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Research paper

Fuzzy hysteresis current control of five phase permanent magnet motor under open-circuit faults

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Abstract

This paper presents a new current controller of a PWM of multiphase PM machines with a fuzzy logic band. With this kind of system it is possible to determine optimal currents references which maximize the torque density of the system when one or two phases are open circuited. We propose in this paper to combine this optimal reference current generation with fuzzy hysteresis control band. This solution allows a good tracking of these unconventional reference currents with a fixed switching frequency for the VSI. The study carried on simulation via software MatLab/Simulink.

Keywords: *Current References; Fault Tolerant Control; Fuzzy Logic Control; Multi-Phase Machine.*

1. Introduction

The use of permanent magnet synchronous machines with a large number of phases supplied by PWM voltage inverters is particularly suitable for demanding specifications in terms of operating safety and / or acoustic discretion and / or high power. Indeed, the multiplication of the number of phases makes it possible, on the one hand, to divide the current and thus to reduce the stresses on the components, but also on the other hand the reduction of the torque ripples and the operation in degraded mode (of one or more phases in default). As a result, these technologies are particularly suited to contexts such as naval propulsion or the automobile. Advances in the field of power electronics and control ensure robust controls of these machines regardless of their mode of operation. Various works have been carried out on multiphase machine powered by voltage inverters [1 - 4]. Some of these studies are based on the decomposition of the multiphase machine into equivalent fictitious machines which are magnetically decoupled [4]. In degraded mode, different methods were presented in [2], [4], [5] to suppress the torque ripple generated by the disconnection of one or more phases of a multiphase machine, based on the change of the current form of one or more active phases of the machine. For a classical structure consisting of a q arm inverter, some authors propose to add an additional arm to control the neutral current [5]. For a single-phase inverter power supply structure, some authors propose to modify the amplitude of the currents in the active phases [6], [7]. However, if the machine operates in the event of a fault (open circuit fault), the torque ripples appear with this conventional control. These undulations are related to the interaction between the asymmetric current system and a symmetric system of electromotive forces. To filter these torque ripples, a generation of adaptive current references is described in this article. In this work, after presenting the theory of multi-machine modelling of multiphase machines, we will focus on the determination of optimal form reference currents in normal and degraded mode, minimizing torque ripple and Joule losses. These optimal references make it possible to minimize torque ripples and Joule losses.

Classical linear controllers (as PID for example) cannot provide a correct tracking of these optimal reference currents because they have a highly dynamical behavior. We propose in this paper to combine this optimal reference current generation with fuzzy hysteresis control band. This kind of solution allows a good tracking of these unconventional reference currents with a fixed switching frequency for the VSI. In the last section, simulation results will be presented and discussed to show the efficiency of the fuzzy logic controller.

2. Multiphase machine modeling

The supply voltage of a 5-phase PM synchronous motor, Fig.1, in the natural base for the k_{th} phase is given by:

$$v_{sk} = R_s i_k + \frac{d\phi_{sk}}{dt} + e_k \tag{1}$$

R_s is the phase resistance of the stator, Φ_{sk} is the stator flux vector created in the k phase by stator currents and e_k is back Electromotive Force (EMF). We consider that the k phases are regularly shifted. Because of this, the linear relation between the current vector and stator flux vector can be obtained [6-10].

$$\vec{\phi}_s = \lambda(\vec{i}) \tag{2}$$

$$[L_s^n]=mat(\lambda,B^n)=\begin{bmatrix} L & M_1 & M_2 & M_2 & M_1\\ M_1 & L & M_1 & M_2 & M_2\\ M_2 & M_1 & L & M_1 & M_2\\ M_2 & M_2 & M_1 & L & M_1\\ M_1 & M_2 & M_2 & M_1 & L \end{bmatrix}$$

