Theoretical and Experimental Assessment of Control Strategies Performances of a BDCM for Industrial applications

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N.Tadrist, H.Zeroug and B.Boukais

Abstract- **In this paper, theoretical and experimental performances of a Brushless DC motor (BDCM) are assessed primarily in open loop control, using several control strategies: square wave, Pulse Width Modulation and Hysteresis. The system is examined based on a simulation model developed under Matlab-Simulink. For accuracy, the real back EMF is taken into account. The simulation results show satisfactory static and dynamic performances over a large speed range, but when compared, they highlight some differences in term torque ripple and speed response according to each control technique. Therefore, the application of these techniques would depend on the requirements of the load operating conditions. A test bench is set up using an industrial motor to demonstrate the effectiveness of the approach used and to validate obtained results.**

Key words: BDCM, DSP, square wave, hysteresis, PWM

I. INTRODUCTION

PERMANENT magnet synchronous machines are widely used thanks to the technological development in the field of magnetic material and the advent of power electronics which made possible until now to have variable supply frequency.

Thus, the synchronous motors associated with converters come to compete with the D.C. motor and the asynchronous motors in applications requiring variable speed [1].

However, emergence of digital field such as DSP and FPGA in motor control evolves performances of control strategies

BDCM is one of the two families of permanent magnet synchronous machines; Owing to their low inertia, high power to weight ration and dynamic responses, there is great interest in BDCM's utilization. The special structure of the stator leads to a trapezoidal back EMF. The most adapted control to this kind of machine is the 120° order, it consists in imposing a square waveform current (see fig1) in the three phases of the machine and that by collecting the rotor position using a Hall effect sensor which provided three signals of 180° and 120° shifted (see fig1), each transistor constituting the inverter led during a third of period, the sequence of commutation corresponds to a succession of six combinations, the passage of a combination to another is carried out all 60° electric according to rotor position [2].

The motor fed is very important and is related to the kind of drive in which the machine is used.

n_tadrist@yahoo.fr, houcinezeroug@yahoo.com
industrial and electrical systems laboratory, electrical and computing faculty. University of sciences and technology Houari Boumediene (USTHB) Algiers. BP N° 32 USTHB 16123 Bab-Ezzouar Algiers, Algeria.
b_boukais@yahoo.com,
Université Mouloud Mammeri, 15200, Tizi-ouzou, Algérie

The square wave control is very interesting for pumps and ventilations where the position is not taken into account. On the other hand PWM and Hystereses controls are interesting when the torque and speed control is needed such as in servo-motors.

In order to study the performance of each strategy, a modelling of the system comprising a BDCM (Brushless DC Motor) and an inverter (see fig.2) on MATLAB/SIMULINK is presented. This one takes account of the supply effect on performances. Three strategies are considered: square wave, hysteresis and PWM. The results of simulations are presented and discussions of the various results obtained are approached.

The implementation of the control techniques, square wave is carried out with tabulation, while the PWM control is established with a DSP TMS320F2812.

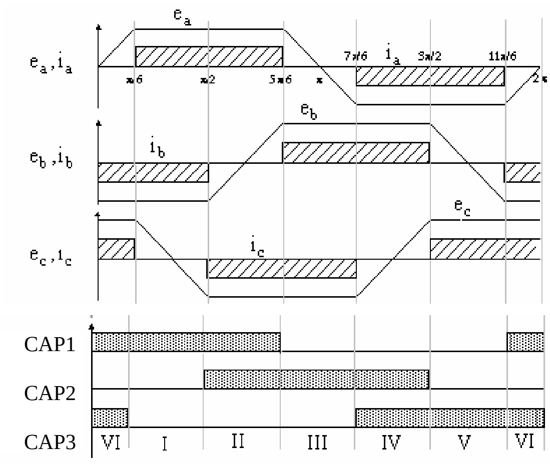

Fig.1. back EMF, phase current and position capture signals

II. MODELING OF THE SYSTEM

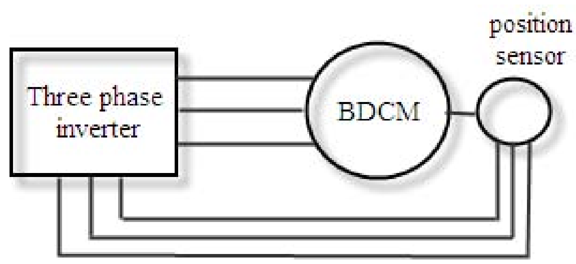

Fig 2: Main parts of system

The supply is an important component which contributes to improve the performances of the machine: Jawad Faiz and al. [3] study the influence supply on torque ripples and the transient response by comparing three control strategies: hysteresis, PWM and predictive. Xi Xiao

