Numerical methods for the electromagnetic modelling of actuators for primary and secondary flight controls

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Abstract: - Prognostics and health management of electromechanical actuators (EMA) must rely on affordable and representative simulation models to be effective in predicting evolution of failures, so to identify them before they occur through the assessment of monitored parameters, leading to on-spot maintenance operations. This paper presents a multi domain model of al EMA, putting special attention on the fidelity of the numerical modelling of the inverter and of the related electromagnetic aspects. Such model permits to simulate the behavior and the types of failure of the electro actuator in a realistic and precise way. The choice of the multi domain simulation is necessary to improve from the simplifying hypotheses that are typically considered in numerical models that are mostly used for prognostic analyses of electro mechanical actuators.

Key-Words: - BLDC Motor, Electromechanical Actuator (EMA), Prognostics, PHM, Numerical Model

1 Introduction

In order to identify incipient failures of primary flight command electromechanical actuators (EMA), several approaches could be employed; the choice of the best ones is driven by the efficacy shown in fault detection/identification, since not all the algorithms might be useful for the proposed purpose. In other words, some of them could be suitable only for certain applications while they could not give useful results for others. Developing a fault detection algorithm able to identify the precursors of the abovementioned EMA failure and its degradation pattern is thus beneficial for anticipating the incoming malfunction and alerting the maintenance crew such to properly schedule the servomechanism replacement.

The fly-by-wire architecture in aeronautics relies on computerized electromechanical systems that control several onboard systems (e.g. regulating the fuel flow feeding the propulsion system, actuating the primary and secondary control surfaces, in order to achieve the aircraft control and stabilization, and performing many other tasks): those systems lead to an improvement in safety and comfort, reducing the fuel consumption and, subsequently, limiting the operative costs. However it is necessary to consider the eventuality of failure conditions and to conceive proper methods able to timely detect these faults and intervene ensuring the aircraft safety.

To these purposes, especially in aeronautics (but also in many other technological fields), several approaches have been developed (e.g. monitoring and diagnostic strategies); in recent years, the above methods have been flanked by new prognostic strategies designed to identify failure in the early stages of its development and to predict when a certain component loses its functionalities and is not further able to operate or to meet desired performances. These prognostic methods are based on analysis and knowledge of possible failure modes and on capability to identify incoming faults, due to aging or wear, by monitoring specific operational parameters (typically called prognostic precursors) [1-2].It must be noted that the development of a prognostics health management (PHM) based fault-tolerant control architecture can increase safety and reliability (by means of a proper detection/identification of the aforesaid impending failures), thereby minimizing the occurrence of unexpected, costly and possibly life-threatening mission failures; reducing unnecessary maintenance actions; and extending system availability and reliability. Therefore, in order to design and test new methodologies prognostic or, at least, to develop prognostic model based algorithms, it is important to define a proper set of numerical models capable of simulating the dynamic response of the EMA system taking into account progressive failures.

It must be noted that these numerical models must be properly designed conjugating, in relation to their use (e.g. preliminary draft, monitoring, validation or testing), precision and accuracy of the simulations with the corresponding computational burden (i.e. use of memory and simulation time). In this regard, it is necessary pay special attention to the modeling of the brushless direct current (BLDC) electric motor which, because of its peculiar characteristics, its multidisciplinary nature and the non-linear features of some phenomena that characterize its behaviors, is certainly the most complex subsystem of the EMA model (or, at least, the most critical to implement and the most onerous from a computational point of view).

The research presented in this paper is focused on the analysis of numerical models simulating the dynamic behaviors of the electric motor types that typically equip the EMAs; in particular the authors' attention has been focused on the three-phase BLDC motors (i.e. a motor type commonly used in flight controls applications) and, starting from models found in literature [3-8], they propose three new numerical models able to perform accurate simulation of the considered EMA taking into account the main effects of some typical progressive faults affecting these electric motors.

