Sensor Fault Detection, Localization and System Reconfiguration Based on a Sliding Mode Observer and Adaptive Threshold of PMSM

Aibeche Abderrezak† and Kidouche Madjid*

†Dept. of Automation, Applied Automation Laboratory, University of Boumerdes, Boumerdes, Algeria

Abstract

This paper deals with an on-line software fault detection, localization and system reconfiguration method for electrical system drives composed of three-phase AC/DC/AC converters and three-phase permanent magnet synchronous machine (PMSM) drives. Current sensor failure (outage), speed/position sensor loss (disconnection) and damaged DC-link voltage sensor are considered faults. The occurrence of these faults on PMSM drive systems might lead to degraded system performance and affects the safety, the maintenance and the service continuity for electrical system drives. The proposed method is based on the monitoring signals of ‘abc’ currents, DC-link voltage and rotor speed/position using measurement chain. In order to have an on-line fault decision, the listed signals are analyzed and evaluated using the generated residuals and the thresholds values obtained from Sliding Mode Current-Speed-DC link voltage Observer (SMCSVO). The novelty in the method is based on faults diagnosis algorithm that combines the use of SMCSVO and adaptive thresholds, so that, the number of false alarms is reduced, the reliability and robustness of the faults detection system are guaranteed. Furthermore, the proposed algorithm performance is experimentally analyzed and tested in real time using dSPACE DS 1104 DSP board.

Key words: Adaptive threshold, Fault diagnosis, Permanent Magnet Synchronous Machines, Sliding mode

I. INTRODUCTION

Recently the significant improvement in the reliability of the variable speed drive systems was developed according to the technological development in power electronics, digital signal processors (DSPs), computer science and electrical engineering. The specified requirements such as protection, safety and continuity of the service mainly protect the both personals and electrical systems that were caused by the managing of the electrical drives systems faults [1]-[3].

According the following advantages of the permanent magnet synchronous machines (PMSMs) drives: high efficiency, high power density with low weight and easy high-speed operation. There are used in the electrical drives systems that become more interesting in the last years. For their advantages, the PMSMs drives are increasingly used in electric traction “vehicles, tramways, high speed trains…” aerospace, aeronautics, nuclear power plants, wind energy conversion systems, and in many industrial applications of variable speed drives [2]-[7].

The PMSM motor drive system is a combination of electrical, electronic and mechanical components. It is composed of power source, rectifier, DC-link bus (filter), inverter VSC (voltage-source converter), PMSM motor drives and control part. The control system is based on the measured information in the motor and the power electronics in real time. Otherwise these components present many faults [6], [8]-[12].

Fortunately different fault-tolerant operation methods by reconfiguring topologies and control strategies are adopted to improve the electrical system reliability [3], [6], [8]-[14].

Recently, sliding mode observer (SMO) is one of the most attractive methods that can accurately estimate the state of the PMSM drives [1], [2], [15], [16]. A disadvantage of this method is that an undesirable chattering phenomenon is inevitable on the estimate variables. To solve this problem, the robust method is proposed in [16] to avoid the used of the low-pass filter and the position compensation, the sign-num and saturation functions are replaced by the sigmoid function.
The extended phase-locked loop (EPLL) algorithm described in [5] combined with SMO is adopted to estimate the rotor speed and reconstruct the rotor position.

The reliability of the PMSM/PWM-VSC drive systems depends on the reliability of the both power conversion systems (rectifiers and inverters) and the measurements sensors [9], [17]-[19]. The reliability of the power conversion systems is analyzed and investigated in [3], [4], [8], [9], [20], and [21]. It is estimated that about 38% of the faults in voltage-source power conversion systems were due to failures of power devices such as IGBT (short circuit and open switch faults) [8]. However, a fault in the sensors (currents, speed, and DC-link voltage) can cause instability in the control loops of the system [11], [12], [18], [19]. The measured data by the current, DC-link voltage and speed/position sensors are extremely important data that will determine the reliability, the control system performances and the efficiency of the PMSM drive systems [10]-[14], [17]-[19].

To guarantee the safety, the maintenance and the service continuity, the accurate and robust algorithm for detection, localization and reconfiguration sensors faults is indispensable. The problems of these sensors are described and detailed in most researches [10]-[14], [17]-[19]. In these papers, the majority of the existing sensors faults diagnostic methods are based on a fixed threshold, these values are depending to the operating conditions (speed, load). This has a negative impact on the performance of these methods, leading to the generation of the false alarms. Accordingly, the proposed method is based on monitoring the evolution of thresholds and residues values of the measured data according to the speed and load of the system, with the proposed method is completely mentioned the independence between the residuals of the system.

We consider that the faults are occurred in the essential sensors of control system. Then, the sliding mode observer is applied to estimate the stator currents, rotor speed/position and DC-link voltage sensors, and the adaptive threshold used to reduce the false alarms. The validity of the proposed algorithm is verified by a comprehensive set of experiments.

II. MATHEMATICAL MODEL OF A PMSM

Generally, the mathematical models of the electrical machines AC drives are based on some simplifying assumptions, such as [1], [6], [7]:

Stator windings are assumed to be perfectly sinusoidally distributed, fundamental component is considered due to the sinusoidal distribution of magnetic fields, and magnetic saturation, hysteresis losses and leakage flux are ignored. With these assumptions, the mathematical model of the PMSM drives can be modeled by using natural (abc) reference frame.

\[
\begin{align*}
\begin{bmatrix} v_{abc}(t) \\ \dot{\lambda}_{abc}(t) 
\end{bmatrix} &= \begin{bmatrix} R_s & L_{abc} \\ L_{abc} & L_{abc} 
\end{bmatrix} \begin{bmatrix} i_{abc}(t) \\ \dot{i}_{abc}(t) 
\end{bmatrix} + \begin{bmatrix} \frac{d}{dt} \lambda_{abc}(t) \\ 0 
\end{bmatrix} \\
\dot{\lambda}_{abc}(t) &= \begin{bmatrix} R_s & L_{abc} \\ L_{abc} & L_{abc} 
\end{bmatrix} \begin{bmatrix} i_{abc}(t) \\ \dot{i}_{abc}(t) 
\end{bmatrix} + \begin{bmatrix} 0 \\ \frac{d}{dt} \lambda_{abc}(t) 
\end{bmatrix}
\end{align*}
\]

where \([v_{abc}(t)]=[v_s(t) v_b(t) v_c(t)]^T\) and \([\dot{i}_{abc}(t)]=[i_s(t) i_b(t) i_c(t)]^T\) are the stator phase voltage and current vectors respectively; \([\lambda_{abc}(t)]=[\lambda_s(t) \lambda_b(t) \lambda_c(t)]^T\) is the stator flux linkage vector; \([R_s]=R_a = R_b = R_c\); \([L_{abc}]\) is the inductance matrix due to the permanent magnet, and \(\theta_{r,abc}\) is the initial electrical phase for three phase machine \(\theta_{r,abc}=0^\circ\) to \(-120^\circ\) to \(-240^\circ\).

