Balancing Voltage Source Direct Torque Control of Induction Motor with Three level Inverter

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***Abstract* – In this paper we present a new control structure for sensorless induction machine dedicated to electrical drives using a three-level voltage source inverter (VSI). The amplitude and the rotating speed of the flux vector can be controlled freely. Both fast torque response and optimal switching logic can be achieved; the selection is based on the value of the stator flux and the torque.**

A novel DTC scheme of induction motors is proposed in order to develop a suitable dynamic. We propose an approach; in wich we enhance the response of torque and flux with optimal switching strategies. However, the middle point voltage of the input DC voltages of the three-level NPC voltage source inverter presents serious problems caused by a fluctuation of the DC voltage sources Ucu Ucl As consequence to these problems, we obtain an output voltage of the inverter which is asymmetric and with an average value different from zero. In this paper, we will present one solution to minimise this fluctuation. This solution uses a clamping bridge to regulate the input voltages of a threelevel inverter VSI NPC. A scheme of Enhanced direct torque control "EDTC" with complete cascade is simulated for an induction motor. The results obtained indicate superior performance over the FOC one without need to any mechanical sensor.

***Key Words* - Induction motor, Direct torque control, Voltage source inverter, , Flux estimators, Switching strategy optimisation, Neutral-point clamped.**

I. INTRODUCTION

The rapid development of the capacity and switching frequency of the power semiconductor devices and the continuous advance of the power electronics technology have made many changes in static power converter systems and industrial motor drive areas. The conventional GTO inverters have limitation of their dc-link voltage. Hence, the series connections of the existing GTO thyristors have been essential in realizing high voltage and large capacity inverter configurations with the dc-link voltage [1]. The vector control of induction motor drive has made it possible to be used in applications requiring fast torque control such as traction [2].

In a perfect field oriented control, the decoupling characteristics of the flux and torque are affected highly by the parameter variation in the machine.

This paper describes a control scheme for direct torque and flux control of induction machines fed by a three-level voltage source inverter using a switching table. In this method, the output voltage is selected and applied sequentially to the machine through a look-up table so that the flux is kept constant and the torque is controlled by the rotating speed of the stator flux. The direct torque control (DTC) is one of the actively researched control scheme which is based on the decoupled control of flux and torque providing a very quick and robust response with a simple control construction in ac drives [3].

In this paper, the authors propose a new cascade for high voltage and high power applications. This cascade lets to absorb, in network, sinusoidal currents with unity power factor. It constitutes by two-level PWM rectifier, clamping bridge, three-level NPC VSI, induction motor controlled by EDTC strategy.

II. THREE-LEVEL INVERTER TOPOLOGY

Fig. 1 shows the schematic diagram of neutral point clamped (NPC) three-level VSI. Each phase of this inverter consists of two clamping diodes, four GTO thyristors and four freewheeling diodes. Table.I shows the switching states of this inverter. Since three kinds of switching states exist in each phase, a three level inverter has 27 switching states.

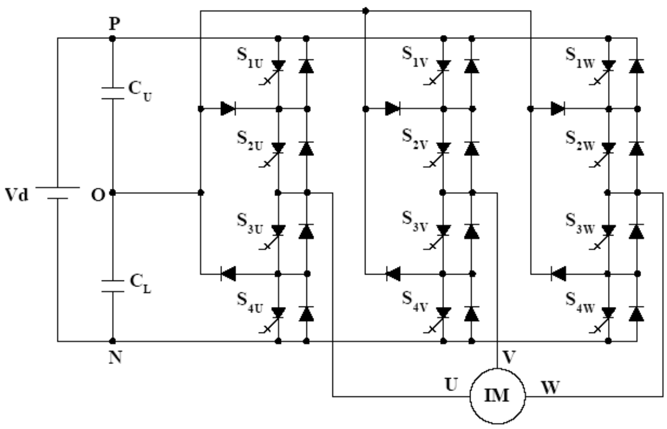

Fig. 1. Schematic diagram of a three-level GTO inverter

Table. I.

