Second-order SMO-based sensorless control of IM drive: experimental investigations of observer sensitivity and system reconfiguration in postfault operation mode

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Abstract
In normal operation mode, sensorless speed-controlled motor drives should be more reliable, less expensive and less bulky than their counterparts with a speed sensor. The sensorless drive structure allows avoiding the electromagnetic and vibratory sensitivity of the mechanical sensor, the additional connecting circuits, additional space for the sensor, its price and maintenance requirements. However, in postfault operation mode, the robustness of speed sensorless control strategies has been poorly addressed in the study. Accordingly, this study deals with an experimental study of the robustness and the availability of speed-controlled induction motor (IM) drives without speed sensor in the presence of inverter open-switches faults. For that purpose, a super twisting algorithm-based observer for motor speed estimation is proposed for experimental investigation. Experimental results are performed upon 3-kW IM drive by using dSPACE digital signal processing controller board. Experimental investigations evaluate the performances of the method used for the control without speed sensor in prefault, postfault and regeneration operation modes.

1 INTRODUCTION

Technological developments in power electronics and numerical control have made the opportunity to have increasingly complex and sophisticated industrial systems. However, the increased reliability requirements, availability and safe operation of these systems are real challenges. In fact, the implementation of speed-sensorless control and diagnostic algorithms for industrial application based on motor drives is considered as a promising solution to minimise the production cost and to improve the productivity.

Speed-sensorless control provides an attractive solution for electrical drives operating in hostile and hard environmental conditions. Replacing the physical sensor by a software part for speed sensing permits to reduce system size and complexity, improve noise immunity, and, in turn, improve the reliability and the maintenance cost. Many speed-sensorless control strategies have been addressed in the study; HF and low-frequency signal injection [1, 2], full- and reduced-order observer [3, 4], model reference adaptive system [5], Kalman filter [6, 7], sliding mode observer (SMO) [8–10] and [11–13] and adaptive full-order observer [14, 15].

Unfortunately, another topic is not well addressed in the literature concerns the machine output signals quality under electrical faults, and the robustness and limitations of the observers used by the electrical sensorless drive structures. Traditionally, sensorless control methods based on model observation require information of all phase currents and voltages, and can therefore only be applied in normal operation mode. In faulty operation mode, a disturbance in one of the observer’s input variables can lead to cumulative or multiplicative errors in the estimation of machine state variables. In the case of a closed-loop control without speed sensor, these inaccurate quantities estimated by the observer will be used as inputs into the main control loops, which would lead to errors in the estimation algorithm and then in the control of the whole system.

Regarding now fault diagnosis (FD) of motor drives, inverter fault is considered as one of the prevalent electrical faults in ac motor drives. In accordance to several statistic studies, it is concluded that the percentage of failures into variable speed drives accounts for approximately 63% of the user-experienced drive failures during the first year of operation. About 70% of them are related to power devices [16, 17],...
especially open-circuit and short-circuit faults [18–19]. Several
diagnostic methods have been proposed in the study to di-
gnose open-circuit faults and are generally classified in Table 1
as signal-based approaches [20–29, 37] and model-based
approaches [30–33]. Reference [16] lists a more comprehensive
bibliography especially for the classical sensored 3-ϕ motor
drives.

Speed-sensorless motor drives under inverter faults are
very little addressed in the study [34–36]. In [34], HF injec-
tion-based and model-based approaches for IPMSM are
analysed with respect to the robustness of sensorless-
controlled electrical drives to line disturbances and inverter
power-switches faults. Experimental results show that, under
fault conditions induced by an open-switch fault, considerable
speed ripples are observed. In turn, this results in a weakness
of the sensorless estimation algorithm. In [36], a diagnostic
approach of inverter faults in a sensorless control of an in-
duction motor (IM) has been proposed. A first-order SMO is
used for simultaneously speed estimation and open-switch fault
detection and identification. The diagnostic algorithm is
based on the fault indices derived from the error between the
measured and estimated current of the faulty inverter legs.
However, since this observer is used to realise the closed-
loop control, the high error used to diagnose the fault leads
to significant estimated speed ripples. In turn, this results in
degradation of the other estimated variables given by the
observer. These affected variables are supposed to be used as
inputs of the FDI process. As a result, conventional diagnostic
approaches may no longer be valid in the case of a speed-sensorless
drives and may result in false alarms since the FD inputs are erroneous.

The main idea of this study comes from the aforementioned
problems raised by [34–36]. Hence, for VSI supplying
a speed sensorless-controlled IM drive, the effect of the
power switches fault must be carefully studied with respect to
the robustness and the availability of the system after the
fault occurrence. Thanks to the advantages of the sliding mode
diagnostics, sensorless-controlled IM drive based on a super-twisting
observer (STO) is proposed for experimental

investigation with respect to single and multiple IGBT open-
switch faults. For that purpose, the effectiveness of the
sensorless control scheme and the ability of the observer to
overcome the induced errors in the input signals are
addressed. In addition, the ability of the system to overcome
the fast transients during the fault occurrence and the system
reconfiguration is experimentally investigated.

The rest of the study is organised as follows. Section 2
presents the IM model and the principle of the vector control.
Section 3 describes the sensorless speed control sensitivity
under IGBT OSF and sets out the involved issues. Section 4
discusses the STA-based observer design. The extensive
experimental investigation of the performances of the studied
IM speed-sensorless control scheme during prefault, postfault
and fault reconfiguration steps is presented in Section 5. Section
6 concludes the research findings.

