Ministry of Higher Education and Scientific Research
University of Bouira, Algeria
Faculty of Sciences and Applied Sciences
Department of Electrical Engineering

وزارة التعليم العالـي والبحث العلمي
جـــامعة البويـــرة
كـلية العلوم والعلوم التطبيقية
قـــسم الهندسة الكهربائية

International Conference on Electronics and Electrical Engineering (IC3E'2020)

UAMOB

2nd International Conference on Electronics and Electrical Engineering (IC3E'2020)
November 16, 2020, University of Bouira, ALGERIA

Ref : IC3E2020_paper_069

Certificate of Participation

This is to certify that the paper entitled:

" Fault Tolerant Control of a Brushless DC Motor based on Backstepping controller "

Authors: Izzeddine DILMI, Abderrahmen BOUGUERRA, Ali DJRIOUI and Larbi CHRIFI-ALAOUI

*Has been presented **(via vision-conference)** in the 2nd **International Conference on Electronics and Electrical Engineering (IC3E'2020)** held at the University of Bouira, Algeria, during **November 16, 2020**.*

General Chair
Dr. Mouloud AYAD

Dean of the Faculty

عميد كلية العلوم و العلوم التطبيقية
بالنيابة
أ. عمـاد مـراد

General Chair
Dr. Kamel SAOUDI

Fault Tolerant Control of Brushless DC Motor based on Backstepping control

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

Abderrahmen Bouguerra
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

Larbi Chrifi-Alaoui
Laboratory of Innovative Technology
University of Picardie Jules Verne, 02880 Cuffies, France

larbi.alaoui@u-picardie.fr

***Abstract*— This paper addresses the Fault Tolerant Control (FTC) passive of BLDCM (Brushless DC Machine) based on Backstepping control. The main idea of the proposed method is to modify a conventional BLDC controller 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 faults to test the robustness of the control laws. A theoretical analysis is presented, and both simulation is presented in order to validate the proposed compensation . The proposed FTC-Backstepping control can achieve favorable tracking performance.**

Keywords*— Brushless DC motor, Fault tolerant control (FTC), Backstepping 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 associated with contacts and gives improved reliability and enhances 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 machine 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 design recursively selects some appropriate functions of state variables as pseudo control inputs for lower dimension subsystems of the overall system [8]. The most appealing point of it is to use the virtual control variable to make the original high order system to be simple enough thus the final control outputs can be derived step by step through suitable Lyapunov functions. A nonlinear velocity controller for an induction motor was designed based on adaptive backstepping approach, in which over parameterization may occur[9].

On the other hand, in the control design and fault tolerance domains, the reappears to very little new theoretical development based backstepping approach. Starting from those works [12] [13]. In general, the FTC approaches can be classified into two types: the active approach and the passive approach as presented in this paper. The survey book [14] reviews the concepts and the state of the art in the field of FTCs, comparative study between these two approaches and the recent advances have been reported in [15] [16].

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 FTC passive control based on Backstepping approach. Finally, the simulation results to demonstrate the robustness of the proposed approach is presented in Section IV.

II. MODELING AND ANALYSIS OF BLDC MACHINE

A. Equations of Electrical and Mechanical of bldc Machine

The model simplified of the BLDC Machine 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 Machine ; 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 [5].

• 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 a of the two transistors and the diode of the freewheel.

• 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.

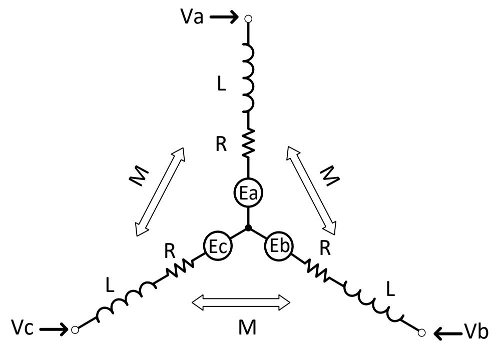


Fig1.The model simplified of the BLDC

B. *Modeling of the BLDC Machine*

Fig.2 show the schematic diagram for controlling the BLDC Machine.

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 [16].