Switching states of a three-level inverter

Switching states	S1	S2	S3	S4	SN
P	**ON**	**ON**	**OFFF**	**OFFF**	**Vd**
0	**OFFF**	**ON**	**ON**	**OFFF**	**Vd/2**
N	**OFFF**	**OFFF**	**ON**	**ON**	**0**

A 2 -level inverter is only able to produce six non-zero voltage vectors and two zero vectors [2]. The representation of the

space voltage vectors of a three-level inverter for all switching states forming a two-layer hexagon centred at the origin of the (d, q) plane and a zero voltage vector at the origin of the plane, as depicted in fig.2. According to the magnitude of the voltage vectors, we divide them into four groups the zero voltage vectors (V0), the small voltage vectors (VI, V4,V7, VI , V13 , V16), the middle voltage vectors (V3 , V6 V9, V12 V15 V18), the large voltage vectors (V2 , V5 , V8 , V11,V14, V17)
The zero voltage vector (ZVV) has three switching states, the small voltage vector (SVV) has two and both the middle voltage vector (MVV) and the large voltage vector (LVV) have only one [1].

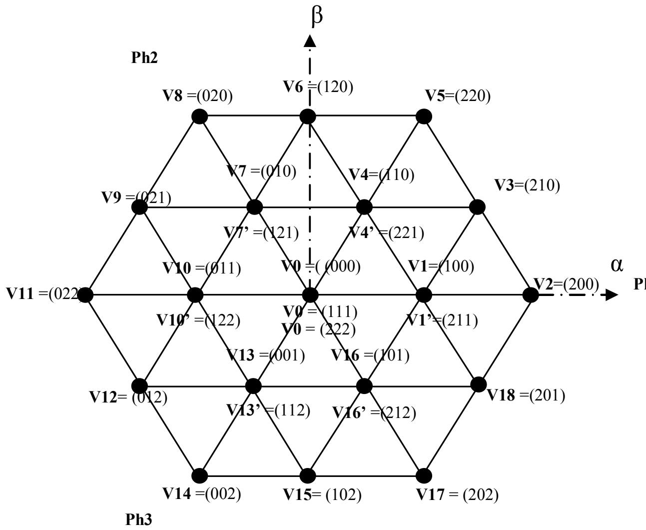

Fig. 2. Space voltage vectors of a three-level inverter

III. INDUCTION MACHINE

Torque control of an induction motor can be achieved on the basis of its model developed in a two axis (d, q) reference frame stationary with the stator winding. In this reference frame and with conventional notations, the electrical mode is described by the following equations:

$$\frac{di_{sd}}{dt}=\frac{1}{\sigma T_r L_s}\varphi_{sd}+\frac{p\Omega}{\sigma L_s}\varphi_{sq}-\frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right)i_{sd}-p\Omega i_{sq}+\frac{1}{\sigma L_s}V_{sd} \quad (1)$$

$$\frac{di_{sq}}{dt}=\frac{1}{\sigma T_r L_s}\varphi_{sq}+\frac{p\Omega}{\sigma L_s}\varphi_{sd}-\frac{1}{\sigma}\left(\frac{1}{T_r}+\frac{1}{T_s}\right)i_{sq}+p\Omega i_{sd}+\frac{1}{\sigma L_s}V_{sq} \quad (2$$

$$\frac{d\varphi_{sd}}{dt}=V_{sd}-R_s i_{sd} \quad (3)$$

$$\frac{d\varphi_{sq}}{dt}=V_{sq}-R_s i_{sq} \quad (4)$$

The mechanical mode associated to the rotor motion is described by:

$$J\frac{d\Omega}{dt}=\Gamma_{em}-\Gamma_r(\Omega) \quad (5)$$

$\Gamma_r(\Omega)$ and Γ_{em} are respectively the load torque and the electromagnetic torque developed by the machine.