The above-mentioned numerical models have been obtained through subsequent developments and specializations and are intended to overcome the typical limitations of the models available in the literature that, being based on simplifying assumptions (e.g. superposition of the effects), are not able to assess in an appropriate manner non-linear effects arising from considered failures (e.g. unbalanced stator circuit or bearings dry friction).

The proposed models, overcoming the aforesaid simplifying assumptions by means of multi-domain numerical models (e.g. using Simulink Simscape or Sim Power System to model the PWM controller or the three-phase stator circuit), make the simulation algorithm properly sensitive to these faults and, then, suitable for the aforesaid prognostic analysis: in particular, these models are able to take into account dry friction, stator turn to turn coil short circuit and rotor static eccentricity.

2 EM Flight Control Actuators

Aeronautical primary flight controls are typically proportional servomechanisms with continuous activation: they must return a force feedback related to command intensity and a properly high frequency response. Since their loss is a critical issue, their reliability must be very high.

Their purpose is to control the dynamic of the aircraft by generating, by means of proper rotation of the related aerodynamic surfaces, unbalanced forces/couples acting on the aircraft itself. In general, these controls are usually conceived to obtain the aircraft rotation around one of the three body axis when one control surface is activated.

Until a few years ago, the actuators mainly used in aeronautical applications were generally hydraulic and precisely hydromechanical or, more recently, electrohydraulic. This typology of actuator, because of its great accuracy, high specific power and very high reliability, is often equipped on current aircrafts, even if on more modern airliners electro-hydrostatic actuators (EHA) or electro-mechanical actuators (EMA) are installed. In the last years the trend towards the all-electric aircrafts brought to an extensive application of novel optimized electrical actuators, such as the electromechanical ones (EMA). To justify the fervent scientific activity in this field and the great interest shown by the aeronautical world, it must be noticed that, compared to the electrohydraulic actuations, the EMAs offer many advantages: overall weight is reduced, maintenance is simplified and hydraulic fluids, which is often contaminant, flammable or polluting, can be elimination. For these reasons, as reported in [9], the use of actuation systems based on EMAs is quickly increasing in several fields of aerospace technology.

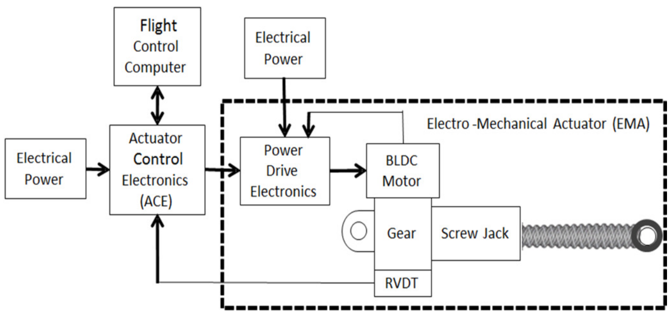

Fig. 1: Electromechanical actuator (EMA) scheme.

As shown in Fig. 1, a typical EMA used in a primary flight control is composed by:

1. An actuator control electronics (ACE) that closes the feedback loop, by comparing the commanded position (FBW) with the actual one, elaborates the corrective actions and generates the reference current *I_ref*;
2. A Power Drive Electronics (PDE) that regulates the three-phase electrical power;
3. An electric motor, often BLDC type.
4. A gear reducer having the function to decrease the motor angular speed and increase its mechanical torque.

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5. A system that transforms rotary motion into linear motion: ball screws or roller screws are usually preferred to acme screws because, having a higher efficiency, they can perform the conversion with lower friction;
6. A network of sensors used to close the feedback rings (current, angular speed and position) that control the whole actuation system (reported in Fig. 1, as RVDT).