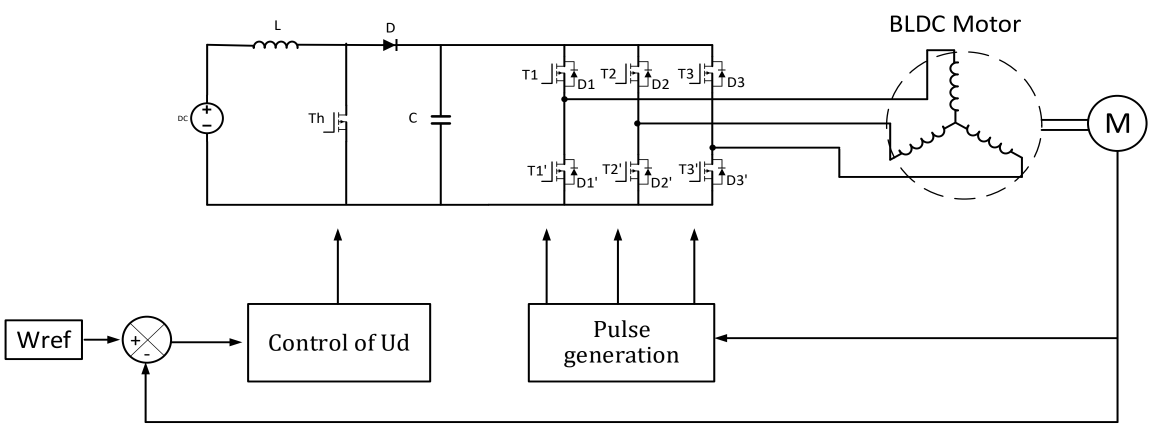


Fig.2 : Block diagram for controlling the BLDC motor

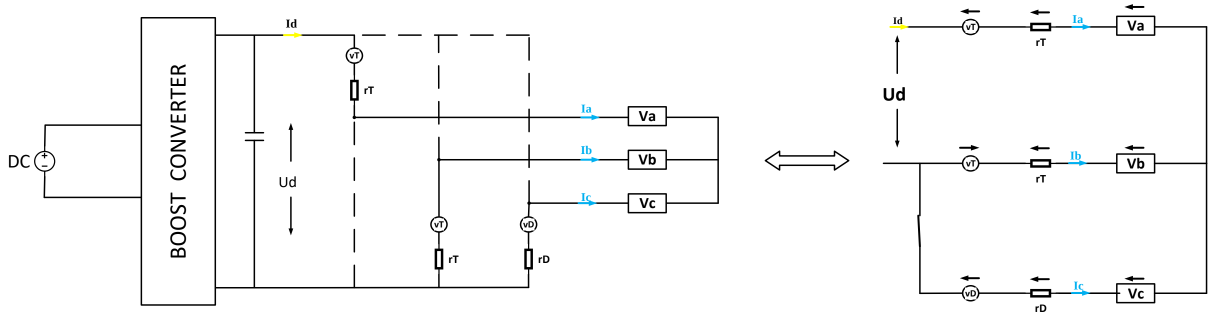


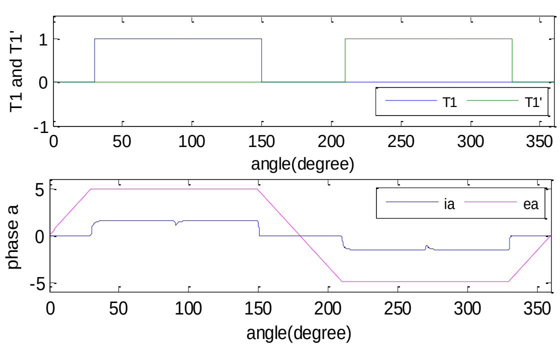
Fig. 3: Equivalent diagram of the motor-switch assembly.

This model can be written as follows:

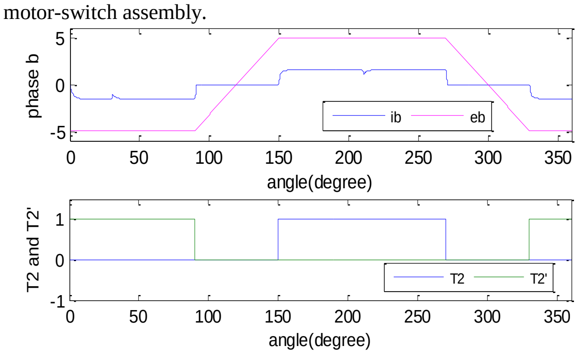
$$\begin{cases} V_a = Ri_a + L_c \dfrac{di_a}{dt} + e_a & (5.a) \\ V_b = Ri_b + L_c \dfrac{di_b}{dt} + e_b & (5.b) \\ V_c = Ri_c + L_c \dfrac{di_c}{dt} + e_c & (5.c) \end{cases}$$

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.