In order to obtain the PMSM model in two axes, the Concordia and Park transformations are usually used to express the variables in stationary and rotational references frames.

The relationship among these references frames are illustrated in Fig.1 and expressed by.

\[
\begin{align*}
\begin{bmatrix} x_d(t) \\ x_q(t) 
\end{bmatrix} &= \begin{bmatrix} \frac{2}{\sqrt{3}} & -\frac{1}{2} & \frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} 
\end{bmatrix} \begin{bmatrix} x_a(t) \\ x_b(t) \\ x_c(t) 
\end{bmatrix} \\
\begin{bmatrix} x_d'(t) \\ x_q'(t) 
\end{bmatrix} &= \begin{bmatrix} \cos(\theta_{re}) & \sin(\theta_{re}) \\ -\sin(\theta_{re}) & \cos(\theta_{re}) 
\end{bmatrix} \begin{bmatrix} x_d(t) \\ x_q(t) 
\end{bmatrix}
\end{align*}
\]

where \(x(t)\) can represent voltage, current or flux variables and \(\theta_{re}\) is the electrical position of the rotor.

![Fig. 1. Layout for PMSM drives in different references frames.](image-url)
(α-β) stationary references frames are represented in equations (5) and (6) respectively.

\[
\begin{align*}
\frac{d i_{sd}^{(s)}}{dt} &= \frac{1}{L_i} i_{sd}^{(s)} - \frac{R_s}{L_i} i_{sd}^{(s)} + \frac{L_d}{L_i} i_{dq}^{(s)} p \omega_m \\
\frac{d i_{dq}^{(s)}}{dt} &= \frac{1}{L_q} i_{dq}^{(s)} - \frac{R_s}{L_q} i_{dq}^{(s)} - \frac{L_d}{L_q} i_{dq}^{(s)} p \omega_m - \frac{2 \lambda_m}{L_q} p \omega_m \\
\frac{d \omega_m}{dt} &= \frac{1}{J} [T_e - B \omega_m(t) - T_d] \\
T_e &= \frac{3}{2} \left[ L_m^{(s)} i_{dq}^{(s)} + \Delta L_{dq} i_{dq}^{(s)} \right]
\end{align*}
\]

where \( i_{sd}^{(s)}, i_{dq}^{(s)} \) are stator currents in the (d-q) reference frame, resistance, \( d \)- and \( q \)-axis inductances respectively, mechanical rotor position, rotor speed, electrical angular rotor speed \( \omega_m = P \omega_m = P \frac{d \theta_m}{dt} \), viscous friction coefficient, inertia, load torque, number of pole pairs, respectively, and \( \Delta L_{dq} = L_s - L_q \), for a salient-pole PMSM \( \Delta L_{dq} \) is zero for a non-salient -pole PMSM.

\[
\begin{align*}
\frac{d i_{sd}^{(s)}}{dt} &= \frac{1}{L_i} i_{sd}^{(s)} - \frac{R_s}{L_i} i_{sd}^{(s)} - \frac{L_d}{L_i} i_{dq}^{(s)} p \omega_m + \eta \sin \theta_re \\
\frac{d i_{dq}^{(s)}}{dt} &= \frac{1}{L_q} i_{dq}^{(s)} - \frac{R_s}{L_q} i_{dq}^{(s)} + \frac{L_d}{L_q} i_{dq}^{(s)} p \omega_m - \eta \cos \theta_re \\
T_e &= \frac{3}{2} \left[ L_m^{(s)} \cos \theta_re i_{sd}^{(s)} - \frac{L_d}{L_i} i_{dq}^{(s)} \sin \theta_re + i_{sd}^{(s)} \sin \theta_re \cos \theta_re \right]
\end{align*}
\]

where, \( \eta = \Delta L_{dq} (\omega_m e_{sd}^{(s)} - S i_{dq}^{(s)}) + \lambda_m \omega_r e \) is the magnitude of the extended back EMF term, \( i_{sd}^{(s)}, i_{dq}^{(s)} \) are stator voltages and currents in the (α-β) reference frame, respectively, and \( S \) is the derivative operator.

III. PROPOSED FAULT DIAGNOSIS METHOD

A. Design of a SMCSV Observer

The information of the PMSM stator currents, rotor speed/position and DC-link voltage is essential to the control system PWM-SVM. In this paper, sliding mode for the currents-speed-DC-link voltage observer “SMCSV” is designed to estimate these informations [15], [16].

Based on (6), the SMCSV can be designed as:

\[
\begin{align*}
\frac{d \hat{i}_{sdq}^{(s)}}{dt} &= \frac{1}{L_d} \hat{i}_{sdq}^{(s)} - \frac{R_s}{L_d} \hat{i}_{sdq}^{(s)} + \Delta L_{dq} \left[ \begin{array}{c} 0 \\ 0 \end{array} \right] \hat{i}_{sdq}^{(s)} - \frac{1}{L_d} \hat{K}_{SMCSV} (\hat{i}_{sdq}^{(s)}) \\
\frac{d \hat{i}_{sdq}^{(s)}(t)}{dt} &= \hat{v}_{sdq}^{(s)} - \frac{R_s}{L_d} \hat{i}_{sdq}^{(s)} - \hat{K}_1 H (\hat{i}_{sdq}^{(s)})
\end{align*}
\]

where \( K_{SMCSV}, K_1 \) are the positives gains constant of the currents and fluxes observer, \( \hat{i}_{sdq}^{(s)} \) and \( \hat{i}_{sdq}^{(s)} \) are the estimated stator currents and fluxes vectors, \( \hat{v}_{sdq}^{(s)} \) is the reconstructed stator voltages vector, \( \hat{i}_{sdq}^{(s)} = \hat{i}_{sdq}^{(s)} - \hat{i}_{sdq}^{(s)} \) and \( \hat{i}_{sdq}^{(s)} = \hat{i}_{sdq}^{(s)} - \hat{i}_{sdq}^{(s)} \) are the current errors between measured and estimated stator currents, and \( H(\hat{i}_{sdq}^{(s)}) = H(\hat{i}_{sdq}^{(s)}) \) are the sigmoid functions based on the error of the estimated stator currents and the actual stator currents. The values of this functions are: \((-1 < H(\hat{i}_{sdq}^{(s)}) < 1)\).