3 Considered BLDC motor models

As previously reported, the main focus of this work is the proposal of new numerical models able to perform more accurate simulations of dynamic responses of a given BLDC motor type taking into account (properly) the considered progressive faults. As a consequence, the authors' models implement only the motor features (rotor speed control ring and related reference current controller, pulse-width modulation (PWM) inverter, electromagnetic model of the stator circuit and related electromechanical model, internal sensors and considered faults).

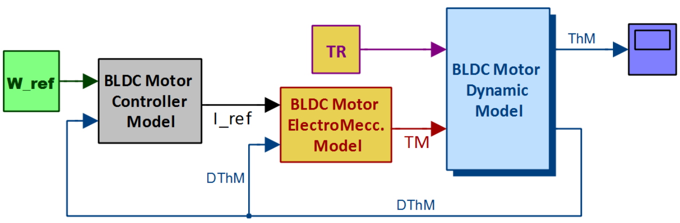

Fig. 2: Schematic of the considered BLDC electric motor block diagram (implemented in Matlab-Simulink).

The proposed models, as schematically shown in Fig. 2, are composed by five subsystems:

1. *W_ref*: input block that generates the different commanded actuation speed input.
2. *BLDC Motor Controller Model*: simulating the actuator control electronics, closing the feedback loops and generating in output the reference current *I_ref*.
3. *BLDC Motor ElecroMecc. Model*: simulating the power drive electronics and the trapezoidal BLDC electromagnetic model, that calculates the mechanical torque developed by the electrical motor as a function of the voltages generated by three-phase electrical regulator.
4. *BLDC Motor Dynamic Model*: simulating the BLDC motor mechanical behavior by a two degree-of-freedom dynamic system.
5. *TR*: input block simulating the eventual external mechanical torque acting on the rotor shaft.

It must be noted that these numerical models are also able to take into account the effects of BLDC motor non-linearities [4,6-7], analogic to digital conversion, offsets and electrical noise acting on the signal lines [10] and rotor bearings dry friction [11].

The original model, simulating the dynamic behavior of a trapezoidal three-phase BLDC motor by means of a simple lumped model, has been developed according to [3-4]. Starting from this model, three different approaches have been studied in order to improve their capability to give more consistent and accurate results with the motor physics and, at the same time, to simulate the aforesaid failure conditions.

The three proposed numerical model are:

1. Simplified Parameters Model (SPM)
2. Circuital Model with Simplified Inverter (CMSI)
3. Circuital Model with Detailed Inverter (CMDI)

The physical data used to implement these numerical algorithms and to run the corresponding simulations are referred to a 4490-048BS Faulhaber BLDC electric motor (as reported in Table 1).

Nominal Voltage	48	[V]
Terminal Resistance, phase to phase	2.130	[Ohm]
Stall Torque	1689	[mNm]
Back-EMF constant	7.871	[mV/rpm]

Table 1: BLDC motor data

3.1 Simplified Parameters Model

Figure 3 represents the SPM as it appears in Matlab Simulink; it must be noted that, with respect to the original model, this model is able to simulate the effects of turn to turn coils short circuit and rotor static eccentricity (i.e. two types of progressive faults considered in this work) by means of a smart numerical algorithm: since these faults modifies the magnetic coupling between the stator and the rotor, the proposed algorithm adjusts the angular modulation of the counter-electromotive force (CEMF) coefficients and thereby the related torque constants. As reported in [9], this algorithm is implemented by the functions *f (u)*, contained in the *BLDC Motor ElecroMecc. Model* block of Fig. 2 and acts on the three CEMF constants *Cei* (one for each of the three phases) modulating their trapezoidal reference values Kei as a function of coil short circuit percentage, static rotor eccentricity and angular position *theta_r*.

$$\mathrm{e\_in} = \mathrm{Ke_i} \cdot \mathrm{Ce_i} \cdot (1 + \zeta \cdot \cos(theta\_r)) \qquad (1)$$

