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ATTESTATION

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Izzeddine DILMI LGE Research Laboratory Department of Electrical Engineering, Faculty of Technology, University of Msila, BP 166 Ichbilia 28000, Algeria
Abderrahmane BOUGUERRA LGE Research Laboratory Department of Electrical Engineering, Faculty of Technology, University of Msila, BP 166 Ichbilia 28000, Algeria
Ali DJRIOUI LGE Research Laboratory Department of Electrical Engineering, Faculty of Technology, University of Msila, BP 166 Ichbilia 28000, Algeria

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An FTC-Adaptive Indirect Control of a Brushless DC Motor

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An FTC-Adaptive Indirect Control of a Brushless DC Motor

IzzeddineDilmi
LGE Research Laboratory Department of Electrical Engineering, Faculty of Technology, University of Msila, BP 166 Ichbilia 28000, Algeria
izzeddine.dilmi @univ-msila.dz

AbderrahmenBouguerra
LGE Research Laboratory Department of Electrical Engineering, Faculty of Technology, University of Msila, BP 166 Ichbilia 28000, Algeria
abderrahmen.bouguerra@univ-msila.dz

Ali Djrioui
LGE Research Laboratory Department of Electrical Engineering, Faculty of Technology, University of Msila, BP 166 Ichbilia 28000, Algeria
ali.djerioui@univ-msila.dz

***Abstract*—This paper addresses a passive Fault Tolerant Control (FTC) of a Brushless DC Motor (BLDC Motor) using an adaptative indirect control. The main idea of the proposed method in this article is to modify the classic controller of BLDC by superposing an appropriate compensation signal to offset the effect of a fault. To facilitate the procedures for setting and controlling the current, we establish a dynamic model for direct current. We introduced a fault to test the robustness of the control laws. The both of theoretical analysis and simulation are presented in order to validate the proposed compensation. Comparing with a Classic PI control, the proposed Adaptative indirect control can achieve favorable tracking performance.**

Keywords*— Brushless DC motor, Fault tolerant control (FTC), Adaptative indirect control, Direct current mode

I. INTRODUCTION

The necessity of more powerful actuators in small sizes in industrial application. The BLDC motors were gradually replacing DC motors and to solve the problem related with contacts and gives improved reliability and improves life, we need to elimination of brushes and commutators. The BLDC motor has the low inertia, high efficiently, high power factor, high torque, lower maintenance and low noise [1] [2].
In general, the BLDC motor is powered through a three-phase inverter transistor that acts as the electronic switch of the phase current, The torque control is then reached at the current control [3]. the directly control of the current is easier than the control of the phase currents required since the reconstitution of these currents .In most cases, a current-controlled voltage inverter is used. As the motor torque is proportional to the DC input of the switch, the interest is the influencing to the current forme in order to optimize the torque and minimize the current [4].

The Backstepping method is a recursive procedure using Lyapunov's theory in the search for the control law with the guaranteed stability. In the Backstepping technique, it is a question of choosing a function of the state as being the entry of a subsystem and of proceeding in the same way recursively until obtaining the command to apply the global system [5], a nonlinear speed controller for an induction motor has been designed based on an adaptive Backstepping approach [6].

On the other hand, in the fields of fault tolerance control (FTC) design, by new Backstepping approaches based on theoretical development. From these works [7] [8]. In general, FTC approaches can be classified into two types: the active and the passive approach's as presented in this article. In the book [9] making a state of the art in the field of FTC, a comparative study between the two main approaches and the advanced work was presented in [10] [11].

The reminder of this paper is presented as follows. A description of the studied system is presented in section I. The Section II develops the dynamic model. The section III is devoted to the passive FTC control based on Backstepping approach. Finally, the simulation results to demonstrate the robustness of the proposed approach is presented in Section IV.

II. MODELINGAND ANALYSISOF BLDC MOTOR

A. Equations of Electrical and Mechanical of bldc Motor

The model simplified of the BLDC Motor is shown in Fig. 1:

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:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_0 & M & M \\ M & L_0 & M \\ M & M & L_0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

where

$$Mi_a + Mi_b = -Mi_c \quad (2)$$

Substituting Equation (2) into (1), the voltage equation of the BLDC motor can be simplified as follows:

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (3)$$

Where v_a, v_a and v_c are the phases voltages of the BLDC Motor; i_a, i_a and i_c are the phases currents; R is the resistance and L is the inductance of the machine which L=L_0-M ; e_a, e_a and e_c are the electromotive forces of the phases.