Many variations of equation (8) can be found in the literature, e.g., using the signum function or the saturation function [1], [2], [15], [16]. In this work the sigmoid function is chosen to replace the signum function to alleviate and reduce the undesirable chattering problem [16]. The property of the sigmoid function can be expressed in the following expression:

\[
H(\hat{i}_{sdq}^{(s)}) = \left[ \frac{2}{1 + \exp(-(a(t) \hat{i}_{sdq}^{(s)}(t)))} - 1 \right]
\]

where “a” is a positive coefficient used to regulate the slope of the sigmoid function.

The PMSM phase voltage \( v_{sa}^{(s)}, v_{sb}^{(s)} \) and \( v_{sc}^{(s)} \) can be reconstituted using the measured DC-bus voltage \( V_{dc,m} \) and the inverter switching states \( S_a, S_b, S_c \):

\[
\begin{align*}
\begin{bmatrix}
  v_{sa}^{(s)} \\
  v_{sb}^{(s)} \\
  v_{sc}^{(s)}
\end{bmatrix} &= \frac{V_{dc,m}}{3} \begin{bmatrix}
  2 & -1 & -1 \\
  -1 & 2 & -1 \\
  -1 & -1 & 2
\end{bmatrix} \begin{bmatrix}
  S_a \\
  S_b \\
  S_c
\end{bmatrix}
\end{align*}
\]

In stationary (α-β) frame, the previous stator voltages can be written as:

\[
\begin{align*}
\begin{bmatrix}
  v_{sd}^{(s)} \\
  v_{sq}^{(s)}
\end{bmatrix} &= \sqrt{3} \begin{bmatrix}
  1 & -1 & -1 \\
  0 & -\frac{2}{\sqrt{3}} & 0 \\
  0 & -\frac{2}{\sqrt{3}} & 0
\end{bmatrix} \begin{bmatrix}
  v_{sa}^{(s)} \\
  v_{sb}^{(s)} \\
  v_{sc}^{(s)}
\end{bmatrix}
\end{align*}
\]

\[
\begin{align*}
V_{dc,m} &= \begin{bmatrix}
  0 \\
  \sqrt{6} \\
  0
\end{bmatrix} \begin{bmatrix}
  S_a \\
  S_b \\
  S_c
\end{bmatrix}
\end{align*}
\]

where \([v_{sdq}^{(s)}]\) is the input voltage to the SMCSV.

Also, the relationship between the switching states \( (S_a, S_b, S_c) \) and the voltage vector \( [v_{sdq}^{(s)}] \) can be expressed below:

\[
\begin{align*}
\begin{bmatrix}
  v_{sd}^{(s)} \\
  v_{sq}^{(s)}
\end{bmatrix} &= \sqrt{3} \begin{bmatrix}
  x \\
  y
\end{bmatrix} = \frac{\sqrt{6}}{2} \begin{bmatrix}
  2S_a - S_b - S_c \\
  S_b - S_c
\end{bmatrix}
\end{align*}
\]

From expression (11), by varying the switching vector, \( [S_a, S_b, S_c]^T \), the α-axis and β-axis voltages can be obtained for the various states.
The DC-link voltage is sensitive to speed variations (speed reversal operations, speed change...) and loads changes (sudden). In fact, in a variation of the DC-link voltage, the output of the control loop is changed and the PWM signals vary in order to maintain the desired speed or torque. This can affect the perfect management of the electrical power and its transfers of the rectifier-inverter and machine [3], [10]-[13], [19]. To avoid these undesirable consequences of the DC-link voltage faults on the performance or possibly on the operating electrical systems safety. So a software redundancy (virtual sensor) should be set up in our system to monitor the DC-link voltage sensor. As result, it is interesting to estimate the DC-link voltage using the rated voltage (constant) and the duty cycles.

The dynamic of the DC link voltage can be defined as:
\[
V_{dc-m} = \mu V_{dc-n}
\]
(12)
where \(\mu\) is a gain determined based on the PWM switching approach.

If the DC-link voltage is not measured, it is estimated by:
\[
\hat{V}_{dc} = \hat{\mu} V_{dc-n}
\]
(13)
where \(V_{dc-n}\) and \(\hat{V}_{dc}\) are the nominal and observed DC-link voltage, respectively.

By accurate estimation of \(\mu\), the real DC-link voltage is determined. So the dynamic estimation error of the DC-link voltage defined by:
\[
\tilde{V}_{dc} = \mu - \hat{\mu} W_{dc-n} = \tilde{\mu} V_{dc-n}
\]
(14)
Substituting the terms with equations (12) and (13) in equation (11), the stator voltages vector \(\hat{v}_{edc}^{(e)}\) are expressed as:
\[
\begin{bmatrix}
\hat{v}_{ed}^{(e)} \\
\hat{v}_{sq}^{(e)}
\end{bmatrix} = V_{dc-m} \begin{bmatrix}
x \\
y
\end{bmatrix} = \hat{\mu} V_{dc-n} \begin{bmatrix}
x \\
y
\end{bmatrix}
\]
(15)
From equation (15) the stator voltages are reconstruction using the nominal DC-bus \(V_{dc-n}\), the estimate coefficient \(\hat{\mu}\) and the states of the power switches:
\[
\begin{bmatrix}
\hat{v}_{sd}^{(e)} \\
\hat{v}_{sq}^{(e)}
\end{bmatrix} = \hat{V}_{dc} \begin{bmatrix}
\hat{x} \\
\hat{y}
\end{bmatrix} = \hat{\mu} V_{dc-n} \begin{bmatrix}
\hat{x} \\
\hat{y}
\end{bmatrix}
\]
(16)
where, \(\hat{v}_{sd}^{(e)}\) and \(\hat{v}_{sq}^{(e)}\) are the estimated stator voltages and represented the new inputs of the SMCSVO.