2 | IM VECTOR CONTROL

The following nonlinear model Equation (1) is widely used to
represent the dynamics of the IM in d-q rotating reference
frame [38]. In this model, the currents $i_{ds}$ the flux $\phi_{ds}$ and
the rotor speed $\omega_r$ represent the state variables. $U_{dq}$ and $\omega_d$
are considered as the control variables. $T_L$ denotes the load
torque. $L_s$ and $L_r$ are the stator and rotor inductances,
respectively. $M$ is the mutual inductance. $R_s$ and $R_r$ are the
stator and the rotor resistances, respectively. $J$ is the motor’s
moment inertia. $\sigma$ is the dispersion coefficient. $\tau_r$ and $\tau_s$
represent, respectively, the rotor and the stator time con-
stant. $n_p$ is the pole-pairs number.

\[
\begin{align*}
\frac{di_{ds}}{dt} &= -\gamma i_{ds} + \omega_r i_{qr} + \frac{1}{\sigma M \tau_r} \phi_{dr} + \frac{1}{\sigma M} \omega_r \phi_{qr} + \frac{1}{\sigma L_s} U_{ds} \\
\frac{di_{qr}}{dt} &= -\omega_r i_{ds} - \gamma i_{qr} + \frac{1}{\sigma M} \omega_r \phi_{dr} + \frac{1}{\sigma \tau_r} \phi_{rs} + \frac{1}{\sigma L_r} U_{dq} \\
\frac{d\phi_{dr}}{dt} &= \frac{M}{\tau_r} i_{ds} - \frac{1}{\tau_r} \phi_{dr} + \omega_d \phi_{qr} \\
\frac{d\phi_{qr}}{dt} &= \frac{M}{\tau_r} i_{ds} - \omega_d \phi_{dr} - \frac{1}{\tau_r} \phi_{qr} \\
\frac{d\omega_r}{dt} &= \frac{n_p^2 M}{J L_r} i_{d} \phi_{dr} - \frac{n_p^2 M}{J L_r} i_{d} \phi_{qr} - \frac{I_f}{J} \omega_{rs} - \frac{n_p}{J} T_i \\
\end{align*}
\]

(1)

with $\sigma = 1 - \frac{M^2}{L_s L_r} \gamma = \frac{1}{\sigma} \left( \frac{1}{\tau_r} + \frac{1}{\tau_s} \right)$
and, the electromagnetic torque is given by:

\[
T_e = \frac{n_p M}{L_r} (i_{d} \phi_{dr} - i_{d} \phi_{qr})
\]

(2)
Here, the field orientation control is used. The objective is to keep the magnitude of the rotor flux linkage constant while the position of rotor frequency changes. For this purpose, the flux component $\phi_{qr}$ must be equal zero ($\phi_{qr} = 0$), whereas the flux component $\phi_{ds}$ is kept constant ($\phi_r = \phi_{ds} + j\phi_{qr} = \phi_r$) where $\phi_r$ is the rotor-flux magnitude. Accordingly, the IM model is reformulated as follows:

\[
\begin{align*}
\frac{di_{ds}}{dt} &= -\gamma i_{ds} + \omega_r i_{qs} + \frac{1 - \sigma}{\sigma M r} \phi_r + \frac{1}{\sigma L_s} U_{ds} \\
\frac{di_{qs}}{dt} &= -\omega_r i_{ds} - \gamma i_{qs} - \frac{1 - \sigma}{\sigma M} \omega_r \phi_r + \frac{1}{\sigma L_i} U_{qi} \\
\frac{d\phi_{dr}}{dt} &= \frac{M}{\tau_r} i_{ds} - \frac{1}{\tau_r} \phi_{dr} \\
0 &= \frac{M}{\tau_r} i_{qs} - \omega_a \phi_r \\
d\omega_r &= \frac{n_s^2 M}{\gamma L_r} i_{qs} \phi_r - f_{\omega} \dot{\omega}_r - \frac{n_p}{f} T_l
\end{align*}
\]

Taking into account the Laplace differential operator, Equation (3) of the IM can be rewritten in $d-q$ rotating reference frame as follows:

\[
\begin{align*}
U_{ds} &= \sigma L_s (s + \gamma) i_{ds} - \sigma L_s \omega_r i_{qs} - \frac{M}{L_r \tau_r} \phi_r \\
U_{qs} &= \sigma L_s (s + \gamma) i_{qs} + \sigma L_s \omega_r i_{ds} + \frac{M}{L_r \tau_r} \phi_r
\end{align*}
\]  

System Equation (4) can be simplified as the following form:

\[
\begin{align*}
U_{ds} &= U_d - E_d \\
U_{qs} &= U_q - E_q
\end{align*}
\]

where

\[
\begin{align*}
E_d &= \sigma L_s \omega_r i_{qs} + \frac{M}{L_r \tau_r} \phi_r \\
E_q &= -\sigma L_s \omega_r i_{ds} - \frac{M}{L_r \tau_r} \omega_r \phi_r
\end{align*}
\]

and

\[
\begin{align*}
U_d &= \sigma L_s (s + \gamma) i_{ds} \\
U_q &= \sigma L_s (s + \gamma) i_{qs}
\end{align*}
\]

The $d-q$ axis reference currents are derived from Equations (2) and (3) as follows:

\[
i_{ds}^* = \frac{\phi_r^*}{M} \\
i_{qs}^* = \frac{L_r}{n_p M} \phi_r T_c
\]

Finally, the vector control scheme is given in Figure 1. Classical PI controllers are used in this scheme for $d-q$ currents control. However, following Equations (5) and (6), feed-forward compensation terms are introduced into the current control loops. An IP controller is used for motor speed regulation. More details about vector control and controllers calculation can be found in [38, 39].