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and al. [4] propose two models of control to minimize torque ripples. Chang-Hee Won and al. [5] propose a control which minimizes torque ripples due to commutation by controlling input DC current, Z.Q.Zhu and al. [6] compared the influence of the DTC and PWM control on the performances of the machine.
In our work, we model system BDCM/inverter and we study the influence of three control strategies on machine performances: square wave, PWM and Hysteresis controls with considering of real back EMF.

System model comprises the model of the machine, the model of the inverter, the model of the order (square wave, MLI and Hysteresis) (see fig.3).

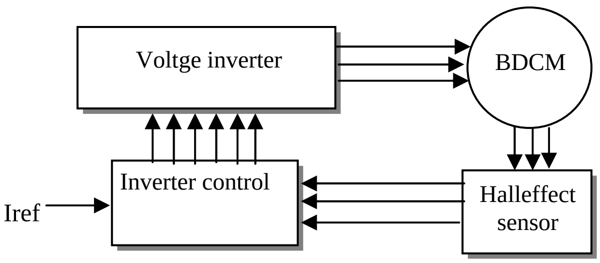

Fig 3. Basic configuration of trapezoidal BDCM drives.

Modeling of 3_phase BDCM:

The machine model is established using abc reference which has more flexibility in calculation.

Voltage equation and flow in the three armatures are

$$\begin{cases} V_a = R i_a + L_c \dfrac{di_a}{dt} + \dfrac{d\phi_{fa}}{dt} = R i_a + L_c \dfrac{di_a}{dt} + e_a \\ V_b = R i_b + L_c \dfrac{di_b}{dt} + \dfrac{d\phi_{fb}}{dt} = R i_b + L_c \dfrac{di_b}{dt} + e_b \\ V_c = R i_c + L_c \dfrac{di_c}{dt} + \dfrac{d\phi_{fc}}{dt} = R i_c + L_c \dfrac{di_c}{dt} + e_c \end{cases} \quad (1)$$

$V_{a, b, c}$: voltage

R : phase resistance

$I_{a, b, c}$

Lc : cyclic inductance

$e_{a, b, c}$: back EMF

$\phi_{fa}, \phi_{fb}, \phi_{fc}$: Rotor flow compared to phase a, b et c

EMF equation

$$e = K\,\omega_m \quad (2)$$

$$\begin{cases} e_a = \dfrac{d\phi_{fa}}{dt} = \dfrac{d\phi_{fa}}{d\theta_e}\dfrac{d\theta_e}{dt} = \dfrac{d\phi_{fa}}{d\theta_e}\dfrac{d(p\theta_m)}{dt} = p\omega_m \dfrac{d\phi_{fa}}{d\theta_e} \\ e_b = \dfrac{d\phi_{fb}}{dt} = \dfrac{d\phi_{fb}}{d\theta_e}\dfrac{d\theta_e}{dt} = \dfrac{d\phi_{fb}}{d\theta_e}\dfrac{d(p\theta_m)}{dt} = p\omega_m \dfrac{d\phi_b}{d\theta_e} \\ e_c = \dfrac{d\phi_{fc}}{dt} = \dfrac{d\phi_{fc}}{d\theta_e}\dfrac{d\theta_e}{dt} = \dfrac{d\phi_{fc}}{d\theta_e}\dfrac{d(p\theta_m)}{dt} = p\omega_m \dfrac{d\phi_c}{d\theta_e} \end{cases} \quad (3)$$

θ_m : Mechanical angle

θ_e : Electrical angle

ω_m : Mechanical velocity

p Number of pair of poles.

$$Te - Tr = J\frac{d\omega_m}{dt} = \frac{1}{p} J \frac{d\omega_e}{dt} = \frac{J}{p}\frac{d^2\theta_e}{dt^2} \quad (4)$$

Te: electromagnetic torque (Nm).
Tr: Load torque (Nm)
J : rotor inertia (Kg.m²)
ωe : Electrical velocity