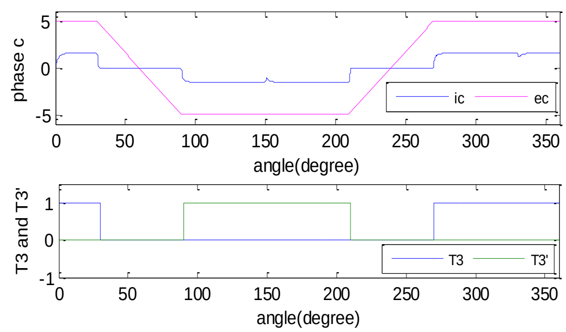
- The model of the machine is generally established in a landmark three-phase (*a*, *b*, *c*) related to the stator due to the trapezoidal shape of the FCEM. For a symmetrical machine winding connected in star and whose permanent magnets are mounted on the surface [16].



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



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



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'*.

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":

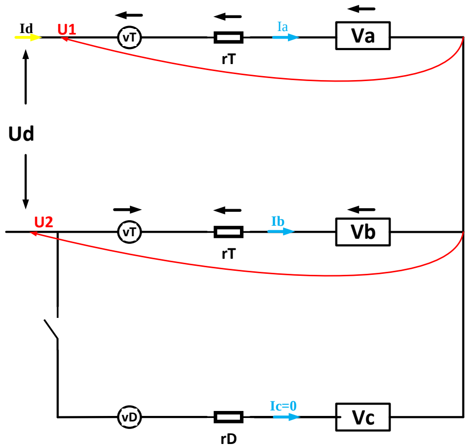


Fig.5 : Structure of the BLDC motor when two phases are supplied

in this mode dynamics DC1 current id is expressed by:

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

2) *DC2 Mode*

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

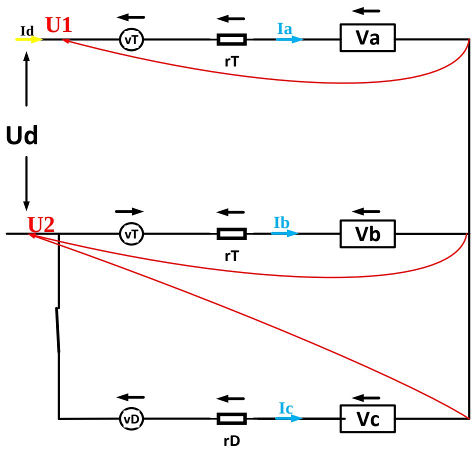


Fig.6: Structure of the BLDC motor when three phases are supplied

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

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

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[17].

A. *Control objective*

The control objective is to design a asymptotically stable speed controller for the BLDC motor to make the mechanical speed follow the reference signals satisfactorily [18].

B. *Nonlinear backstepping controller design*

in this work we design systematically a nonlinear backstepping speed controller based on suitable Lyapunov function and adaptation laws .

The compact form of the system can be written as follows:

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

where

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

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:

$$\begin{bmatrix} \dot{z}_1 \\ \dot{z}_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{j}(-f_d z_1 - C_r + k_v z_2 \\ \frac{1}{L'}(2v_t - E'R'z_2) \end{bmatrix} + \begin{bmatrix} 0 \\ 1 \end{bmatrix} \times U \qquad (9)$$

Step 1 :

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

so

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

where

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

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

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

then

$$\dot{V}(e) = e\underbrace{\left(\frac{1}{j}(-f_d z_1 - C_r + k_v z_2) - \dot{z}_{1d}\right)}_{-\alpha_1 e} \qquad (14)$$

$$\frac{1}{j}(-f_d z_1 - C_r + k_v z_2) - \dot{z}_{\mathbf{1d}} = -\alpha_1 e \qquad (15)$$

and we put $\frac{1}{j}(-C_r + k_v z_2)$ as a virtual control

so we have

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

and

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

Step 2 :

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

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

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

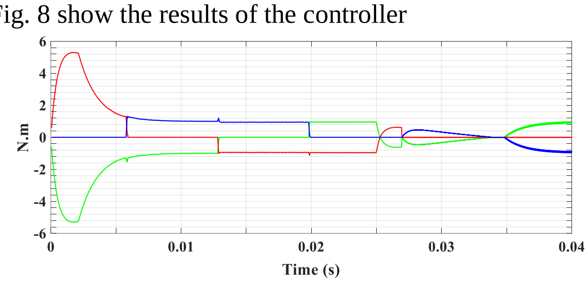
Results and discussion

In this section, simulations results are presented to illustrate the performance and robustness of proposed control law when applied to the BLDC MACHINE . The parameters values of the motor as shown in Tab. 1.