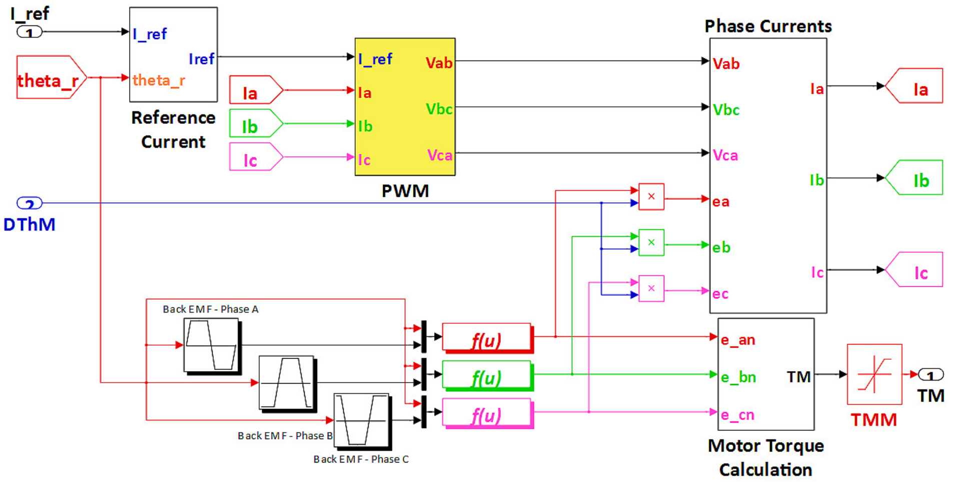

Fig. 3: SPM – Schematic of *BLDC Motor Controller Model* block (implemented in Matlab-Simulink).

where i = a, b and c represents the three phases and ζ refers to the rotor static eccentricity. As reported in [1], the so obtained constants (*e_an, e_bn* and *e_cn,* also called *normalized CEMFs*) are used to calculate the corresponding CEMFs (*ea*, *eb*, *ec*) and to evaluate the mechanical couples (*Cea*, *Ceb*, *Cec*) generated by the three motor phases.

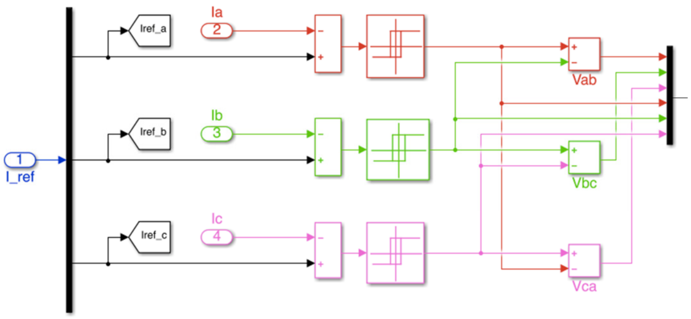

Fig. 4: SPM – Schematic of *PWM* block.

The *PWM* block (Fig. 4) has been modeled by means of a simplified model based upon a relay logic: the control of the piloted tension on every phase has been realized through a Simulink Relay block, driven by the difference between the reference current *Iref_a,b,c* and the corresponding phase current *Ia,b,c*; the *PWM* block implements a hysteresis control that, as a function of the differential current, gives as output three phase-phase tensions *Vab*, *Vbc* and *Vca*.

The *Phase Currents* block (Fig.5) calculates the three phase currents in function of the comparison between the outputs of the PWM block, which are the three tensions *Vab*, *Vbc* and *Vca*, and the CEMF values *ea*, *eb* and *ec*. The net between these phase-phase tensions and the corresponding CEMFs determines the effective inputs of the *Phase Currents Calculations* block (shown in Fig. 6).

