Investigation and Comparative Study of a New Direct Torque Control Strategy based on a Well-Balanced Multilevel Inverter

Mouna ESSAADI, Mohamed KHAFALLAH
Hassan II University-ENSEM
BP 8118, Oasis, Casablanca, Morocco

Hamid Chaikhy
Laboratory of Engineer Sciences for Energy (LabSIPE),
National School of Applied Sciences, University Chouaib Doukkali, El Jadida, Morocco

Abstract:- This work proposes a comparative analysis between classical twelve sectors direct torque control (12_DTC) and a new twelve sectors direct torque control (12_DTC_3L).This new strategy is using a neutral point piloted (NPP) three level inverter is compared to 12_DTC.Many simulation results are presented showing the two torques, flux and stator current distortions and harmonics. To conclude, a comparison between 12_DTC and 12_DTC_3L is given.

Keywords:- *12_DTC, 12_DTC_3L, NPP, torque dynamic, stator current ,flux, performances.*

I. INTRODUCTION

For the last two decades, DC motors were replaced by AC motors. Induction machines (IM) have been widely used in industry. Due to their highly coupled non-linear structure, a high performance control of IM is a challenging problem. FOC has been till now employed in high performance IM industrial application. However it depends on parameter identification to obtain similar advantages to DC motor performance [1][2][3].Nowadays, a new strategy has been created. DTC has various advantages, such as fast dynamic response and robustness [4-7], therefore,DTC has been widely used in industrial applications. Per contra, DTC presents more important torque ripple and higher total harmonics distortion.Many researches have been realized to improve conventional DTC. Enhanced DTC algorithms based on new modulation approaches have been achieved. DTC using duty-cycles [5-9] were given to reduce torque ripple. To have constant switching frequency, these algorithms use simple modulator [10]. Many other algorithm's based methods have been developed to diminish torque and flux ripples while keeping the benefit of a fast dynamic response. For instance, direct torque and flux control (DTFC) [11][12], dead-beat control[13], predictive DTC [14][15] and space vector modulated SVM_ DTC[16], twelve sectors direct torque control still the best DTC method in almost the majority of all these types of method's performances[17] .Using hardware's based methods,DTC can also be improved using multilevel inverters.

Multilevel inverters have made revolutionary changes in the utilization of power electronics in high voltage and high power applications [18]. The basic concept involves generating output AC waveforms from small voltage steps by using series connected capacitors or isolated DC sources [19]. The small voltage steps in the output voltage produce lower harmonic distortion, higher efficiency when compared with the conventional two level voltage source inverters [20] [21].

The 3L_NPC inverter is widely used in high power medium voltage applications [22] [23]. The major disadvantage of this topology is the unequal loss distribution among the switches; however it also generates unequal junction temperature distribution which confines the inverter maximum output power [24]. Moreover as the levels of the inverter increase the unequal switching of the semiconductor devices also increase and so the voltage unbalance between the DC link capacitors also increases As the neutral point is actively piloted, three levels neutral point piloted inverter (3L_NPP) (Figure.2) is an attractive topology which can overcome the unequal loss distribution problem of the 3L_NPC inverter and improve the power ability [25-27]. In 3L_NPP inverter topology two switches connected in series are added for the purpose of clamping instead of clamping diodes as in 3L_NPC. In order to improve the 12_DTC's performances, in terms of reducing torque ripples, this work gives a comparative analysis between 12_DTC a 12_DTC_3L, in terms of torque, flux and stator current performances based on simulation results.

II. PRINCIPLE OF 12_ DTC

Since M. Depenbrock and I. Takahashi proposed DTC for IM in the middle of 1980's, more than decade has passed. It is getting more and more popular nowadays [28]. The instantaneous values of the stator flux and torque are calculated from the stator variable by using a closed loop estimator [29]. As shown in Fig. 1, stator flux and torque can be controlled directly and independently by properly selecting the inverter switching configuration.

