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# Fault-tolerant control via four-leg inverter of a full-electric propulsion system for lightweight fixed-wing UAVs

Gianpietro Di Rito<sup>1,2</sup>, Aleksander Suti<sup>1</sup> and Roberto Galatolo<sup>1</sup>

 <sup>1</sup> Dipartimento di Ingegneria Civile e Industriale, Università di Pisa, Sez. Aerospaziale, Via Caruso 8, Pisa I-56122, Italy
 <sup>2</sup> e-mail: gianpietro.di.rito@unipi.it

Abstract. The work deals with the development and the performance characterization of a novel control strategy for the detection, isolation and accommodation of coil faults in a threephase Permanent Magnet Synchronous Motor (PMSM), used to drive the propeller of a modern lightweight fixed-wing UAV. The health-monitoring algorithms on motor currents (used to detect the open-circuit fault and to activate the control reconfiguration) are based on a slope method, associated to the evaluation of the current phasor trajectory in the Clarke plane. Actually, when an open-circuit fault occurs in PMSM driven by a standard three-leg converter, the typical circular trajectory of the current phasor in the Clarke plane collapses into a linear track and relevant torque ripples are generated. On the other hand, if the PMSM is driven by a four-leg converter, a control reconfiguration can be applied: the fourth leg of the power bridge is in stand-by when the system operates without faults, but it is enabled to regulate the current flowing at the central point of the Y connection of the 3-phase PMSM. The performances of the fault-tolerant algorithms are assessed via detailed nonlinear simulation of the propulsion system (including propeller loads, electrical faults, mechanical transmission compliance, digital signal processing and sensors errors). The results demonstrate that the healthmonitoring algorithms and the fault-tolerant control strategies permit to obtain extremely small detection and isolation latencies, and negligible performance degradation in terms PMSM torque.

**Keywords**: fault-tolerant systems, permanent magnet synchronous motors, four-leg converter, health-monitoring, UAV.

#### 1. Introduction

The unmanned aerial vehicle market, though the dramatic economic consequences of the COVID-19 pandemic, is expected to grow with a Compound Annual Growth Rate (CAGR) of 17.54% from 2020 to 2023, up to reach \$2.25 billion by 2023 [1]. Thanks to lower emissions (both noise and CO2), better efficiency, improved diagnosis and prognosis, and on the wave of the steady enhancements of energy storage devices, most of the future UAVs will be equipped with electric propulsion systems. Though the electric propulsion is expected to perform better than internal combustion engines, several reliability and safety issues are still open points, especially for long-endurance UAVs. In particular, conventional architectures based on three-phase Permanent Magnets Synchronous Machines (PMSM) driven by three-leg inverters are vulnerable to motor phase faults, since they generate relevant torque oscillations and consequent unsafe UAV operations. A possible solution can be given by propulsion

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1 systems with redundant motors, but the stringent requirements in terms of weight and envelope often impede their application. An alternative solution (which this work refers to) can be obtained by using a single motor driven by a four-leg inverter, in which an additional couple of switches are installed from power supply to ground to control, in case of phase fault, the central point of the Y connection of the three-phase motor. The additional leg thus operates as a stand-by device, and its effectiveness strictly depends on the performances of the Fault Detection and Isolation (FDI) technique.

A survey of the most relevant research activities in recent years on FDI of electric motors' phases has been carried out by the authors [2]. In particular, Khalaief [3] and Huang [4] realized a FDI by merging the Fast Fourier Transform (FFT) of the current measurements with a fault signature technique [5], in order to firstly detect the Internal Stator Winding Failure (ISWF) and then to identify the failed phase. In fact, in case of an open coil, the orientation of the current phasor obtained via Clarke transform is strictly correlated to which phase is failed. Despite of the good FDI performances, the most relevant limitation of this method was related to the use of FFT analysis itself, since it requires the monitoring of the stator currents for one or more electrical cycles after the fault to perform the detection.