IV. PROPOSED DIRECT TORQUE CONTROL USING A THREE-LEVEL INVERTER

Basically, DTC schemes require the estimation of the stator flux and torque. The stator flux evaluation can be carried out by different techniques depending on whether the rotor angular speed or (position) is measured or not. For sensorless application, the "voltage model" is usually employed [6]. The stator flux can be evaluated by integrating from the stator voltage equation.

$$\varphi_s(t)=\int(V_s-R_sI_s)dt \quad (6)$$

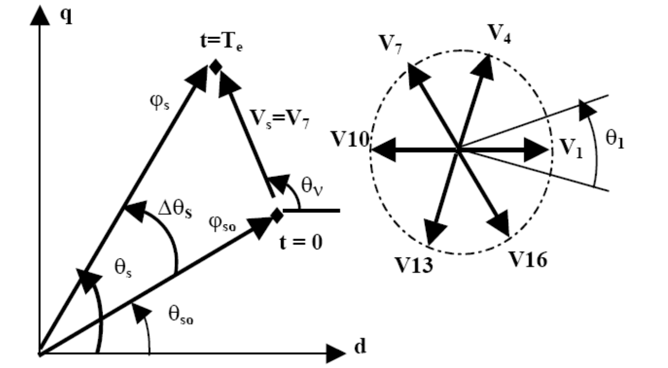

Fig. 3. Flux deviation

This method is very simple requiring the knowledge of the stator resistance only. The effect of an error in Rs is usually neglected at high excitation frequency but becomes more serious as the frequency approaches zero.
The deviation obtained at the end of the switching period Te can be approximate by the first order Taylor Series as below [6].

$$\Delta\varphi_s\approx V_s\cdot T_e\cdot\cos(\theta_v-\theta_s) \quad (7)$$

$$\Delta\varphi_s\approx T_e\cdot\frac{V_s\cdot\cos(\theta_v-\theta_s)}{\varphi_{so}} \quad (8)$$

Considering the combination of states of switching functions Su, Sv, Sw. Fig.3 shows the adequate voltage vector selection, we can increase or decrease the stator flux amplitude and phase to obtain the required performance. The electromagnetic torque is estimated from the flux and current information as [2]:

$$\Gamma_{em}=p(i_{sq}\varphi_{sd}-i_{sd}\varphi_{sq})$$

Fig.4. shows a block diagram of the DTC scheme developed by I. Takahashi [2]. The reference values of flux, φ^*_s , and torque Γ^*_{em} , are compared to their actual values and the resultant errors are fed into a multi-level comparator of flux and torque. The stator flux angle θ_s is calculated by:

$$\theta_s = \arctan \frac{\varphi_{sq}}{\varphi_{sd}} \quad (9)$$

and quantified into 6 levels depending on which sector the flux vector falls into. Different switching strategies can be employed to control the torque according to whether the flux has to be reduced or increased.

Each strategy affects the drive behavior in terms of torque and current ripple, switching frequency and two or four quadrant operation capability.

Assuming the voltage drop $\left(R_s \cdot I_s\right)$ small, the head of the stator flux φs moves in the direction of stator voltage Vs at a speed proportional to the magnitude of Vs according to:

$$\Delta\varphi_s = V_s T_e \quad (10)$$

The switching configuration is made step by step, in order to maintain the stator flux and torque within limits of two hysteresis bands. Where Te is the period in which the voltage vector is applied to stator winding. Selecting step by step the voltage vector appropriately, it is then possible to drive φs along a prefixed track curve [6].

