SPEED SENSOR FAULTS DIAGNOSIS IN AN INDUCTION MOTOR VECTOR CONTROLLED DRIVE

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ABSTRACT

Many induction motor speed controllers contain a speed or position sensor. This last is required to provide accurate measurement. A faulty speed sensor decreases the controller performance dramatically. Hence, a fault diagnosis and detection technique is necessary. This paper deals with several faults which affect the speed sensor used in an induction motor vector controlled drive. Three different faults are considered; offset fault, uncertainty of measurement, and total loss of feedback information. Then a detection strategy is suggested based on the computation of the energy of the average standard deviation of speed data. Simulation on Matlab/Simulink and experiments were carried out to show the effect of each fault on the vector control performance and to verify the effectiveness of the proposed detection scheme.

Keywords: speed sensor fault, induction motor, field oriented control, average standard deviation, energy of a signal

1. INTRODUCTION

Sensors are devices that transform a physical signal to an electrical one (usually a current or voltage). The use of these elements is unavoidable in most engineering applications, especially for monitoring and control. They provide calculators with the necessary data for decision making. In different fields, such as industry and transportation, having reliable sensors is mandatory. However, these sensors are prone to many faults, which may affect the system performance. Usually, speed control requires speed or position sensors. In induction machine vector control schemes, the accuracy of the speed sensor signal is crucial. This component may undergo several faults which can be listed in four major types as follows:

- Constant faults in which the sensor's signal remains constant despite the variation of the rotor position [1, 2].
- Bias, offset and excessive noise due to measurement considered as additional faults [2–12].
- Gain fault where the encoder signal is amplified [13].
- Intermittent or total loss of feedback information [14–24].

In tachometric sensors, either DC generators or alternators, the intermittent fault is usually due to rotor eccentricity [15, 25] or attrition of the brushes or bearings. Whereas the variation of electrical parameters, such as resistances and inductances, in some operating conditions produces offset faults. Note that, the loss of feedback signal may occur due to electrical link disconnection or the breakdown of the sensor. Besides, the weakness of the light source (LED) or the degradation of the phototransistor in rotary encoders causes uncertain measurements [2, 15]. In both types of sensors, the mechanical sliding of the encoder can also cause an inaccuracy of measurement. Such faults do not cause an immediate change in average speed, but a significant change in its standard deviation [23].

Some experts designed robust encoders with the ability to maintain acceptable functionality despite their faulty state [26]. Yet, more researches are being conducted to detect and isolate speed sensor faults. The classical way to detect any malfunction implies hardware redundancy [27], so the signals of the faulty sensors and the healthy ones are compared to generate fault indicators. But since the advent of electronic calculators, model based methods gained more interest. This brought forward the concept of analytical redundancy where virtual sensors (estimators, filters, observers) such as Kalman filter, Luenberger observer and MRAS estimate the speed signal from other available measurements [1–5, 8–15, 17–20, 22, 28–30]. Moreover, two recent sets of techniques have been developed. The first one is based on signal processing, such as wavelet packet decomposition [15, 31] [15, 35], hodographs [32], adaptive thresholds [33], least squares regression [6], parity space [21] and average standard deviation [23]. The second one involves machine learning techniques such as fuzzy logic [34, 35], artificial neural networks [24] and genetic algorithms [32].

This paper investigates the effect of speed sensor faults on the induction machine control, and then it suggests a new detection approach. The advantage of this last resides in its low cost, simplicity of implementation and efficiency. The paper is organized as follows. Firstly, an introduction presenting a literature review on the subject. Section two is dedicated to field oriented control of the induction motor. Three speed sensor faults are explained in section three. Simulation results are shown in section four, while a detection technique is suggested in the fifth section. The experimental results of speed sensor faults and their detection are shown in section six. At last, a conclusion is presented in section seven.

