Speed Control of a Brushless DC Motor (BLDCM) Based on Fuzzy Gain-Adaptive PI

Abderrahmen Bouguerra, Keltoum Loukal and Samir Zeghlache

***Abstract*-- this paper presents a comparison between a fuzzy gain adaptive controller and a conventional PI controller used for speed control of a Brushless DC motor (BLDCM) or electronically commutated (ECM). First, we establish a dynamic model for direct current to the input of the switch that the electromagnetic torque of BLDCM is proportional to this current. This model is intended to facilitate the procedures for setting and controlling the current, and an adaptive PI controller is proposed for the speed control of BLDCM in the presence of the variations parametric, A fuzzy-Type 1 inference system is used to adjust in real-time the controller gains. The obtained results show the efficacy of the proposed method.**

***Index Terms*-- brushless DC motor, direct current model, Type-2 Fuzzy Logic Control, speed control.**

I. Introduction

Recently, the DC motors have been gradually replaced by the BLDC motors since the industrial applications require more powerful actuators in small sizes. Elimination of brushes and commutators also solves the problem associated with contacts and gives improved reliability and enhances life. The BLDC motor has the low inertia, large power to volume ratio, and low noise as compared with the permanent magnet DC servo motor having the same output rating [1]-[3].

In general, the BLDCM is supplied through a three-phase inverter transistor that acts as the electronic switch of the phase current, the control of the torque is then up to a current control i_d [4]. The control of the phase currents required since the reconstitution of these currents which is not easy. It is easier to directly control of the current. In most cases using a voltage inverter current controlled. As the engine torque is proportional to the DC input of the switch where the interest to influence the form of the current to optimize torque and to minimize the current [5]. The control strategy based on PI gain scheduling, a number of methods have been proposed in the literature for PID gain scheduling [6] a stable gain-scheduling PID controller is developed based on grid point concept for nonlinear systems. Different gain scheduling methods were studied and compared [7, 8], a new PID scheme is proposed in which the controller gains were scheduled by a fuzzy inference scheme. Many method and research works in this domain in [9-12]. The interested readers can find a brief review of different fuzzy PID structures in [13].

The remainder of this paper is organized as follows. In section I, the model of three-phase BLDCM Section II develops the dynamic model. Section III is devoted to the PI gain adaptive control based on the type-2. The simulation results to demonstrate the effectiveness of the proposed approach is presented in Section IV, Finally in the conclusion are set out the essential findings of this work.

II. Equations of Electrical and Mechanical of BLDCM

The model simplified of the BLDCM is shown in figure 1:

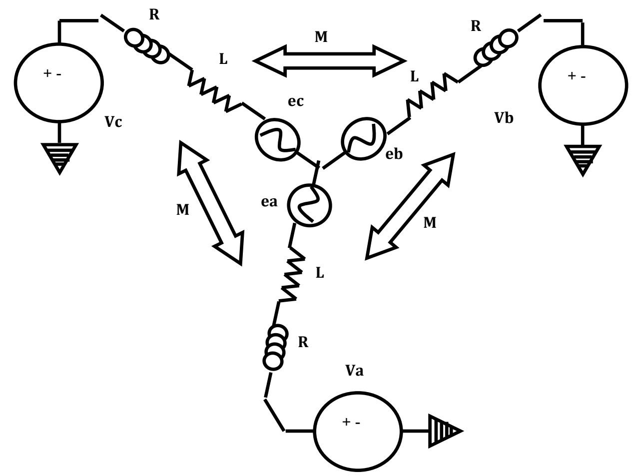

Figure 1. The model simplified of the BLDCM

For a symmetrical winding and a balanced system (Fig. 1), the vector of voltages across the three phases of the BLDC motor is given by:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where v_a, v_b and v_c are the phase voltages of the BLDCM, i_a, i_b and i_c are the phase currents, R and L are the resistance and inductance of the machine, e_a, e_b and e_c are the electromotive forces of the phases. The electric torque is given by:

$$C_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \quad (2)$$

Where C_e is the electromagnetic torque.