In this work, the FDI of the motor phase faults is fully realized by using the current signature technique [2, 5] and a fault accommodation technique, based on new frame transformation [2] is designed to maintain the propulsion performances. The paper is articulated into three parts. The first one is dedicated to the description of the nonlinear model of the system, while the second focuses on the design of FDI algorithms and to the control accommodation technique. A summary of simulation results is finally proposed, by highlighting the applicability of the strategy, which succeeds in detecting, isolating open-circuit fault and eliminating torque oscillations after the fault.

# 2. System dynamic modelling

The electromechanical section of the reference propulsion system is basically composed of a threephase PMSM with Y winding driving, through a mechanical coupling joint, a twin fixed-pitch propeller (i.e., APC 22x10E [6]).

A CON module operates the closed-loop control, of the motor currents (via Field-Oriented Control, FOC), based on a proportional-integrative regulators with anti-windup compensation. While a MON module executes the health monitoring algorithms, among which one is particularly dedicated to the FDI of the motor open-phase faults.

# 2.1. Aerodynamic and mechanical section

The dynamics of the mechanical section has been modelled as in [7] and with reference to the scheme depicted in Figure 1(a),  $J_p$  ( $J_{em}$ ) and  $\theta_p$  ( $\theta_{em}$ ) are the inertia and the angular position of the propeller (electrical machine) respectively.  $Q_d$  is the gust-induced disturbance torque and  $Q_{em}$  is the motor torque. The propeller resistant torque  $Q_p$  is proportional to the torque coefficient  $C_Q$ . The propeller advance ratio and diameter are indicated with AR and  $D_p$  respectively,  $\rho$  is the air density and  $V_a$  is the UAV forward speed, while  $K_{gb}$  and  $C_{gb}$  are the stiffness and the damping of the mechanical coupling joint.

# 2.2. PMSM section

The model of the three-phase PMSM is developed by considering the basic assumptions proposed in [8] and with reference to the schematics in Figure 1(a), where the phase drop voltage vector has been indicate with  $\mathbf{V}_{abc} = [V_a - V_n, V_b - V_n, V_c - V_n]^T$ , the stator current vector with  $\mathbf{i}_{abc} = [i_a, i_b, i_c]^T$  while  $\mathbf{e}_{abc}$  is the back-electromotive force vector. The motor phases resistance and inductance are R and L respectively and  $V_n$  is the neutral point voltage.

When applying the FOC technique to three-phase PMSMs, two reference frame transformations are applied to the stator-referenced vectors, Figure 1(a), namely the Clarke transform (from a, b, c to

 $\alpha, \beta, \gamma$  frame) and Park transform (from  $\alpha, \beta, \gamma$  to d, q, z frame). By applying the Clarke and Park's

transformations based on Power Invariance Method (PIM) [9], we have:  

$$T_{P}T_{c} = \sqrt{\frac{2}{3}} \begin{bmatrix} c(n_{d}\theta_{em}) & c(n_{d}\theta_{em} - 2\pi/3) & c(n_{d}\theta_{em} + 2\pi/3) \\ -s(n_{d}\theta_{em}) & -s(n_{d}\theta_{em} - 2\pi/3) & -s(n_{d}\theta_{em} + 2\pi/3) \\ \sqrt{2}/2 & \sqrt{2}/2 & \sqrt{2}/2 \end{bmatrix}$$
(1)

where for the sake of compactness the functions cos() and sin() have been indicated with c() and s() respectively.

Hence, the Clarke-Park transform permits to conveniently express the motor torque as:

$$Q_{em} = \sqrt{3/2} \lambda_m n_d i_q = k_t i_q , \qquad (2)$$

where  $k_t$  is the torque constant  $n_d$  is the number of pole pairs and  $\lambda_m$  is the rotor magnet flux linkage of the PMSM.