2. INDIRECT FIELD ORIENTED CONTROL OF THE INDUCTION MOTOR

Vector control by rotor flux orientation is a widely used and an effective technique. Its aim is the separate

regulation of torque and rotor flux similarly to the independently excited DC motor. To achieve this purpose, "d" axis is fixed to the rotor flux so ϕ_{rq} becomes null. The induction machine model after flux orientation is given below:

$$
\begin{cases}
\phi_r = \phi_{rd} = L_r i_{rd} + L_m i_{sd} \rightarrow i_{rd} = \frac{1}{L_r}(\phi_{rd} - L_m i_{sd}) \\[2mm]
\phi_{rq} = 0 = L_r i_{rq} + L_m i_{sq} \rightarrow i_{rq} = -\frac{L_m i_{sq}}{L_r} \\[2mm]
v_{sd} = R_s i_{sd} + \sigma L_s \frac{d}{dt} i_{sd} + \frac{L_m}{L_r}\frac{d}{dt}\phi_r - \omega_e \sigma L_s i_{sq} \\[2mm]
v_{sq} = R_s i_{sq} + \sigma L_s \frac{d}{dt} i_{sq} + \omega_e \left(\frac{L_m}{L_r}\phi_r + \sigma L_s i_{sd}\right) \\[2mm]
v_{rd} = 0 = R_r i_{rd} + \frac{d}{dt}\phi_r \rightarrow \tau_r \frac{d}{dt}\phi_r + \phi_r = L_m i_{sd} \\[2mm]
v_{rq} = 0 = R_r i_{rq} + \omega_{sl}\phi_r \rightarrow \omega_{sl} = \frac{L_m}{\tau_r \phi_r} i_{sq} \\[2mm]
T_e = p\frac{L_m}{L_r}\phi_{rd} I_{sq}
\end{cases}
$$

$$(1)$$

We notice from the model that there's a coupling between the stator voltages and currents. In other words, we cannot control the two currents i_{sd} and i_{sq} independently. Thus, we have to eliminate the coupling terms e_d and e_q. These two are formulated respectively by the equations (2) and (3).

$$e_d = \omega_e \left(\frac{L_m}{L_r}\phi_r + \sigma L_s i_{sd}\right) \tag{2}$$

$$e_q = \frac{L_m}{L_r}\frac{d}{dt}\phi_r - \omega_e \sigma L_s i_{sq} \tag{3}$$

So the stator equations become as follows:

$$v_{sd}^* = R_s i_{sd} + \sigma L_s \frac{d}{dt} i_{sd} \tag{4}$$

$$v_{sq}^* = R_s i_{sq} + \sigma L_s \frac{d}{dt} i_{sq} \tag{5}$$
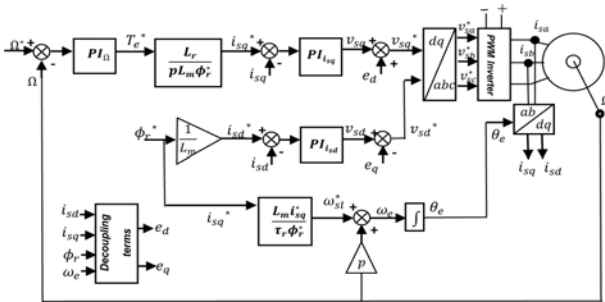

Fig. 1 Block scheme of the indirect field oriented control

Rotor flux and torque are controlled indirectly by i_{sd} and i_{sq} currents. i_{sd}^* is a steady component because its value is set and determined from the rotor flux reference. While i_{sq}^* is obtained from torque reference which is the output of the PI speed controller. The slip frequency is estimated from ϕ_r and i_{sq} then summed with the rotor electric speed to get the synchronous frequency.

The block scheme of the indirect field oriented control is depicted in Fig. 1.

3. SPEED SENSOR FAULTS

3.1. Offset Fault

An offset fault represents a constant shift between the actual speed and its value measured by the sensor. This fault is simulated by adding a constant positive value to the speed so $\Omega_F = \Omega + \Delta\Omega$.

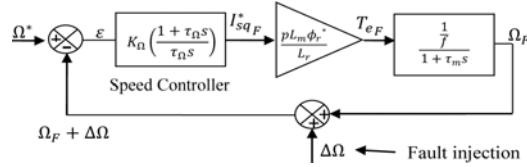The speed control loop becomes as shown on Fig. 2.