The electric torque is given by:

$$C_e = \frac{(e_a i_a + e_b i_b + e_c i_c)}{\omega_r} \quad (4)$$

Where C_e is the electromagnetic torque and ω_r is the angular velocity.

The law of meshes is applied to obtain the equations of currents in the three phases [12].

• Sub-interval 1: the main current i_d flows in the two excited phases through the two transistors turned on, a circular current flow in the third phase through of the two transistors and the diode of the free wheel.

• Sub-interval 2: the current i_d flows in the two excited phases, the diode is blocked, and the current vanishes in the third phase.

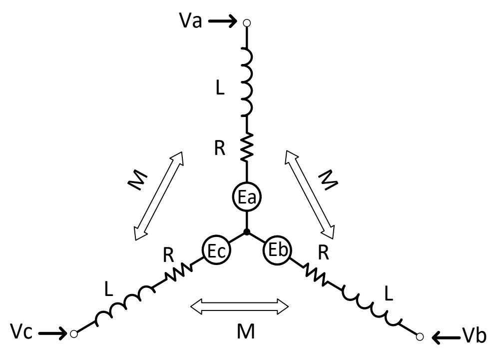


Fig. 1. The model simplified of the BLDC

B. *Modeling of the BLDCMotor*

Fig.2 show the schematic 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 [11].