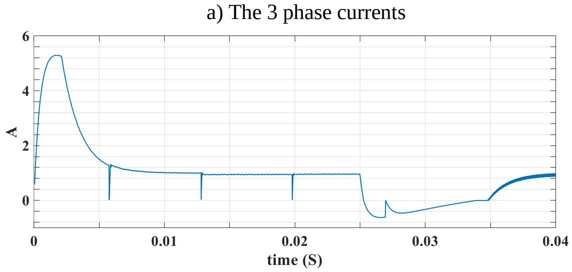
Table 1: BLDC Motor Parameters

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)

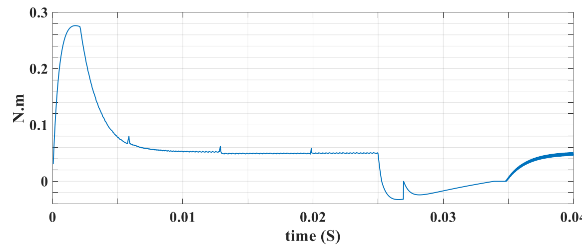
Fig. 8 show the results of the controller



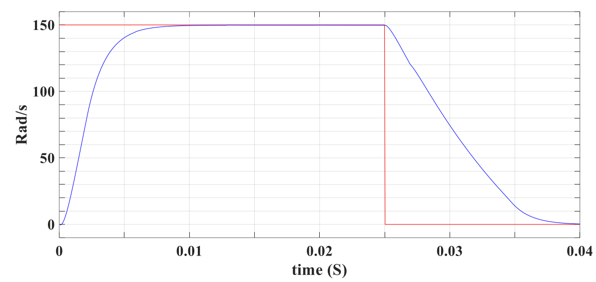
a) The 3 phase currents



b) Form of continuous current id



c) The engine torque Ce



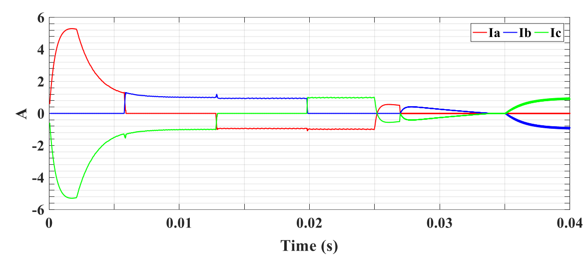
d) Form of speed

Fig. 7: Response of the motor using Backstepping controller

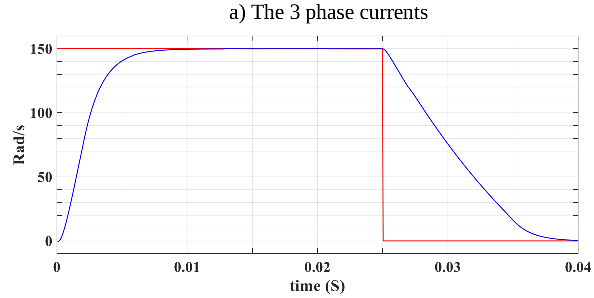
1) A robustness test :

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

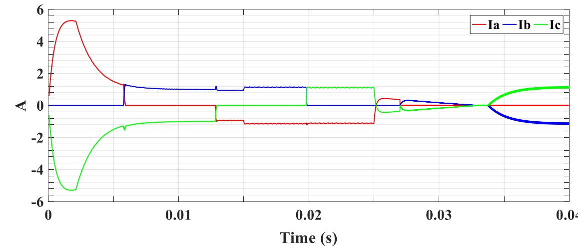


b) Form of speed

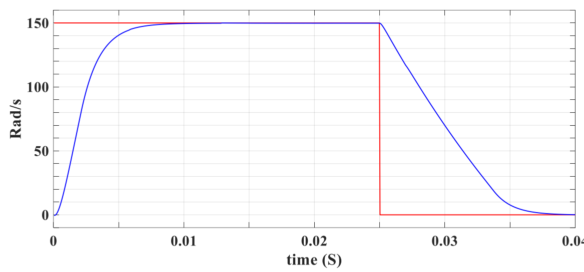
Fig.8: Response of the motor using Backstepping controller under the parametric variation

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

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 systems 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 MACHINE . 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.