Fig. 2 Block scheme of speed control loop with a speed sensor fault

3.2. Uncertain Measurement Fault

This fault is performed on Matlab by adding a random value to the measured speed, so $\widetilde{\Omega_F} = \Omega_{healthy} + |\Delta\Omega|$. Then the expression of the actual speed becomes as follows:

$$\Omega_F = \frac{\gamma\Omega^*}{1+\gamma} - \frac{\gamma|\Delta\Omega|}{1+\gamma} \tag{6}$$

Where:

$$\gamma = K_\Omega \left(\frac{1+\tau_\Omega s}{\tau_\Omega s}\right)\left(\frac{pL_m\phi_r^*}{L_r}\right)\left(\frac{\frac{1}{f}}{1+\tau_m s}\right) \tag{7}$$

3.3. Zero Feedback Fault

This fault is the most dangerous because the sensor stops functioning and gives no output signals. This occurs suddenly and in a very short time where "τ_{Fault}" is smaller than the mechanical time constant $\tau_{Fault} < \tau_{Mec}$ [23]. On Matlab, the simulation is simply done by multiplying the speed by zero.

4. SIMULATION RESULTS AND DISCUSSION

To show the influence of the mentioned faults on the control technique, a simulation has been performed on Matlab, where each fault is activated at t = 11s. Fig. 3a), 3b), 3c), and 3d) represent successively; The phase current, the three phase currents on "dq" reference frame, the torque and the rotor speed.

The motor prompts an inrush current when the reference speed goes from zero to 100 rad/s, then it keeps the same amplitude. Speed controller incites more current to cancel the effect of the offset fault once it is applied. So the magnitude of the phase currents rises, hence, the same is noticed when they are transformed to the synchronous reference frame. The torque is and image of the I_{sq} current, thus it behaves the same way. The actual speed decreases by 10 rad/s to compensate the effect of the sensor fault.

Since the uncertainty of measurement fault is intermittent, it causes pulsation of machine variables.

The phase current manifests many fluctuations (Fig. 3a)). The fault effect is more noticeable on I_{sq} current and torque, while the actual speed pulsates and doesn't follow its reference perfectly. Zero feedback fault is the most severe. The increasing of phase current results the torque and speed to rise. I_{sq} current is limited between -6 A and 6 A so the speed doesn't diverge to a high value.
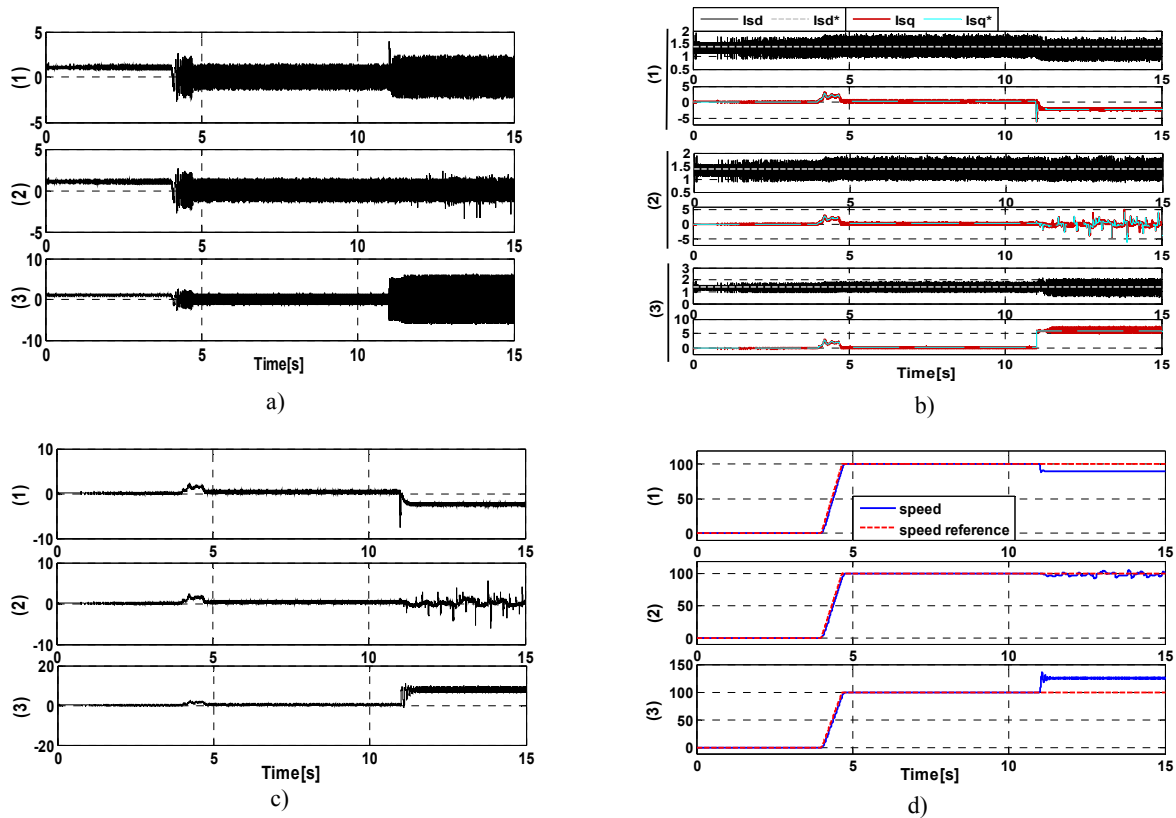