III. Modeling of the BLDCM

Figure 2 show the schematic diagram for controlling the BLDCM:

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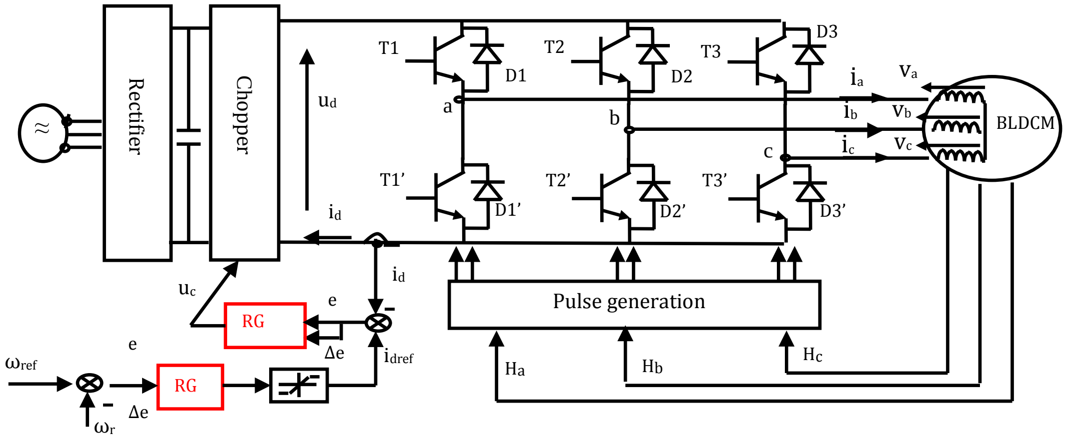


Figure 2. Block diagram for controlling the BLDC motor

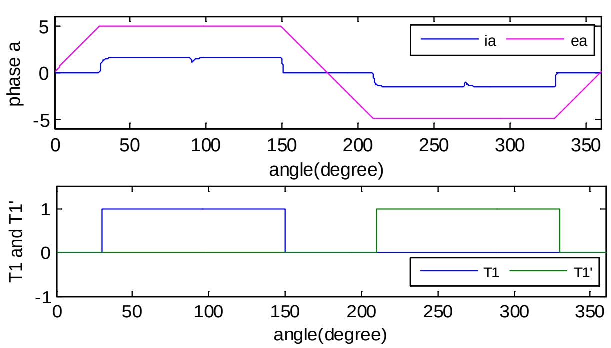
We will make the following assumptions:

- The six transistors *T1*, *T2*, *T3*, *T1'*, *T2'* and *T3'* have identical characteristics. In the state "OFF" and in the state "ON" are respectively represented by an infinite impedance and threshold voltage v_T in series with a dynamic resistance r_T.
- Similarly, it is assumed that the diodes *D1*, *D2*, *D3*, *D1'*, *D2'* and *D3'* has an infinite impedance in the state OFF and in the state ON are threshold voltage v_D in series with a dynamic resistance r_D.
- The model of the machine is generally established in a landmark three-phase (*a*, *b*, *c*) related to the stator due to the trapezoidal shape of the FCEM. For a symmetrical machine winding connected in star and whose permanent magnets are mounted on the surface [14].