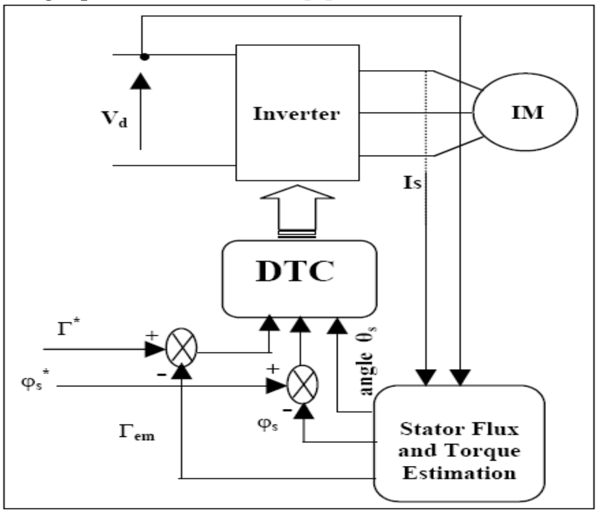

Fig. 4. Block diagram of direct torque control

Assuming the stator flux vector lying in the k-th sector (k=1,2,...6) of the (d, q) plane, in the case of three-level inverter, to improve the dynamic performance of DTC at low speed and to allow four-quadrant operation, it is necessary to involve the voltage vectors V_{k-1} and V_{k-2} n torque and flux control.

V. SWITCHING STRATEGY PROPOSED FOR AN ENHANCED DIRECT TORQUE CONTROL

According to this strategy, the stator flux vector is required to rotate in both positive and negative directions. By this, even at very low shaft speed, large negative values of rotor angular frequency can be achieved, which are required when the torque is to be decreased very fast. Furthermore, the selection strategy represented in each table allows good flux control to be obtained even in the low speed range. However, the high dynamic performance, which can be obtained using voltage vectors having large components tangential to the stator vector locus, implies very high switching frequency.

For flux control, let the variable E_φ $(E_\varphi = \varphi_s^* - \varphi_s)$ be located in one of the three regions fixed by the contraints:

$$E_\varphi \prec E_{\varphi\min} \ , \ E_{\varphi\min} \le E_\varphi \le E_{\varphi\max} \ , \ E_\varphi \succ E_{\varphi\max} \quad (11)$$

The suitable flux level is then bounded by $E_{\varphi\min}$ and $E_{\varphi\max}$ Flux control is made by a two-level hysteresis comparator.

Three regions for flux location are noted, flux as in fuzzy control schemes, by $E_{\varphi n}$ (negative), $E_{\varphi z}$ (zero) and $E_{\varphi p}$ (positive).

A high level performance torque control is required. To improve the torque control, let the difference $(E_\Gamma = \Gamma^*_{em} - \Gamma_e)$ belong to one of the five regions defined by the contraints:

$$E_\Gamma \prec E_{\Gamma\min2} \ , \ E_{\Gamma\min2} \le E_\Gamma \le E_{\Gamma\min1} \ , \ E_{\Gamma\min1} \le E_\Gamma \le E_{\Gamma\max1} \ ,$$
$$E_{\Gamma\max1} \le E_\Gamma \le E_{\Gamma\max2} \ \ and \ \ E_{\Gamma\max2} \prec E_\Gamma \quad (12)$$

The five regions defined for torque location are also noted, as in fuzzy control schemes by $E_{\Gamma nl}$ (negative large), $E_{\Gamma ns}$ (negative small), $E_{\Gamma z}$ (zero), $E_{\Gamma ps}$ (positve small), $E_{\Gamma pl}$ (positive large). The torque is then controlled by a hysteresis comparator built with two lower bounds and two upper bounds. A switching table is used to select the best output voltage depending on the position of the stator flux and desired action on the torque and stator flux. The flux position in the (d, q) plane is quantified in twelve sectors. Alternative tables exist for specific operation mode. Comparing with switching table for the case of a two-level inverter, it is easily possible to expand the optimal vector selection to include the larger number of voltage vectors produced by three-level inverter [4] ,[5]. The appropriate vector voltage is selected in the order to reduce the number of commutation and the level of steady state ripple.