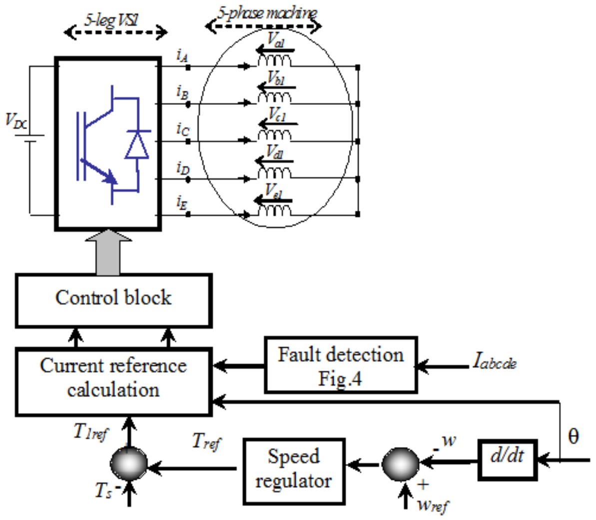

Fig. 1: 5-Phase PM Machine Supplied by A VSI Drive.

Where L is the phase inductance, M_1 is the mutual inductance between two adjacent phases (±2π/5 electrical shift), and M_2 is the mutual inductance between two phases shifted of ±4π/5.

A direct control in the natural base is possible, for example, one could gain direct control by imposing references sinusoidal. However, good tracking can be difficult to obtain because the references vary with high dynamics when they are related to the speed of the machine. To simplify this study and establish a simple and efficient control scheme, it is possible to work in a frame where the flux equations are magnetically decoupled. This is achieved when the voltage (1) are written in new frame by applied a generalized Concordia transform defined in [6-10].

In this new frame, the voltage equations are expressed in 1D and two 2D subsystems, which are magnetically decoupled. These three subsystems are associated with three fictitious machines, which are respectively called a homopolar machine, main machine, and secondary machine (3).

The equivalent diagram for each of these systems is given in Fig.2, where x can represent the main machine, secondary or homopolar (x = z, p, s). The components of the three corresponding subsystems are respectively noted with indices [z, (α_p, β_p), (α_s, β_s)].

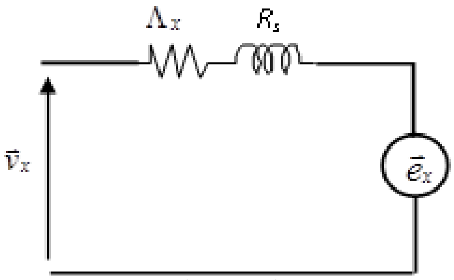

Fig. 2: Equivalent Diagram for Each of Three Fictitious Machines.

$$\begin{cases} \vec{v}_z=R_s\vec{i}_z+\Lambda_z\dfrac{d\vec{i}_z}{dt}+\vec{e}_z\\ \vec{v}_{\alpha\beta-p}=R_s\vec{i}_{\alpha\beta-p}+\Lambda_p\dfrac{d\vec{i}_{\alpha\beta-p}}{dt}+\vec{e}_{\alpha\beta-p}\\ \vec{v}_{\alpha\beta-s}=R_s\vec{i}_{\alpha\beta-s}+\Lambda_s\dfrac{d\vec{i}_{\alpha\beta-s}}{dt}+\vec{e}_{\alpha\beta-s} \end{cases} \tag{3}$$

With Λ (z, p, s), e(z, p, s) are respectively inductance and electromotive force for zero sequence, primary and secondary machines. Where:

$$\begin{cases} \Lambda_p=L-2\left[M_1\cos\left(\dfrac{2\pi}{5}\right)+M_2\cos\left(\dfrac{\pi}{5}\right)\right]\\ \Lambda_s=L-2\left[M_1\cos\left(\dfrac{\pi}{5}\right)+M_2\cos\left(\dfrac{3\pi}{5}\right)\right] \end{cases} \tag{4}$$

The EMF vector of five-phase permanent-magnet machine in the natural base can be written:

$$\vec{e}=e_1\vec{x}_1+e_2\vec{x}_2+e_3\vec{x}_3+e_4\vec{x}_4+e_5\vec{x}_5 \tag{5}$$

$$e_k=\sum_{h=1}^{\infty}E^h\sin\left(h(p\theta-(k-1)\frac{2\pi}{5})\right)$$

As the motor is wye-coupled, the current zero sequence component is null. So the generator electromagnetic torque is:

$$\begin{cases} T_{em}=\dfrac{\vec{e}\,\vec{i}}{\Omega}=\dfrac{\vec{e}_z\,\vec{i}_z+\vec{e}_p\,\vec{i}_p+\vec{e}_s\,\vec{i}_s}{\Omega}\\ T_{em}=\dfrac{\vec{e}_p\,\vec{i}_p+\vec{e}_s\,\vec{i}_s}{\Omega}\Rightarrow T_{em}=T_p+T_s \end{cases}$$