3 | SENSORLESS SPEED CONTROL SENSITIVITY UNDER IGBT OSF AND PROBLEM STATEMENT

The main goal of this section is to study the potentialities and characteristics of an STA-based observer for sensorless control IM drive in postfault operation mode. The considered fault is an open circuit of power switches into the VSI. A simplified block diagram of the speed sensorless control as well as the topology of the inverter are illustrated in Figure 2.

This structure regroups an IM drive, a three-phase VSI and a magnetic powder brake. The VSI consists of three-legs, and each leg consists of two IGBTs with freewheeling diodes. A software observer-based sensor is used to provide the actual rotor speed used by the vector control of the motor.

Former research studies, as in [36], investigated experimentally the behaviour of the described system based on a speed sensorless IM drive under faulty VSI. For that purpose, a first-order SMO based on the electrical part of the classic IM model, in $(\alpha\beta\gamma)$ frame, described in [36, 40] and given in Equation (10) is proposed for rotor speed estimation.

![Figure 1](image-url)
The work given here aims essentially to minimise the fault impact and ensures the stability and continuity of the electrical drive operation under inverter fault. For that purpose, a super-twisting-based observer is proposed for test. As illustrated in Figure 4, the choice of this observer is justified by the fact that the estimated rotor speed, which is considerably impacted under inverter fault, is not involved on the estimation of the currents and flux when an STA-based observer is used (Figure 4(b)). These assertions are illustrated in the sequel with some experimental results carried out on IM for healthy and faulty operation mode considering the reconfiguration steps, too.

4 | SUPER TWISTING ALGORITHM-BASED OBSERVER

The stator current and the rotor fluxes described in the conventional model in Equation (10) are strongly coupled and all depend on the rotor speed. Consequently, in unwanted conditions generated by an IGBT open-circuit fault, a disturbance in a single state variable directly affects the dynamic of the other variables of the sensorless controlled IM, resulting in estimation errors in the observation loop. These estimation errors in turn contribute to the rapid degradation of the sensorless control and to the divergence or shutdown of the motor. In order to reduce this strong coupling between state variables when designing the observation technique, the electrical part of the IM model in the stationary reference frame (α, β) in terms of stator current and rotor flux is rewritten as follows:

\[
\begin{aligned}
\dot{i}_{an} &= -\gamma i_{an} + \frac{K}{\tau_r} \phi_{ar} + \alpha_r K \beta_r + \frac{1}{\sigma L_s} v_m \\
\dot{i}_{bn} &= -\gamma i_{bn} + \frac{K}{\tau_r} \phi_{br} + \alpha_r K \beta_r + \frac{1}{\sigma L_s} v_m \\
\dot{\phi}_{ar} &= \frac{M}{\tau_r} i_{ar} - \frac{1}{\tau_r} \phi_{ar} - \omega_r \alpha_r \\
\dot{\phi}_{br} &= \frac{M}{\tau_r} i_{br} - \frac{1}{\tau_r} \phi_{br} - \omega_r \beta_r \\
\end{aligned}
\]
F I G U R E 4  Observer electrical variables dependence of estimated rotor speed: (a) model-based observer where estimated currents and flux dependent of estimated speed $\dot{\omega}$, and (b) STA-based observer where the estimated currents and flux are not dependent of estimated speed $\dot{\omega}$.

\[
\begin{align*}
\dot{i}_{as} &= -R_s i_{as} - \left( \frac{M}{\tau_r} i_{as} - \frac{1}{\tau_r} \phi_{ar} - \omega_r \phi_{br} \right) a + b v_{as} \\
\dot{i}_{bs} &= -R_s i_{bs} - \left( \frac{M}{\tau_r} i_{bs} - \frac{1}{\tau_r} \phi_{br} + \omega_r \phi_{ar} \right) a + b v_{bs} \\
\dot{\phi}_{ar} &= \frac{M}{\tau_r} i_{as} - \frac{1}{\tau_r} \phi_{ar} - \omega_r \phi_{br} \\
\dot{\phi}_{br} &= \frac{M}{\tau_r} i_{bs} - \frac{1}{\tau_r} \phi_{br} + \omega_r \phi_{ar}
\end{align*}
\] (11)

with $a = \frac{M}{\alpha L_r}$, $b = \frac{M}{\beta L_r}$.