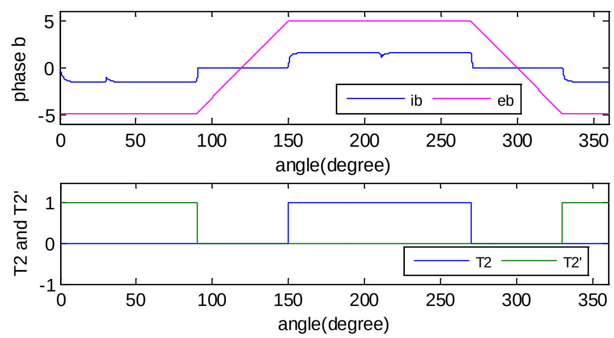
This model can be written as follows:

$$\begin{cases} V_a = Ri_a + L_c \dfrac{di_a}{dt} + e_a & (3) \\ V_b = Ri_b + L_c \dfrac{di_b}{dt} + e_b & (4) \\ V_c = Ri_c + L_c \dfrac{di_c}{dt} + e_c & (5) \end{cases}$$

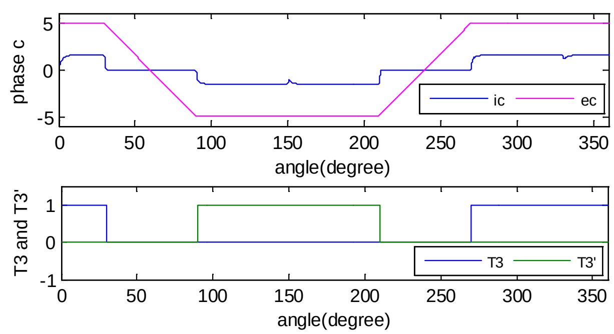
Depending on the position of the inductor, the current i_d is switched in phase at the time the trapezoidal FCEM in this phase has its flat part positive or negative "Fig. 3", "Fig. 4".



a. Current i_a and FCEM e_a and pulses T1 and T1'

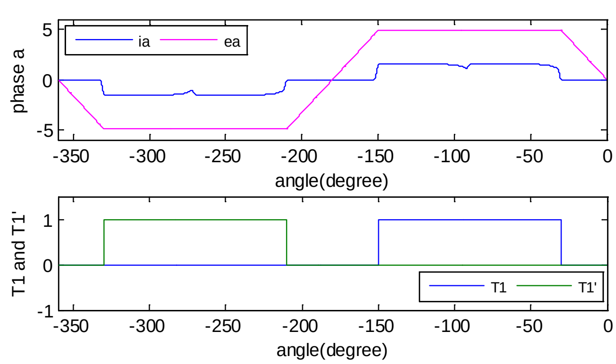


b. Current i_b and FCEM e_b and pulses T2 and T2'

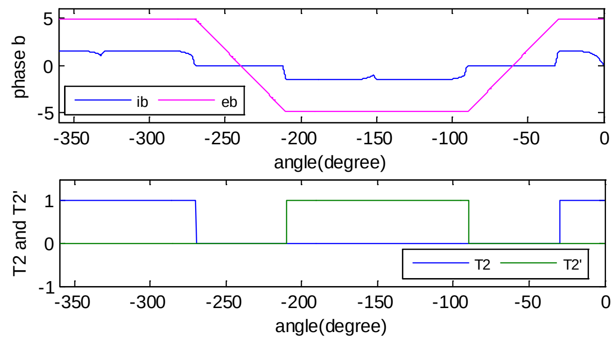


c. Current i_c and FCEM e_c and pulses T3 and T3'

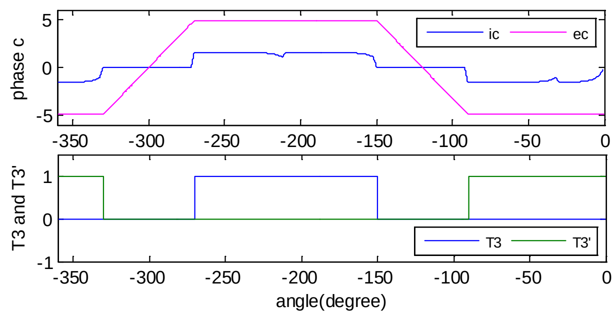
Figure 3. Control pulses of transistors for the direct sense.



a. Current i_a and FCEM e_a and pulses T1 and T1'



b. Current i_b and FCEM e_b and pulses T2 and T2'



c. Current i_c and FCEM e_c and pulses T3 and T3'

Figure 4. Control pulses of transistors for reverse rotation

From the signals of the Hall sensors, the sequence is generated by choosing a sequence of notice pulses of transistors well defined "Fig. 3", "Fig. 4", there are 6 distinct intervals noted *IT*. The opening of the 2 transistors of an arm of the electronic switch produces the conduction of a diode D_p and D_n. This corresponds to setting a series of phase with the remaining 2 in parallel in these intervals are denoted *ID* and *ID'*.