Where T_p, T_s, Ω are respectively: the torque of main machine, the torque of secondary one and the generator speed. It is possible to control the main and the secondary machines independently, since both of them are magnetically decoupled, the system behaves as if there are two independent machines mechanically coupled. Each of these two 2D machines is characterized by a particular harmonic family. PrM harmonic family contains the 1st, 9th and 11th harmonics and SdM family contains the 3rd, 7th and 13th ones. We can then consider that the main machine has p pairs of poles and the secondary machine has 3p pairs of poles. Since the machine is connected in star so the homopolar current, i_z is canceled. Based on (3), we can control the main machine and secondary one independently [3], [8], [10].

3. Current reference extraction

The electromagnetic torque T_{em} is given by (7), with ε the speed normalized back electromotive force vector:

$$T_{em}=\frac{\vec{e}.\vec{i}}{\Omega}=\vec{\varepsilon}.\vec{i}$$

In a normal operation, minimizing copper losses for maximum and constant torque T_{max}, optimal current references for each phase must be calculated [10]. In order to minimize the current norm the scalar product $\vec{\varepsilon}.\vec{i}$ must be maximized, therefore $\vec{i}$ and $\vec{\varepsilon}$ must be collinear as:

$$\vec{i}_{ref} = A.\vec{\varepsilon} = A\frac{\vec{e}}{\Omega} \quad (8)$$

$$A = \frac{T_{max}}{\left\|\frac{\vec{e}}{\Omega}\right\|^2} \quad (9)$$

Based on (8) and (9), we can generate the reference current vector from a scalar reference torque (T_{max}). To ensure the multiphase motor operation continuity with minimum copper losses and to minimize torque ripple when an open phase fault occurs, a new adaptive control strategy has been proposed in [10], [11]. In this method the faulty phases are firstly detected. Then a new system is considered. The new system only comprises the healthy phases. For example, in case of one or two faulty phases the new EMF vector ($\vec{\boldsymbol{e}}'$) for each healthy phase (here the first phase) is given by:

$$e_1' = e_1 - \frac{1}{q'}\sum_{k=1}^{q} h_k e_k \quad (10)$$

Where q' is the active phase number and $h_k = 1$ for an active phase and $h_k = 0$ for a faulty one. Therefore (8) is rewritten as follows:

$$\vec{\boldsymbol{i}}_{ref} = A'\frac{\vec{\boldsymbol{e}}'}{\Omega} \text{ with } A' \frac{T_{max}}{\left\|\frac{\vec{\boldsymbol{e}}'}{\Omega}\right\|^2} \quad (11)$$

This strategy remains valid in normal and faulty operations to achieve a constant and filtered torque at minimum copper losses. The general structure of this online adaptive strategy is given in Fig. 3.

Classically PM machine has trapezoidal EMF. Fig. 3 presents the waveform of the EMF of such 5 phase PM machine. This EMF waveform corresponds to experimental measurements in a 5-phase PM machine of low power. Table 1 presents the harmonic contents of this EMF waveform. A common practice in addressing PMSM control problem is to use a classical linear control approach [1, 8]. Hence, it is possible in normal operation to use a conventional controller as a PID or PI, which gives good reference in current tracking (these references are constant at steady state in the two d-q frames). However, in fault mode, the current references have a high dynamic behavior in the natural frame and even in the rotating d-q frames, linear controller based on the association of the generalized park transform presented previously and the use of PI or PID cannot provide a correct tracking of these current references. Nonlinear and robust control is needed to take into account these control problems. In our case, we propose a fuzzy hysteresis band controller to satisfy all the requirements (dynamic and filtering)

4. Five phase permanent magnet motor current regulation

4.1. PID regulator

The five-phase permanent magnet motor is associated with a current-controlled PWM inverter. The core of this system is the control section, which must be able to derive the reference current waveform. We first use a PID controller, the control loop of the secondary and main machines currents is made in the two d-q rotating frame as defined in section 2 [11]. One can notice that in the fault case these current references have a high dynamic behavior in the natural frame and even in the rotating d-q frames in fault case. The current regulator parameters are calculated for each fictitious machine characteristics.