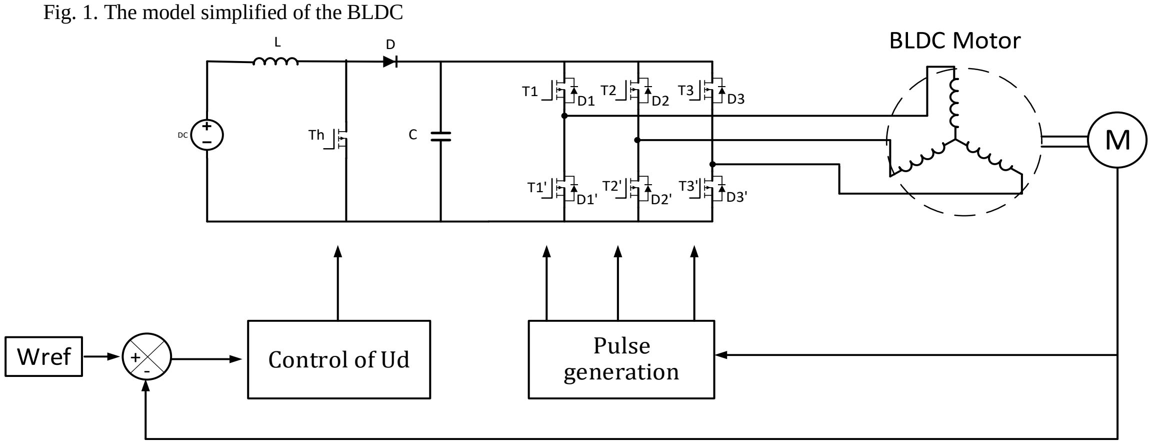


Fig. 2. Block diagram for controlling the BLDC motor

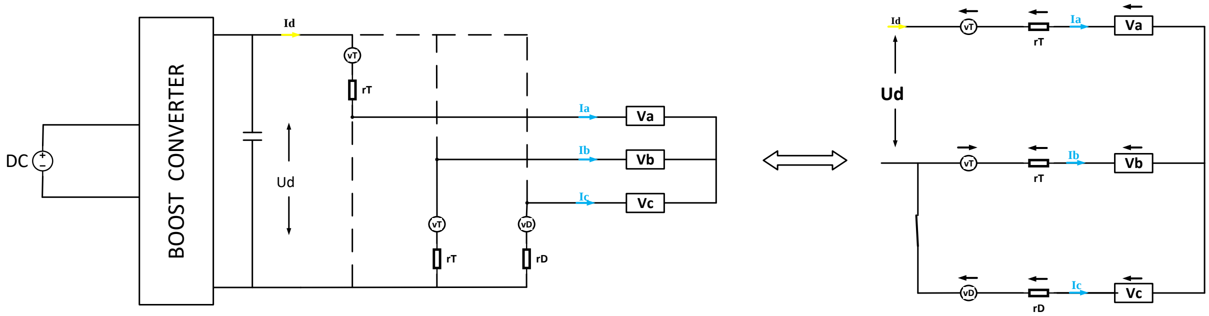


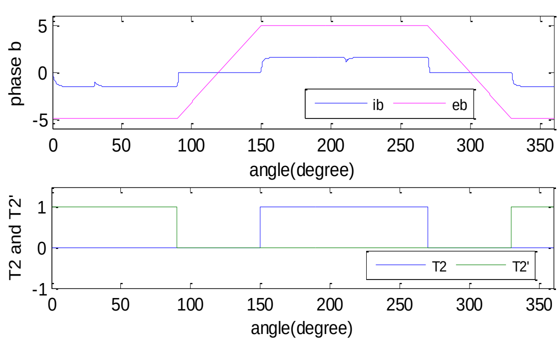
Fig. 3. Equivalent diagram of the motor-switch assembly.

This model can be written as follows:

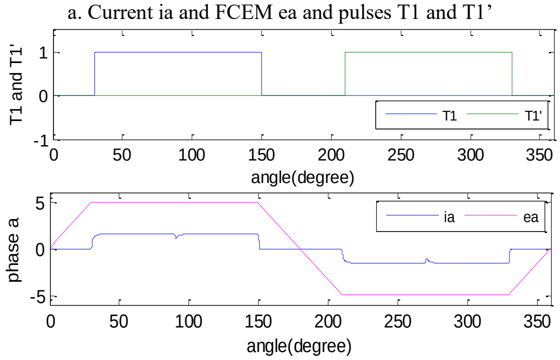
$$\begin{cases} V_a = Ri_a + L_c \dfrac{di_a}{dt} + e_a & (5.a) \\ V_b = Ri_b + L_c \dfrac{di_b}{dt} + e_b & (5.b) \\ V_c = Ri_c + L_c \dfrac{di_c}{dt} + e_c & (5.c) \end{cases}$$

Depending on the position of the inductor, the current i_d is switched in phase at the time the trapezoidal FCEM in this phase Fig. 3.

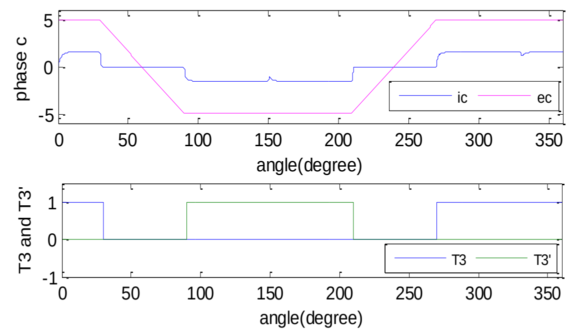
- The model of the machine is generally established in a landmark three-phase (*a*, *b*, *c*) related to the stator due to the trapezoidal shape of the FCEM. For a symmetrical machine winding connected in star and whose permanent magnets are mounted on the surface [11].



a. Current ia and FCEM ea and pulses T1 and T1'



b. Current ib and FCEM eb and pulses T2 and T2'



c. Current ic and FCEM ec and pulses T3 and T3'

Fig. 4. Control pulses of transistors for the direct sense.

From the signals of the Hall sensors, the sequence is generated by choosing a sequence of notice pulses of transistors well defined Fig. 5, 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'*.