From (7), (13) and (16), the design of a sliding mode for the currents, fluxes and DC-link voltage observers is synthesized:
\[
\begin{align*}
\frac{d}{dt} \hat{z}_{sd}(s) &= \frac{1}{L_d} \hat{v}_{sd}^{(e)} - \frac{R_s}{L_d} \hat{z}_{sd}(s) + \omega r e \Delta L_{dc} - \frac{L_d}{L_d} K_{SMO} \hat{H}(\hat{z}_{sd}(s)) \\
&= \frac{1}{L_d} \frac{d}{dt} \hat{z}_{sd}(s) \\
\frac{d}{dt} \hat{z}_{sq}(s) &= \hat{v}_{sq}^{(e)} - \frac{R_s}{L_d} \hat{z}_{sq}(s) + K_J \hat{H}(\hat{z}_{sq}(s)) \\
\end{align*}
\]
(17)
where \(K_{SMO}\) and \(K_J\) are the back-EMF voltages components.

The sliding surface \(S_n\) can be defined as:
\[
S_n = [\hat{z}_{sd}(s) \hat{z}_{sq}(s) \hat{z}_{sd}(s) \hat{z}_{sq}(s) \hat{\mu}] = [0 \ 0 \ 0 \ 0 \ 0]
\]
(20)
By accurately selecting \(K_{SMO}, K_J\) and \(\hat{\mu}\), the candidate Lyapunov function \(V = S_n^T S_n / 2 > 0\) and \(dV/dt < 0\) can be guaranteed, so as the observer stability.

To analyze the stability, consider the following Lyapunov function.
\[
V = \frac{1}{2} \left( (\hat{z}_{sd}(s))^2 + (\hat{z}_{sq}(s))^2 + (\hat{z}_{sd}(s))^2 + (\hat{z}_{sq}(s))^2 + \hat{\mu}^2 \right) > 0
\]
(21)
The time derivative of Lyapunov function is found as:
\[
\dot{V} = -\hat{\mu} \frac{d}{dt} \hat{\mu} + \frac{d}{dt} \frac{d}{dt} \hat{z}_{sd}(s) + \hat{\mu} \frac{d}{dt} \hat{z}_{sq}(s) + \hat{\mu} \frac{d}{dt} \hat{z}_{sd}(s) + \hat{\mu} \frac{d}{dt} \hat{z}_{sq}(s) + \frac{d}{dt} \hat{\mu}
\]
(22)
where \(K_e\) is a positive updating gain of the DC-link voltage observer. Substituting the current and flux derivation terms with (17) and r-arranging the (22) is derived.
\[
\dot{V} = -\hat{\mu} \frac{d}{dt} \hat{\mu} + \frac{d}{dt} \frac{d}{dt} \hat{z}_{sd}(s) + \frac{d}{dt} \hat{\mu}
\]
(23)
To ensure the negativity of equation (23) the adaptive gains can be designed by:
\[
\hat{\mu} = K_{\mu} V_{dc-n} \left[ \frac{1}{L_d} \hat{v}_{sd}^{(e)} + \frac{1}{L_d} \hat{v}_{sq}^{(e)} \right] + \frac{1}{L_d} \frac{d}{dt} \frac{d}{dt} \hat{z}_{sd}(s) + \frac{d}{dt} \hat{\mu}
\]
(24)
\[
K_{SMO} = \frac{[\hat{z}_{sd}(s) \hat{v}_{sd}^{(e)} + \hat{z}_{sq}(s) \hat{v}_{sq}^{(e)}]}{[\hat{z}_{sd}(s) H(\hat{z}_{sd}(s)) + \hat{z}_{sq}(s) H(\hat{z}_{sq}(s))]} - \frac{1}{L_d} \frac{d}{dt} \frac{d}{dt} \hat{z}_{sd}(s) + \frac{d}{dt} \hat{\mu}
\]
(25)
If the sliding mode is enforced, the back EMF voltages components can be estimated in the form:
\[
\begin{align*}
\dot{\bar{c}}_{sd} & = -\lambda_m \dot{\theta}_r e \sin(\dot{\theta}_r e) \pm K_{SMO} H(\ddot{\bar{c}}_{sd}) \\
\dot{\bar{c}}_{sq} & = \lambda_m \dot{\theta}_r e \cos(\dot{\theta}_r e) \pm K_{SMO} H(\ddot{\bar{c}}_{sq}) \\
\end{align*}
\] (25)

Then the estimated rotor position can be extracted from the estimated back EMF voltages components, can be expressed as follows:

\[
\dot{\theta}_r = \arctan2[-\bar{c}_{sd}, \bar{c}_{sq}] \equiv \arctan2[-H(\ddot{\bar{c}}_{sd}), H(\ddot{\bar{c}}_{sq})] \\
\] (26)

The block scheme of this algorithm is shown in Fig. 2 and the proposed SMCSVO combined by EPLL structure is illustrated in Fig. 3.

\[
\begin{align*}
\dot{E}_{sd}(\dot{\theta}_r) &= \sin
\dot{E}_{sq}(\dot{\theta}_r) &= \cos
\end{align*}
\]

Fig. 2. Extended PLL block scheme.

\[
\begin{align*}
\dot{\theta}_r &= \text{EPLL}
\end{align*}
\]

Fig. 3. Structure of the proposed observer.

Using the Extended Phase Locked Loop “EPLL” algorithm the rotor speed is observed from:

\[
\dot{\omega}_r = \left( K_p + \frac{K_i}{S} \right) \omega(t) = \left( K_p + \frac{K_i}{S} \right) 10^9 \left( \ddot{\theta}_r - \dot{\theta}_r \right) \\
\] (27)

where \( \dot{\theta}_r \) is the argument of the feedback signals, represents the estimated rotor position, \( \dot{\theta}_r \) represents the argument of the input waveforms and \((K_p,K_i)\) are the proportional and integral gains of the PI controller, respectively.

### B. Proposed Fault Diagnosis Method

#### B.1. Hardware and Software System Configuration

The Hardware and software system configuration of a sensors fault diagnosis for PMSM drive system using Sliding Mode Currents-Speed-DC-link Voltage Observer (SMCSVO) is shown in Fig. 4, including the control system, a software supervision, protection system, a PMSM, a voltage source inverter (VSI), an AC source and Data acquisition system based on the available measurements (phase currents, DC-link voltage, and mechanical rotor speed/position).

