Three-Level Inverter With an Uncertainty Observer Using RBFN '', IEEE Trans. on Energy Conv, vol.20.no.2,Janury 2005. pp. 276- 283

[10] Joon Hyoung Ryu, Kwang Won Lee, and Ja Sung Lee," A Unified Flux and Torque Control Method for DTC-Based Induction-Motor Drives", IEEE Trans. on Power Electron., vol.21.no.1,Janury 2006. pp. 234 - 242.

[11] Yongchang Zhang, Jianguo Zhu, Wei Xu, and Youguang Guo, "Simple Method to Reduce Torque Ripple in Direct Torque Controlled Permanent Magnet Synchronous Motor by Using Vectors with Variable Amplitude and Angle",IEEE.2010, This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.,p12

[12] Liliang Gao, John E. Fletcher and Libo Zheng," Low Speed Control Improvements for a 2-level 5-phase Inverter-Fed Induction Machine Using Classic Direct Torque Control", IEEE 2010,This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication.p10.

[13] Farid Khoucha, Mouna Soumia Lagoun, Abdelaziz Kheloui and Mohamed El Hachemi Benbouzid," A Comparison of Symmetrical and Asymmetrical Three-Phase H-Bridge Multilevel Inverter for DTC Induction Motor Drives", IEEE Transact. On Enrg..Conv.,2010, This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.p.9

[14] M. Aktas V. Turkmenoglu, ,'' Wavelet-based switching faults detection in direct torque control induction motor drives", IET Sci. Meas. Technol., 2010, Vol. 4, Iss. 6, pp. 303–310

[15] Jef Beerten, Jan Verveckken, and Johan Driesen," Predictive Direct Torque Control for Flux and Torque Ripple Reduction", IEEE Transact. On Ind. Elec, Vol.57, No.1 January 2010, pp 975- 985,pp.404- 412.

[16] Masood Hajian, Jafar Soltani, Gholamreza Arab Markadeh, and Saeed Hosseinnia" Adaptive Nonlinear Direct Torque Control of Sensorless IM Drives With Efficiency Optimization", IEEE Transact. On Ind. Elec, Vol.57, No.3 March 2010, pp 975- 985

[17] Giuseppe Buja, Fellow, and Roberto Menis, " Steady-State Performance Degradation of a DTC IM Drive Under Parameter and Transduction Errors", IEEE Transact. On Ind. Elec, Vol.55, No.4 April 2008 ,pp 1749-1760.

[18] Yongchang Zhang, Jianguo Zhu, Zhengming Zhao, Wei Xu, David G. Dorrell, "An Improved Direct Torque Control for Three-Level Inverter-Fed Induction Motor Sensorless Drive", This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication,IEEE Trans.Power Electron., vol.21.no.5, November2010.pp1-12.

[19] Saad Sayeef, Gilbert Foo, and M. F. Rahman, "Rotor Position and Speed Estimation of a Variable Structure Direct-Torque-Controlled IPM Synchronous Motor Drive at Very Low Speeds Including Standstill", ", IEEE Transact.On Ind. Elec, Vol. 57, No.11,November2010 ,pp 3715-3723.

[20] Farid Khoucha, Soumia Mouna Lagoun, Khoudir Marouani, Abdelaziz Kheloui, and Mohamed El Hachemi Benbouzid, "Hybrid Cascaded H-Bridge Multilevel-Inverter Induction-Motor-Drive Direct Torque Control for Automotive Applications", IEEE Transact.On Ind. Elec, Vol.57, No.3 March 2010 ,pp 892- 899

[21] Moez Ayadi, Mohamed Amine Fakhfakh, Moez Ghariani and Rafik Nej, Electro-Thermal Simulation of a Three Phase Inverter with Cooling , Journal of Modelling and Simulation of Systems, vol. 1. n. 3, 2010, June 2010, pp. 163-170.