System model under simulink is shown on fig.4

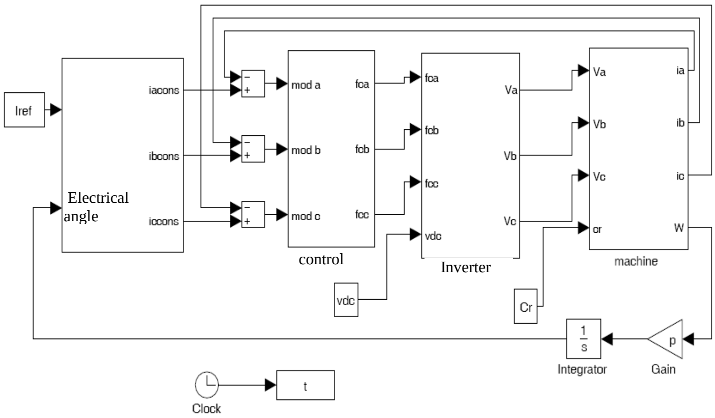

Fig.4 : Simulink model of motor drive

A. Square wave control

Motor is fed with square wave voltage, i.e. the transistors function without switching for all period of conduction [7]. Simulation results (speeds, phase voltage, phase current and DC link) for a power supply of 40V and load torque of 0.035Nm are presented on figures 5, 6, 7and 8:

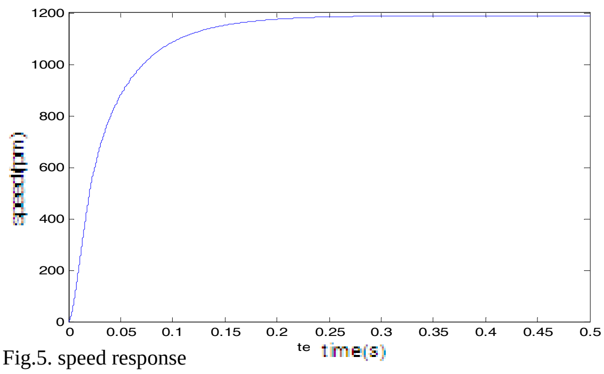

Fig.5. speed response

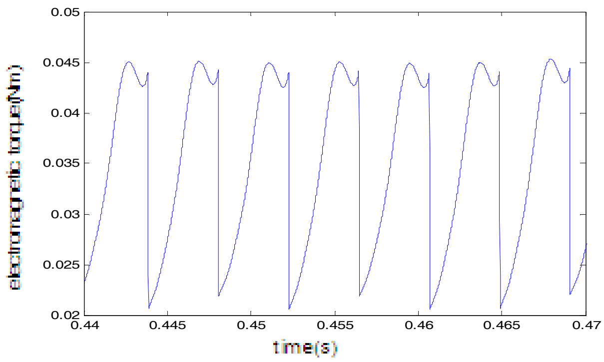

Fig.6. Electromagnetic torque

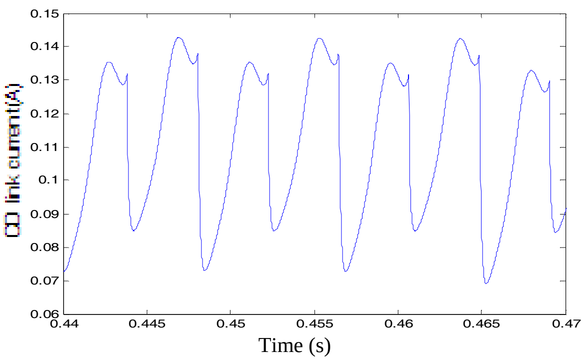

Fig.7. DC link current

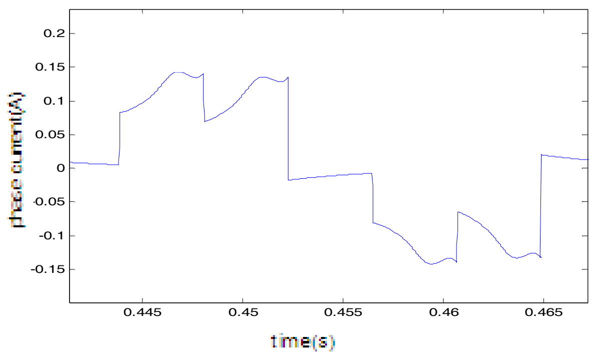

Fig.8. variation of phase a current

Simulation results join the theoretical waveforms, i.e. a rectangular alternative with appearance of commutation phenomena when current transfers from phase to another. The effect of commutation appears also on the phase voltage where 6 commutations per period are visible