To perform the proposed configuration, the following steps are necessary:

- Sensing and processing of currents, rotor speed/position and DC-link voltage.
- Accurate measurements of currents, rotor speed/position and DC-link voltage.
- Measure the stator phase currents of the PMSM using Hall-effect current transducers: The fault diagnosis method is based on hardware redundancy with additional current sensors (two on each phase) and estimated current using software algorithm (see Fig. 5(a)), the advantage of this technical is increased and guaranteed the reliability.

- Measure the rotor speed/position (\(\omega_r\) or \(\theta_r\)) using a rotor position encoder.
- Accuracy of currents, rotor speed/position and DC-link voltage observers.
- Perform the space vector pulse width modulation (SVPWM) based on generate the gate signals for the voltage source inverter (VSI).
- Perform the fault diagnosis algorithm based on generate of the signification coefficients: \(F_{dx}, \dot{F}_{dx}, F_{dx}, \dot{F}_{dx}\) and \(F_{dx}\).
- Efficiency of software protection to inhibit the drive system in case of an DC-link over-voltage/under-voltage, over-current, over-speed, ground fault and major faults. These functions are performed by a hardware and software configuration.

#### B.2. Sensor fault detection, localization and reconfiguration

##### B.2.1. Current Sensor FDLR Unit

The proposed fault detection, localization and reconfiguration (FDLR) algorithm of current sensor is based on the sliding mode current observer (SMCO) model and the current coefficients calculation. Tow coefficients are
calculated: one from measured current $F_{kx}$ and the other through the observed current $\hat{F}_{kx}$. The values of $F_{kx}$ and $\hat{F}_{kx}$ are used in the FDLR method. There are defined as follows:

$$
\begin{align*}
F_{kx} &= \frac{\text{RMS}(I_{kx})}{\text{Mean}(I_{kx}) + \varepsilon} \\
\hat{F}_{kx} &= \frac{\text{RMS}(\hat{I}_{kx})}{\text{Mean}(\hat{I}_{kx}) + \varepsilon}
\end{align*}
$$

where $k=a,b,c$ is the number of phases, $x=1,2$ is the number of current sensors (two per phase) and $\varepsilon$ is a too small positive constant used to avoid the singularity into terms $F_{kx}$ and $\hat{F}_{kx}$. Under normal operating conditions, the coefficients values are approximately equal to $(\pi/2\sqrt{2} = 1.111)$.

When in the case of current sensor fault “outage” occurs, the coefficients values will have different behaviors instantaneous evolution, being therefore practical for diagnostic purpose. So, the comparison between the two coefficients allows the detection, localization and reconfiguration of the faulty current sensor. The main idea of the proposed FDLR method is to use the $\hat{F}_{kx}$ as adaptive threshold for $F_{kx}$, and both coefficients are independent of the variations in current, speed and load transients. So, the adaptive thresholds are calculated:

$$
S_k = \hat{F}_k + \zeta_k
$$

where $\zeta_k$ is a positive gain used to guarantee the robust diagnosis and good separation between $F_{kx}$ and $\hat{F}_{kx}$, these value $0<\zeta_k<1$.

In order to diagnose the current sensor fault, the following residuals variables are considered:

$$
r_{kx} = S_k - F_{kx} + k_1
$$

So, six residues are generated for current sensors. These values are compared with thresholds values to detect faults. $k_1$ is a positive gain $0<k_1<1$.

### TABLE I

INCIDENCE TABLE WITH A 6-SENSORS RECONFIGURATION

<table>
<thead>
<tr>
<th>Sensors $k_x$</th>
<th>Faulty Flags $(I_{kx})$</th>
<th>State ph(k)</th>
<th>Residuals</th>
<th>Phase (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fault</td>
<td>0 0</td>
<td>1</td>
<td>$r_{kx} &gt; s_1$ and $r_{kx} &gt; s_3$</td>
<td>$I_{r_{kx}} = 0.5(I_{kx} + I_{\hat{kx}})$</td>
</tr>
<tr>
<td>$k1$</td>
<td>1 0</td>
<td>2</td>
<td>$r_{k1} &lt; s_1$ and $r_{k1} &lt; s_2$</td>
<td>$I_{r_{k1}} = I_{k1}$</td>
</tr>
<tr>
<td>$k2$</td>
<td>0 1</td>
<td>3</td>
<td>$r_{k2} &lt; s_1$ and $r_{k2} &lt; s_3$</td>
<td>$I_{r_{k2}} = I_{k2}$</td>
</tr>
<tr>
<td>$k1$ and $k2$</td>
<td>1 1</td>
<td>4</td>
<td>$r_{k1} &lt; s_1$ and $r_{k2} &lt; s_3$</td>
<td>$I_{r_{k1},r_{k2}} = I_{k1} + I_{k2}$</td>
</tr>
</tbody>
</table>

$x=1,2, k=(a,b,c), i=(a,b,c), j=(a,b,c), \text{where } i \neq k, i \neq j \text{ and } j \neq k, 0: \text{healthy operations, 1:Faulty operations}$

The fault flags of current sensors can be given as:

$$
\text{Flag } I_{kx} =
\begin{cases}
0 & \text{if } r_{kx} < S_k \text{ Healthy operations} \\
1 & \text{if } r_{kx} > S_k \text{ Faulty operations}
\end{cases}
$$

The logic circuit presented in Fig. 5(a) can identify the faulty sensor for a phase current fault and reconfiguration system for current sensor fault. Table I illustrate the configuration structure for this diagnosis system.

#### B.2.2. Speed sensor FDLR Unit

Before the occurrence of a speed sensor fault, the PMSM motor control system is based on a vector controlled algorithm with speed sensor feedback. After a speed sensor fault is detected, the PMSM motor control system is based on a vector controlled algorithm with speed sensorless feedback using sliding mode speed observer (SMSO) model Fig. 4.

Two coefficients are calculated:

$$
\begin{align*}
F_o &= \frac{\omega_{re} - \hat{\omega}_r}{\omega_{re} + \omega_{nom}} \\
\hat{F}_o &= \frac{\hat{\omega}_r}{\omega_{nom}}
\end{align*}
$$

Under normal operating conditions, the values of the two coefficients are different $F_o \approx 0$ and $0 < \hat{F}_o < 1$. When a speed sensor is faulty “outage”, the coefficients values are equal $F_o = \hat{F}_o$.