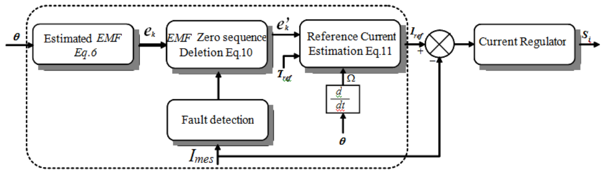

Fig. 3: Block Diagram of Reference Current Extraction.

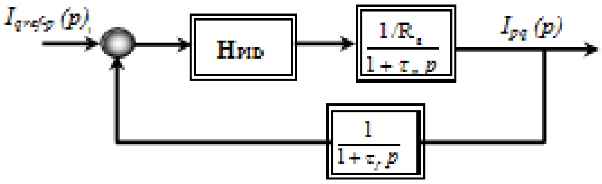

Fig. 4: Functional Diagram of the Current Control for the Main Machine Q-Axis with PID Regulator.

To realize a good compromise between stability and dynamic performances involving each machine, one choice is to choose the damping coefficient ξc equal to 0.7 and select the cut-off frequency ($f_c=\omega_c/2\pi=1000Hz$) by respecting the criterion related to rapidity of the closed loop system and the criterion of filtering. Fig 4 presents a functional diagram of control for the q-axis for the main machine.

4.2. Fuzzy hysteresis band current control

The current control strategies, often used, can be classified in the hysteresis current control, the ramp comparison control methods (natural, asymmetrical or optimal PWM) associated with linear controller and the predicted current control. The first method is very simple and easy to implement, but has the disadvantage of an uncontrollable high switching frequency. This high frequency produces a great stress for the power transistors and induces important switching losses. The second and third methods allow operating at a fixed switching frequency and are usually performed by software using the system parameters. In this case, the operating conditions must be known to meet sufficient and accurate control [12]. Consequently, a fuzzy hysteresis band circuit control is involved for our application. To improve this control, an adaptive and fuzzy hysteresis band current control technique is studied in [13]. This modulation technique also consists in reducing the errors between the reference currents and the currents absorbed by the motor with constant frequency. Adaptive hysteresis control is based on the dynamic tuning of the hysteresis band to keep the switching frequency constant [14]. This strategy has been used, for example, to control the currents of a three-phase machine in [15] and [16]. For a desired fixed frequency, the calculation algorithm updates the width of the Hysteresis Band HB_a as a function of the current references and the EMF. By similar method that proposed in the references for a three-phase machine [16], the expression of the adaptive band is given by [13].

$$HB_a = \frac{a'V_{dc}}{4.f_c.L_s}\left[\,1-\frac{L_s^2}{a'^2V_{dc}^2}\left(\frac{e}{L_s}+\frac{dI_{ref}}{dt}\right)^2\,\right] \quad (12)$$

V_{dc} is the DC bus voltage, f_c the switching frequency, L_s is the inductance of a stator phase and a' is mean coefficient of the output voltage of the inverter given by [17]. Fig. 5 shows the block diagram of the adaptive hysteresis band current control using (12). Current control with an adaptive hysteresis band current control needs a precise knowledge of the MSAP parameters (L_s and V_{dc}). To improve MSAP performances, (12) is implemented in our case with fuzzy logic. In order to establish a fuzzy logic controller, input and output variables must be treated. The electromotive force wave e'(t) and the current reference slope, dI_{ref}/dt, are selected as input variables and HB as output variable.

The following step is to determine the set of linguistic values associated control to each variable. Triangle memberships are chosen. Each input variables is transformed into linguistic size with five fuzzy subsets, PL: positive large, PM: positive medium, PS: positive small, EZ: zero, NL: negative large, NM: negative medium, NS: negative small and for the output variables are: PVS: positive very small, PS: positive small, PM: medium positive, PL: positive large, PVL: positive very large. Then, Fig. 6 shows the membership functions of the input and the output variables. The resulting rule is presented in Table 2.