REFERENCES

[1] T. J. E Miller, "Brushless Permanent-Magnet and Reluctance Motor Drives", Clarendon Press, Oxford 1989.

[2] K. Ohishi, M. Nakao, K. Ohnishi and K. Miyachi, "Microprocessor-Controlled DC Motor for Load-Insensitive Position Servo System", IEEE Trans. Ind. Electron., Vol. 34, No. 1, 1987, pp. 44-49.

[3] Y. Dal, Ohm and J. H. Park, "About commutation and current control Methods for brushless motors", 29th annual IMCSD symposium, San Jose 1999.

[4] K. Ang, G. Chong, and Y. Li, "PID control system analysis, design, and technology", IEEE Trans. Control System Technology, Vol. 13, No. 4, July 2005, pp. 559-576.

[5] K. D. Young, V. I. Utkin, and Ü. Özgüner, "A control engineer's guide to sliding mode control", IEEE Trans. Control Sys. Tech., Vol. 7, No. 3, 1999, pp. 328-342.

[6] S. V. Drakunov and V. I. Utkin, "Sliding mode control in dynamic systems", Int. J. Control, Vol. 55, No. 4, 1992, pp. 1029-1037.

[7] F. Barrero, A. Gonzalez, A. Torralba, E. Galvan and L. G. Franquelo, "Speed control of induction motors using a novel fuzzy sliding-mode structure", IEEE Trans. on Fuzzy Systems, Vol. 10, No. 3, 2002, pp. 375-383.

[8] Krstic, M., Kanellakopoulos, I., & Kokotovic, P. (1995).Nonlinear and adaptive control design. New York: Wiley.

[9] Shieh, H. J., & Shyu, K. K. (1999). Nonlinear sliding-mode torque control with adaptive backstepping approach for induction motor drive.IEEE Transactions on Industrial Electronics, 46(2), 380–389.

[10] O. Barambones, A. J. Garrido, F. J. Maseda and P. Alkorta, "An adaptive sliding mode control law for induction motors using field oriented control theory", IEEE Conference on Computer Aided Control System Design, Munich, Germany, 4-6 Oct. 2006, pp. 1008-1013.

[11] A. Tahour, H. Abid, A. G. Aissaoui, "Speed Control of Switched Reluctance Motor Using Fuzzy Sliding Mode", Advances in Electrical and Computer Engineering, 2008, Vol. 8 (15), No. 1 (29), pp. 21-25.

[12] ZHANG, Duo, LIU, Guohai, ZHOU, Huawei, et al. Adaptive sliding mode fault-tolerant coordination control for four-wheel independently driven electric vehicles. IEEE Transactions on Industrial Electronics, 2018, vol. 65, no 11, p. 9090-9100.

[13] BA, Dang Xuan, YEOM, Hoyeon, KIM, Jihoon, et al. Gain-adaptive robust backstepping position control of a BLDC motor system. IEEE/ASME Transactions on Mechatronics, 2018, vol. 23, no 5, p. 2470-2481.

[14] M. Prashant, L. Jinfeng and D. C. Panagiotis, "Fault-tolerant process control methods and applications", London: Springer-Verlag; 2013.

[15] Y. M. Zhang, J. Jiang, "Bibliographic review on reconfigurable fault-tolerant control systems", Annu. Rev. Control, Vol. 32, No. 2, 2008, pp. 229-52.

[16] H. Mekki, O. Benzineb, D. Boukhetala, M. Tadjine and M. Benbouzid, "Sliding mode based fault detection, reconstruction and fault tolerant control scheme for motor systems", ISA Transactions, Vol. 57, July 2015, pp. 340-351.

[17] ZHOU, Jianguo et WANG, Youyi. Real-time nonlinear adaptive backstepping speed control for a PM synchronous motor. Control Engineering Practice, 2005, vol. 13, no 10, p. 1259-1269.

[18] Krause, P. C. (1995).Analysis of electric machinery(2nd ed.). NewYork: McGraw-Hill.