ISSN No:-2456-2165

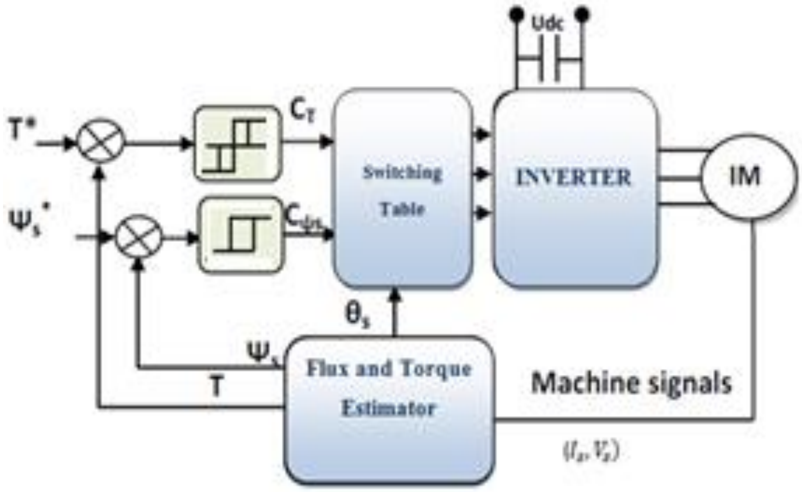


Fig. 1: block diagram of the DTC control technique

By using an α-β stationary stator reference frame, the stator flux linkage ψ_s and electromagnetic torque are calculating by using: $\psi_s = \sqrt{{\psi_{\alpha s}}^2 + {\psi_{\beta s}}^2}$ (1)

Where:

$$\psi_{\alpha s} = \int_0^t \ (V_{\alpha s} - R_s \, I_{\alpha s}) \, dt \quad (2)$$

$$\psi_{\beta s} = \int_0^t \ (V_{\beta s} - R_s \, I_{\beta s}) \, dt \quad (3)$$

The angle θ_s is equal to:

$$\theta_s = \frac{\psi_{\beta s}}{\psi_{\alpha s}}) \quad (4)$$

$$T = p[\ \psi_{\alpha s} \, I_{\beta s} - \psi_{\beta s} \, I_{\alpha s}] \quad (5)$$

The error between the estimated torque and the reference torque T* is the input of a three level hysteresis comparator, whereas the error between the estimated stator flux magnitude ψ_s and he reference stator flux magnitude $\psi_s *$ is the input of a two level hysteresis comparator.

Figs. 2 and 3 illustrate the torque and flux comparators, respectively.

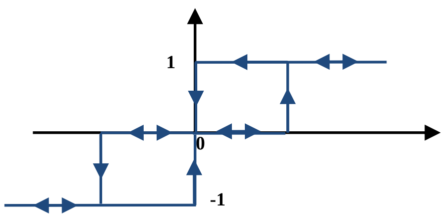


Fig. 2: Torque hysteresis comparator.

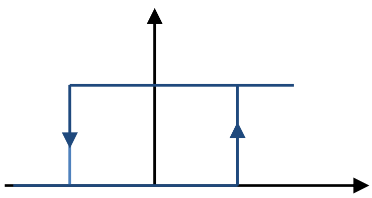


Fig. 3: Flux hysteresis comparator.

The selection of the appropriate voltage vector is based on the switching table given in Tab. 1. The input quantities are the flux sector and the outputs of the two hysteresis comparators.

To determine stator vector voltage to be applied, we begin by dividing the circular trajectory of the stator flux into six symmetrical sectors referred as the inverter voltage vectors [30].

Then, we study the effect of each stator voltage on the flux and torque. When the stator flux is in sector Si, the vectors V_{i+1}or V_{i-1} are selected to increase its amplitude, and V_{i+2}or V_{i-2} to decrease it. However V_{i+1}or V_{i+2} increase the torque and V_{i-1}or V_{i-2} decrease it. Fig. 4 shows the effect of those different choices in sector S1.

Outputs of hysteresis Comparators		Sector					
$C_{\psi s}$	C_{Te}	*1*	*2*	*3*	*4*	*5*	*6*
1	1	$\underline{V}_2$	$\underline{V}_3$	$\underline{V}_4$	$\underline{V}_5$	$\underline{V}_6$	$\underline{V}_1$
	0	$\underline{V}_7$	$\underline{V}_0$	$\underline{V}_7$	$\underline{V}_0$	$\underline{V}_7$	$\underline{V}_0$
	-1	$\underline{V}_6$	$\underline{V}_1$	$\underline{V}_2$	$\underline{V}_3$	$\underline{V}_4$	$\underline{V}_5$
0	1	$\underline{V}_3$	$\underline{V}_4$	$\underline{V}_5$	$\underline{V}_6$	$\underline{V}_1$	$\underline{V}_2$
	0	$\underline{V}_0$	$\underline{V}_7$	$\underline{V}_0$	$\underline{V}_7$	$\underline{V}_0$	$\underline{V}_7$
	-1	$\underline{V}_5$	$\underline{V}_6$	$\underline{V}_1$	$\underline{V}_2$	$\underline{V}_3$	$\underline{V}_4$