IV. Continuous Model of BLDC Motor

Is characterized by two distinct modes:

A. DC1 Mode

DC1 mode corresponds to the two phases in series "Fig.5":

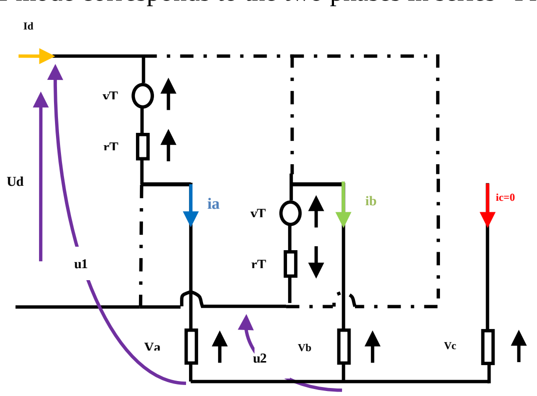


Figure 5. Structure of the BLDC motor when two phases are supplied

This mode is then *ITj* intervals, we assume that the dynamic resistances of the components are identical:

$$r_\tau = r_D = r \qquad (6)$$

In this case the voltage node checks:

$$u_d = u_1 - u_2 \qquad (7)$$

Where u_1 and u_2 are respectively represented the voltage of the neutral point to positive terminal and the voltage of the neutral point to the negative terminal of the continuous bus.

$$\begin{cases} u_1 = V_a + v_T + ri_a \\ u_2 = V_b - v_T + ri_b \end{cases} \qquad (8)$$

By replacing v_a and v_b their respective expression (3) and (4), as i_a=i_d and i_b=-i_d, u_1 and u_2 are givens by:

$$\begin{cases} u_1 = Ri_d + L_c \dfrac{di_d}{dt} + e_a + v_T + ri_d & (9) \\ u_2 = -Ri_d + L_c \dfrac{di_d}{dt} + e_b - v_T - ri_d & (10) \end{cases}$$

Therefore u_d is given by:

$$u_d = 2(R+r)i_d + 2L_c \frac{di_d}{dt} + (e_a - e_b) + 2v_T \qquad (11)$$

For the two phases in series, the FCEM present their party platform in opposition, so we have:

$$-e_b = e_a = E = k_e |\omega_r| \qquad (12)$$

With k_e the coefficient of the FCEM and ω_r the rotation speed of the motor. Finally in this mode dynamics DC1 current id is expressed by:

$$2L_c \frac{di_d}{dt} = u_d - 2(R+r)i_d - 2E - 2v_T \qquad (13)$$

B. DC2 Mode

In this mode, a phase in series with the other two phases in parallel "Fig.5":

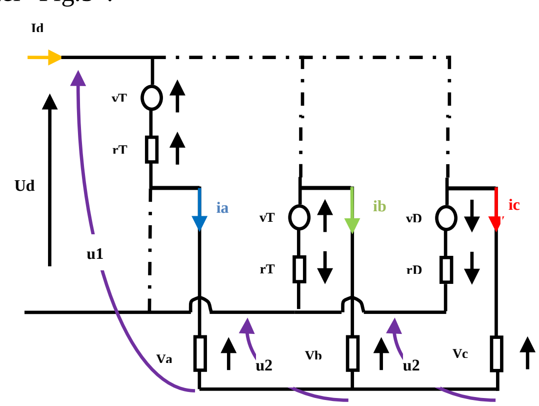


Figure 6. Structure of the BLDC motor when three phases are supplied

In this case the dynamics of the current i_d check in DC2 mode: are given by:

$$3L_c \frac{di_d}{dt} = 2u_d - 3(R+r)i_d - 2E - 3v_T + v_D \qquad (14)$$

V. Fuzzy Type-1 Gain-Adaptive Strategy

Conventional PI controllers are is a generic control loop feedback mechanism (controller) widely used in industrial control systems.