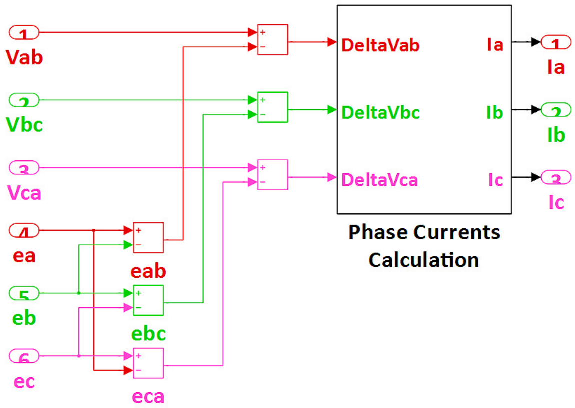

Fig. 5: SPM – Schematic of *Phase Currents* block.

In *Phase Currents Calculations* block, the three branches of the stator electric circuit have been modeled by means of three simplified ohmic-inductive (RL) numerical models (assuming that branches are electrically balanced, symmetrically loaded and mathematically modelled as linear, and therefore applying the superposition of effects), integrating the three differential equations representing the physical phenomena.

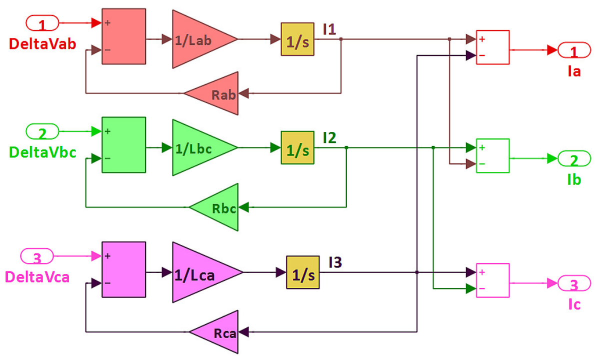

Fig. 6: SPM – *Phase Currents Calculations* block.

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Since phase currents are known, the total motor torque can be computed; the sum of the three phase currents, multiplied by their respective *normalized CEMFs* constants *e_an, e_bn* and *e_cn* gives the corresponding value of the total motor torque TM.

$$\mathrm{TM} = Ia \cdot e\_an + Ib \cdot e\_bn + Ic \cdot e\_cn \qquad (2)$$

However, this value is limited by means of a Simulink Saturation block in order to take in account the operating limitations of the real system.

3.2 Circuital Model with Simplified Inverter

In order to make the system more reliable and sensitive to the different typologies of failure, the Simplified Parameters Model (SPM) has been modified introducing some improvements. Those have been made in order to better represent the physical behavior of the BLDC motor considered.

In particular, the *Phase Currents Calculations* block has been modified substituting the original simplified RL linear lumped parameters model reported in Fig. 6 with the corresponding circuital model (Fig. 8); this physical model is based on the equivalent stator electrical circuit shown in Fig. 7 and it is implemented by the equation system reported in (3) and (4).

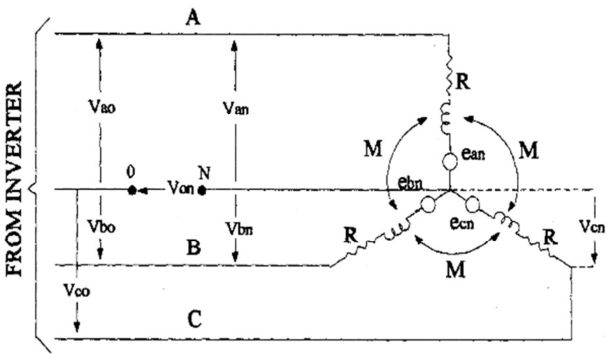

Fig. 7: Schematic of equivalent stator electrical circuit.

$$\begin{cases} v_a = R \cdot i_a + L \cdot \dfrac{di_a}{dt} + M \cdot \dfrac{di_b}{dt} + M \cdot \dfrac{di_c}{dt} + e_a \\ v_b = R \cdot i_b + M \cdot \dfrac{di_a}{dt} + L \cdot \dfrac{di_b}{dt} + M \cdot \dfrac{di_c}{dt} + e_b \\ v_c = R \cdot i_c + M \cdot \dfrac{di_a}{dt} + M \cdot \dfrac{di_b}{dt} + L \cdot \dfrac{di_c}{dt} + e_c \end{cases} \qquad (3)$$

$$i_a + i_b + i_c = 0 \qquad (4)$$

The abovementioned mathematical model has been therefore employed to develop a multidomain model implemented in Sim Power System (a dedicated physical modelling tool embedded into the Matlab-Simulink numerical simulation environment).