**Figure 1.** UAV propulsion system reference scheme. (a) Mechanical transmission schematics. (b) Three-phase PMSM schematics (one pole pair);

### 3. Fault-tolerant Control Strategy

The proposed fault-tolerant control strategy addresses the open circuit faults of the three-phase PMSM, and it is based on two sections:

- > FDI algorithm, performing the fault detection and isolation;
- > Fault accommodation technique, performing the adaptation of the control laws to maintain adequate system performances if a major fault is detected and isolated.

#### 3.1. FDI algorithm

To detect and isolate the open circuit faults, the current signature analysis approach has been applied [3, 4]. This approach uses the stator current signals only (no additional measurements wrt to those necessary for the system closed-loop control are needed) and offers very good FDI performances.

In normal operating conditions, when a PMSM provides torque, the current phasor in the Clarke's frame draws a circular trajectory. Conversely, if an open circuit fault occurs the current phasor in the Clarke's frame collapses into a linear segment. In particular, if the phase *a* opens, the current phasor draws a linear segment along the  $\beta$  axis. Similarly, if an open circuit affects phase *b* or phase *c*, the current phasor will draw linear segments, having slopes  $1/\sqrt{3}$  and  $-1/\sqrt{3}$  respectively, Figure 2(a).

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The current signature analysis thus performs the FDI of open circuit faults, by evaluating the current phasor trajectory in the Clarke's plane: if it is circular, no faults are detected; if it draws a linear segment, an open circuit is detected and, depending on the orientation of the segment in the Clarke's plane, the fault is also located to a specific phase.

The developed FDI algorithm on motor currents implements two logic sections, executed in series: Fault Detection Logic (FDL) and the Fault Isolation Logic (FIL).

The FDL and the FIL are schematically described by the flowchart in Figure 2(b). Though they have the same structure, they are executed on different quantities. In particular, at each k-th monitoring sample, if the error  $\Delta i_{\alpha\beta\gamma}|_x$  (where x=abc, a, b or c, Eqs. (3)-(4)) becomes smaller than a pre-defined threshold ( $\varepsilon$ ), a fault counter  $f_{c_x}$  is increased by 2, otherwise it is reduced by 1. When  $f_{c_x}$  reaches a maximum value ( $n_{th}$ ), the algorithm outputs the Boolean fault flag signal  $flag_x$  to true. If the above-mentioned algorithm is performed on the quantity  $\Delta i_{\alpha\beta\gamma}|_{abc}$ , the FDL is obtained and the Boolean fault flag signal  $flag_{abc}$  will represent the detection of a fault. On the other hand, if the algorithm refers to  $\Delta i_{\alpha\beta\gamma}|_a$ , the FIL is obtained and the Boolean fault flag signal  $flag_a$  will represent the isolation of the fault on phase a (similar considerations apply when the algorithm is referred to  $\Delta i_{\alpha\beta\gamma}|_b$  or  $\Delta i_{\alpha\beta\gamma}|_c$ .

$$\Delta i_{\alpha\beta\gamma}|_{abc} = \max(\Delta i_{\alpha\beta\gamma}|_{a}, \Delta i_{\alpha\beta\gamma}|_{b}, \Delta i_{\alpha\beta\gamma}|_{c})$$
(3)

$$\Delta i_{\alpha\beta\gamma}|_{a} = |i_{\alpha}|$$

$$\Delta i_{\alpha\beta\gamma}|_{b} = \left|i_{\beta} - \frac{i_{\alpha}}{\sqrt{3}}\right|$$

$$\Delta i_{\alpha\beta\gamma}|_{a} = \left|i_{\beta} + \frac{i_{\alpha}}{\sqrt{3}}\right|$$
(4)



**Figure 2.** (a) Trajectories of the current phasor in the Clarke's plane. (b) Flow chart of the FDI algorithm on motor currents

# 3.2. Fault accommodation technique

When an open circuit fault occurs, the currents in the Park's plane contain oscillatory contributes, and so the motor torque output. Hence, to maintain the motor performances after the fault, the control should act in order to restore the current phasor in the Park's plane as it was before the fault.