Fig. 3 a) Phase current, b) Currents on "dq" reference frame, c) Torque, d) Speed. And from top to bottom for each subfigure; data plot corresponding to (1) offset fault, (2) uncertain measurement fault, (3) zero feedback fault.

5. SPEED SENSOR FAULT DETECTION

The detection of speed sensor faults is done in two steps:

- Sliding a window whose length is $20 \times (sampling\ time)$ which computes the average standard deviation of 20 points from the beginning of speed data by the following formula [23]:

$$\overline{\sigma_\Omega} = \frac{\sum_{i=1}^{20} \sqrt{(\Omega_i - \overline{\Omega_i})^2}}{20} \qquad (8)$$

- Faults produce impulses using formula (8), to turn these last into a constant or rising signal, their energy is calculated by formula (9):

$$E(\overline{\sigma_\Omega}) = \int_{-\infty}^{+\infty} |\overline{\sigma_\Omega}|^2 dt \qquad (9)$$

The same calculations are performed on the speed reference, then a residue is generated as follows:

$$Residue = |E(\overline{\sigma_\Omega}) - E(\overline{\sigma_{\Omega^*}})| \qquad (10)$$

When the residue exceeds a preset threshold, a fault detection signal goes from zero to one. The bloc scheme of the technique is represented by Fig. 4. To mask the effect of the transient stats and torque load, the average standard deviation signal is compared to a prior threshold to make only the faults signatures pass. Simulation of the technique on Matlab has given