By substituting the terms in brackets corresponding to the flux derivatives by $(\dot{\phi}_{ar}, \dot{\phi}_{br})$, the model dedicated to observation becomes:

\[
\begin{align*}
\dot{i}_{as} &= -R_s i_{as} - a \phi_{ar} + b v_{as} \\
\dot{i}_{bs} &= -R_s i_{bs} - a \phi_{br} + b v_{bs} \\
\dot{\phi}_{ar} &= \frac{M}{\tau_r} i_{as} - \frac{1}{\tau_r} \phi_{ar} - \omega_r \phi_{br} \\
\dot{\phi}_{br} &= \frac{M}{\tau_r} i_{bs} - \frac{1}{\tau_r} \phi_{br} + \omega_r \phi_{ar}
\end{align*}
\] (12)

4.2 | Design of the STA-based SMO

To apply the STA on the IM model, the following variable change has to be performed:

\[
\begin{align*}
\dot{z}_1 &= i_{as} \\
\dot{z}_2 &= i_{bs} \\
\dot{z}_3 &= -\dot{\phi}_{ar} = -\frac{M}{\tau_r} i_{as} + \frac{1}{\tau_r} \phi_{ar} + \omega_r \phi_{br} \\
\dot{z}_4 &= -\dot{\phi}_{br} = -\frac{M}{\tau_r} i_{bs} + \frac{1}{\tau_r} \phi_{br} - \omega_r \phi_{ar}
\end{align*}
\] (14)

By substituting the Equation (14) in the Equation (12), the dynamic current model becomes:

\[
\begin{align*}
\dot{z}_1 &= -R_s \dot{z}_3 + az_3 + b v_{as} \\
\dot{z}_2 &= -R_s \dot{z}_4 + az_4 + b v_{bs}
\end{align*}
\] (15)

4.1 | Super-twisting algorithm

The STA is classified among the high-order (second-order) sliding-mode algorithms, where it was introduced by Levant in 1993 [41]. It was widely used later for control in [42, 43] and for SMO in [44, 45].

\[
\begin{align*}
\dot{x}_1 &= f(x_2) + \gamma |e_1|^{0.5} \text{sign}(e_1) + \rho_1 \\
\dot{x}_2 &= \xi \text{sign}(e_1) + \rho_2
\end{align*}
\] (13)

where $e_i = x_i - \hat{x}_i$, $x_i$ is the state variables, $\gamma$ and $\xi$ are the observation gains, $\rho_1$ and $\rho_2$ are the perturbation terms [11].

The STA can be written as follows:

The robustness and the finite-time convergence of the STA and the STA-based observer have been addressed in [45–49]. Accordingly, the stability has been proved by Lyapunov methods. In addition, since the finite-time convergence of the observer is proved, it can be designed independently of the controller [45].

By applying the STA described in Equation (13) to the current and flux model, the second-order SMO can be expressed as follows:

\[
\begin{align*}
\dot{\hat{z}}_1 &= -R_s \hat{z}_3 + az_3 + b v_{as} + \gamma_1 |e_1|^{0.5} \text{sign}(e_1) \\
\dot{\hat{z}}_3 &= \xi_1 \text{sign}(e_1) \\
\dot{\hat{z}}_2 &= -R_s \hat{z}_4 + az_4 + b v_{bs} + \gamma_2 |e_2|^{0.5} \text{sign}(e_2) \\
\dot{\hat{z}}_4 &= \xi_2 \text{sign}(e_2)
\end{align*}
\] (16)

where $e_i = (z_i - \hat{z}_i)_{i=1,2}$ are the current estimation errors, \text{sign}(\cdot) indicates the sign function. $\gamma_i$ and $\xi_i$ denote the STO gains. 

According to STA in Equation (6), the perturbation terms $\rho_1$ and $\rho_2$ can be defined as:
\[
\left\{ \begin{array}{l}
\rho_1 = -R_i b z_1 + b v_{at} \\
\rho_2 = -R_i b z_2 + b v_{eb}
\end{array} \right. \quad (17)
\]

More details about the stability and the finite-time convergence of the STA can be found in [45–47]. The application and the experimental validation of the STA-based observer when the electric drive operates free of any fault can be also found in [11–13].

After applying the STA to IM model, it is important to note that the current and flux observation model in Equation (16) becomes independent of the rotor flux and estimated rotor speed. It is only expressed as a function of the stator currents (\(z_1, z_2\)), the currents errors (\(e_1, e_2\)) and the stator voltages (\(v_{ia}, v_{ib}\)). Flux derivatives are calculated through the sliding mode theory using the sign of errors between the estimated and measured currents. Since the faulty condition generated by the VSI power switch devices is related to the phase currents, then, the STO model in Equation (16) which is now free of the estimated rotor speed and rotor flux (\(\omega_r, \phi_r\)) can provide more accurate estimation outputs in degraded operating mode.

### 4.3 Rotor speed estimation

The estimated rotor fluxes are expressed in function of the rotor speed, then substituting the flux model Equation (12) in Equation (14) yields:

\[
\begin{align*}
\dot{z}_3 &= -\dot{\phi}_{ar} = -\frac{M}{\tau_r} i_{ar} + \frac{1}{\tau_r} \phi_{ar} + \omega_r \dot{\phi}_{br} \\
\dot{z}_4 &= -\dot{\phi}_{br} = -\frac{M}{\tau_r} i_{br} + \frac{1}{\tau_r} \phi_{br} - \omega_r \dot{\phi}_{ar}
\end{align*}
\tag{18}
\]

From the second-order SMO model Equation (16) and the rotor flux model Equation (18), the estimated rotor speed can be expressed as follows:

\[
\dot{\omega}_r = \frac{(\dot{\phi}_{br} - M i_{br}) z_3 - (\dot{\phi}_{ar} - M i_{ar}) z_4}{-\phi_{ar} - \phi_{br} - \phi_{br} M i_{br} + \phi_{ar} M i_{ar}}
\tag{19}
\]

with (\(-\dot{\phi}_{ar} = \hat{z}_3\)) and (\(-\dot{\phi}_{br} = \hat{z}_4\)).