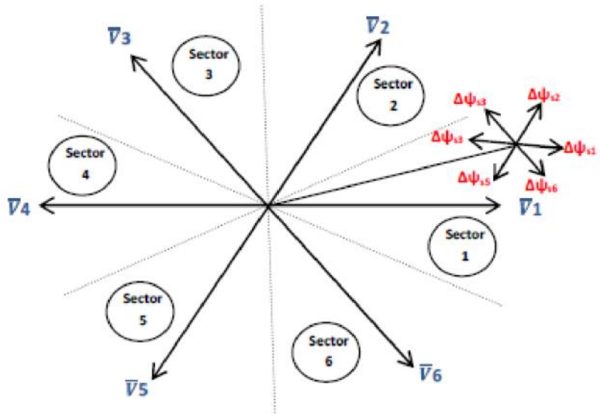


Fig. 4: Effect of different Vs choices on the torque and stator flux in sector S1.

In C_DTC there are two states per sector i that present a torque ambiguity which are $\underline{V}_i$ and$\underline{V}_{i+1}$. Therefore, they are never used. In a same way, in M_DTC there are two states per sector i that introduce flux ambiguity which are $\underline{V}_{i+2}$and $\underline{V}_{i+5}$, so they are never used either. If the stator flux locus is divided into twelve sectors [31] instead of just six, all six active states will be used per sector and the problem of ambiguity of both flux and torque will be solved. This new stator flux locus is introduced in Fig.5.

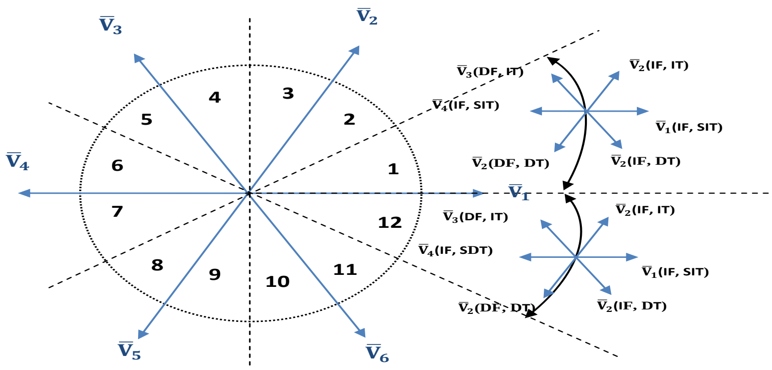


Fig. 6: Twelve sectors modified DTC(12_DTC).IT/DT/IF /DC/SIT/SDT: Increase Torque/ Decrease torque/Increase flux/ Decrease Flux/Small increase of Torque/Small decrease of torque.

It's clearly noticed in Tab. 4 that all the six vectors are used, disappearing all ambiguities. Switching table of the 12_DTC becomes Tab.5. It is obvious that V1 will produce a large increase in flux and a small increase in torque in sector S12. On the contrary, V2 will increase the torque in a large proportion and the flux in a small one. It is reasonable to deduce that the torque error should be divided in the number of intervals that later on will be measured. Therefore, the hysteresis block should have four hysteresis level at is suggested in Tab.5.

ISSN No:-2456-2165

Sector		1	2	3	4	5	6	7	8	9	10	11	12
$C_{\psi s}$	C_{Te}												
1	2	$\underline{V_2}$	$\underline{V_3}$	$\underline{V_3}$	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$	$\underline{V_5}$	$\underline{V_6}$	$\underline{V_6}$	$\underline{V_1}$	$\underline{V_1}$	$\underline{V_2}$
	1	$\underline{V_2}$	$\underline{V_2}$	$\underline{V_3}$	$\underline{V_3}$	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$	$\underline{V_5}$	$\underline{V_6}$	$\underline{V_6}$	$\underline{V_1}$	$\underline{V_1}$
	-1	$\underline{V_1}$	$\underline{V_1}$	$\underline{V_2}$	$\underline{V_2}$	$\underline{V_3}$	$\underline{V_3}$	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$	$\underline{V_5}$	$\underline{V_6}$	$\underline{V_6}$
	-2	$\underline{V_6}$	$\underline{V_1}$	$\underline{V_1}$	$\underline{V_2}$	$\underline{V_2}$	$\underline{V_3}$	$\underline{V_3}$	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$	$\underline{V_5}$	$\underline{V_6}$
0	2	$\underline{V_3}$	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$	$\underline{V_5}$	$\underline{V_6}$	$\underline{V_6}$	$\underline{V_1}$	$\underline{V_1}$	$\underline{V_2}$	$\underline{V_2}$	$\underline{V_3}$
	1	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$	$\underline{V_5}$	$\underline{V_6}$	$\underline{V_6}$	$\underline{V_1}$	$\underline{V_1}$	$\underline{V_2}$	$\underline{V_2}$ *	$\underline{V_3}$	$\underline{V_3}$
	-1	$\underline{V_7}$	$\underline{V_5}$	$\underline{V_0}$	$\underline{V_6}$	$\underline{V_7}$	$\underline{V_1}$	$\underline{V_0}$	$\underline{V_2}$	$\underline{V_7}$	$\underline{V_3}$	$\underline{V_0}$	$\underline{V_4}$
	-2	$\underline{V_5}$	$\underline{V_6}$	$\underline{V_6}$	$\underline{V_1}$	$\underline{V_1}$	$\underline{V_2}$	$\underline{V_2}$	$\underline{V_3}$	$\underline{V_3}$	$\underline{V_4}$	$\underline{V_4}$	$\underline{V_5}$