B. PWM control

Pulse Width Modulation control consists in chopping the continuous supply voltage of the inverter to impose an instruction of current for each transistor, Simulink PWM model is shown in fig9

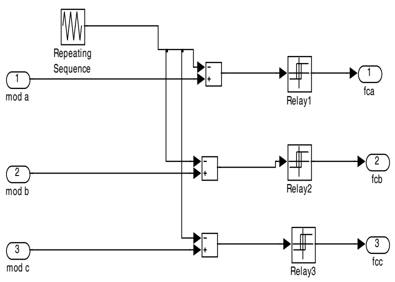

Fig.9. PWM diagram control model

Simulation is carried out for a supply voltage of 45V and a load torque of 0.5Nm. The PWM frequency is 20 KHz Under PWM control, the results of simulation are presented on figures 10, 11, 12 and 13 which represent respectively: speed in rpm, input DC current and phase current according

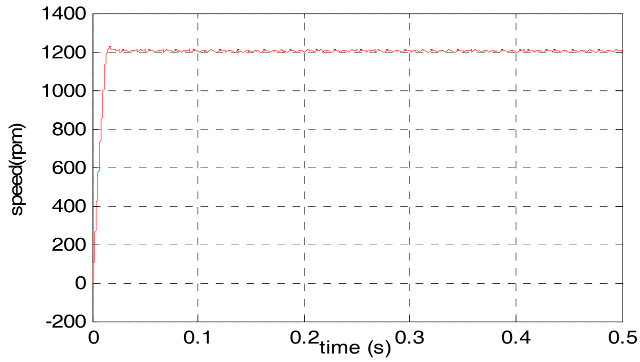

Fig.10. speed response

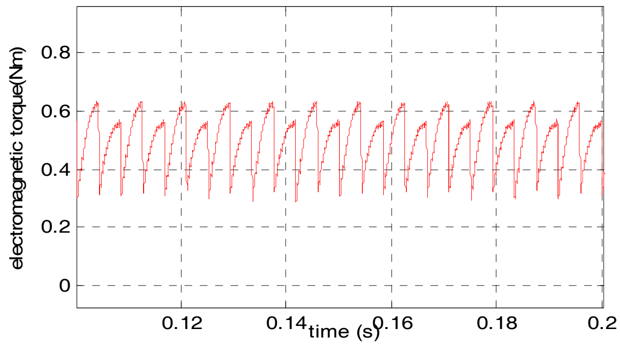

Fig.11. electromagnetic torque

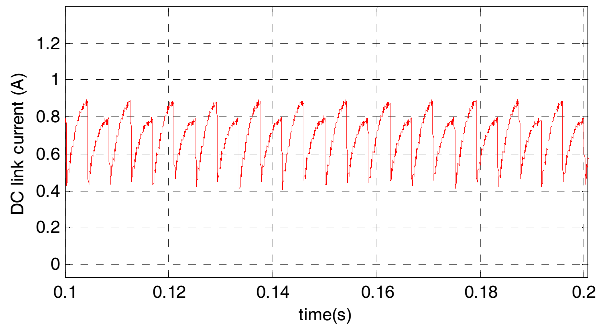

Fig.12. DC link current

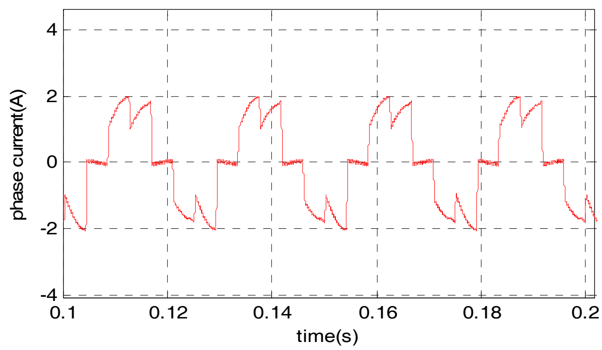

Fig. 13. Variation of phase a current

B. Hysteresis control

In hysteresis current control, three independent controllers, one for each phase is employed. The motor phases current are compared with the reference current. The logic states fca, fcb, and fcc depend on the result of the comparison.