In order to diagnose the speed sensor fault, the following residual variable is defined:

$$
r_o = S_o - F_o + \zeta_o
$$

where $S_o = \hat{F}_o$ is the adaptive threshold and $\zeta_o$ is positive gain used to guarantee the robust diagnosis and to ensure a very short time for fault detection, the value of $\zeta_o$ is chosen $0 < \zeta_o < 0.1$.

The scheme of the speed sensor FDI unit is given by:

- If $r_o > S_o$, define Flag $\omega = 0$ and $\omega_{re,rec} = \omega_{re,n}$: normal.
- If $r_o < S_o$, define Flag $\omega = 1$ and $\omega_{re,rec} = \hat{\omega}_r$: fault.

where $\omega_{re,rec}$ is the output of the speed sensor and $\hat{\omega}_r$ is the output of the speed observer (SMO). Flag $\omega$ is the speed sensor fault Flag, Flag $\omega = 1$ means that a speed sensor fault is detected, if it is zero under normal conditions. The logic circuit presented in Fig. 5(b) can identify the faulty sensor for a speed fault and reconfiguration system for speed sensor fault.

#### B.2.3. DC-link voltage sensor FDLR Unit

The proposed fault detection, localization and reconfiguration (FDLR) algorithm of DC-link voltage sensor is based on the sliding mode voltage observer (SMVO) model, and the calculation of the DC-link voltage coefficients. Two coefficients are calculated: one from measured DC-link voltage $F_{dc}$ and the other through the
observed DC-link voltage $\hat{F}_{dc}$. The values of $F_{dc}$ and $\hat{F}_{dc}$ in the used FDLR method are defined as follows:

$$F_{dc} = \frac{V_{dc,m} - \hat{V}_{dc}}{V_{dc,m} + V_{dc,n}}$$

$$\hat{F}_{dc} = \frac{\hat{V}_{dc}}{V_{dc,n}}$$

(35)

The fault of DC-link voltage sensor is detected by a comparison of the measured and observed DC-link voltage. In the case of normal operating conditions, the coefficients values $F_{dc} \to 0$ and $\hat{F}_{dc} \to 1$.

When in the case of DC-link voltage sensor is faulty “outage”, the coefficients values are equal $F_{dc} \approx \hat{F}_{dc}$.

In order to diagnose the DC-link voltage sensor fault, the following residual variable is defined:

$$r_{dc} = S_{dc} - F_{dc} + \hat{\hat{u}}_{dc}$$

(36)

where $S_{dc} = \hat{F}_{dc}$ is the adaptive threshold, and $\hat{\hat{u}}_{dc}$ is positive gain used to guarantee the robust diagnosis to ensure a very short time for fault detection, the value of $\hat{\hat{u}}_{dc}$ is chosen: $0 < \hat{\hat{u}}_{dc} < 0.5$. The scheme of the DC-link voltage sensor FDI unit is given by:

- If $r_{dc} > S_{dc}$, define Flag $V_{dc} = 0$ and $V_{dc,rec} = V_{dc,m}$: normal;
- If $r_{dc} < S_{dc}$, define Flag $V_{dc} = 1$ and $V_{dc,rec} = V_{dc,c}$: fault.

where $V_{dc,rec} = V_{dc,app}$ is the input of the PWM-SVM controller, Flag $V_{dc}$ is the DC-link voltage sensor fault Flag. When a sensor fault is detected, the fault flag $V_{dc}$ is set to 1, if it is zero under normal conditions. The logic circuit presented in Fig. 5(c) can identify the faulty sensor for a DC-link voltage fault and reconfiguration system for DC-link voltage sensor fault. A general scheme for sensors FDLR of proposed method is shown in Fig. 6.

### IV. EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Experiment Stand Description

To permit practical testing of the proposed algorithm developed in this paper an implementation in real time is too necessary. The principal objective of this implementation is to show in real time the behavior of the real electrical system in healthy and faulty or degraded operations.

The architecture of the experimental system is shown in Fig. 7. The experimental platform is based on a 3 kW PMSM supplied by a voltage source inverter controlled by PWM-SVM techniques and dSPACE DS1104 controller board is used to validate and test the proposed algorithm in real time. The schematic of the experimental platform is presented in Appendix.

![Fig. 7. Experimental setup of the 3kW PMSM drive with DS1104 Controller.](image)

The main components of the experimental system are described in the following sections:
- **PMSM**: A 3 kW, 360 V, 100 Hz, 8-pole, three phases star connected. The parameters of the PMSM machine are obtained from tests (DC tests, DC step test for identification $L_d$ and $L_q$, Back EMF test, and speed decay test) in Laboratory of Applied Automation (LAA/FHC/UMBB Algeria) are reported in Appendix A.
- The PMSM is fed by a SEMIKRON inverter IGBT PWM-VSI whose data are reported in Appendix B.
- A DC generator with variable resistor is used to load the PMSM machine for testing the performance of proposed algorithm with and without load.
- The stator phase currents and DC-link voltage are measured by Hall type sensors LEM LA 55-P and LV 25-P respectively.
- The position encoder 1024-pulse/rev used for rotor position measurement and the board’s library is used to decode the position from the encoder digital signals.
- Microprocessor Control System: To control the PMSM, a dSPACE DS1104 control board is used which consists of a
The dSPACE Real-Time Interface (RTI) and Matlab Real Time Workshop (RTW), the Simulink model is automatically converted into C-code which is compiled and downloaded to the control board program memory. This provides a fast and easy way to implement and test the control schemes in real time. RTI consists of a set of I/O interface blocks which connects the Simulink model to the real world [1], [6], [9], [17].

Experimental controls are performed by ControlDesk (ver 3.7.2) which is used to monitor different signals (currents, voltages, speed/position, duty cycles...) and to tune parameters. It is also interfaced with Simulink (MATLAB R2010a), ControlDesk performs the necessary experiment tasks using a graphical interface.

B. Experimental Results

Prior to each operation, DC-offsets of currents, speed and DC-link voltage are measured and must be eliminated and the measured noises of such signals are filtered by a first order low-pass filter. The results presented in this section have three main goals. Firstly, they intend to demonstrate the performance of SMCSVO with and without sensors faults, secondly, to show diagnostic immunity to false alarms resulting from transients (speed, currents, loads...), and, thirdly, to explain the capabilities to diagnose sensors faults.

The performances of the proposed method have been tested as following: Speed reversal and profile change operations with healthy sensors (Fig. 8); Evaluation of FDLR unit with currents sensors fault (Fig. 9); Evaluation of FDLR unit with speed sensor fault (Fig. 10); Evaluation of FDLR unit with DC-link voltage sensor fault (Fig. 11).