Table 1: Harmonic Contents of the Back EMF the Experimental 5-Phase PMSM

Harmonic number	1	3	5	7
Relative RMS Amplitude	100	23	7.31	0.82

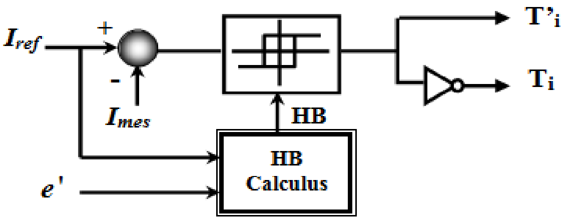

Fig. 5: Simplified Model for Fuzzy Hysteresis-Band Current.

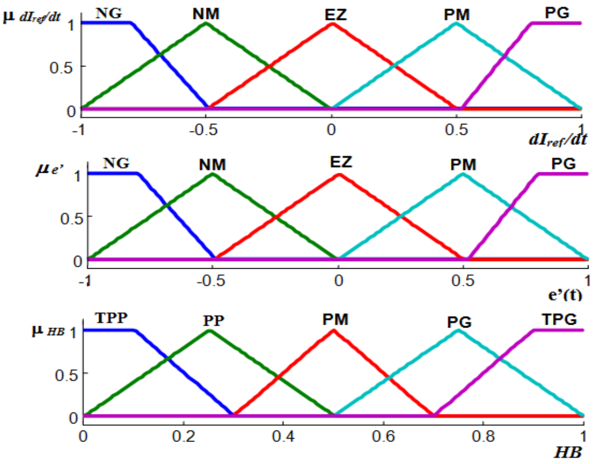

Fig. 6: Membership Functions for Input Variables Diref/ Dt, vs. (T) and Output Variable HB.

Table 2: Rules of Inference for Fuzzy Hysteresis Current Control

dIref/ dt e'(t)	NG	NM	EZ	PM	PG
NG	PP	PP	PM	PP	PP
NM	PP	PM	PG	PM	PP
EZ	TPP	PM	TPG	PM	TPP
PM	PP	PM	PG	PM	PP
PG	PP	PP	PM	PP	PP

5. Simulation

Simulations of the whole system in healthy and fault operation modes are presented to evaluate the fault-tolerant capabilities of a 5-phase PMSM using the presented control approach. It consists in the combination of two strategies, an adaptive current generation described in 3, and fuzzy hysteresis band described in 4. The maximum value of the adaptive fuzzy band (H_{max}) is equal to 0.2p.u. To validate the proposed method several tests has been done using Matlab/Smulink. Figs 7 and 8 respectively show the results obtained using a PID regulator and fuzzy hysteresis band in faultless mode. We then observe that we have a good follow up of reference current with a constant torque for the 2 types of regulation.The steady state tracking error is negligible in the adaptive band case. The objective of control is to minimize these losses for a given couple. For this purpose, the PID control and Fuzzy Hysteresis Band (FHB) appear much more efficient in normal mode. They allow obtaining a torque of good quality with negligible ripple. Figs 9 and 10 show simulation results with two non-adjacent open circuited phases (1 and 3) at full speed, respectively for the PID controller and for fuzzy hysteresis band controllers. For this case, we also observe that we have a good tracking of the reference current with a constant torque for both types of control with superiority of the fuzzy hysteresis band controller.

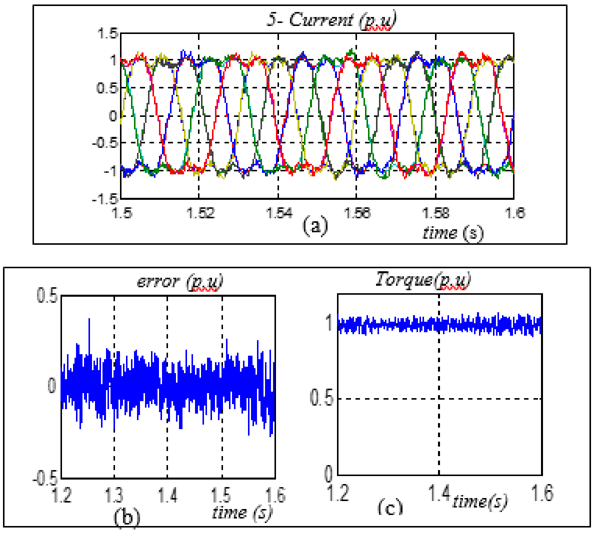

Fig. 7: Simulation in Normal Operation Case Of PID: (A) 5- Current in Five Phases of Machine, (B) Torque, (C) Current Error.