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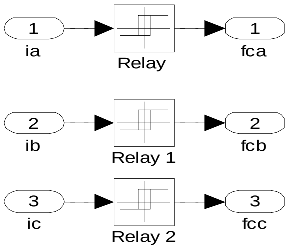

Fig.14. hysteresis diagram control model

The results of simulation presented in follows are carried out with the same conditions as in PWM control, The hysteresis band was selected with 5% of the maximum value of the current. Figures 15, 16, 17 and 18 are respectively speed, electromagnetic torque, DC link current and phase current.

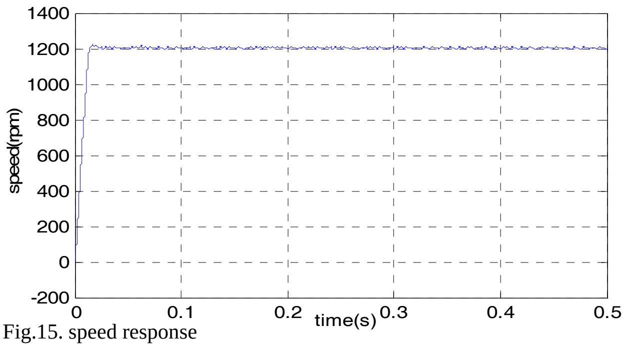

Fig.15. speed response

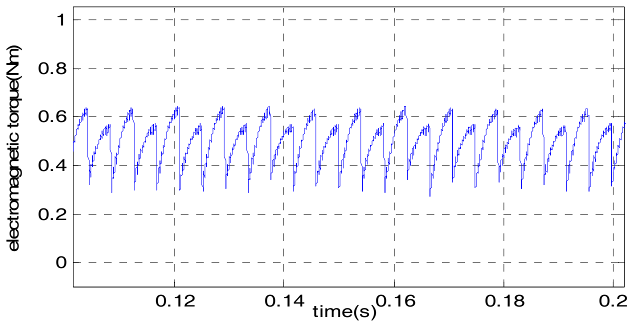

Fig.16. electromagnetic torque

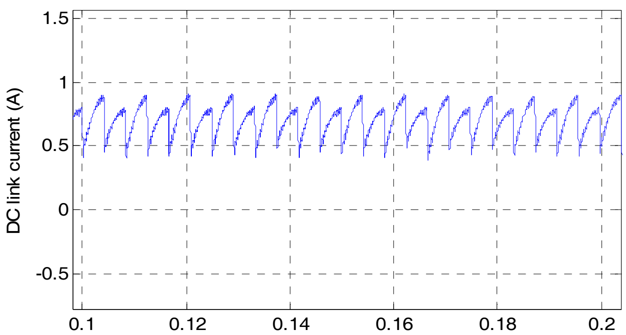

Fig.17. DC link current time(s)

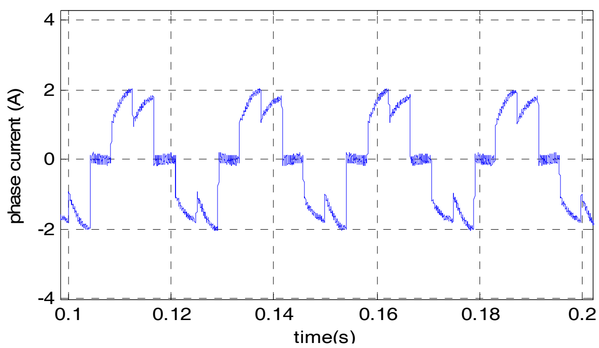

Fig.18. variation of phase a current

III. DISCUSSION OF SIMULATION RESULTS

For the square wave control, speed response appears higher when compared to other control techniques, particularly in the high speed range. This is highlighted in Table 1.

