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COMPENSATION METHODS OF CURRENT AND SPEED SENSOR FAULTS FOR A VECTOR CONTROLLED INDUCTION MOTOR DRIVE SYSTEM*

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Abstract: Chosen speed and current sensor fault detectors for a vector controlled induction motor drive system have been presented. Systems based on the artificial intelligence (neural network) and simple algorithmic systems were analyzed and tested in various drive conditions. The influence of chosen sensor faults on performance of the drive system has been presented. The compensation strategy was proposed and tested. A fault tolerant drive, based on hardware redundancy, has been developed and presented. Simulation and experimental results are obtained in direct field oriented control algorithm (DFOC) on the laboratory set-up with rapid prototyping card Micro Lab Box DS1202 by dSpace.

Keywords: *DFOC, speed sensor, current sensor, detector, fault tolerant drive*

1. INTRODUCTION

Advanced electric drive systems, used in various industrial applications, require undisturbed information obtained from stator current and rotor speed sensors to the proper work of the vector control algorithms [4, 20]. Those sensors are very sensitive and can be easily broken [4]. Therefore, during the last few years, fault-tolerant control systems (FTCS) became a very active research field for many research groups [6–8, 10, 17, 20]. In the electric motor drives, these systems can generally be classified to passive (PFTCS) and active (AFTCS) ones [7, 12]. The former group is designed to use robust control techniques to ensure that the closed loop system remains insensitive to certain faults so that the impaired system continues to operate with the same controller and system structure [7]. Active FTC systems use detectors or observers to identify failure condition [7, 12]. The stable operation of the drive can be obtained by the additional sensors, estimators, control loops or redundant elements [7].

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The main goal of this paper is to demonstrate a detection and compensation algorithm of current and speed sensor failures for the vector direct field oriented control (DFOC) of induction motor drive system. The solutions proposed are based on active detection system (artificial neural networks) and the redundancy of the drive. Simulations and experimental results of the proposed fault tolerant control system have been presented.

2. SPEED AND STATOR CURRENT SENSOR FAULT ANALYSIS

One of the most important signals used in the vector controlled induction motor drive systems is the information from the speed sensor (e.g., resolver, incremental encoder, etc.) [4, 17, 18]. In the case under study, an incremental encoder was used, hence the information about the motion of the motor is carried by the changes in the state of channels A and B. The speed of the motor can be calculated by measuring the frequency of these points or the time elapsed between them [15, 17]. This measurement sensor is not robust and can be damaged [18]. Failures of incremental speed sensors can be divided into three types [5] which are shown in Table 1. Depending on the coefficient γ, the angular velocity retrieved from the sensor can be intermittent or zero [9].

Table 1. Classification of speed sensor failures [5]

Type of speed sensor failure	Value retrieved from the speed sensor	Coefficient γ
Total failure	$\omega_m^{\mathrm{enc}} = (1-\gamma)\omega_m^{\mathrm{real}}$	$\gamma = 1$
Interruption of specific pulses		$\gamma = [0, 1]$
Failure of individual pulses		$-1 < \gamma < 1$

ω_m^{enc} – measured rotor speed, ω_m^{real} – real rotor speed, γ – constant coefficient.

In Figure 1, the influence of the speed sensor fault on the properties of the DFOC algorithm is presented. Drive is started from zero to the nominal speed. For $t = 1$ s drive is loaded with half of the nominal torque value m_{oN}. The speed sensor fault occurred at $t = 2$ s. It is visible that after the speed sensor fault abnormal situations are observed. The drive is stable but the real speed of the motor is increasing because the control system (PI speed controller) sets maximum possible value of the reference electromagnetic torque. In these conditions, the motor reaches maximum speed value (ca. $1.4\omega_{mN}$) and keeps this value at that level despite changes of the reference speed because of the lack of information from sensor in the control structure. After that, stator current component i_{sy} decreases to the value from the previous (pre-fault) state, despite the reference current value stays at the maximum level ($i_{sy}^{\mathrm{ref}} = 2$ p.u.).