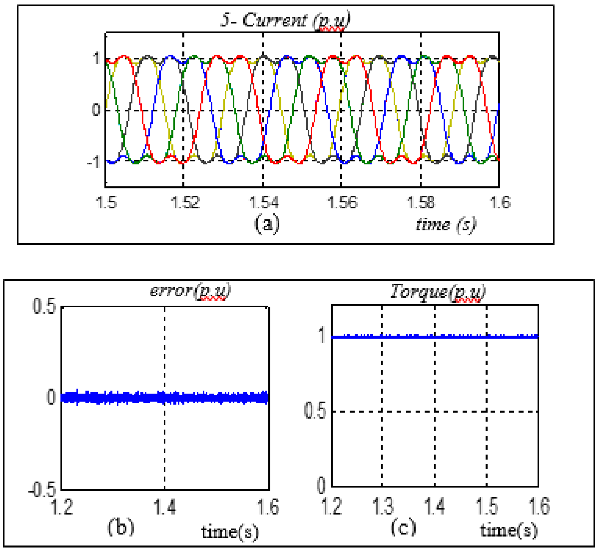

Fig. 8: Simulation in Normal Operation Case Of FHB: (A) Current in Five Phases of Machine, (B) Torque, (C) Current Error.

Figs. 11 and12 show simulation results with two adjacent open circuited phases (phases 1 and 2). This fault mode corresponds to the most critical configuration. If we want to maintain the nominal torque, it should be noted that the appearance of these faults leads to a significant increase in peak currents and therefore losses by Joule effect in the phases. To manage the current dynamics, the use of PID control leads to severe and unacceptable tracking errors. Therefore, the PID finds its limits in terms of particular monitoring in reference current waveforms with steep slopes. As a result, the actual current is delayed relative to it reference, the error is then greater inducing torque ripples. The control by fuzzy hysteresis band allows both to have a very good tracking of reference with a low error and minimization of torque ripples. Note that the torque ripple is divided by 3 compared to PID controller. The proposed control strategy is more efficient, in particular to reduce the ripple of the torque, maintain the torque around its nominal value and minimize copper losses, even in the worst case.

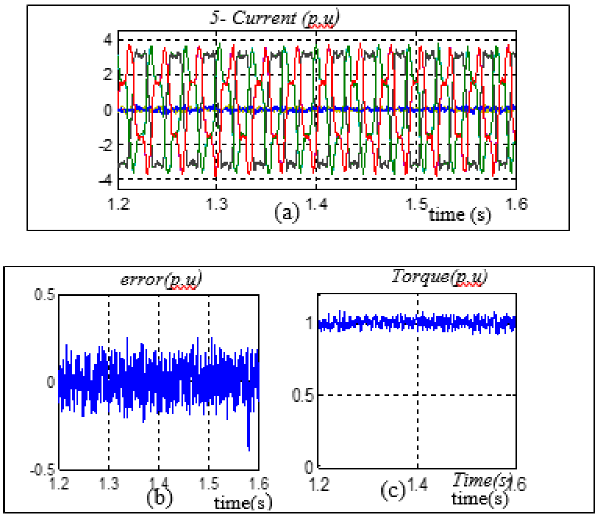

Fig. 9: Simulation Results for Two Non-Adjacent Open Circuited Phases, (PID): (A) 5- Current (B) Torque, (C) Current Error.