Table 2: Switching table of the 12_DTC

III. PRINCIPLE OF THREE LEVEL NPP INVERTER

The structure of the 3L_NPP inverter is shown in figure 7 below.

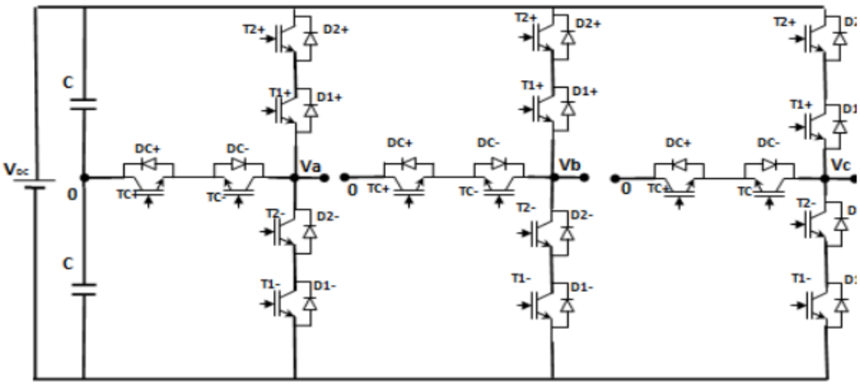


Fig. 7:Structure of the 3L_NPP

The output voltage can be given as : [31]

$$V = \frac{2}{3}(V_{ao} + k.V_{bo} + k^2 V_{co}) \quad (1)$$

Where, V_{ao}, V_{bo} and V_{co} are the voltages generated by the converter and k=.$e^{j2\pi/3}$The inverter phase terminal voltage is shown:

$$V_{xo} = S_x.\frac{V_{dc}}{2} \quad (2)$$

where x = {a, b, c} .The S_x is the switching state of the phase x, i.e., P state, S_x = 1, where the inverter output terminal is connected to the positive rail of the dc-link; O state, S_x = 0, where the inverter output terminal is connected to the NP of the dc-link; and N state, S_x = –1, where the inverter output terminal is connected to the negative rail of the dc-link. All the space voltage vectors are shown in Fig.8 that a 3L_NPP inverter can generate. [32]

ISSN No:-2456-2165

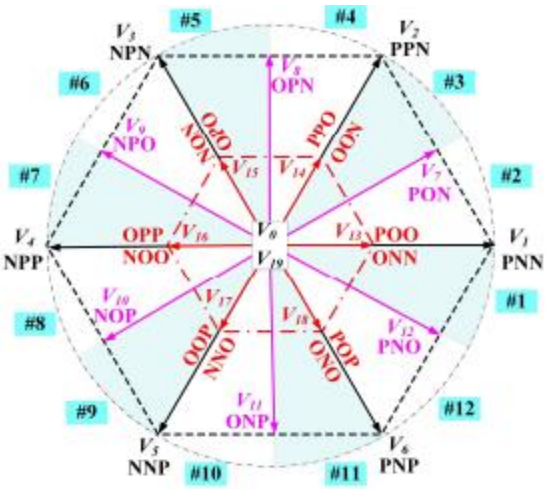


Fig. 8: vectors tension generated by Tree level inverter

Table II is the switching table of a conventional 12_DTC_3L [32] to determine the proper voltage vector.