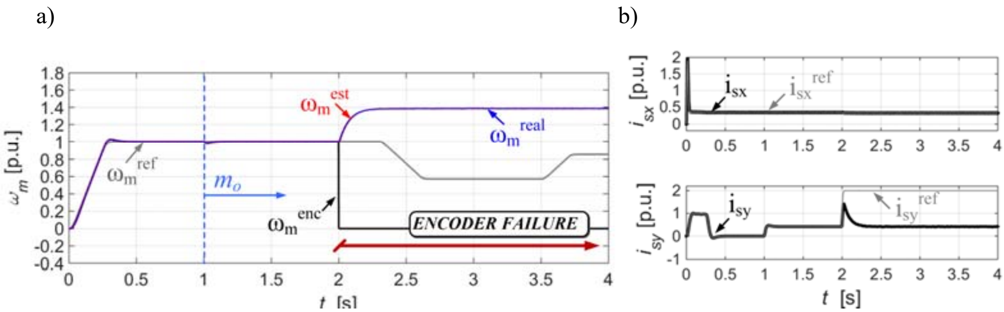

Fig. 1. Transients of measured, estimated and real speed (a), and stator current components (b) for a total failure of the speed sensor in a DFOC structure (simulation results)

Other very important components in the electrical drive systems are current and voltage sensors. Their uninterrupted operation is essential and necessary for the proper work of vector control algorithms. Those sensors, as any electronic device, can be easily broken. The drive system and estimation techniques can work stably without information from the stator voltage sensor but cannot work properly without signals from the stator current sensors [19, 20]. This signal is used for state variable reconstruction [19] and in the internal control loop.

The current sensor may indicate erroneous measurements due to saturation of the magnetic core or phase shift signal in the feedback loop. Basic types of damage to current sensor are shown in Table 2.

Table 2. Classification of stator current sensor failures

Type of the fault	Current value retrieved from the sensor
Variable gain	$i_A = (1-\gamma)I_m \sin(\omega t + \phi)$
Phase shift	$i_A = I_m \sin(\omega t + \varphi) + I_{\text{offset}}$
Signal limit	$i_A = I_m^{\text{sat}} \sin(\omega t + \varphi),\ I_m^{\text{sat}} < I_m$
Noise	$i_A = I_m \sin(\omega t + \phi) + n(t)$
Lack of signal	$i_A = 0$
Intermittent signal	$i_A = I_m \sin(\omega t + \varphi),\ I_m = \{0, 1\}$

I_m – current amplitude, $\omega = 2\pi f$, f – frequency, ϕ – initial phase.

The influence of the stator current sensor faults on the properties of the DFOC algorithm are presented in Fig. 2 (for faulted sensor in phase A) and in Fig. 3 (for faulted sensor in phase B). The drive is started from zero to the nominal speed. The stator current sensor fault occurred at t = 2 s. The drive was loaded similarly as in the previous case.

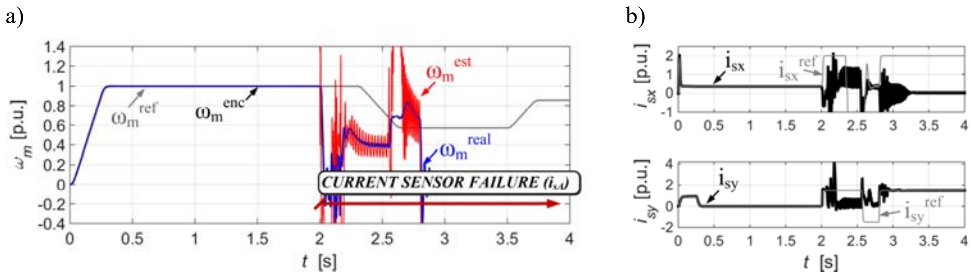

Fig. 2. Transients of measured, estimated and real speed (a), and stator current components (b) for a total failure of the speed sensor in a DFOC structure (simulation results)

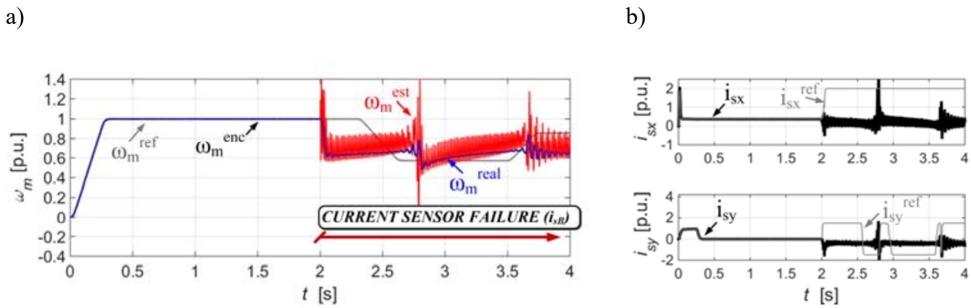

Fig. 3. Transients of measured, estimated and real speed (a), and stator current components (b) for a total failure of the speed sensor in a DFOC structure (simulation results)

After current sensor fault, in both situations oscillations on the current components *x*-*y* and rotor speed (estimated and measured) are visible. The amplitude of these distortions depends on the fault type, its localization and the moment of failure. The worst behaviour however is observed for a fault in phase A. It is obvious that estimation of basic state variables such as electromagnetic torque, rotor flux and speed is impossible at this state.