The block diagram describing the design steps of the SMO based on STA is shown in Figure 5. The stator currents are first estimated using actual currents and voltages as inputs, then the current estimation error is used for the estimation of flux derivatives. Finally, the rotor speed is estimated through the STA-based observer outputs (\(\hat{z}_{12}, \hat{z}_{34}, \phi_{abr}\)). As the IGBT OSF is related to the inverter phase currents, it is important to note that when using the STA-based observer, the estimation of currents is totally independent of the motor variables (rotor flux and rotor speed), it depends only on the real variables provided by the current sensors for the inverter phase currents (\(z_1 = i_{ar}, z_2 = i_{br}\)) and the output block control for the stator voltages (\(v_{ia}, v_{ib}\)).

The good accuracy of the observer based on the STA to estimate the motor state under faulty operating conditions.

The finite-time convergence of the second-order SMO based on STA is proved in [45]. Thus, the observer can be designed independently of the controller. Therefore, the choice of the STA-based SMO’s gains will be studied in this section.

By making a variable change such that:

\[
\begin{align*}
z_5 &= \hat{z}_3 \\
z_6 &= \hat{z}_4
\end{align*}
\tag{20}
\]

The current and flux IM model Equation (12) can be re-expressed as follows:

\[
\begin{align*}
\dot{z}_1 &= -R_i b z_1 + a z_3 + b v_{as} \\
\dot{z}_2 &= -R_i b z_2 + a z_4 + b v_{bs} \\
\dot{z}_3 &= z_5 \\
\dot{z}_4 &= z_6
\end{align*}
\tag{21}
\]

By defining \(\hat{X}\) as the error between the actual and the estimated states:

\[
\hat{X} = [\hat{X}_1 \quad \hat{X}_2]^T
\]

with \(\hat{X}_1 = \begin{bmatrix} z_1 - \hat{z}_1 \\ z_2 - \hat{z}_2 \end{bmatrix} = \begin{bmatrix} e_1 \\ e_2 \end{bmatrix}\) and \(\hat{X}_2 = \begin{bmatrix} z_3 - \hat{z}_3 \\ z_4 - \hat{z}_4 \end{bmatrix}\)

Then, error dynamics are given by:

\[
\begin{align*}
\dot{\hat{X}}_1 &= \begin{pmatrix} \hat{z}_1 - \hat{\hat{z}}_1 \\ \hat{z}_2 - \hat{\hat{z}}_2 \end{pmatrix} = a \begin{pmatrix} z_3 - \hat{z}_3 \\ z_4 - \hat{z}_4 \end{pmatrix} - \begin{pmatrix} \gamma_1 |e_1|^{\frac{1}{2}} \text{sign}(e_1) \\ \gamma_2 |e_2|^{\frac{1}{2}} \text{sign}(e_2) \end{pmatrix} \\
\dot{\hat{X}}_2 &= \begin{pmatrix} \hat{z}_3 - \hat{z}_3 \\ \hat{z}_4 - \hat{z}_4 \end{pmatrix} = \begin{pmatrix} \hat{z}_3 \\ \hat{z}_4 \end{pmatrix} - \begin{pmatrix} \gamma_1 \text{sign}(e_1) \\ \gamma_2 \text{sign}(e_2) \end{pmatrix}
\end{align*}
\tag{22}
\]
The error dynamics in Equation (22) can be rewritten in the following canonical form:

\[
\dot{\tilde{X}}_1 = a\tilde{X}_2 - \gamma_{1,2} \left| \tilde{X}_1 \right|^{\frac{1}{2}} \text{sign} \left( \tilde{X}_1 \right) \tilde{X}_2 = \tilde{F} \left( X_1, X_2, \tilde{X}_2 \right) \\
- \xi_{1,2} \text{sign} \left( \tilde{X}_1 \right) \tag{23}
\]

where \( \tilde{F} \left( X_1, X_2, \tilde{X}_2 \right) \) represents the derivatives of \( \tilde{z}_3 \) and \( \dot{\tilde{z}}_4 \). It is expressed as a function of \( X_1, X_2 \) and \( \tilde{X}_2 \).

\[
\gamma_{1,2} = \begin{pmatrix} \gamma_1 \\ 0 \\ \gamma_2 \end{pmatrix}
\]
denotes the gains related to the estimation of stator currents \( (\tilde{z}_1, \tilde{z}_2) \).

\[
\xi_{1,2} = \begin{pmatrix} \xi_1 \\ 0 \\ \xi_2 \end{pmatrix}
\]
denotes the gains related to the estimation of flux derivatives \( (\tilde{z}_3, \tilde{z}_4) \).

Assuming that the system states in Equation (21) are bounded, then there is a constant \( f^+ \) so that the following inequality is checked [45]:

\[
\left| \tilde{F} \left( X_1, X_2, \tilde{X}_2 \right) \right| \leq f^+ 
\tag{24}
\]

Therefore, this inequality must be verified for all three components \( X_1, X_2 \) and \( \tilde{X}_2 < 2\sup X_2 \).