Let us assume that an open circuit is occurred to phase a: if the central point of the Y connection is not isolated, but a neutral point current  $i_n$  can be regulated, the zero-sequence current in the Clarke's plane can be set to:

$$i_{\gamma} = -\sqrt{2}i_{\alpha} \tag{5}$$

By imposing  $i_{\gamma} = -\sqrt{2}i_{\alpha}$  in Eq. (1) the current references for the other two phases after the fault  $i_{b_f}^*$  and  $i_{c_f}^*$  will be given by Eq. (6):

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$$\begin{cases} i_{b_{f}}^{*} = \sqrt{2} \left( -\frac{\sqrt{3}}{2} i_{\alpha}^{*} + \frac{1}{2} i_{\beta}^{*} \right) = \sqrt{2} c \left( n_{d} \theta_{em} + \frac{7\pi}{6} \right) i_{d}^{*} - \sqrt{2} s \left( n_{d} \theta_{em} + \frac{7\pi}{6} \right) i_{q}^{*} \\ i_{c_{f}}^{*} = \sqrt{2} \left( -\frac{\sqrt{3}}{2} i_{\alpha}^{*} - \frac{1}{2} i_{\beta}^{*} \right) = \sqrt{2} c \left( n_{d} \theta_{em} + \frac{5\pi}{6} \right) i_{d}^{*} - \sqrt{2} s \left( n_{d} \theta_{em} + \frac{5\pi}{6} \right) i_{q}^{*} \end{cases}$$
(6)

where  $i_{\alpha}^{*}$ ,  $i_{\beta}^{*}$  and  $i_{d}^{*}$ ,  $i_{q}^{*}$  are the current references before the fault in the Clarke and Park's frames respectively. The neutral point current reference after the fault  $i_{n_{f}}^{*}$  is instead

$$i_{n_f}^* = -\sqrt{3}i_{\gamma} = \sqrt{6}c(n_d\theta_{em})\,i_d^* - \sqrt{6}\,s(n_d\theta_{em})\,i_q^*\,. \tag{7}$$

By following a similar approach, the current references for the open circuit occurred to phase b and c can be obtained. In general, can be observed that if one compares the reference currents in normal conditions with the those given by Eq. (6), it can be stated that to maintain the torque performance, the amplitude of the currents in the healthy phases must increase by  $\sqrt{3}$  and shifted by 60° in terms of electrical angle (Figure 8), while the amplitude of the neutral point current must be  $\sqrt{3}$  times those on the healthy state phases, as confirmed by [11-14].

It is worth noting that Eq. (6) can be conveniently simplified in terms of module (1) and phase angle ( $\varphi$ ) of the current phasor in the Park's frame [10]:

$$\begin{cases} i_{xf}^{*} = \sqrt{2} I c (n_{d} \theta_{em} + \varphi + \frac{7\pi}{6}) \\ i_{yf}^{*} = \sqrt{2} I c (n_{d} \theta_{em} + \varphi + \frac{5\pi}{6}) \\ i_{wf}^{*} = 0 \\ i_{mf}^{*} = \sqrt{6} I c (n_{d} \theta_{em} + \varphi) \end{cases}$$
(8)

Now, as outlined in [2,13,14], since all the current references in the stator frame are synchronous with the rotor motion, Eq. (8), they can be expressed into a rotating frame by applying two transformations, Figure 3:

- from the planar reference  $(x_f, y_f, n_f)$ , to a planar reference frame  $(\alpha_f, \beta_f, \gamma_f)$ , in which the  $\alpha_f$  axis has opposite direction wrt the neutral current axis  $n_f$ ;
- from the planar reference  $(\alpha_f, \beta_f, \gamma_f)$  to a planar rotating frame  $(d_f, q_f, z_f)$ , defined hereafter.