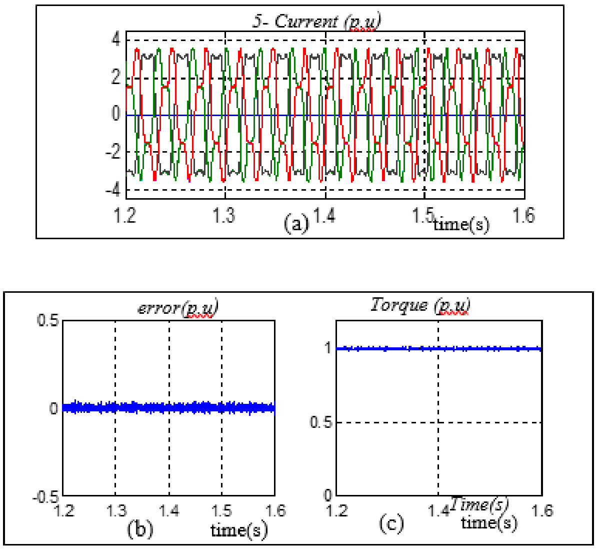

Fig. 10: Simulation Results for Two Non-Adjacent Open Circuited Phases, (FHB): (A) 5- Current (B) Torque, (C) Current Error.

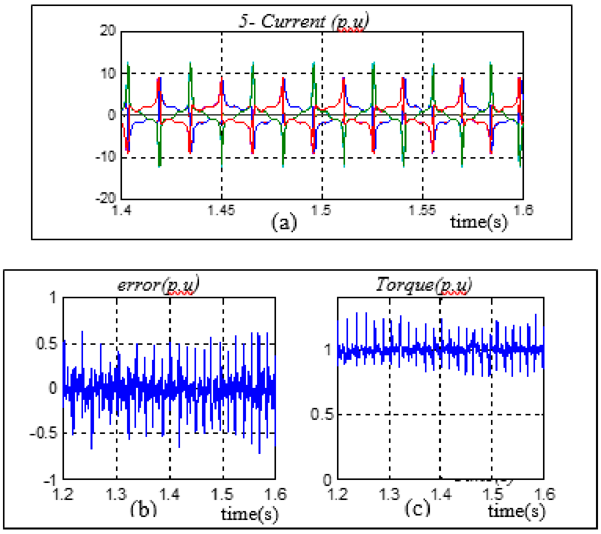

Fig. 11: Simulation Results for Two Non-Adjacent Open Circuited Phases, (PID): (A) 5-Current (B) Torque, (C) Current Error.

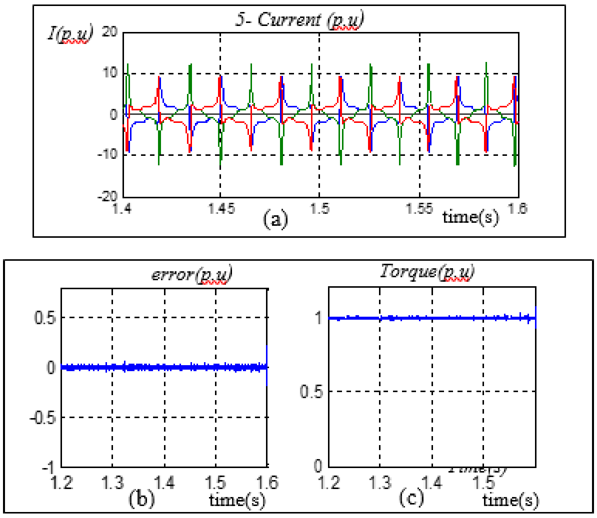

Fig. 12: Simulation Results for Two Non Adjacent Open Circuited Phases, (FHB): (A) 5-Current (B) Torque, (C) Current Error.

6. Conclusion

The objective of this work is to a smooth torque with minimal losses even in severe fault conditions of a 5-phase PM Motor. For this, we propose fuzzy hysteresis band controller associated to new strategy to generate current references of a 5-phase PM Motor. This strategy can handle degraded (open-phase) and normal modes by using the same algorithm to generate online reference currents and the same control architecture. In high speed and fault case conditions

Under high speed and / or failure conditions, the PID controller has difficulty tracking current references resulting in less controlled oscillatory torque and additional Joule losses. In this case, the new fuzzy hysteresis band command that maintains a constant switching frequency is more appropriate because it improves the dynamic performance of the drive, as well as the torque quality and the Joule effect losses. The simulation results confirm the robustness and viability of the proposed approach that can easily be adapted to other more severe constraints.

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