When using PWM technique, torque ripple are slightly lower than is in the hysterisis case. This difference is more apparent in the high speed range. This is illustrated in table 2 (speed of 1200 rpm, torque of 0.035Nm)

With regard to speed response, the hysterisis control produce better speed and torque responses in comparison with PWM in high speed range. However, at the low speed range, their behavior is similar

TABLE.1
TORQUE RIPPLE RATIO AND TIME RESPONSE FOR THREE STRATEGIES

	Square wave	PWM	Hysteresis
Time response (s)	0.25	0.023	0.021
Torque ripple %	71.4	141	288

Torque ripples are very important for hysteresis and PWM controls than the square wave control; the response time is more interesting for the last one. But this does not include that order MLI and Hysteress are to be eliminated because speed controls, position and torque are used with these two orders things which are not possible with the full wave.

For applications such as the servomechanisms, where controls speeds and positions are required, the choice between PWM and Hyseresis is crucial. This choice depends on the required performances.

According to simulation, the rates of ripples are more important in case of Hysteresis but responses are faster with this order while going especially towards high speeds and great loads. The table 2 outlines some results for the rates torque ripples. With load torque of 1Nm

TABLE 2
COMPARAISON BETWEEN PWM AND HYSTERESIS

	TORQUE RIPPLE (%)		
Voltage	PWM	Square wave	Hysteresis
45	50	40	60
100	60	40.2	75
120	60	40.5	65
190	70	40.7	80

IV. IMPLEMENTATION OF CONTROL STRATEGIES (square wave and PWM techniques)

In order to examine the performance of the system, and hence to show the effectiveness of the proposed modelling, an experimental system was built. This system is composed of an industrial BDC motor fed through a 03 phase voltage inverter slightly overrated according the motor template. This motor, with concentric winding, (see appendix) was coupled to a PMSM run as a generator for loading. The power circuit consists of 6 IGBT transistors (MG50Q2YS40). The circuit driver was built with IR2130 circuit which delivers 6 driving signals to the transistors. A current protection inherent to this circuit was used, monitoring the dc current in DC bus. As for the controller, a DSP kit from Texas Instruments, namely the TMS320F2812 dedicated mainly to perform the basic control tasks was used. An interface circuit was designed to

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alleviate any voltage and current incompatibility between the controller output and driving circuit. Further, Hall Effect based sensors were built and used for current and voltage measurements. Fig.19 highlights the components used in the testing bed. Tests were performed for various load and speed conditions, in particular for 500, 1000 and 1500rpm .

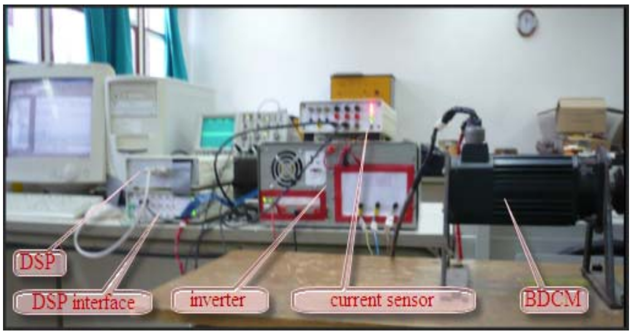


Fig.19. main board of the drive

A. *Implementation of square wave control*

This control is carried out using a look up which exploits the three output signals of the sensor to produce the six transistors control signals taking into account the control character 120° of the BDCM.

The experimental results are given in figures 20. 21 and 22 which represent respectively: line voltage, phase current and DC link current 25.5V power supply, a torque load of 0.3Nm, a speed of 685 rpm.