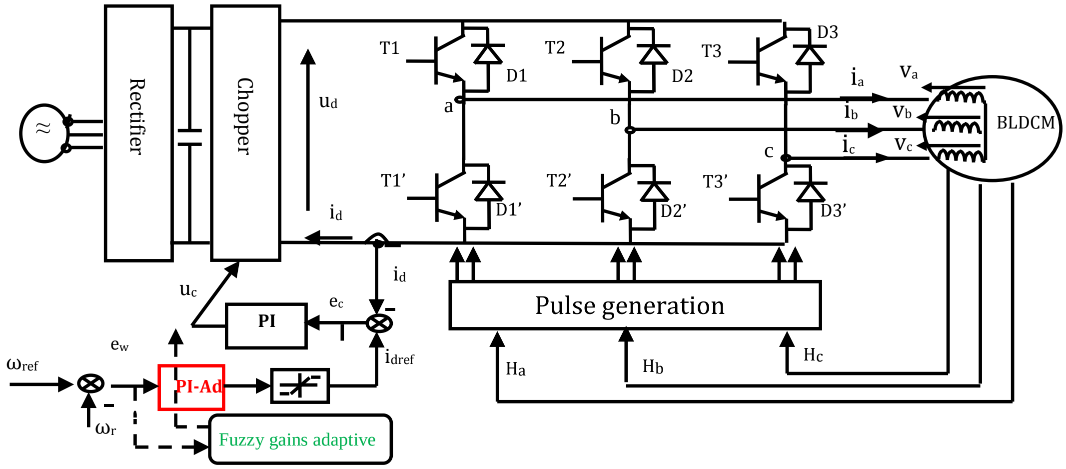


Figure 7. Control scheme for BLDCM using the Fuzzy Type-1 Gain Adaptive PI Controller

They are simple and easy to use due to the fact that they do not need any mathematical model of the controlled process or complicated theories. But one of the main drawbacks of these controllers is that there is no certain way for choosing the control parameters which guarantees the good performance.

Although PI controllers are robust against structural changes and uncertainties in the system parameters, their performance may be affected by such changes or may even lead to system instability. Therefore in real world applications these gains need to be fine-tuned to keep the required performance.

To overcome this shortcoming, Fuzzy Type-1 Gain Adaptive PI Controller is used to tune PI gains online where the tracking error and the change of the tracking error are used to determine control parameters.

The control scheme for BLDCM using the Fuzzy Type-1 Gain-Adaptive controller is presented in Figure 7.

A set of linguistic rules in the form of (15) is used in the Fuzzy Type-1 Gain Adaptive PI Controller structure:

$$if\ e(k)\ is\ A_i\ and\ \Delta e(k)\ is\ B_i\ then\ K_p\ is\ C_i\ and\ K_i\ is\ D_i \quad (15)$$

Where A_i, B_i, C_i and D_i are fuzzy sets corresponding to $e(k)$, $\Delta e(k)$, K_p and K_i respectively. The membership functions for the input are defined with the Gaussian shapes (Figure 8), and the output variables K_p and K_i with the singleton shapes (Figures 9 and 10).

All the fuzzy sets for input and output values are normalized for convenience.