Assuming that the Equation (24) is reached and the assumption of the state boundedness is true too, the STO’s gains in Equation (16) are chosen satisfying the following two inequalities:

\[
\begin{align*}
\gamma_{1,2} &> \sqrt{\frac{2}{\xi_{1,2} - f^+} \left( \xi_{1,2} + f^+ \right) \left( 1 + c_{1,2} \right)} \\
\gamma_{1,2} &> \sqrt{\frac{2}{\xi_{1,2} - f^+} \left( \xi_{1,2} + f^+ \right) \left( 1 + c_{1,2} \right)} 
\end{align*} 
\tag{25}
\]

where \( c_{1,2} \) are selected constants bounded as \( c_{1,2} \in [0, 1] \).

**Theorem 1**: Assuming that the observer parameters \( (\xi_{1,2}, \gamma_{1,2}) \) are selected according to the condition in Equation (25) and that the condition in Equation (24) is valid for the system Equation (21), then, the estimated states based on the STO converge in finite-time to their corresponding real states. The proof of the convergence theorem of the STA-based observer in finite-time is treated and well explained in [45].

The block diagram of the studied electromechanical conversion chain based on IM speed sensorless control is depicted in Figure 6. This structure is based on field oriented vector control of three phase VSI. The mechanical speed sensor is substituted by an SMO based on the STA. This observer uses as inputs the stator currents and voltages (\( i_{safb}, v_{safb} \)) for the estimation of rotor speed (\( \omega_r \)). IGBT OSFs in the inverter are generated using magnetic relays controlled by Matlab/Simulink and dSPACE card.

## 5 EXPERIMENTAL PROTOTYPE AND RESULTS INVESTIGATION

### 5.1 Experimental prototype

The test bench used for the experimental evaluation is depicted in Figure 7. It regroups a 3-kW IM, a VSI, a powder brake and magnetic-relays based electronic circuit for fault injection. The parameters of the IM and the inverter used in the experiments are given in Table 2. The sensorless speed scheme is tested in a closed-loop vector control. Hence, the IFOC control and the STA-based SMO are implemented using a dSPACE system with DS1104 controller board. The 3-\( \phi \) inverter is constructed by using SEMIKRON IGBT components. The PWM-inverter is running with a switching frequency of 5 kHz. Dedicated fast analogue circuits (magnetic relays) are used for real-time open-switch fault generation into the VSI feeding the IM. Therefore, to inject an open-switch fault, these magnetic relays, by a simple command from the dSPACE controller card, keep the switching signal of the faulty transistor in ‘OFF’ state.

### 5.2 Experimental results

This section verifies the robustness of the control algorithm under healthy conditions and then in postfault operation modes. Three tests investigate the IM drive sensorless control using STA observer during inverter fault occurrence, isolation and reconfiguration modes:

**Test 1**: The first test is performed to validate the performance of the control algorithm in healthy operating conditions.
accuracy of the STA-based observer and the robustness of the speed sensorless control system in postfault operation mode.

**Test 3:** This test investigates the sensorless speed-control of the IM drive behaviour under fault tolerant control transition, since this step should be applied after.

### 5.2.1 | Test 1: Prefault operation mode

To test the effectiveness of the SMO during sudden speed change and speed reversal experimental results are presented in Figure 8. This figure shows the experimental waveforms of the reference, actual and estimated rotor speeds and the measured and estimated inverter output currents in $\alpha$-$\beta$ axis. In a steady state, The sensorless drive is running at 1000 rpm and at $t = 9.5$ s a step transition of the reference speed from 1000 rpm to -1000 rpm is applied.

Regarding the performance of the STO sensorless control algorithm, the estimated stator currents ($i_a$, $i_b$) depicted in Figure 8(a) follow perfectly the measured ones in steady state. However, light errors are observed in start-up and rotor speed inversion steps. In addition, as depicted in Figure 8(b), good speed estimation accuracy is obtained in steady state and during reference speed transients where the estimated speed tracks the actual speed. In conclusion, the obtained results clearly show good performance of the STA-based sensorless control of the IM in terms of trajectory tracking and estimation accuracy in prefault operation mode. The next tests investigate the sensitivity of the observer in postfault operation mode due to inverter open-circuit fault.

### 5.2.2 | Test 2: Postfault operation mode

This section investigates the STA-based sensorless control performance under single and multiple open-switch faults in the VSI. A first experiment is performed when IGBT $T_d$ is opened. The time-domain waveforms of the output inverter currents, the measured and the estimated rotor speeds are illustrated in Figure 9. The performances of the sensorless control algorithm are analysed with respect to the accuracy estimation of the inverter output currents and the ripple ratio of the estimated and measured speeds in postfault condition. The ripple ratio of the actual speed $\langle \omega_r \rangle$ is given by the following relation:

$$\tau_{\omega r} = \frac{\omega_r \text{Max} - \omega_r \text{Min}}{\langle \omega_r \rangle} \times 100$$  \hspace{1cm} (26)$$

where $\langle \omega_r \rangle$ represents the average value of the actual speed around the steady state operation mode. $\omega_r \text{Max}$ and $\omega_r \text{Min}$ denote the maximum and minimum value of the velocity ripples in the positive and negative direction, respectively. A fault condition is applied to IGBT $T_d$ at $t = 4.83s$. After the fault occurrence, the corresponding phase current $i_b$ suddenly drops