the results shown on Fig. 5. The residue stays in zero till the fault is applied, so the average standard deviation of the speed presents an impulse in the offset fault case Fig. 5a) and a series of impulses when the measurement is inaccurate or the speed signal is totally lost Fig. 5b), c). These signatures are transformed to a constant or rising signal by calculating their energy. Consequently, the residue exceeds the threshold which indicates the faulty state of the speed sensor.
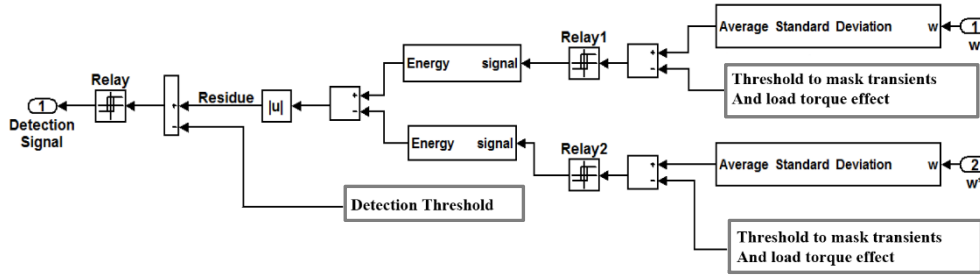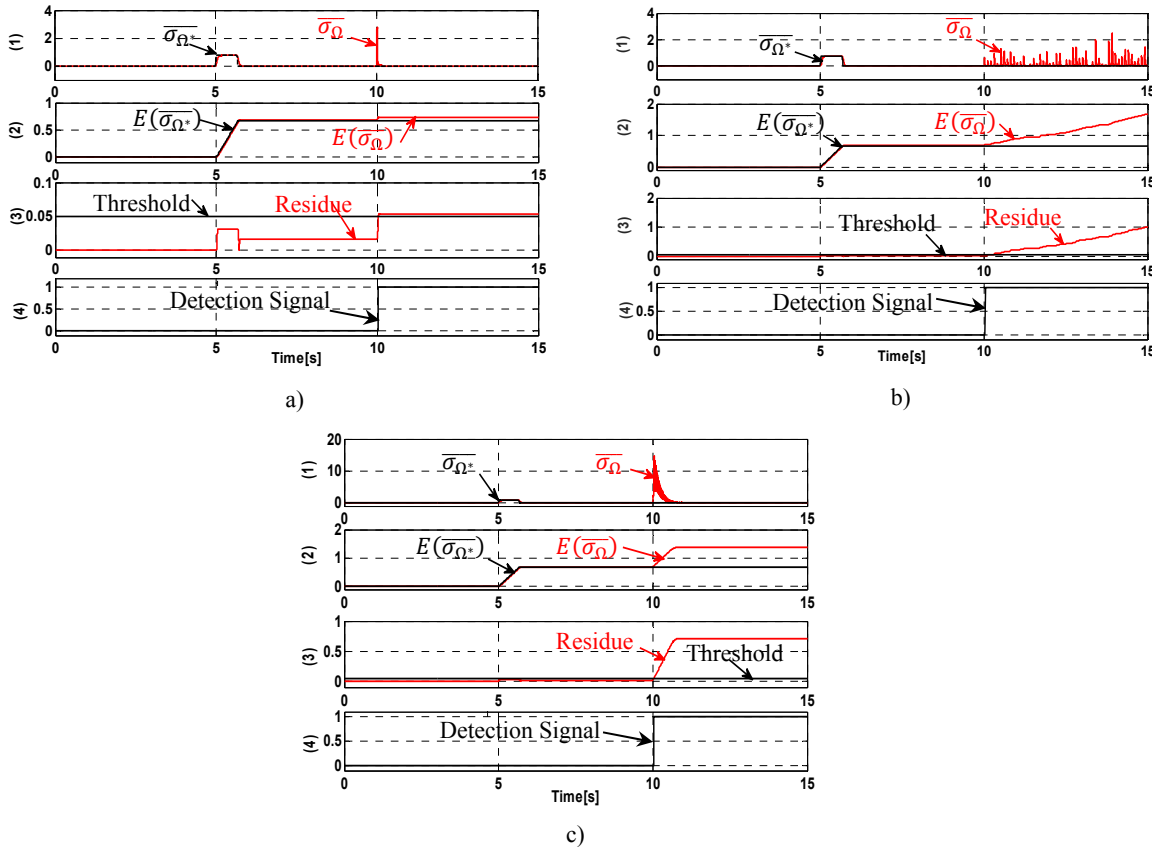
Fig. 4 Speed sensor fault detection scheme

Fig. 5 Detection results for: a) Offset fault, b) Uncertain measurement fault, c) Zero feedback fault. (1) Average standard deviation of speed and speed reference, (2) Energy of the average standard deviation of the speed and speed reference, (3) Residue and detection threshold, (4) Detection signal.

6. EXPERIMENTAL VALIDATION

To verify the simulation results, the same tests are carried out on an induction motor controlled via a Dsp1104. The experimental setup is illustrated in Fig. 6. Currents are measured using three LA25-NP transducers, and a tachometric generator is coupled to the shaft to measure the speed. All Faults are performed in the experiment similarly to the simulation. Fig. 7a), 7b), 7c) and 7d) represent successively phase current, three phase currents on "dq" reference frame, torque, rotor