The sequences supply of the BLDC motor are shown in Table.1

Table 1 sequences supply of the BLDC Motor

Sequences supply		The components in conduction
1	π/6→π/2	T1, T2' and D3'
2	π/2→5π/6	T1, T3' and D2
3	5π/6→7π/6	T2, T3' and D1'
4	7π/6→3π/2	T2, T1' and D3
5	3π/2→11π/6	T3, T1' and D2'
6	11π/6→2π & 0→π/6	T3, T2' and D1

C. Continuous Model of BLDC Motor

Is characterized by two distinct modes:

1) DC1 Mode

DC1 mode corresponds to the two phases in series "Fig.6":

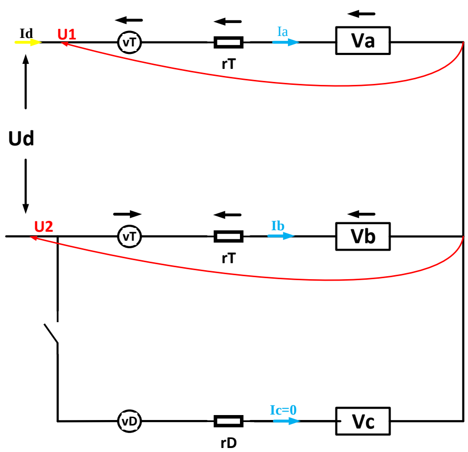


Fig. 5. Structure of the BLDC motor when two phases are supplied

In this mode dynamics DC1 current id is expressed by:

$$2L_c\frac{di_d}{dt}=u_d-2\left(R+r\right)i_d-2E-2v_T \qquad (6)$$

2) DC2 Mode

In this mode, a phase in series with the other two phases in parallel "Fig.7":

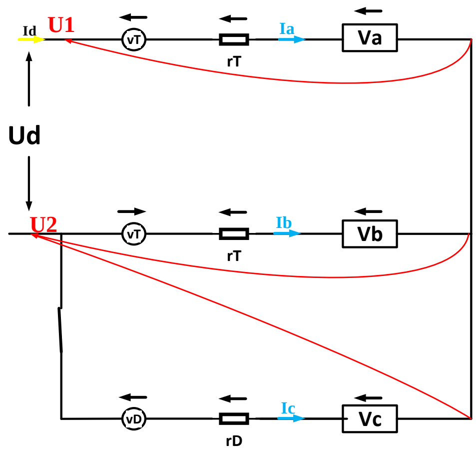


Fig. 6. Structure of the BLDC motor when three phases are supplied

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

$$3L_c\frac{di_d}{dt}=2u_d-3\left(R+r\right)i_d-2E-3v_T+v_D \qquad (7)$$

III. Backstepping Control of The BLDC Motor

Recently, a Backstepping control is developed control method for nonlinear system. The Backstepping technique is featured by the final controller as well as the laws can be derived systematically step by step. Which is shown in the following procedures [13].

A. Control objective

The main objective of the FTC control is to provide a speed regulator for the BLDC motor so that the mechanical speed satisfactorily follows the reference signals [14].

B. Nonlinear backstepping controller design

In this work we design systematically a nonlinear Backstepping speed controller based on suitable Lyapunov function.

The form of the system can be written as follows:

$$\dot{x}=f\times x+g\times U \qquad (8)$$

where

$$x=\begin{bmatrix}\omega & i_d\end{bmatrix},\quad f=\begin{bmatrix}\frac{1}{j}(-f_d\omega-C_r+k_vi_d\\ \frac{1}{j}(2v_t-E'R'i_d)\end{bmatrix},\ g=\begin{bmatrix}0\\1\end{bmatrix}$$

and

$U=u_d$

We define the new variable as follows:

$z_1=\omega$

$z_2=i_d$

The state-space equations of system can be written as:

$$\begin{bmatrix}\dot{z}_1\\ \dot{z}_2\end{bmatrix}=\begin{bmatrix}\frac{1}{j}(-f_dz_1-C_r+k_vz_2\\ \frac{1}{L'}(2v_t-E'R'z_2)\end{bmatrix}+\begin{bmatrix}0\\1\end{bmatrix}\times U \qquad (9)$$

Step 1 :