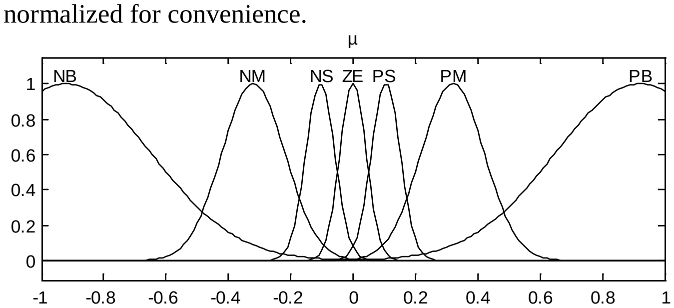


Figure 8. Membership function for $e(k)$ and $\Delta e(k)$ [15]

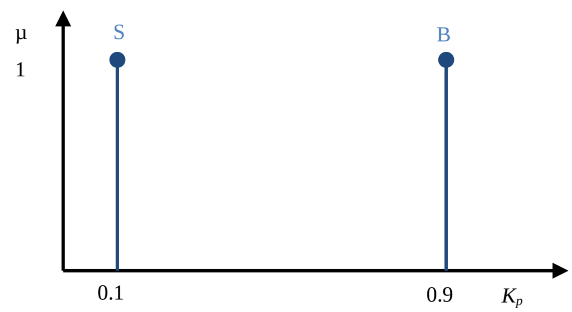


Figure 9. Membership function for gain K_p and K_i [15]

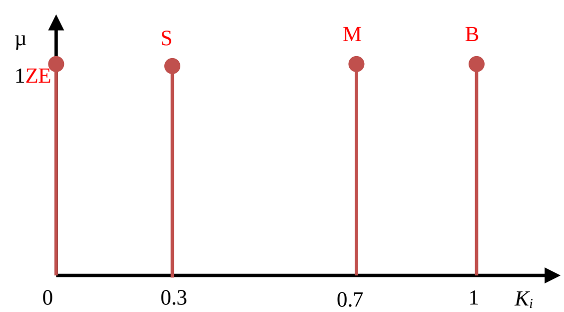


Figure 10. Membership function for gain K_p and K_i [15]

Table 1 and 2 show the linguist rules used in the Fuzzy Gain Adaptive PI Controller. In these tables, N, B, M, represent negative, big and medium for the outputs function and NB, NM, NS, ZE, PS, PM, PB represent negative, big, negative big, medium, negative medium, negative small, zero, positive small, positive medium, and positive big respectively for the inputs function.

In this work, the controller fuzzy rules are gathered in Table 1 and 2.

TABLE 1 FUZZY TUNING RULES FOR K_p [15]

		$\Delta e(k)$						
		NB	NM	NS	ZE	PS	PM	PB
$e(k)$	NB	B	B	B	B	B	B	B
	NM	S	B	B	B	B	B	S
	NS	S	S	B	B	B	S	S
	ZE	S	S	S	B	S	S	S
	PS	S	S	B	B	B	S	S
	PM	S	B	B	B	B	B	S
	PB	B	B	B	B	B	B	B

TABLE 2. FUZZY TUNING RULES FOR K_i [15]

		$\Delta e(k)$						
		NB	NM	NS	ZE	PS	PM	PB
$e(k)$	NB	B	B	B	B	B	B	B
	NM	M	M	B	B	B	M	M
	NS	S	M	M	B	M	M	S
	ZE	ZE	S	M	B	M	S	ZE
	PS	S	M	M	B	M	M	S
	PM	M	M	B	B	B	M	M
	PB	B	B	B	B	B	B	B

The generated surfaces for the Fuzzy Gain Adaptive PI Controller are shown in Figure 11 and 12.