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**Table 2** VSI, IM and STO parameters

| VSI (IPM- SEMIKRON IGBT) |  |
|---------------------------|--|
| DC-link voltage           | 540 V |
| Dead time                 | 4 $\mu$s |
| PWM switching frequency   | 5 kHz |
| IM                        |  |
| Rated power               | 3 kW |
| Rated speed               | 1430 rpm |
| Rated frequency           | 50 Hz |
| $(R_s, R_r)$              | 2.3 $\Omega$, 1.55 $\Omega$ |
| $(L_s, L_r)$              | 0.261 H |
| $J$                       | 0.02 kg m$^2$ |
| $M$                       | 0.249 H |
| STO                       |  |
| $\xi_{1,2}$               | 19000 |
| $\xi_{1,2}$               | 4500 |

*Note: The detection, location and isolation of the faulty inverter-leg.*
to zero and flows only in the positive direction. Direct current components (dc values) are consequently added to the remaining currents corresponding to the healthy phases ($i_a$, $i_c$).

Regarding the estimation performance of the STO and based on the zoomed views of the inverter output currents in Figure 9(b), it can be observed that the estimated stator currents still follow their corresponding measured signals with good estimation accuracy.

The estimated rotor speed depicted in Figure 9(c) undergoes a relatively low disturbance but remains close to the reference speed due to the ripples. The ripples ratio $\tau_m$ of the estimated and measured speeds is relatively equal with a value about 3.5%, which demonstrates the good performance of the STO in terms of trajectory tracking and estimation accuracy under single IGBT open-circuit fault.

The dynamic behaviour of the speed sensorless IM drive under load operating condition and multiple IGBT open-circuit fault is illustrated in Figure 10. The motor operates at a reverse speed of $-1000$ rpm and 50% of the nominal load torque. The fault is applied to the lower and upper IGBTs, $T_3$ and $T_6$, of the second and the third inverter legs, respectively, at $t = 12.59$ s. The fault occurrence results in the loss of one current alternation of each faulty legs ($i_b$, $i_c$).

Figure 10(b) shows the experimental waveforms of measured and estimated speed and the current representing the image of the torque (stator current in $dq$ frame $i_q$). It can be observed that the measured and estimated speed is disturbed following the occurrence of the fault while the estimated inverter output currents ($i_a$, $i_b$, $i_c$) given by the zoomed views displayed in Figure 10(a) present a good
estimation accuracy comparing to the high estimation error registered by the previous based observer methods presented in [36, 50, 51]. The estimated currents remain continuously closed to the measured ones ($i_a, i_b, i_c$) with a relatively small error. This confirms the contribution of the STA applied to the IM model Equation (11) to obtain an estimation of the stator currents and rotor flux in which the rotor speed is not involved in the correction term, as depicted in Figure 4 and Equation 9. So, the perturbation caused by the fault condition across the estimated speed did not reflex on the rotor flux estimation and the estimated inverter output currents. Compared to the reference speed fixed at -1000 rpm, the ripples ratio is still relatively close to 3.3% for the estimated speed and 6% for the measured one. The increase in the ripples ratio compared to the previous test (single IGBT open-circuit fault) is due to the increased load torque as well as the introduction of a multiple IGBT open-circuit fault. It is important to note that the continuity of operation of IM drive is maintained to the high robustness and performance of the used STO for the sensorless control under inverter fault conditions. This is not the case in [34–36, 50, 51] where the estimation of stator currents and/or rotor speed is hardly disturbed or completely failed.

A comparative study quantifying the current estimation error for different used model-based observers is presented in Table 3. This study shows that during the faulty operation mode generated by the occurrence of an IGBT open-circuit fault, the two SMO observers used in [36] and [50] demonstrate a failure of current estimation with a considerable error between the measured and the estimated currents. This considerable estimation error leads to cumulative errors in the estimation of the remain motor state variables and consequently to a high ripple in rotor speed, which, in addition to excessive motor overheating, can lead to sensorless control failure. In contrary, when using the STO, a good estimation accuracy of the stator currents is recorded during the appearance of the fault.

Similar to the comportment of the speed sensored IM drive (with speed sensor) in postfault operation mode, the ripples ratio of $q$-axis current shown in the second subplot of Figure 10(c) is relatively high, about 156%. Since the electromagnetic torque is directly dependent on this disturbed current, the recorded ripples reflect the high level of the mechanical vibrations which can lead to additional faults in the electrical drive system. Therefore, early detection and compensation of the fault are in high demand to protect the system and ensure its continuous operation under safe conditions.

In the next, the fault compensation step is investigated. Its implementation requires first and foremost the information provided by the diagnosis and isolation steps. Accordingly, the sequence including fault detection and fault isolation is implemented and uses the method addressed in [28]. This method is fast and allows detecting the fault in an early stage to achieve the isolation and reconfiguration of the electrical drive system.