Let us assume that the open circuit is occurred on the phase a: with reference to Figure 3(a), we have:

$$\begin{bmatrix} i_{af}^{*} \\ i_{\beta f}^{*} \\ i_{\gamma f}^{*} \end{bmatrix} = \mathbf{T}_{Caf} \begin{bmatrix} i_{bf}^{*} \\ i_{cf}^{*} \\ i_{nf}^{*} \end{bmatrix} = \begin{bmatrix} \sqrt{3}/2 & \sqrt{3}/2 & -1 \\ 1/2 & -1/2 & 0 \\ 0 & 0 & -1/\sqrt{3} \end{bmatrix} \begin{bmatrix} i_{bf}^{*} \\ i_{cf}^{*} \\ i_{nf}^{*} \end{bmatrix},$$
(9)

**Figure 3.** Planar reference frame transformations after an open circuit on (a) phase *a*; (b) phase *b*; (c) phase *c*.

while the current phasor in the rotating frame is:

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$$\begin{bmatrix} i_{df}^{*} \\ i_{qf}^{*} \\ i_{zf}^{*} \end{bmatrix} = \mathbf{T}_{Paf} \begin{bmatrix} i_{\alpha f}^{*} \\ i_{\beta f}^{*} \\ i_{\gamma f}^{*} \end{bmatrix} = \begin{bmatrix} p_{11} c(n_{d}\theta_{em}) & p_{12} s(n_{d}\theta_{em}) & 0 \\ p_{21} s(n_{d}\theta_{em}) & p_{22} c(n_{d}\theta_{em}) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} i_{\alpha f}^{*} \\ i_{\beta f}^{*} \\ i_{\gamma f}^{*} \end{bmatrix},$$
(10)

By substituting Eq (10) into Eq.(9) and by recalling Eq.(6), can be obtained:

$$\begin{bmatrix} i_{df}^{*} \\ i_{qf}^{*} \\ i_{zf}^{*} \end{bmatrix} = \frac{\sqrt{2}}{2} I \begin{bmatrix} \left[ \frac{p_{12}}{2} - \left( \frac{3}{2} + \sqrt{3} \right) p_{11} \right] c(\varphi) - \left[ \frac{p_{12}}{2} + \left( \frac{3}{2} + \sqrt{3} \right) p_{11} \right] c(\varphi + 2n_d \theta_{em}) \\ \begin{bmatrix} p_{22} \\ 2 \end{bmatrix} \left[ \left[ \frac{p_{22}}{2} + \left( \frac{3}{2} + \sqrt{3} \right) p_{21} \right] s(\varphi) + \left[ \frac{p_{22}}{2} - \left( \frac{3}{2} + \sqrt{3} \right) p_{21} \right] s(\varphi + 2n_d \theta_{em}) \\ -2 c(\varphi + n_d \theta_{em}) \end{bmatrix}$$
(11)

Thus, by imposing  $i_{df}^* = i_d^*$  and  $i_{qf}^* = i_q^*$ , we have:

$$p_{11} = -p_{21} = -\sqrt{2} (3 + 2\sqrt{3})^{-1}, \qquad p_{12} = p_{22} = \sqrt{2}$$
(12)

As a final result, the transformation matrix from the stator reference frame  $(b_f, c_f, n_f)$  to the rotating frame  $(d_f, q_f, z_f)$  is given by:

$$\boldsymbol{T}_{Paf}\boldsymbol{T}_{Caf} = \begin{bmatrix} k_2 \, s(n_d\theta_{em}) - k_1 \, c(n_d\theta_{em}) & -k_2 \, s(n_d\theta_{em}) - k_1 \, c(n_d\theta_{em}) & k_3 \, c(n_d\theta_{em}) \\ k_1 \, s(n_d\theta_{em}) + k_2 \, c(n_d\theta_{em}) & k_1 \, s(n_d\theta_{em}) - k_2 \, c(n_d\theta_{em}) & -k_3 \, s(n_d\theta_{em}) \\ 0 & 0 & -\frac{1}{\sqrt{3}} \end{bmatrix}, \quad (13)$$

where:

$$k_1 = \sqrt{6} (6 + 4\sqrt{3})^{-1}, \qquad k_2 = \frac{1}{\sqrt{2}}, \qquad k_3 = \sqrt{2} (3 + 2\sqrt{3})^{-1},$$
(14)