Sector		1	2	3	4	5	6	7	8	9	10	11	12
$C_{\psi s}$	C_{Te}												
1	*2*	$\underline{V}_2$	$\underline{V}_8$	$\underline{V}_3$	$\underline{V}_9$	$\underline{V}_4$	$\underline{V}_{10}$	$\underline{V}_5$	$\underline{V}_{11}$	$\underline{V}_6$	$\underline{V}_{12}$	$\underline{V}_1$	$\underline{V}_7$
	1	$\underline{V}_{14}$	V_{14}	$\underline{V}_{15}$	$\underline{V}_{15}$	$\underline{V}_{16}$	$\underline{V}_{16}$	$\underline{V}_{17}$	$\underline{V}_{17}$	$\underline{V}_{18}$	$\underline{V}_{18}$	$\underline{V}_{13}$	13_9
	-*1*	$\underline{V}_{18}$	$\underline{V}_{18}$	$\underline{V}_{13}$	$\underline{V}_{13}$	$\underline{V}_{14}$	$\underline{V}_{14}$	$\underline{V}_{15}$	$\underline{V}_{15}$	$\underline{V}_{16}$	$\underline{V}_{16}$	$\underline{V}_{17}$	$\underline{V}_{17}$
	-*2*	$\underline{V}_8$	$\underline{V}_6$	$\underline{V}_9$	$\underline{V}_1$	$\underline{V}_{10}$	$\underline{V}_2$	$\underline{V}_{11}$	$\underline{V}_3$	$\underline{V}_{12}$	$\underline{V}_4$	$\underline{V}_7$	$\underline{V}_5$
0	*2*	$\underline{V}_{11}$	$\underline{V}_3$	$\underline{V}_{12}$	$\underline{V}_4$	$\underline{V}_7$	$\underline{V}_5$	$\underline{V}_8$	$\underline{V}_6$	$\underline{V}_9$	$\underline{V}_1$	$\underline{V}_{10}$	$\underline{V}_2$
	1	$\underline{V}_{15}$	$\underline{V}_{15}$	$\underline{V}_{16}$	$\underline{V}_{16}$	$\underline{V}_{17}$	$\underline{V}_{17}$	$\underline{V}_{18}$	$\underline{V}_{18}$	$\underline{V}_{13}$	$\underline{V}_{13}$	$\underline{V}_{14}$	$\underline{V}_{14}$
	-*1*	$\underline{V}_{17}$	$\underline{V}_{17}$	$\underline{V}_{18}$	$\underline{V}_{18}$	$\underline{V}_{13}$	$\underline{V}_{13}$	$\underline{V}_{14}$	$\underline{V}_{14}$	$\underline{V}_{15}$	$\underline{V}_{15}$	$\underline{V}_{16}$	$\underline{V}_{16}$
	-*2*	$\underline{V}_5$	$\underline{V}_{11}$	$\underline{V}_6$	$\underline{V}_{12}$	$\underline{V}_1$	$\underline{\square}_7$	$\underline{\square}_2$	$\underline{\square}_8$	$\underline{\square}_3$	$\underline{\square}_9$	$\underline{\square}_4$	$\underline{\square}_{10}$

Table 3: Switching table of the 12_DTC_3L

IV. SIMULATION RESULTS AND DISCUSSION

This section is aimed to give a contribution for a comparison between direct torque control methodologies (12_DTC and 12_DTC_3L).

The simulation has been carried out by using MATLAB SIMULINK on a 1.5KW induction machine. Fig.9 presents the two DTC commands: 12_DTC and 12_DTC_3L in terms of Torque, flux and current performances. Fig.5-a shows the two responses to a step change command from 0 N.m to 10 N.m at 0.0 s, the comparison between the two methods shows clearly that 12_DTC_3L reduce remarkably torque ripples compared with 12_DTC, but both of the methods gives a good torque dynamic responses. Fig.5-b shows the two flux responses to a flux reference equal to 1 Wb, in term of flux dynamic response, 12_DTC_3L give a very good performance comparing with 12_DTC , that means, trajectory of stator flux established more quickly than that of 12_DTC (Fig.5-c). In term of steady state stator current distortions, the better performance is given by 12_DTC_3L by reducing the THD till 5.90%. Tab.4 gives a comparative analysis between 12_DTC and 12_DTC_3L in terms of different performances studied before.