speed. We notice that the experimental figures are almost similar to those produced by simulation. The only difference is the noise due to measurement and the raise in speed response time. Faults detection is performed by the same scenario, where the residue represents the error between the energy of the average standard deviation of the speed and its reference. According to (Fig. 8), the experimental test proves the efficiency of the suggested detection scheme, since experimental results are almost similar to those of simulation.
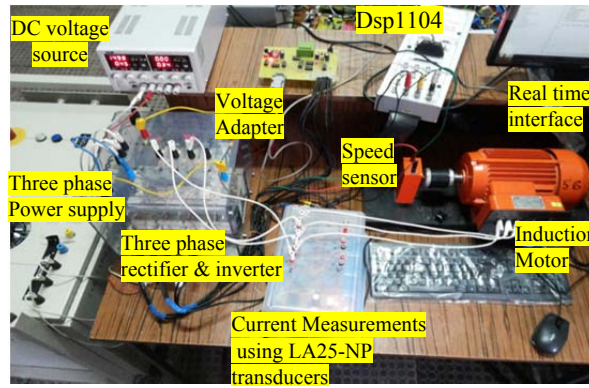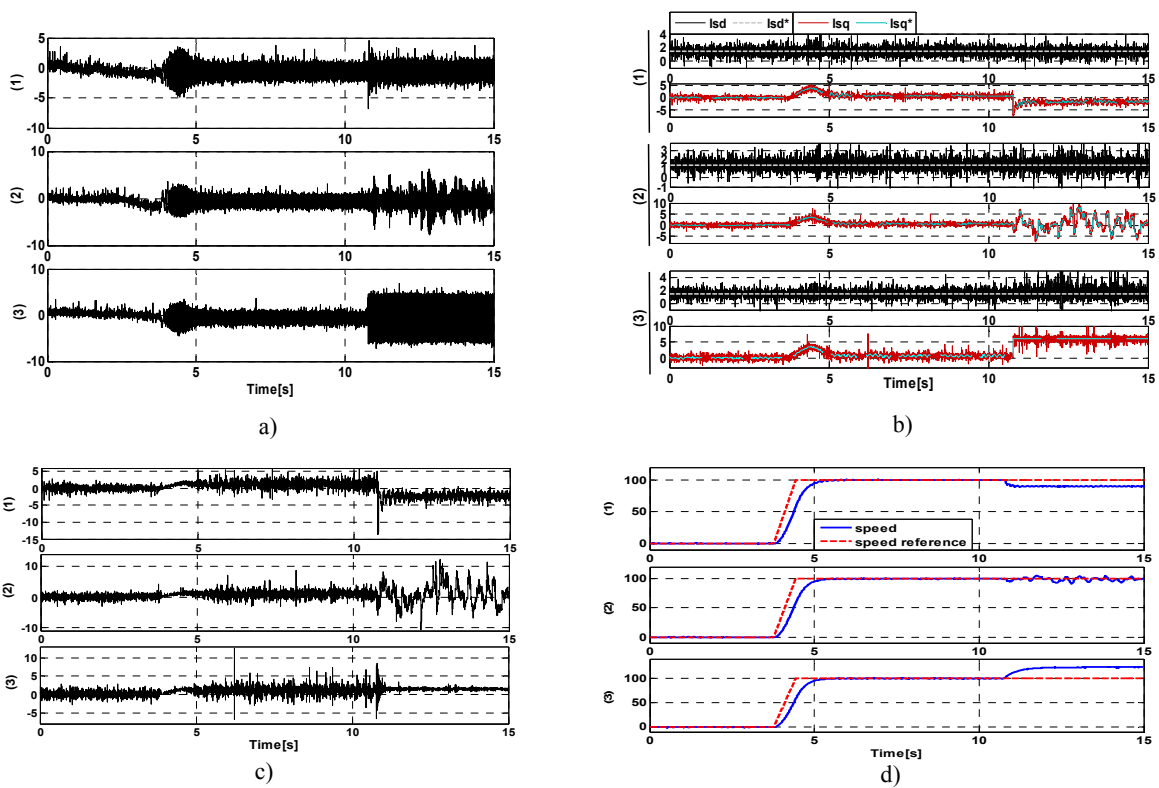
Fig. 6 Picture of the experimental setup
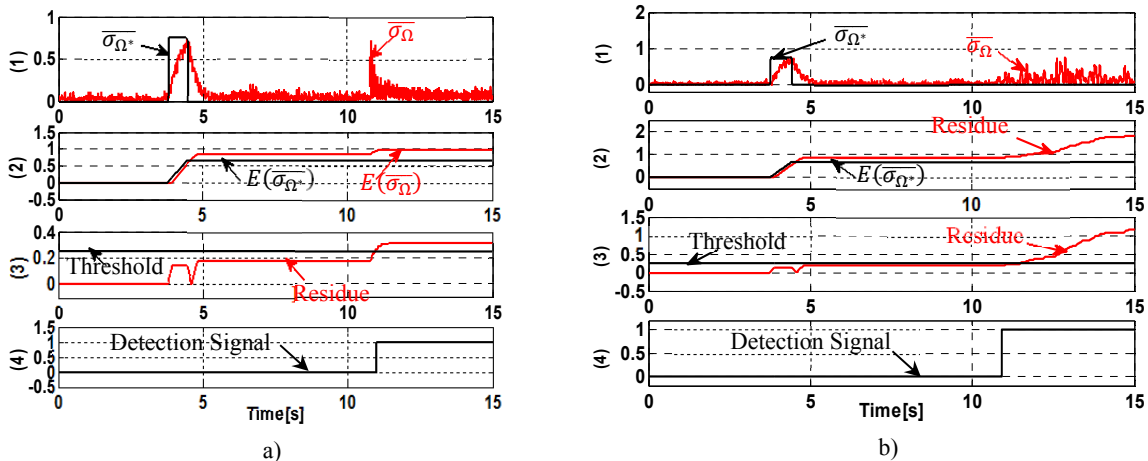