By using a similar approach for the open circuits to the other phases of the motor (see Figure 3(b)-(c)), a generalized definition of the transformation matrixes can be obtained [2].

The last step to define the fault accommodation technique requires the calculation of the phase voltage references for the motor drive, which are given by the inverse reference frame transformations in the failed conditions.

$$\begin{bmatrix} V_{bf}^*\\ V_{cf}^*\\ V_{nf}^* \end{bmatrix} = \left( \boldsymbol{T}_{Paf} \boldsymbol{T}_{Caf} \right)^{-1} \begin{bmatrix} V_{d_f}^*\\ V_{q_f}^*\\ V_{z_f}^* \end{bmatrix},$$
(15)

Again, as made for the direct transformation, a generalized definition of the inverse transformation matrixes can be obtained, [2].

#### 4. Simulation Results

The effectiveness of the fault-tolerant control strategy has been tested by using the nonlinear model of the propulsion system. The model has been entirely developed in the MATLAB/Simulink environment, and its numerical solution is obtained via the Runge-Kutta method, with a 10<sup>-5</sup>s integration step. Both the closed-loop control and the health-monitoring functions are executed at 20 kHz sampling rate.

All the simulations started (t=0 s) with the PMSM in normal conditions, driving the propeller at 5800 rpm (related to a trim levelled flight at sea level, at 26 m/s speed).

The effectiveness of the fault-tolerant control strategy has been assessed through two test campaigns, obtained by applying or not the developed algorithms. In these simulations, an open circuit to a motor phase is injected at t=50 ms during steady-state conditions.

If no mitigation actions are undertaken such torque values can irreversibly damage the low resistant component of the drivetrain (e.g., bearings) causing in turn the failure of the propulsion system entirely. Thanks to the fault tolerant control the performances degradation after fault are reduced and the FDI technique identifies and isolates the faulted phase within 15ms, Figure 4 (a).

The relevant post fault oscillations of the quadrature voltage are minimized when the accommodation technique is applied, Figure 5.

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As expected due to the phase *a* disconnection the remaining healthy phases are forced to a pushpull status until the neutral path is employed, Figure 6.



**Figure 4.** Normalized motor torque with open circuit on phase *a* at t=50 ms (Qem | max =4.2Nm). (a) without accommodation. (b) with accommodation.



**Figure 5.** Normalized quadrature voltage with open circuit on phase *a* at t=50 ms (V | lim =330 V). (a) without accommodation. (b) with accommodation.



**Figure 6.** Normalized phase currents with open circuit on phase a at t=50 ms (I|<sub>lim</sub> =92 A). (a) without accommodation. (b) with accommodation.

### 5. Conclusions

A fault-tolerant control strategy for a three-phase PMSM, based on the combination of a FDI algorithm with an accommodation technique, has been developed and characterized in terms of fault-detection, isolation latencies and accommodation capabilities. A nonlinear model of the electrical

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propulsion system used to drive a light-weight UAV propeller, has been developed and used to evaluate the algorithm's performances by simulating single phase open circuit during a trim levelled flight of the UAV. The FDI algorithm, based on current signature method, performs a fault latency lower than 13 msec. The accommodation technique, based on the three-phase PMSM central point drive through a four-leg inverter topology, permits to totally restore the propulsion system pre-fault torque performances. Future developments of the research will be focused on the integration of a nonideal four-leg inverter model first and experimental verification then.

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