The switching strategy in the order of the sector θ_s , is illustrated by each table. The flux and torque control by vector voltage has in nature a desecrate behavior. In fact, we can easily verify that the same vector could be adequate for a set of value of θ_s .

θ_1

cflx					
ccpl	ce	2	1	-1	-2
2	1	**V5**	**V4’**	**V16’**	**V17**
	-1	**V5**	**V4**	**V16**	**V17**
1	1	**V4’**	**V4’**	**V16’**	**V16’**
	-1	**V4**	**V4**	**V16**	**V16**
-1	1	**V7’**	**V7’**	**V13’**	**V13’**
	-1	**V7**	**V7**	**V13**	**V13**
-2	1	**V8**	**V7’**	**V13’**	**V14**
	-1	**V8**	**V7’**	**V13**	**V14**

θ_2

cflx					
ccpl	ce	2	1	-1	-2
2	1	**V8**	**V7’**	**V1’**	**V2**
	-1	**V8**	**V7**	**V1**	**V2**
1	1	**V7’**	**V7’**	**V1’**	**V1’**
	-1	**V7**	**V7**	**V1**	**V1**
-1	1	**V10’**	**V10’**	**V16’**	**V16’**
	-1	**V10**	**V10**	**V16**	**V16**
-2	1	**V11**	**V10’**	**V16’**	**V17**
	-1	**V11**	**V10**	**V16**	**V17**

θ_3

cflx					
ccpl	ce	2	1	-1	-2
2	1	**V11**	**V10’**	**V4’**	**V5**
	-1	**V11**	**V10**	**V4**	**V5**
1	1	**V10’**	**V10’**	**V4’**	**V4’**
	-1	**V10**	**V10**	**V4**	**V4**
-1	1	**V13’**	**V13’**	**V1’**	**V1’**
	-1	**V13**	**V13**	**V1**	**V1**
-2	1	**V14**	**V13’**	**V1’**	**V2**
	-1	**V14**	**V13**	**V1**	**V2**

θ_4

cflx					
ccpl	ce	2	1	-1	-2
2	1	**V14**	**V13’**	**V7’**	**V8**
	-1	**V14**	**V13**	**V7**	**V8**
1	1	**V13’**	**V13’**	**V7’**	**V7’**
	-1	**V13**	**V13**	**V7**	**V7**
-1	1	**V16’**	**V16’**	**V4’**	**V4’**
	-1	**V16**	**V16**	**V4**	**V4**
-2	1	**V17**	**V16’**	**V4’**	**V11**
	-1	**V17**	**V16**	**V4**	**V11**

θ_5

cflx					
ccpl	ce	2	1	-1	-2
2	1	**V17**	**V16’**	**V10’**	**V11**
	-1	**V17**	**V16**	**V10**	**V11**
1	1	**V16’**	**V16’**	**V10’**	**V10’**
	-1	**V16**	**V16**	**V10**	**V10**
-1	1	**V1’**	**V1’**	**V7’**	**V7’**
	-1	**V1**	**V1**	**V7**	**V7**
-2	1	**V2**	**V1’**	**V7’**	**V8**
	-1	**V2**	**V1**	**V7**	**V8**

θ_6

cflx					
ccpl	ce	2	1	-1	-2
2	1	**V2**	**V1’**	**V13’**	**V14**
	-1	**V2**	**V1**	**V13**	**V14**
1	1	**V1’**	**V1’**	**V13’**	**V13’**
	-1	**V1**	**V1**	**V13**	**V13**
-1	1	**V4’**	**V4’**	**V10’**	**V10’**
	-1	**V4**	**V4**	**V10**	**V10**
-2	1	**V5**	**V4’**	**V10’**	**V11**
	-1	**V5**	**V4**	**V10**	**V11**

VI. CAPACITOR VOLTAGE BALANCING ALGORITHM

We know that the group small voltage vector "SVV" is divided into two sub-groups of vectors which do not have the same action on the voltage of neutral point voltage of the inverter. On the assumption that $U_0 = U_{Cl}$, use of the vectors of the first sub-group, this vectors obtained with combinations where 1 or 2 states is equal 1, the remaining states being 0, causes to increase the neutral point voltage Uo of the inverter. On the other hand, the use of the vectors of the other sub-group of the "SVV" group, vectors obtained for combinations where 1 or 2 states is 1, the remaining states being 0, causes to decrease it (opposite effect).