Fig. 7 a) Phase current, b) Currents on "dq" reference frame, c) Torque, d) Speed. And from top to bottom for each subfigure; data plot corresponding to (1) offset fault, (2) uncertain measurement fault, (3) zero feedback fault.
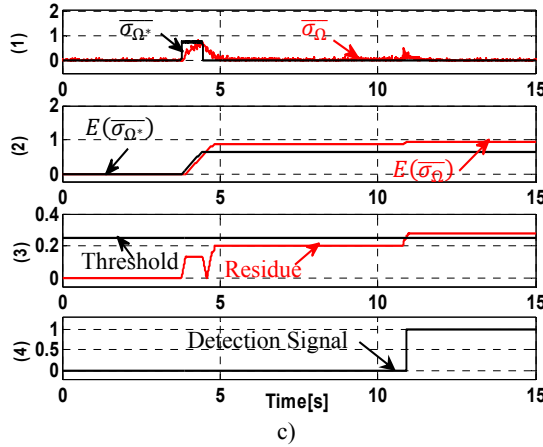
Fig. 8 Detection results for: a) Offset fault, b) Uncertain measurement fault, c) Zero feedback fault. (1) Average standard deviation of speed and speed reference, (2) Energy of the average standard deviation of the speed and speed reference, (3) Residue and detection threshold, (4) Detection signal.

7. VALIDATION WITH LOAD TORQUE AND VARIOUS SPEEDS

To verify the validity of the proposed detection approach with load torque and variable speed, a simulation has been performed. In this section, only uncertain measurement fault is considered. Fig. 9 shows the fault effect on the different variables. From Fig. 10 we notice that the detection approach is still efficient under the load and with variable speed. In order to insure the robustness of the fault detector, the threshold to mask transient states and load effects (see Fig. 4) should be superior to the highest value of the average standard deviation generated by a load torque or variation in speed reference.

8. CONCLUSION

This paper has dealt with three types of speed sensor faults, offset, inaccurate measurement and the zero feedback fault. The effect of each one of them on the vector control of an induction motor is presented, then, a new detection scheme is proposed. Faults are basically detected by the calculation of the energy of the average standard deviation of the speed and its reference, then the two energies are compared in order to generate a fault detection signal.

The defective speed sensor has to be quickly isolated because it lowers the performance of the induction motor control, which leads to an enhanced type of control having a fault tolerance feature.