Fig. 8 shows the experimental results of estimated rotor speed/position, stator currents and DC-link voltage including stator fluxes and back EMF voltages using sliding mode observer. In this test, the performance of the proposed diagnostic method is verified during speed reversal operation [450rpm to -450rpm, \( T_s=15\% \), \( T_m=507.6V, \varepsilon=10^{-5} \), \( \xi_k=0.01, \xi_m=0.04, \xi_{dc}=0.05 \)] with healthy sensors.

The values of the dynamic coefficients \( \mu \) and \( \hat{\mu} \) of DC-link voltage are practically equal see Fig. 8(h). The significant values of the residuals and thresholds generated are presented in Fig. 8(i), (j) and (k). The instantaneous values evolution of speed residual and threshold tracks the speed profile with healthy sensors. The speed residual \( r_w \) value always stays upper their corresponding threshold \( S_w \). Besides to that, the instantaneous values evolution of currents residuals \( r_c \) always stay lower their corresponding thresholds \( S_c \), and the instantaneous values evolution of DC-link voltage residual \( r_{dc} \) always stay lower their corresponding threshold \( S_{dc} \).

Fig. 8(i), (j) and (k): no false alarms are generated (all flags remain zero see Fig. 8(i)), which demonstrates that the proposed FDLR method resists to speed and load variations without generating any false alarms.

In order to ensure the verification of the proposed method “SMCSVO”, an important test with faulty sensors is presented in Fig. 9, 10 and 11.

In order to ensure the verification of the proposed method “SMCSVO”, an important test with faulty sensors is presented in Fig. 9, 10 and 11.
Sensor Fault Detection, Localization and System Reconfiguration Based on a Sliding Mode Observer and …

(c). Measured and observed rotor position.

(f). Measured and observed DC-link voltage.

(g). Zoom: Observed DC-link voltage using SMO.

(h) Dynamic coefficients of DC-link voltage \( \mu \) and \( \hat{\mu} \).

(i). Residuals generation and thresholds of current sensors fault.

(j). Residual generation and threshold of speed sensor fault.

(k). Residual and threshold of DC-link voltage sensor fault.

(l). Fault flags.

Fig. 8. Evolution of the proposed SMCSVO during speed reversal operations with healthy sensors.

The experimental results presented in Fig. 9 illustrate the diagnostic method capabilities to diagnose currents sensors fault in measurement chain. Operating conditions are: \( \omega_{in}=450 \text{rpm}, T_L=15\% \ T_n, V_{dc,n}=507.6V \). The parameters of FDLR algorithm are selected as: \( \epsilon=0.000055, \zeta=0.5, \frac{\xi_1}{\xi_2}=0.04, \xi_2=0.5 \).

The fault detection, localization and reconfiguration algorithm for current sensor faults is presented in the section (III.B.2). The scheme is based on hardware redundancy with 6 sensors (two measurements of each phase current). A multport switch is used to select the appropriate input, which is indicated by the control port Fig. 5(a) (first input indicates the state of phase).

In healthy operation, the mean value of measurements is used as input of the control loop and in the SMCSVO block.

Fig. 9(a): The fault occurs at time \( t_f=1.4278s \) (outage of sensor a1) the controller detects and isolates the fault and reconfigure from measured \( I_{a1} \) to the measured \( I_{a2} \), the control is reconfigured at \( t_d=1.4880s \). During the transient \( (\Delta t_d=60.2ms) \), the value of \( I_{d,a} \) is used in the control loop and in the SMCSVO block.

Fig. 9(b): Next fault occurs at time \( t_f=6.0793s \) (outage of sensor a2) the controller detects and isolates the fault and reconfigure from measured \( I_{a2} \) to the measured \( I_{a1} \), and the control is reconfigured at \( t_d=6.1395s \). During the transient \( (\Delta t_d=60.2ms) \), the value of \( I_{d,a} \) is used in the control loop and in the SMCSVO block. Practically \( \Delta t_d=\Delta t_d \).
The experimental results presented in Fig. 10 illustrate the diagnostic method capabilities to diagnose speed sensor fault in measurement chain. Operating conditions are: \( \omega_{ref}=450 \text{rpm} \), \( T_L=15\%Tn \), \( V_{dc}=507.6 \text{V} \). The parameters of FDLR algorithm are selected as \( c=0.00005 \), \( \zeta_i=0.04 \), \( \xi_w=0.5 \).

The fault detection, localization and reconfiguration algorithm for speed sensor faults is presented in the section (3.2.2.B). The scheme is based on software measured and hardware estimated speed. A multiport switch is used to select the appropriate input, which is indicated by the control port (first input indicates the state of sensor speed).

In healthy operation, the value of measured speed is used as input of the control loop and in the SMCSVO block. When the sensor speed is disagreement, the FDLR unit detects and isolates the speed sensor and reconfigure from observed speed.

The experimental results presented in Fig. 10 illustrate the diagnostic method capabilities to diagnose speed sensor fault in measurement chain. Operating conditions are: \( \omega_{ref}=450 \text{rpm} \), \( T_L=15\%Tn \), \( V_{dc}=507.6 \text{V} \). The parameters of FDLR algorithm are selected as \( c=0.00005 \), \( \zeta_i=0.04 \), \( \xi_w=0.5 \).

The fault detection, localization and reconfiguration algorithm for speed sensor faults is presented in the section (3.2.2.B). The scheme is based on software measured and hardware estimated speed. A multiport switch is used to select the appropriate input, which is indicated by the control port (first input indicates the state of sensor speed).

In healthy operation, the value of measured speed is used as input of the control loop and in the SMCSVO block. When the sensor speed is disagreement, the FDLR unit detects and isolates the speed sensor and reconfigure from observed speed.

Fig. 9. Detection, localization and reconfiguration of phase ‘a’ current sensors faults (faults occurs at time: sensor (a1) \( tf=1.4278 \) s and sensor (a2) \( tf=6.0793 \) s).