DTC control *Performances*	12_DTC	12_DTC_3L
Torque Dynamic response	Fast (8 ms)	Fast (8 ms)
Torque in steady state	ripples	Less ripples
Flux in steady state	More ripples	Less ripples
Stator current in steady state	Distortions (TDH=6.65%)	Less distortions (TDH=5.90%)
Switching frequency	Important (six ssitches)	Less important (twelve switches)

Table 4: Switching table of the 12_DTC_3L a comparative analysis between 12_DTC, and 12_DTC_3L in terms of different performances

V. CONCLUSION

In this paper, investigation and comparative study of 12_DTC_3L based on NPP inverter. Conventional 12_DT have been compared with 128DTC83L, this strategy presents excellent performances in term of reducing torque ripples, fast flux dynamic response and reducing stator current distortions compared to 12_DTC.

REFERENCES

[1.] R.Ramya, A.Abhijith, SH. Raju S, M Aditya Bhat and M. Thilak “DTC and IFOC feasability analysis on torque control schemes of induction machine,” Undergraduate Academic Research Journal (UARJ), ISSN: 2278 – 1129, Volume-2, Issue-3,4,p.4-8 ,2012

[2.] H.Chaikhy, M. Khafallah, A. Saad, and M. Es-saadi “Analysis of the variation effect of induction machine parametersfor vectorial control”, Canadian Journal on Electrical and Electronics Engineering Vol. 2, No. 7,p.270-274, July 2011.

[3.] R.Toufouti S.Meziane ,H. Benalla“Direct torque control for induction machine using intelligent techniques, ”Journal of Theoretical and Applied Information Technology,p.35-44,2007

[4.] Y. Ren, Z. Q. Zhu, and J. Liu, “Direct torque control of permanent magnet synchronous machine drives with a simple duty ratio regulator,” IEEE Trans. Ind. Electron., vol. 61, no. 10, pp. 5249–5258, Oct. 2014.

[5.] Z. Zhang, Y. Zhao, W. Qiao and L. Qu, "A Space-Vector-Modulated Sensorless Direct-Torque Control for Direct-Drive PMSG Wind Turbines," in IEEE Transactions on Industry Applications, vol. 50, no. 4, pp. 2331-2341, July-Aug. 2014.

[6.] G. S. Buja, and M. P. Kazmierkowski, “Direct Torque Control of PWM Inverter-Fed AC Motors - A Survey,” IEEE Trans. Ind. Electron., vol. 51, no. 4, pp. 744-757, Aug. 2004.

[7.] G. Abad, M. A. Rodriguez, and J. Poza, “Two-Level VSC Based Predictive Direct Torque Control of the Doubly Fed Induction Machine With Reduced Torque and Flux Ripples at Low Constant Switching Frequency,” IEEE Transactions on Power Electron., vol. 23, no. 3, pp. 1050–1061, May 2008.

[8.] Y.-S. Choi, H. H. Choi, and J.-W. Jung, “Feedback linearization direct torque control with reduced torque and flux ripples for IPMSM drives,” IEEE Trans. Power Electron., vol. 31, no. 5, pp. 3728–3737, May 2016.

[9.] L.M Alsoffiani and K,B.LEE, Enhanced Performance of constant Frequency torque Controller based Direct torque Control of induction machines with increased Torque loop bandwith,” IEEE Transactions on Industrial Electronics, vol 67, no.12,pp?10168-10179,Dec2020

[10.] G. Foo, S. Sayeef, and M. F. Rahman, “Low-speed and standstill operation of a sensorless direct torque and flux controlled IPM synchronous motor drive,” IEEE Trans. Energy. Conv., vol. 25, no. 1, pp. 25–33, Mar. 2010.

[11.] Y. Xu, C. Morito and R. D. Lorenz, "Extending High-speed Operating Range of Induction Machine Drives Using Deadbeat- Direct Torque and Flux Control With Precise Flux Weakening," IEEE Transactions on Industry Applications, vol. 55, no. 4, pp. 3770-3780, July-Aug. 2019.

[12.] J. S. Lee, C.-H. Choi, J.-K. Seok, and R. D. Lorenz, “Deadbeat- torque and flux control of interior permanent magnet synchronousmachines with discrete time stator current and stator flux linkage observer,” IEEE Trans. Ind. Appl., vol. 47, no. 5, pp. 1749–1758, Jul./Aug. 2011.

[13.] M. H. Vafaie, B. M. Dehkordi, P. Moallem, and A. Kiyoumarsi Minimizing torque and flux ripples and improving dynamic response of PMSM using a voltage vector with optimal parameters,” IEEE Trans. Ind. Electron., vol. 63, no. 6, pp. 3876-3888, June. 2016.

[14.] F. Ban, G. Lian, J. Zhang, B. Chen and G. Gu, "Study on a Novel Predictive Torque Control Strategy Based on the Finite Control Set for PMSM,"IEEE Transactions on Applied Superconductivity”, vol. 29, no. 2, pp. 1-6, March 2019.