Stabilization of $\mathbf{z}_1$ to $z_{1\mathbf{d}}$

so

$$e=z_1-z_{1\mathbf{d}} \qquad (10)$$

where

$$\dot{e}=\dot{z}_1-\dot{z}_{1\mathbf{d}} \qquad (11)$$

$$V\left(e\right)=\frac{1}{2}e^2 \qquad (12)$$

$$\dot{V}\left(e\right)=e\dot{e} \qquad (13)$$

then

$$\dot{V}\left(e\right)=e\underbrace{\left(\frac{1}{j}\left(-f_dz_1-C_r+k_vz_2\right)-\dot{z}_{1d}\right)}_{-\alpha_1e} \qquad (14)$$

$$\frac{1}{j}\left(-f_dz_1-C_r+k_vz_2\right)-\dot{z}_{1\mathbf{d}}=-\alpha_1e \qquad (15)$$

and we put $\frac{1}{j}\left(-C_r+k_vz_2\right)$ as a virtual control

so we have

$$\frac{1}{j}\left(-C_r + k_v z_2\right) = \frac{1}{j} f_d z_1 + \dot{z}_{\mathbf{1d}} - \alpha_1 e \qquad (16)$$

and

$$e_1 = \frac{1}{j}\left(-f_d z_1 - C_r + k_v z_2\right) - \dot{z}_{\mathbf{1d}} + \alpha_1 e \qquad (17)$$

Step 2 :

$$V\left(e, e_1\right) = \frac{1}{2} e^2 + \frac{1}{2} e_1^2 \qquad (18)$$

$$\dot{V}\left(e, e_1\right) = e\dot{e} + e_1 \dot{e}_1 \qquad (19)$$

$$U = \frac{j}{\alpha_1}\left(\left(\alpha_1 - \frac{f_d}{j}\right)\dot{z}_1 + \frac{k_v}{j}\dot{z}_2 + \alpha_2 e_1 - \ddot{z}_{\mathbf{1d}}\right) + 2v_t - E'R'z_2 \qquad (20)$$

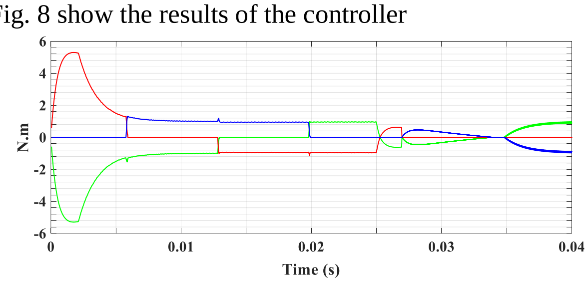
Results and discussion

In this section, simulations results are presented to illustrate the performance and robustness of proposed control law when applied to the BLDC Motor. The parameters values of the motor as shown in Table. 2 [15].

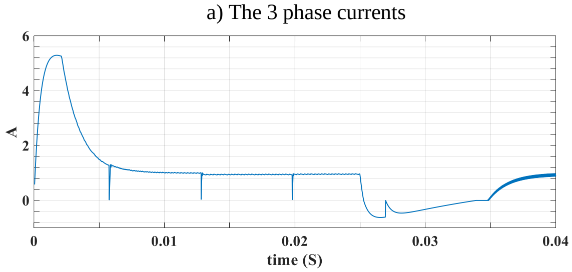
Table 2: BLDC Motor Parameters

Item	Symbol	Data
resistance of phase	R	4Ω
phase inductance	Lc	0.002H
inertia constant	J	4.65e-6kg.m2
Back-EMF Constant	ke	26.1e-3V/rd.s-1
coefficient of friction	kf	1.5e-006N.m/rd.s-1
supply voltage	un	48(V)
rated current	In	2(A)

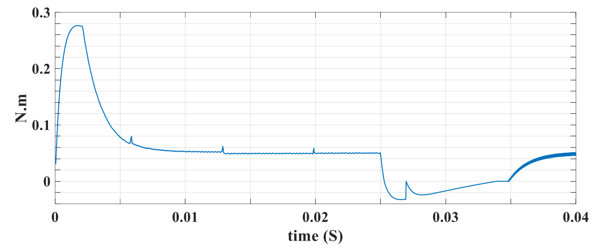
Fig. 8 show the results of the controller