### Graphs and Diagrams

- **(a)** Current sensors faults (a1 outage): Measured phase ‘a’ current \( I_{a1} \) and \( I_{a2} \), observed \( I_{a,obs} \) and reconfigured \( I_{a,rec} \) currents.
- **(b)** Current sensors fault (a2 outage): Measured phase ‘a’ current \( I_{a1} \) and \( I_{a2} \), observed \( I_{a,obs} \) and reconfigured \( I_{a,rec} \) currents.
- **(c)** Residuals generation and thresholds of current sensors fault.
- **(d)** Zoom: Residuals generation and threshold of current sensor (a1) fault of phase (a).
- **(e)** Zoom: Residuals generation and threshold of current sensor (a2) fault of phase (a).
- **(f)** Fault flags.
The experimental results presented in Fig. 11 illustrate the diagnostic method capabilities to diagnose DC-link sensor fault ‘disconnection’ in measurement chain. The fault diagnostic performance is analyzed with sensor fault. A reference speed of 450 rpm with a load torque equal to 15% of the rated torque and a DC-link voltage equal to $V_{dc,n}$. The parameters of FDLR algorithm are selected as $\varepsilon = 0.00005$, $\zeta = k_i = 0.5$, $\xi = 0.04$, $\xi_{dc} = 0.5$.

In this test, the DC-link voltage sensor information is lost at $t_f = 2.4248s$. Nevertheless, the DC-link voltage observer is maintained approximately equal to rated DC-link voltage (507V). The FDLR unit controller detects and isolates the fault and reconfigures from measured DC-link voltage to the estimated one and the control is reconfigured at $t_d = 2.4252s$. During the transient ($\Delta t_d = 0.4ms$), the value $V_{dc,rec}$ is used to calculate the PWM signals.

Fig. 11. Detection, localization and reconfiguration of DC-link voltage sensor fault.

In this paper, a fault detection, localization and system reconfiguration of phase currents, speed/position and DC-link voltage sensors in three PMSM drives has been proposed, where the sliding mode observer is used to estimate the stator currents, rotor speed/position and DC-link voltage. The integrating of adaptive threshold with the SMO improves the safety and the reliability of the PMSM drives system. The stability conditions of the SMO have been proved and verified with Lyapunov stability analysis.

Moreover, the feasibility and effectiveness of the sensor fault diagnosis method have been carried out by real-time experimental tests (from prototype developed in the laboratory).
APPENDIX

APPENDIX A

TABLE II. SPECIFICATIONS OF THE TEST PMSM

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated voltage $V_n$</td>
<td>V</td>
<td>360</td>
</tr>
<tr>
<td>Rated current $I_n$</td>
<td>A</td>
<td>5.9</td>
</tr>
<tr>
<td>Rated power $P_n$</td>
<td>kW</td>
<td>3</td>
</tr>
<tr>
<td>Rated frequency $f_n$</td>
<td>Hz</td>
<td>100</td>
</tr>
<tr>
<td>Base speed $\omega_b$</td>
<td>rpm</td>
<td>1500</td>
</tr>
<tr>
<td>Rated torque $T_n$</td>
<td>N.m</td>
<td>19</td>
</tr>
<tr>
<td>Rated torque $T_a$</td>
<td>N.m</td>
<td>19</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters determined by tests</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated of pole pairs $N_p$</td>
<td>/</td>
<td>4</td>
</tr>
<tr>
<td>Armature resistance $R_a$</td>
<td>Ω</td>
<td>2.144</td>
</tr>
<tr>
<td>d-axis inductance $L_d$</td>
<td>mH</td>
<td>27.1</td>
</tr>
<tr>
<td>q-axis inductance $L_q$</td>
<td>mH</td>
<td>28.8</td>
</tr>
<tr>
<td>Magnet flux Linkage $\psi_{m}$</td>
<td>Wb</td>
<td>0.2960</td>
</tr>
<tr>
<td>Inertia moment $J$</td>
<td>kg.m²</td>
<td>0.0032</td>
</tr>
<tr>
<td>Friction coefficient $B$</td>
<td>N.m/s/rad</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

TABLE III. SPECIFICATIONS OF THE PWM VSI (FROM SEMIKRON DATASHEET)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-link Voltage ($V_{dc}$) max</td>
<td>V</td>
<td>750</td>
</tr>
<tr>
<td>Alternative Voltage ($V_a$ max)</td>
<td>V</td>
<td>1200</td>
</tr>
<tr>
<td>Current line max ($I_{dc}$)</td>
<td>A</td>
<td>30</td>
</tr>
<tr>
<td>Rated Power</td>
<td>kW</td>
<td>10</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>kHz</td>
<td>15</td>
</tr>
<tr>
<td>Saturation Voltage</td>
<td>V</td>
<td>2.2</td>
</tr>
<tr>
<td>Threshold Voltage (IGBT)</td>
<td>V</td>
<td>1.7</td>
</tr>
<tr>
<td>Power Supply (Drives)</td>
<td>V</td>
<td>0/+15</td>
</tr>
<tr>
<td>Filtrage Condensateurs (2 series)</td>
<td>2200 μF/400V</td>
<td></td>
</tr>
<tr>
<td>Dead-Time</td>
<td>μsec</td>
<td>4</td>
</tr>
<tr>
<td>Switching Device</td>
<td>IGBT</td>
<td></td>
</tr>
<tr>
<td>SEMIDRIVER</td>
<td>SKHI 22</td>
<td></td>
</tr>
</tbody>
</table>

APPENDIX B

Fig. 12. Experimental platform in our laboratory (LAA/FHC/University of Boumerdes Algeria).

REFERENCES


Aibeche Abderrezak was born in Bouhatem-Mila Algiers, Algeria. He received his B.S. degree and Magister degree in electrical engineering from the University M’Hamed Bougara of Boumerdes FHC-UMBB Algeria, in 2001 and 2009. He has been with the Department of Maintenance, Electrical Engineering Option, University of Boumerdes FSI-UMBB, Algeria, since 2013. Currently, he is researcher member at Laboratory Applied Automation (LAA) University M’Hamed Bougara of Boumerdes. His research interest includes power converters, sensorless control of AC drives, fault diagnosis and fault tolerant of AC drives and renewable energy.

Kidouche Madjid was born in Bordj-Menaiel, Algeria, in 1955. He received his M.Sc. and Ph.D. degrees in electrical engineering from the University of Pennsylvania, USA. He has been with the Department of Automation, University of Boumerdes, Algeria, since 1990. He is a professor in the said institution. Currently, he is supervisor at Laboratory Applied Automation (LAA), Team "Analysis of Complex Systems" University M’Hamed Bougara of Boumerdes. His current research interest is in the area of control systems, with emphasis on nonlinear and large-scale dynamical systems.