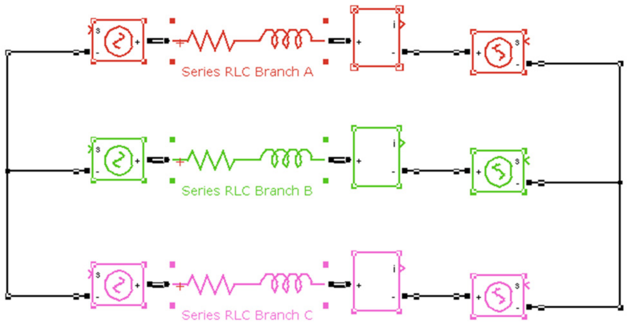

Fig. 8: Schematic of equivalent stator circuital model implemented in Matlab Simulink Sim Power System.

With respect to the aforesaid SPM, the CMSI is able to calculate the instantaneous value of each current phase (*Ia*, *Ib*, *Ic*) also in case of unbalanced electromagnetic system (e.g. partial short circuit on a stator branch or rotor static eccentricity).

3.3 Circuital Model with Detailed Inverter

Unlike the previous case, in which the inverter block has been represented by means of a simplified algorithm (*PWM* block), the CMDI model proposes a more detailed representation of the real device.

As shown in Fig. 10, in this case the architecture of the *BLDC Motor Controller Model* has been modified (with respect to the previous cases SPM and CMSI) placing the aforesaid *Inverter* block between the *PWM* and the *Phase Currents* blocks (according to the circuital layout of the real system).

It must be noted that, with respect to the previous case (Fig. 4), the *PWM* block developed for the CMDI model has been formally modified in order to allow its interaction with the proposed *Inverter* model but, from a conceptual point of view, its operating logic is not appreciably changed: in the previous models this block was conceived in order to give as output the three phase-phase currents *Vab*, *Vbc* and *Vca*, whereas,in this case, the Relay blocks are used to directly drive the four transistor of the H bridge of the detailed inverter model (giving three Boolean outputs *qa*, *qb* and *qc*).

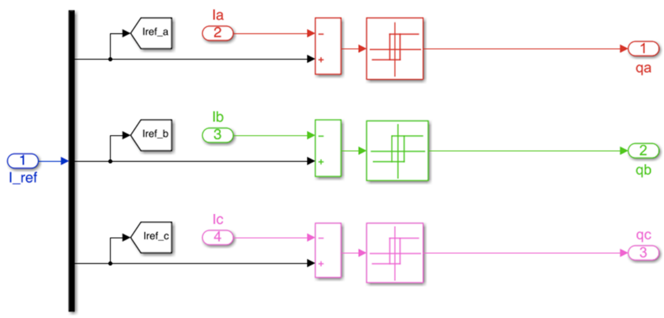

Fig. 9: CMDI – Schematic of *PWM* block.