The total interruption of measurement signal from the current and speed sensor is the most dangerous type of failure that may occur in electric motor drives. It is extremely crucial for safety operation of these systems to implement additional diagnostic features to prevent these situations. Such systems should perform possibly the quickest or even instant response to the occurrence of faulted scenario and should provide certain identification and localization of faulted sensor without mistaken isolation of a properly functioning component.

3. CONTROL STRUCTURES OF INDUCTION MOTOR FAULT TOLERANT DRIVE

In this paper, a well-known DFOC structure for the induction motor is presented [20]. In this method, the information about the rotor flux vector, stator currents and rotor speed are necessary to the proper operation of the drive system. A general scheme of the drive is presented in Fig. 4. In the system analyzed, four sensors are used: an incremental encoder to measure angular velocity, a volt-age sensor in DC link of the frequency converter and two stator current sensors.

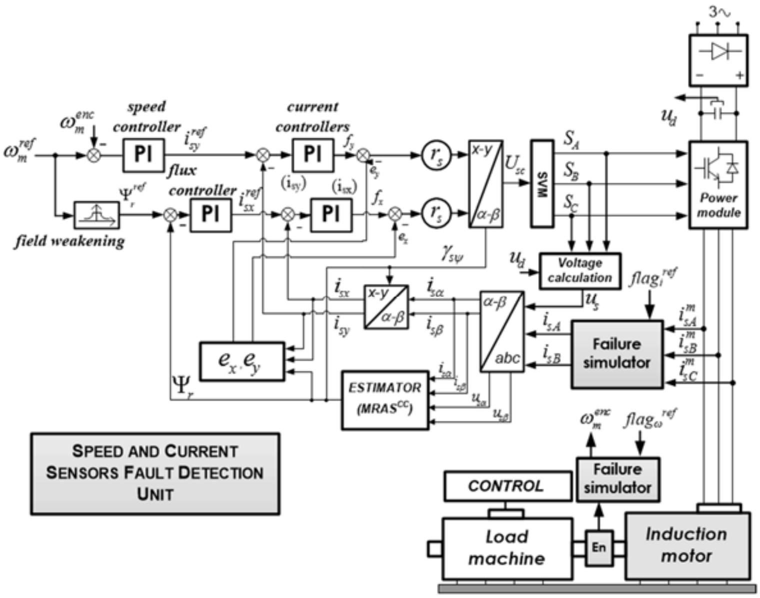

Fig. 4. A scheme of direct field oriented control structure for an induction motor drive

a) b)

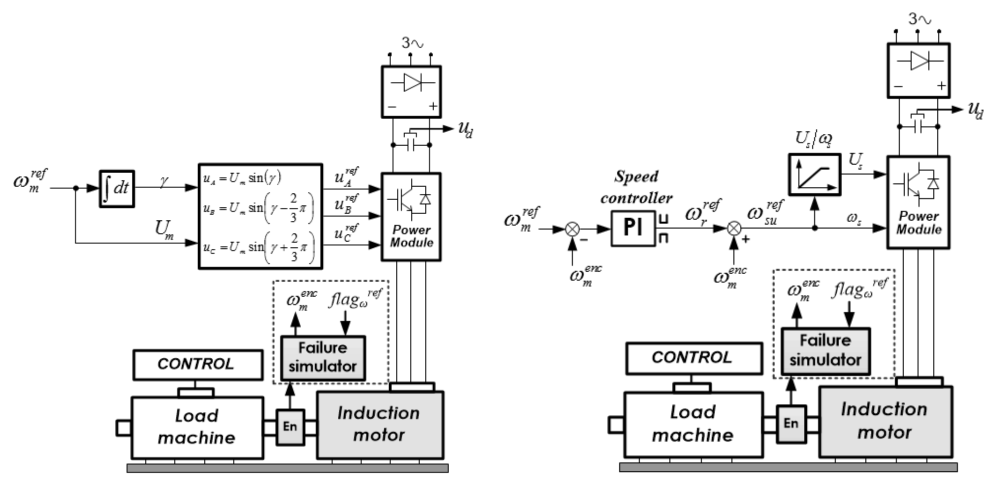

Fig. 5. A scheme of the scalar control algorithm: a) open loop structure, b) closed loop control structure