Thus, if one decided to use only the vectors of one of the two sub-groups, in this case the direct control then become equivalent to the direct control of the couple of the induction machine supplied with a 2-levels inverter where DC voltage is equal to the one of the voltages of the condenser.

However the input voltage of the 3-levels inverter is maintained constant (13) and is equal:

$$V_d = U_{Cu} + U_{Cl} \qquad (13)$$

The use of the vectors of the first sub-group will have for effect to increase the value of the neutral point voltage Uo . However if we chose $U_0 = U_{Cl}$, the terminal voltage of the condenser Cl will increase and that of the condenser Cu will decrease until being cancelled. It is thus not possible to control the machine by using only the vectors of one sub-group

If we take for example the two vectors V4 and V4' which belong each one to one of the two sub-groups of the " SVV " group. They have both the same action on the module of stator flux and the value of the electromagnetic torque. On the other hand, they have contrary actions on the value of the neutral point voltage Uo. The first will increase it while the second will decrease it. With this property one can control the variations of Uo by maintaining them in a band of hysteresis centered around the value of reference which is null.

After having measured the voltages of the two condensers, we can calculate the variation (14) which exists between the two and which corresponds to an imbalance of the two condensers:

$$\varepsilon_t = U_{Cl} - U_{Cu} \qquad (14)$$

We use hysteresis controller with 2 states to maintain the error in a band of hysteresis of width. $2.\Delta V_d$

If, $\varepsilon_t < -\Delta V_d$ or if $\varepsilon_t > -\Delta V_d$ that means that imbalance between the two condensers becomes unacceptable in a direction or the other. In the first case, it will be necessary to impose a voltage vector which will have as an action to increase the neutral point voltage Uo of the inverter; the second, one will impose a voltage vector which will have as an action to decrease it.

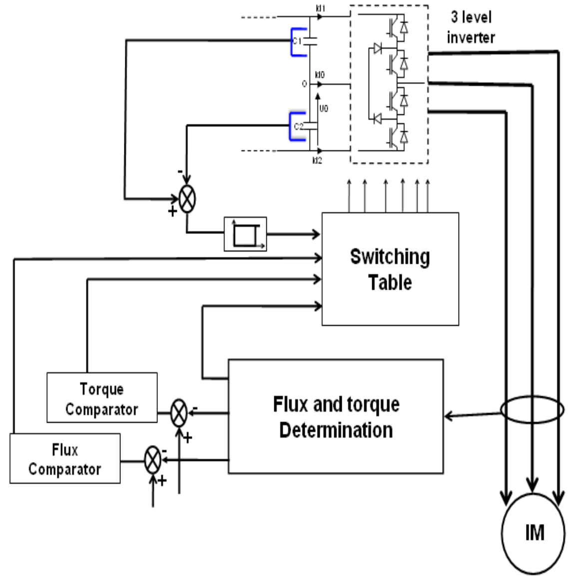

Fig. 5. Voltage unbalancing of the inverter capacitors

VII. THE SIMULATION RESULTS

The goodness of the proposed DTC algorithm has been verified in simulation on a PC. All simulations have been performed in the Matlab/Simulink environment. The used flux and torque contraints are expressed in percent with respect to the flux and torque reference values.

$E_{\varphi\max} = 3\%$, $E_{\varphi\min} = -3\%$, $E_{\Gamma\min1} = -0.8\%$, $E_{\Gamma\min2} = -3\%$, $E_{\Gamma\max1} = 0.8\%$, $E_{\Gamma\max2} = 3\%$

The simulation result illustrates both the steady state and the transient performance of the proposed torque control scheme.