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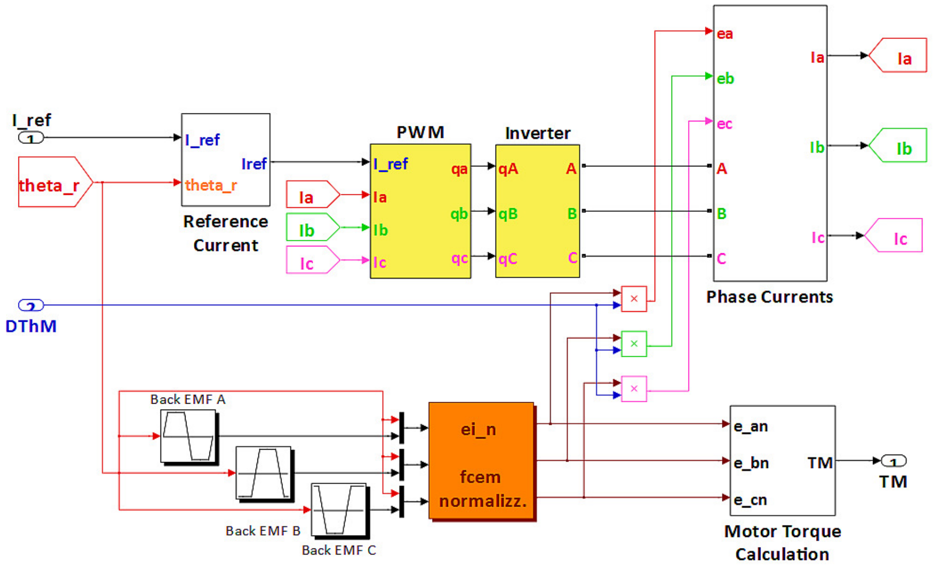

Fig. 10: CMDI – Schematic of *BLDC Motor Controller Model* block (implemented in Matlab-Simulink).

In order to provide a more accurate modelling of the inverter that controls the commutations of the stator three-phase circuit, also this component has been implemented by means of a multidomain Sim Power System block: in particular, the inverter circuit, realized by means of four MOS-FET (Metal–Oxide Semiconductor Field Effect Transistor) have been modelled by a universal bridge block.
Also in this case, the three outputs of the universal bridge block (i.e. the supply voltages of the three phases *A*, *B* and *C*) have been given as input of the *Phase Currents* computation block.

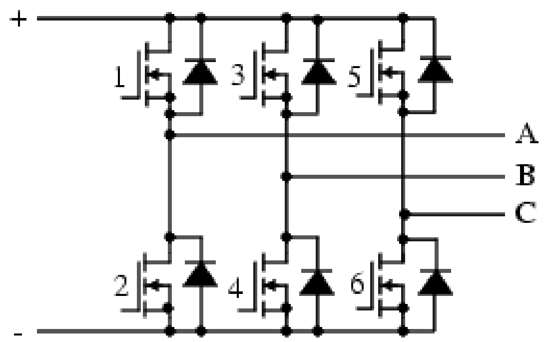

Fig. 11: Schematic of three phase transistor inverter.

4 Results

In order to evaluate the performance of the proposed numerical models, several simulations, related to different combinations of commanded actuation speed input *w_ref*, external load *TR* and progressive failures have been performed; the obtained results have been compared each other putting in evidence the eventual inconsistencies and criticality.

The results reported in the following figures have been obtained giving an input speed command *w_ref* higher than the corresponding saturation rotor speed and considering an external load *TR*, applied at time = 0.15 [s], amounting to 50% of the corresponding stall load (i.e. corresponding to the motor stall torque TMM = 1689 [mNm]).

It must first highlight how, in nominal condition (NC), the dynamic response of the circuital models (CMSI and CMDI) are practically overlapping: In fact, excluding the specific failure conditions of the inverter (simulated only by its circuital model BMDI), the two models are almost equivalent.

Figure 12 allows comparing each other the time histories of the rotor speed that have been simulated, in the said input and load conditions, by SPM (red line) and BMDI (blue line). The SPM model describes the stator circuit by means of a simplified representation that, instead of on the non-linearity and the interactions between the three branches of the said circuit, tends to overestimate the rotor speed and, vice versa, does not show the ripple speed that, as reported in [12], generally characterizes the mechanical response of BLDC motors.

Figures 13 and 14 show, respectively, a detail of the time evolution of the phase currents of the stator circuit calculated by means of the simplified model SPM and the more detailed model BMDI.