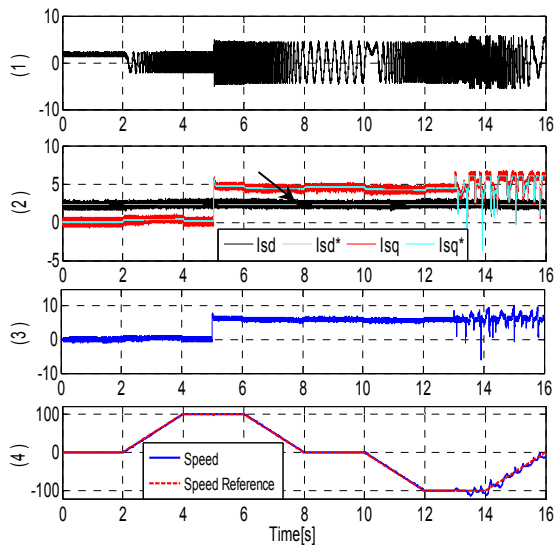**Fig. 9** The effect of uncertain measurement fault on: (1) Phase current, (2) Phase currents on dq reference frame, (3) Torque and Speed.
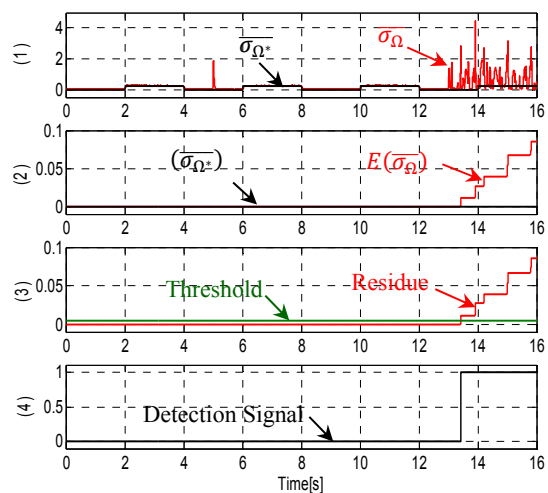

Fig. 10 Detection results for uncertain measurement fault, (1) Average standard deviation of speed and speed reference, (2) Energy of the average standard deviation of the speed and speed reference, (3) Residue and detection hreshold, (4) Detection signal.

APPENDIX A: NOMENCLATURE AND SYMBOLS

v_{sd}, v_{sq}	Direct and Quadrature stator voltages.
v_{sd}^*, v_{sq}^*	Decoupled, direct and Quadrature stator voltages.
e_d, e_q	Coupling terms on d,q axes.
v_{rd}, v_{rq}	Direct and Quadrature rotor voltages.
i_{sd}, i_{sq}	Direct and Quadrature stator currents.
i_{rd}, i_{rd}	Direct and Quadrature rotor currents.
ϕ_{rd}, ϕ_{rd}	Direct and Quadrature rotor fluxes.
Ω, Ω^*	Actual rotor speed, reference rotor speed.
$\Delta\Omega$	Injected speed sensor fault.
R_s, R_r	Stator resistance, rotor resistance.
L_s, L_r, L_m	Cyclic rotor inductance, Cyclic rotor inductance, Cyclic mutual Inductance.
σ	Leakage factor, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$.
ω_e, ω_{sl}	Stator frequency, slip frequency.
θ_e	Angle that fulfills $\omega_e = \frac{d\theta_e}{dt}$.
T_e	Electromagnetic torque.
ϕ_r^*	Reference flux.
p	Number of pole pairs.
f	Motor friction coefficient.
J	Inertia constant of motor.
τ_m	Motor mechanical time constant.
$\widetilde{\Omega_F}$	Measured speed by the faulty sensor.
$\overline{\sigma_\Omega}$	Speed average standard deviation.
$E(\overline{\sigma_\Omega})$	Energy of the average standard deviation.

APPENDIX B: RATED DATA OF THE INDUCTION MOTOR

Table 1 Rated data of the Induction Motor

Rated values		Rated parameters	
Voltage (Δ/Y)	220/380 [v]	R_s, R_r	12.75, 5.1498 [Ω]
Current (Y)	2.7 [A]	L_s, L_r, M	0.4991, 0.4331, 0.4331 [H]
Power	0.9 [kW]	J	0.0035 [kg.m^2]
Pole pairs (p)	2	f	0.001 [Nm/rd/s]

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BIOGRAPHIES

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