Fig.20. line voltage

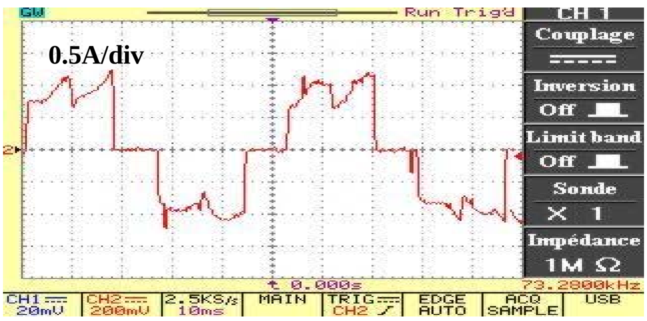


Fig.21. phase a current

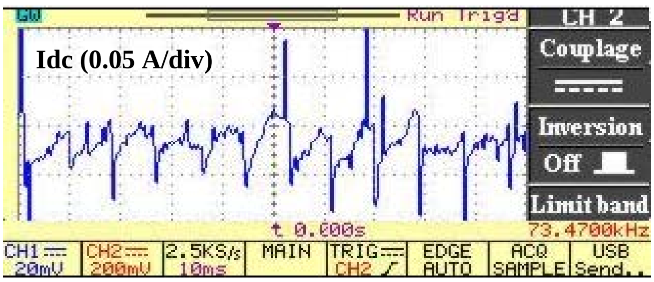


Fig.21 DC link current

B. *Implementation of PWM control*

The edge detection makes it possible to generate PWMI for each transistor; the frequency of the PWM is set to 20 Khz and is chosen in order to have lower torque ripples [8]. The implementation of the control program is carried out with the TMS320F2812. The software C2000 allows us the compilation of the program and loading executable code in DSP memory by emulator.

The choice of the mode `real-time' gives us the possibility of varying PWM ratio in real-time through Watch Windows. Motor is linked by collecting the signals of the sensor with CAP1 CAP2 and CAP3's DSP

The program control execution is done while making function the program injected into DSP memory,

The signals of Hall effect sensor are treated by the DSP, we increase supply voltage of inverter until 45V, the ratio of the PWM being initially with 0, we increase ratio of 0 up to 50%, the engine starts gradually with low speed until reaching the speed corresponding to 662tr/mn

The choice of the phases to be fed is very important because it is necessary to fix the EMF with the currents of the 3 phases of the machine. A good match of sensor signals with phase sequence is necessary to enable the motor to start with sufficient torque and the right direction. The experimental results are presented on figures 23, 24 and 25

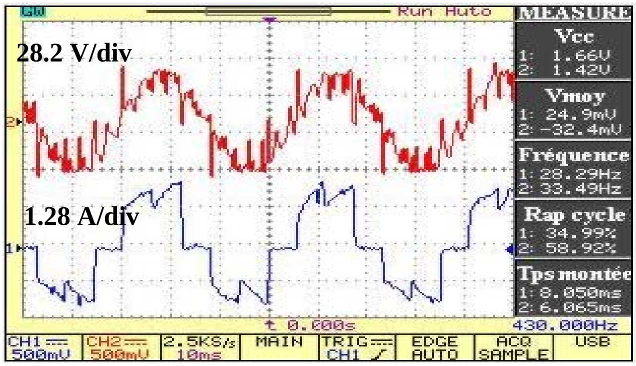


Fig.23 line voltage (trace above), phase current (trace below)

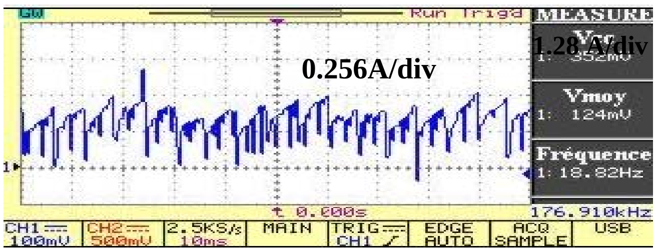
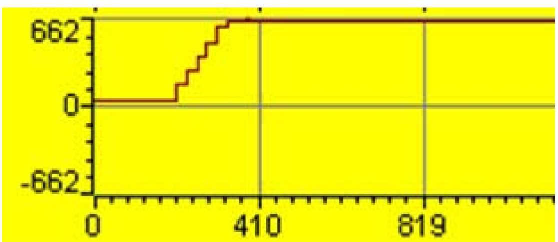


Fig.24 DC link current Idc



Time (ms)

fig.25. speed response (rpm)

in order to compare experimental results to those of simulation, a test is carried out with a DC link voltage 35v