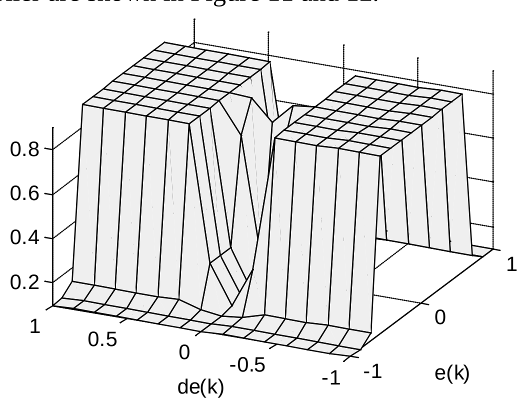


Figure 11. Surface for K_p

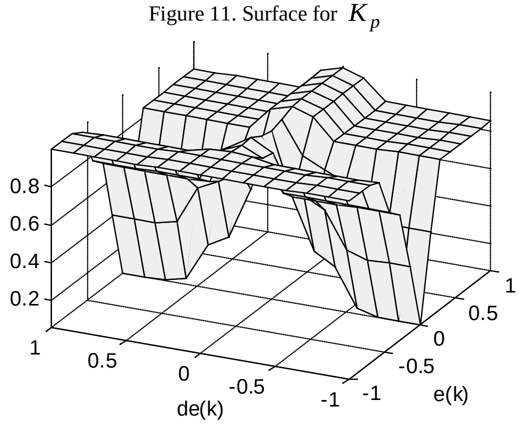


Figure 12. Surface for K_i

VI. SIMULATION RESULTS

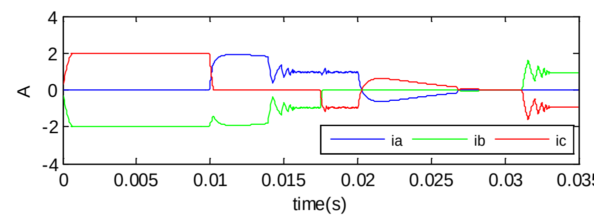
The machine used is characterized by the following:

TABLE 3 PARAMETERS OF BLDC MOTOR [16]

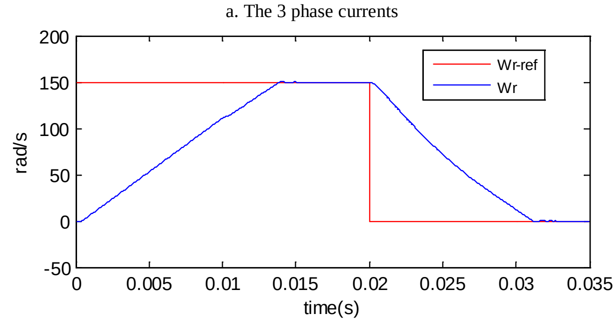
Item	Symbol	Data
resistance of phase	R	4Ω
phase inductance	L_c	0.002H
inertia constant	J	4.65e-6kg.m2
Back-EMF Constant	k_e	26.1e-3V/rd.s-1
coefficient of friction	k_f	1.5e-006N.m/rd.s-1
supply voltage	u_n	24(V)
rated current	I_n	1(A)

The power components are modeled by conduction regime threshold voltages and resistances following dynamics: v_T=0.8 (V),v_D=0.8(V),r_T=0.075Ω, r_D=0.05 Ω.

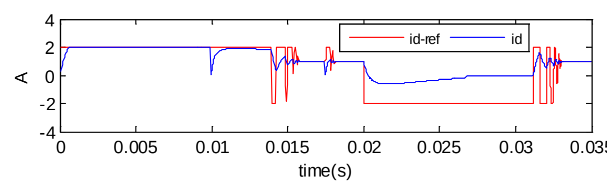
The motor control is based on the cascade structure of Figure 2 and 7; the output I_c of the speed controller *PI-add* and the current setting i_d is made by the regulator *PI* and that provides the signal u_c. The test of control by Fuzzy Gains PI adaptive and PI controllers is performed to a level of speed value *(150rd/s)* for the direct sense during the time interval *[0s, 0.02s]* and then applying a zero reference $\omega_{ref}=0$ in the interval *[0.02s, 0.035s]*. The nominal load torque *0.5N.m* and parametric perturbations are applied throughout the test.