**Figure 10** Experimental results of the sensorless control based on ST observer under inverter fault operating mode: simultaneous IGBT OSF ($T_1$ and $T_2$) (50% Cn, -1000 rpm) (a) Real and estimated stator currents. (b) Zoomed view of the real and the estimated currents. (c) Real and the estimated speeds and indirect stator current
5.2.3 | Test 3: Fault compensation

A fault compensation technique is applied in order to analyse the sensorless control robustness during the transient states due to the fault occurrence, the fault isolation and the system reconfiguration steps. These evaluations permit to verify the immunity of the STO in postfault operation mode and its ability to reconstruct the estimated variable states. Various fault tolerant control strategies are applied in fault tolerant systems to ensure full or partial restoration of electrical drive functionality [52, 53]. The used fault compensation strategy is based on hardware redundancy as illustrated in Figure 10. An additional leg (\(T_7\), \(T_8\)), not used in prefault operation mode, is used to replace the faulty one, as depicted in Figure 11. In this topology, the triacs are used to isolate the failed leg and connect the fourth redundant leg. The open-switch fault is introduced in the upper IGBT T5. Once the fault detection step is accomplished, the inverter topology is modified so that the faulty motor winding becomes connected to the redundant leg.

The obtained experimental results of the fault tolerant sensorless control of IM drive based on the STO are illustrated in Figure 12. Experimental results show that the estimated current and speed are always closed to the measured ones in healthy operation mode. Good performances are also obtained after the fault occurrence in the VSI since the STA-based observer continues to correctly operate and confirmed its ability to overcome the disturbances caused by the occurrence and isolation phases of the fault at \(t = 6\) s and \(t = 6.013\) s, respectively, with improved system stability and good estimation accuracy. The maximum recorded error between measured and estimated speeds (sublots 2 and 3) during the transition phases is relatively small (about 3.7%), indicating the good performance of the observer for reconstructing the estimated state of the electrical drive under severe and transient operating conditions. It is also important to note that the estimated speed ripple rate \(\tau \omega\) is low (about 4.2%) in comparison to the first-order SMO investigated in [36], where the estimation of rotor flux and stator currents depends on the rotor speed (see Figure 3).

As announced in the aforementioned section, these experimental investigations aim to analyse the behaviour of the sensorless IM drive and to compare it with its homologue classical controlled structure (with speed sensor). Thus, these results are validated by comparing them to those presented in [54], where the hardware redundancy reconfiguration strategy used is applied with a conventional system based on an IM controlled by a mechanical speed sensor. In [54], after the compensation of the OSF, the system took about one second to restore its steady state operating mode with a speed ripple rate \(\tau \omega\) of about 25%. Based on the presented results, it can be concluded that sensorless control based on the STA performs comparably to a conventional system with speed sensor during the transient states due to the detection, isolation and compensation steps. This convergence of behaviours and the functional stability of the motor during these transient states are very important from FD point of view. Therefore, the diagnostic approaches developed in the

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**TABLE 3** Comparative study of current estimation error quantity given by different observers under faulty conditions

| Type of control | Observer | Fault type | Current estimation accuracy |
|-----------------|----------|------------|-----------------------------|
| Speed-sensored control | SMO | OSF | Failed |
| Speed-sensorless control | SMO | OSF | Failed |
| **This work** Speed-sensorless control | SMO-based STA | OSF | Maintained: good estimation |

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**FIGURE 11** Block diagram of the redundant inverter topology

**FIGURE 12** Experimental waveforms of fault tolerant sensorless control based on STO under IGBT open-circuit fault
study for IM with speed sensing can remain available in the case of an STO-based speed sensorless scheme to diagnose inverter OSFs.

6 | CONCLUSIONS AND DISCUSSION

A second-order SMO based on the STA has been proposed for experimental investigation in order to analyse its robustness under healthy operating conditions and in the presence of inverter faults. The inverter faults are single and double open circuit of the power switches. To improve the reliability of the speed sensorless controlled IM drives and to assess the observer’s accuracy under transient stages, a reconfiguration strategy based on hardware redundancy has been applied. The SMO based on the STA has confirmed its best quality by maintaining good IM state estimation performance even in the postfault operation mode and during transient states. This has ensured a better operating stability of the speed sensorless motor drive and has guaranteed its continuity of operation.

This study raises prospects for further in-depth studies related to the relationship between the power asymmetry generated by the inverter switch fault and the rotor speed dependency on the stator currents estimation model. It also allows future research on fault diagnosis and monitoring of damaged drives powering motors operated in the speed-sensorless mode.

NOMENCLATURE

FD fault diagnosis
FDI fault detection identification
HF high frequency
FTC fault tolerant control
IFOC indirect field oriented control
IGBT insulated gate bipolar transistor
IM induction motor
IPMSM interior permanent magnet synchronous motor
MRAS model reference adaptive system
OSF open switch fault
SMO sliding mode observer
STA super twisting algorithm
STO super twisting observer
VSI voltage source inverter
PMSG permanent magnet synchronous generator
PWM pulse width modulation
\(i_{abc}, i_{alpf}, i_{dq}\) three phase stator currents, stator current in \(\alpha-\beta\) reference frame, stator current in \(d-q\) reference frame
\(\epsilon_i\) current estimation errors
\(v_{alpf}\) stator voltage components
\(\phi_{alfr}\) rotor fluxes
\(\omega_r, \hat{\omega}_r\) actual and estimated rotor speeds
\(\hat{x}\) the estimation state of \(\chi\)

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