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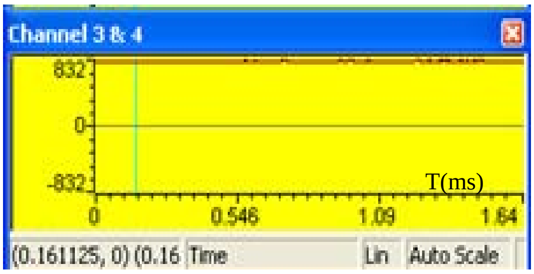
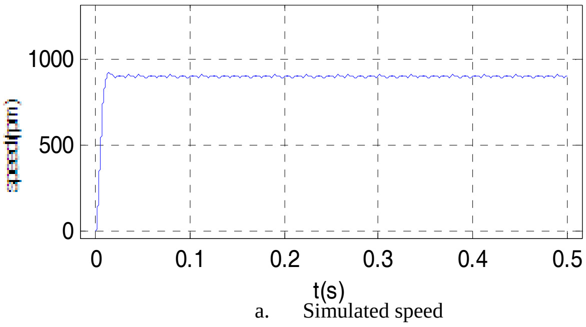
and load torque of 0.33Nm. Figures 26, 27 and 28 compare between simulated an experimental results,



b. Experimental speed (rpm)



a. Simulated speed

Fig.26. comparison between simulated and experimental speed

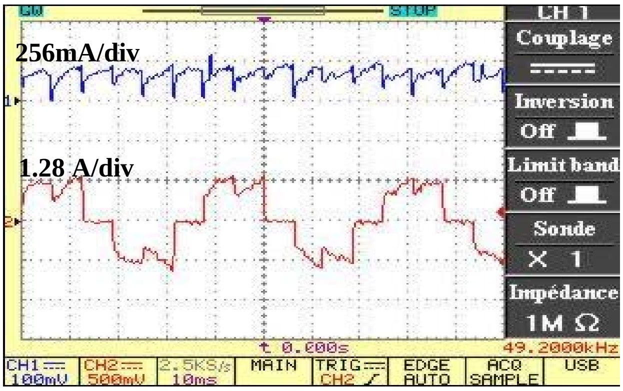


Fig.27 DC link current (trace above), Experimental phase (trace below)

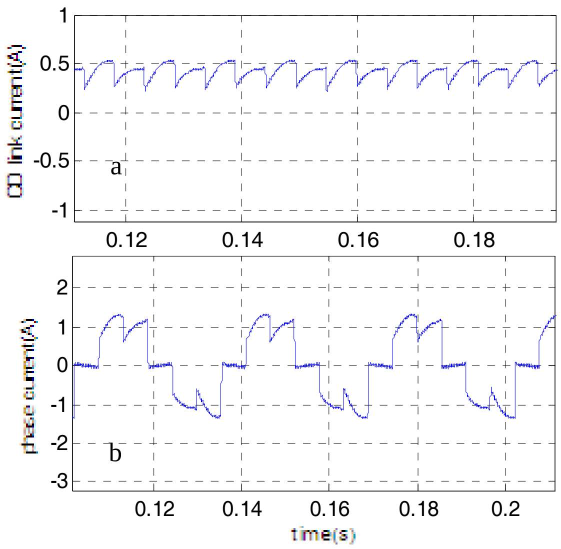


Fig.28 a.: simulated DC link current, b. simulated phase a current

V. DISCUSSION OF EXPERIMENTAL RESULTS

When the motor is running at speed of 600 rpm, the experimental results show that the DC link current and hence the torque, exhibits a higher variation in the case of the PMW strategy, in comparison with square wave technique. This situation is verified even over a large speed range. However, it will gradually decrease when the duty cycle becomes close to 1. This is well highlighted through the experimental results shown in Fig26.

Further, the test bed has enables us to conduct experimentation to assess the dynamic performances in term of speed response. In fact, the implementation of the PWM technique has shown rapid speed responses corresponding to a given duty cycle desired, to meet various speed references. The time responses are found to be a far lower than in the square wave control.

VI. CONCLUSION

In this paper, an analysis of the performances of the BDCM using three control strategies: square wave, PWM and Hysteresis, is carried out in an open control. The simulation results show that the performances present differences in term of torque ripple and transient responses, when compared to each other. Square control is found to be interesting as a low cost solution where high efficiencies and dynamics are not required in applications such as the pumps and ventilations. However, PWM and Hysteresis strategies are more suited towards applications of servomechanisms where speed and position control are desired. Nevertheless, their applications remain subject to the operating conditions required by the load in terms of speed and torque responses. The experimental results agree to the simulation ones, and validate the approach described, whereby system performances were assessed.

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Appendix

$$P = 700W \; ; In = 4.8A \; ; Te = 1,5Nm$$

$$L_C = 0.00284H \; ; p = 2 ; R = 1.25\Omega$$

$$J = 128\ 10\text{-}5 kgm^2$$

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