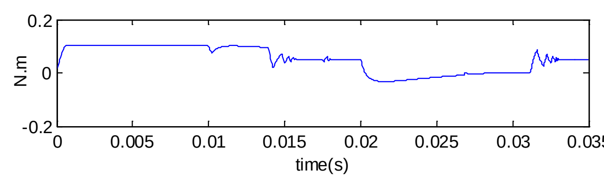
a. The 3 phase currents



b. Form of speed

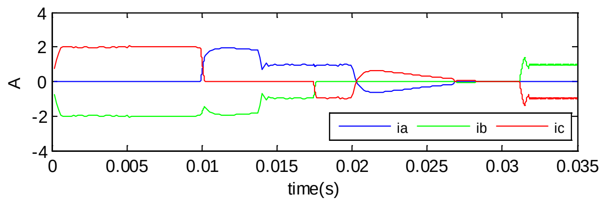


c) Form of the continuous current i_d

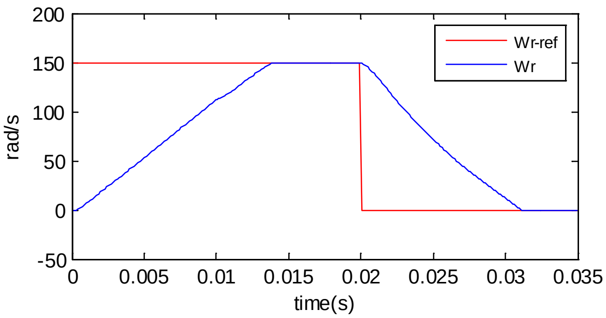


d. The engine torque C_e

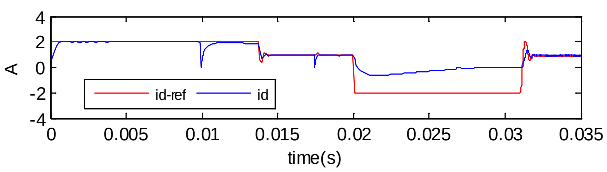
Figure 13. Response of the motor using PI controller



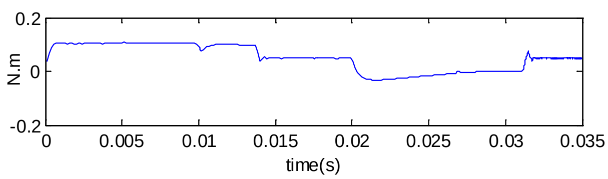
a. The 3 phase currents



b. Form of speed



c) Form of continuous current i_d



d. The engine torque C_e

Fig. 13. Response of the motor using Fuzzy Type-2 Gains PI adaptive controller

Finally, Figure 12 and 13 show the simulation results of the proposed method with error of *0.0140 rd/s* for PI controller and *0.0144 rd/s* for Fuzzy Type-1 Gain-Adaptive controller. We note that I_{ref} is saturated to the value *2(A)* until the speed is away from the reference value. Then when ω_r achieved static value adjustment, the value I_{ref} is necessary to compensate the load torque. During operation mode of the motor I_d is positive *(t=0s to t=0.02s)*, it follows strong reference I_{ref} . In braking mode where the current *id* is negative either *(t = 0.02 at t = 0.035)*, the current *id* does not reference I_{ref} because of the low kinetic energy of the machine.

VII. Conclusion

In this paper, the speed regulation of BLDCM with two controllers, traditional PI and Fuzzy Gain Adaptive PI controllers has been designed and simulated. To do this, we have established the dynamic model of the DC input of the switch. The comparative study shows that the Fuzzy Gain Adaptive IP controller can be improve the performances of speed of the BLDCM control. The simulation results have confirmed the efficiency of the Fuzzy Gain Adaptive PI controller for different working conditions.

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