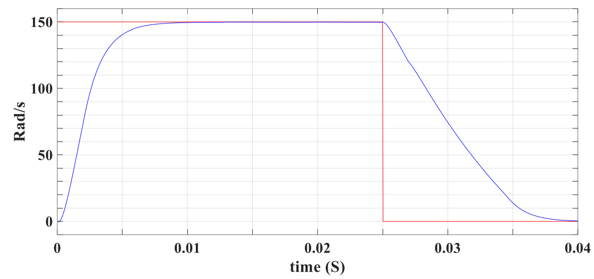
a) The 3 phase currents



b) Form of continuous current id



c) The engine torque Ce



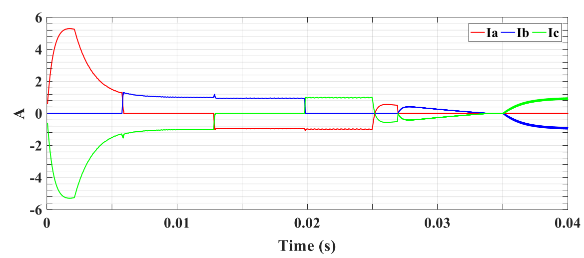
d) Form of speed

Fig. 7. Response of the motor using Backstepping controller

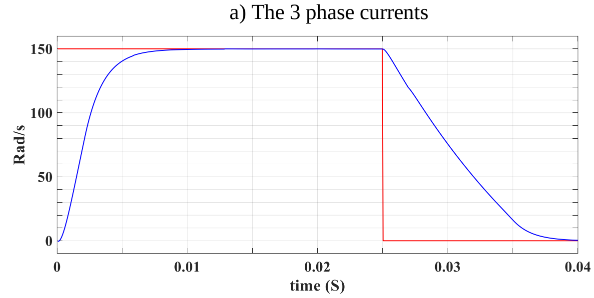
1) A robustness test :

Test 1:

At time t = 0.015 s a robustness test is carried out where an external additive defect represented by a perturbation which is a 20% increase in the resistance phase, a 30% reduction in the cyclic inductance, 10% of the excitation flux and The nominal load torque 0.055 N.m The results are shown in Fig. 7.



a) The 3 phase currents

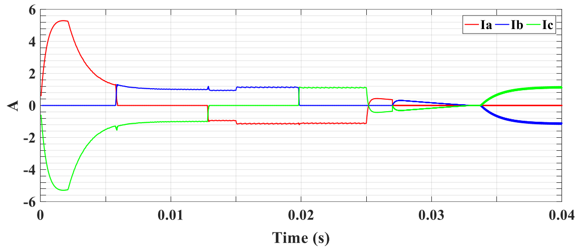


b) Form of speed

Fig. 8. Response of the motor using Backstepping controller under the parametric variation

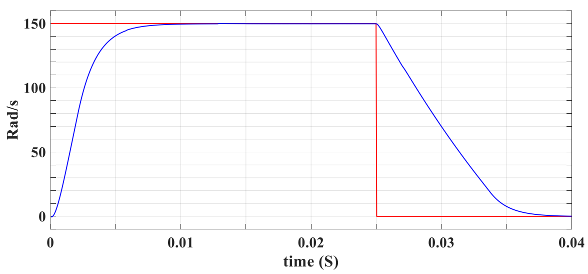
Test 2:

the second test represented by a 40% increase in the resistance phase, a 40% reduction in the cyclic inductance, 20% of the excitation flux and The nominal load torque 0.065during the time interval [0.015s, 0.04s].The results are shown in Fig. 8.



a)

The 3 phase currents



b) Form of speed

Fig. 9. Response of the motor using Backstepping controller under the parametric variation

	Adaptive indirect	PI
Test1	8.6325e-05	0.1825
Test2	7.6986e-05	0.2479

2) *Result discussion*

- After the test, the speed remains practically insensitive to the perturbation.
- BLDC motor speed control testing shows that Backstepping control provides good performance even in the presence of an external fault.

IV. CONCLUSION

This paper presents a method of Backstepping based fault tolerant control scheme for BLDC motor with parameter variations faults. To achieve our goal a continuous mathematical model of BLDC motor was presented. Based on this model, we synthesized the Backstepping control of the BLDC Motor. The obtained simulation results illustrate the good performance of the proposed method in the case of the fault (parameter variations) for tow scenario. This work allowed us to conclude that the Backstepping method can tolerate some important faults such as: variation of parameter and the variation of reference.

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