It must be noted that the simplified model (Fig. 13) describes correctly the phase switchings in function of the electrical rotor position but, unlike the detailed model (Fig. 14), is not able to properly simulate the electrical dynamics of the stator circuit and the related switching transients (e.g. the current ripple, said two-phase-on, described in [13])

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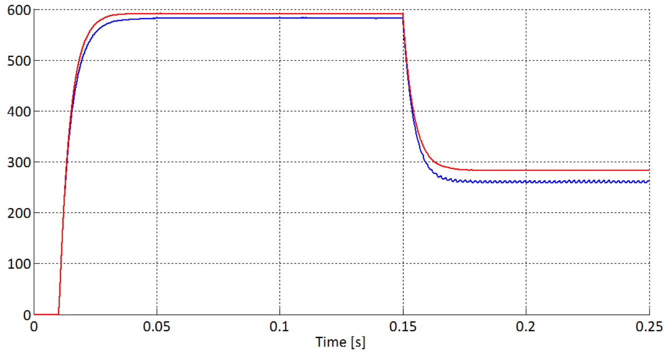

Fig. 12: Evolution of the BLDC motor rotor speed in NC: SPM (red) and BMDI (blue).

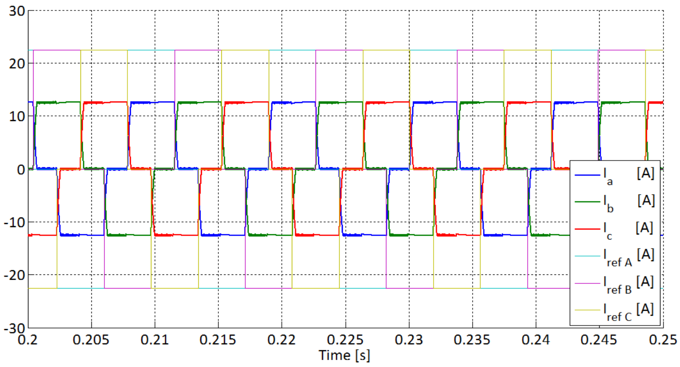

Fig. 13: Particular of winding phase currents (SPM).

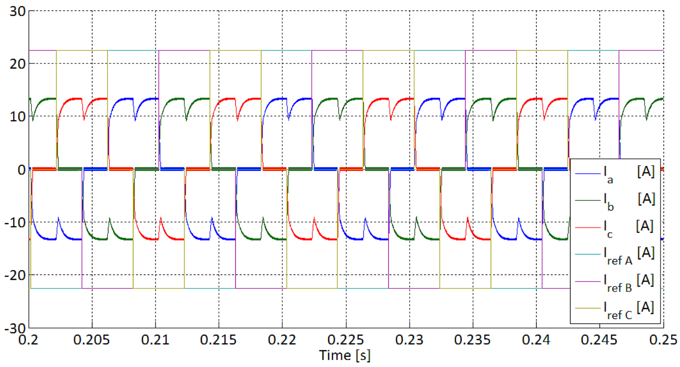

Fig. 14: Particular of winding phase currents (BMDI).

3 Conclusions

The research presented in this paper is focused on the analysis of numerical models simulating the dynamic behaviors of the electric motor types that typically equip the EMAs In order to conceive effective analytical tools for the development of prognostic algorithms, authors propose three new numerical models able to perform accurate simulation of the considered BLDC motor taking into account the main effects of some typical progressive faults affecting these electric devices.

The comparison between the proposed models puts in evidence that the development of multi-domain model (obtained by implementing the inverter and the stator circuit by Sim Power System) allows you to simulate more faithfully the behavior of the system and to take account of faults and abnormal behavior. The introduction of these numerical models, having a more versatile and reliable approach to the aforesaid problems, has led to define more useful and effective tools for prognostic analysis.

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