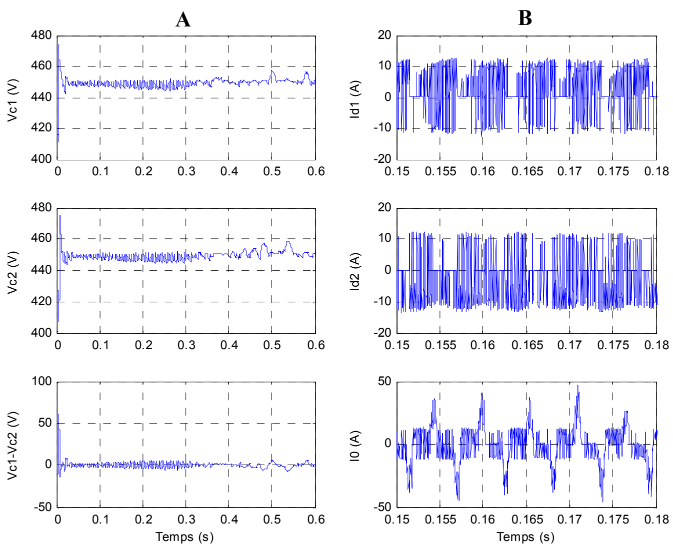

Fig. 6. A) DC input voltage of the inverter Vc1-Vc2 and their difference Vc1-Vc2
B) input currents of the 3-level inverter

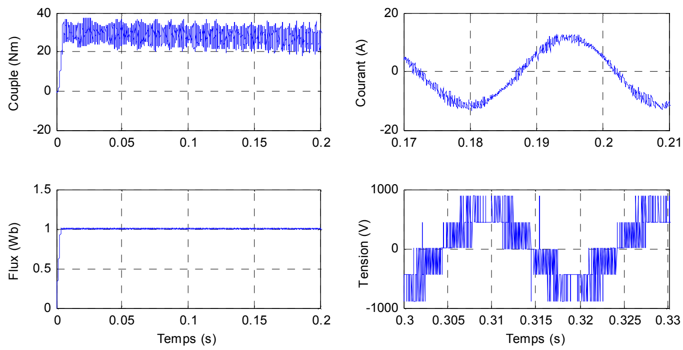

Fig. 7. Performances of the DTC drive associated to its supply at nominal reference of the flux and torque.

from figure (6-A), It can be observed that with the control algorithm the voltages in the capacitors C1 and C2 follow their references and the and difference between them is practically low, On the figure (6-B) we can see that the inputs currents in the inverter Id1 et Id2 have the same form but they have are in phase opposition, the mean value of the Id0 current are equal to zero.

From The figure (7) ,the flux the torque oscillates around their reference values (respectively 1 Wb and 50 N.m), a few torque ripples, and the response time is very short taking into account the time add by the use of the algorithm without any need of more powerful processors.We can see that both of The voltage and current qualities (wave forme , harmonics) are very good which prove also the utility of this simple algorithm .

VIII. CONCLUSION

This paper presents a very simple method of the Direct Torque Control algorithm to be applied to 3-level Diode clamped inverters. The effect of proposed method has been proved by simulations. It is concluded that the proposed control produces better results for transient state operation. And it is suitable for high-power and high-voltage applications. We enhance the DTC approach by introducing two multi-level hysteresis comparators for flux and torque control. We impose the flux angle detection procedure by defining twelve sectors of space and establish a larger table of knowledge rules with optimal switching strategies.

Also, the neutral point voltage can be easily controlled by introducing a clamping bridge to solve the usual problem of unbalanced voltages input in three-level VSI.NPC. From this analysis high dynamic performance, good stability and precision are achieved; the results obtained are full of promise to use this system in high voltage and great power applications as electrical traction.

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