[15.] M. N. Uddin and M. M. Rahman, "Online Torque-Flux Estimation- Based Nonlinear Torque and Flux Control Scheme of IPMSM Drive for Reduced Torque Ripples," IEEE Transactions on Power Electronics, vol. 34, no. 1, pp. 636-645, Jan. 2019.

[16.] Sridhar R. Pulikanti, Mohamed S. A. Dahidah, Vassilios G. Agelidis, SHE-PWM switching strategies for Active Neutral Point Clamped Multilevel Converters, AUPEC, 2008

[17.] J. Manguelle, Convertisseurs multi-niveaux asymétriques alimentés par transformateurs multi-secondaires basse fréquence : Réaction au réseau d'alimentation, Thèse de doctorat en génie électrique, Ecole Polytechnique Fédérale de Lausane, 2004.

[18.] J. Rodriguez, S. Bernet, P. Steimer, and I. Lizama, “A survey on neyutral-point-clamped inverters,” IEEE Trans. Ind. Electron., no.7, pp. 2219-2230, July 2010.

[19.] J. Rodriguez, J. Lai, and F. Peng, “Multilevel Inverters; a survey of topologies, controls, and applications,” IEEE Trans. Ind. Electron., Vol.49, no. 4, pp. 724-738, Aug. 2002.

[20.] T. Bruckner, S. Bernet and P. Steimer, “Feed farward loss control of three level active 3L_NPC converters”, IEEE Trans. On Ind. Appl., vol. 43, no. 6, pp. 1588-1596, Dec. 2007.

[21.] V. Guennegues ; B. Gollentz ; F. Meibody-Tabar ; S. Rael ; A converter topology for high speed motor drive applications; 13th European Conference on Power Electronics and Applications, 2009. EPE '09, Barcelona.

[22.] *ChirineBenzazah, Mustapha AitLafkih, and LoubnaLazrak*International Journal of Innovation and Applied Studies ISSN 2028-9324 Vol. 9 No. 2 Nov. 2014, pp. 841-852© 2014 Innovative Space of Scientific Research Journals.

[23.] N.Schibili, T.Nguyen, A.Rufer, IEEE trans, A Three-Phase Multilevel Converter for High-Power Induction Motors On Power Elect. Vol. 13 N°.5(1998). [9] P. Mehta, A. Kunapara Investigations on A3L_NPC Multilevel Inverter used for Even loss Balancing International Journal on Recent and Innovation Trends in Computing and Communication ISSN: 2321-8169 Volume: 3 Issue: 2 025– 027 February 2015.

[24.] H.Chaikhy, M. Khafallah, A. Saad and K. Chikh “Comparison between FOC and DTC for induction machine” J. Name Stand. Abbrev., in press.between a conventional and an intelligent direct torque control for induction machine”,International review on modelling and simulation(IREMOS),Vol.4, No.6,p.2811-2816,December2011.

[25.] Takahashi,T. Noguchi, T: A new quickresponseand high-efficiency control strategy of induction motor, IEEE Trans. On IA, Vol.22,N°.5, Sept/Oct 1986, PP.820-827.

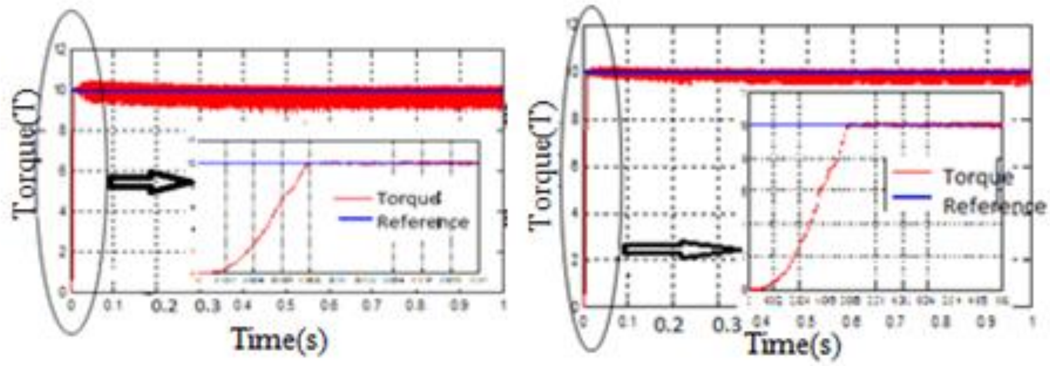
[26.] H.Chaikhy, M. Khafallah, A. Saad,M.Es-saadi, K. Chikh “Evaluation des performances des commandes vectorielles de la machine à induction”,Revue de génie industriel 2011, 6, 23-32.

[27.] B. Mokhtari1, A. Ameur, M. F. Benkhoris, L. Mokrani1 and B. Azoui “Experimental DTC of an Induction Motor Applied to Optimize a Tracking System” International Conference on Renewable Energies and Power Quality (ICREPQ’12) Santiago de Compostela (Spain), 28th to 30th March, 2012.

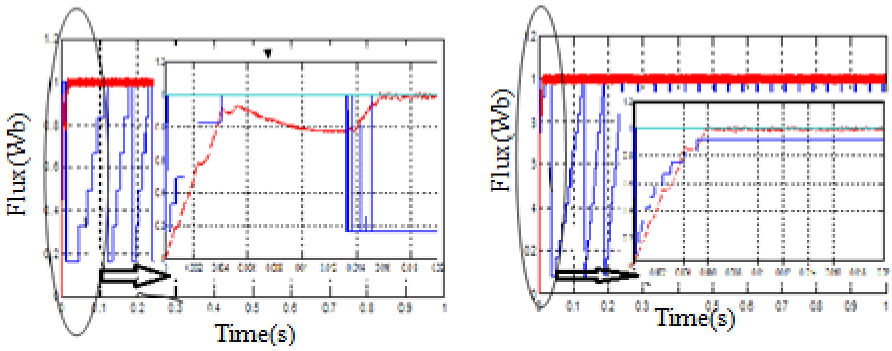
[28.] Z. Wang, M. H. Mahmud, M. H. Uddin, B. McPherson, B. Sparkman, Y. Zhao, and J. R. Fraley, “A Compact 250 kW Silicon Carbide MOSFET based Three-Level Traction Inverter for Heavy Equipment Applications,” in Proc. 2018 IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1129-1134, 2018.

[29.] J. Pou, R. Pindado, D. Boroyevich and P. Rodriguez, "Evaluation of the low-frequency neutral-point voltage oscillations in the three-level inverter," IEEE Trans. on Ind. Electron., vol. 52, no. 6, pp. 1582-1588, Dec. 2005.

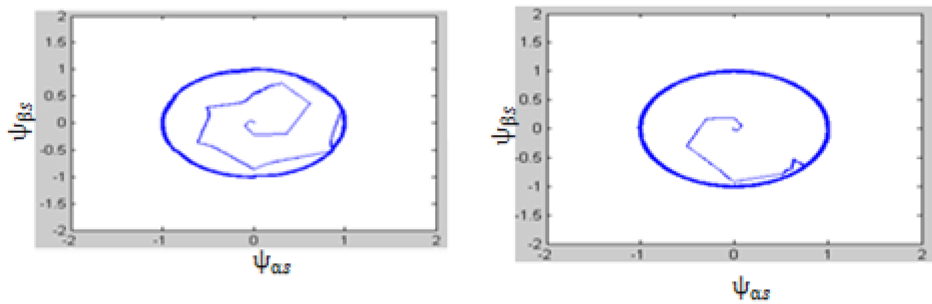
[30.] D. Mohan, X. Zhang and G. H. B. Foo, "A Simple Duty Cycle Control Strategy to Reduce Torque Ripples and Improve Low-Speed Performance of a Three-Level Inverter Fed DTC IPMSM Drive," IEEE Transactions on Industrial Electronics, vol. 64, no. 4, pp. 2709- 2721, April 2017.



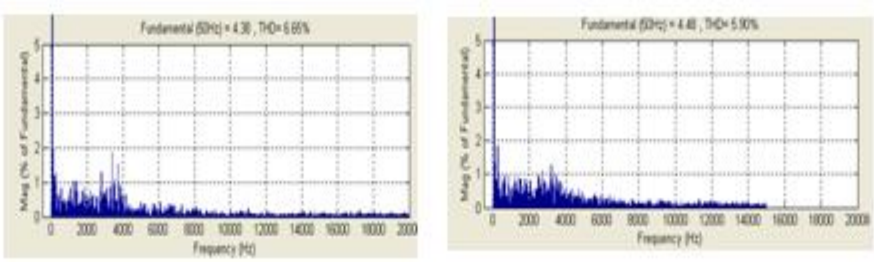
(a)



(b)



(c)



(d)

Fig. 9: Comparison between: 12_DTC and 12_DTC_3L
in term of (a) torque, (b) flux performances in steady state and transient conditions,(c) stator flux circle and(d) THD