Another induction motor control algorithm used in the paper is scalar control in two versions: open loop – without any sensors (Fig. 5a) and closed loop – with rotor speed control loop (Fig. 5b). The main disadvantage of these methods are worse dynamical properties of the motor during dynamical states than in the case of vector control algorithms. However, the main advantage of scalar algorithms is the fact that they can provide a stable operation of the drive without information from the internal and external signals, at the cost of lower performance. This factor is essential in the fault tolerant motor drives with increased level of safety. Both scalar and vector control algorithms are used in complete fault tolerant drive.

3.1. SPEED AND STATOR CURRENT FAULTS DETECTION ALGORITHM

In this part of the chapter, the detection algorithms of the speed and stator current sensor faults are presented. In both cases, for direct field oriented control structure, the one-way artificial neural network is used. One of the most effective ways of learning this type of neural networks is by Levenberg–Marquardt algorithm [1, 2]. It combines the convergence of the Gauss–Newton algorithm near minimum and the method of gradient descent for the greater distance from the minimum. The Levenberg–Marquardt algorithm performs in each iteration a compromise learning strategy between the linear model and gradient method approach [3, 13, 16]. The L–M algorithm is one of the fastest and most reliable training algorithms. However, the memory requirements increase proportionally to the square of the number of weights in the network. This prevents its use in relation to the more complicated and large-size networks [3, 13, 16].

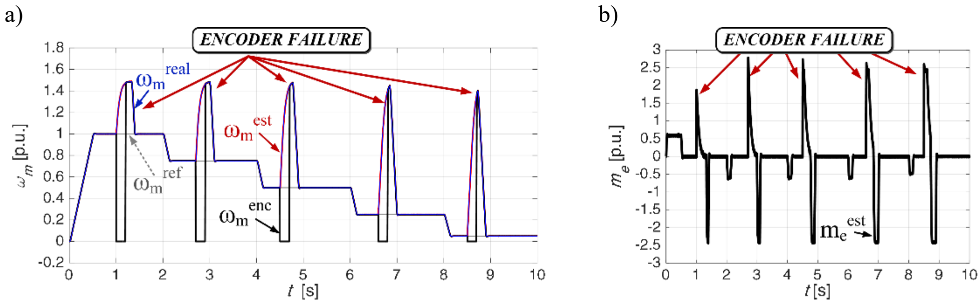

Fig. 6. Transients of measured, estimated and real speed (a), and electromagnetic torque (b) during neural network learning process of the total failure of the speed sensor in a DFOC structure (simulation results)

During the learning process, the reference speed value was changed in the vector control system (Fig. 6). At first, the drive runs at a rated speed which at appropriate time points was reduced. During the drive operation, a total interruption of the measurement sensors loop occurred. Moreover, for each type of measurement sensor, different signals from internal control loop are used. These signals may indirectly or directly depend on disturbed measure.

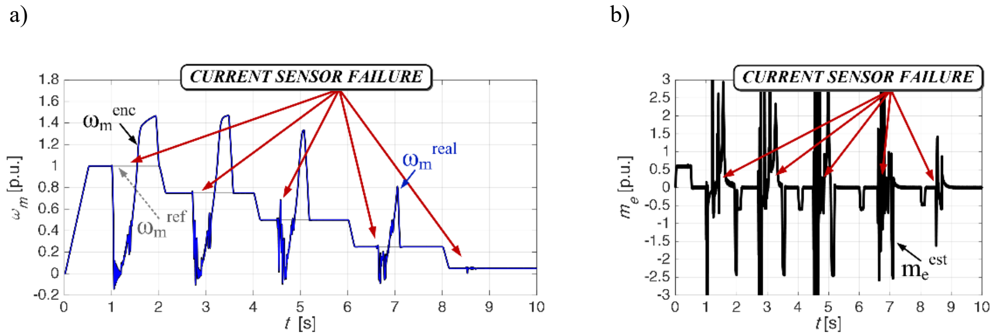

Fig. 7. Transients of measured and real speed (a), and electromagnetic torque (b) during neural network learning process of the total failure of the current sensor (phase A) in a DFOC structure (simulation results)

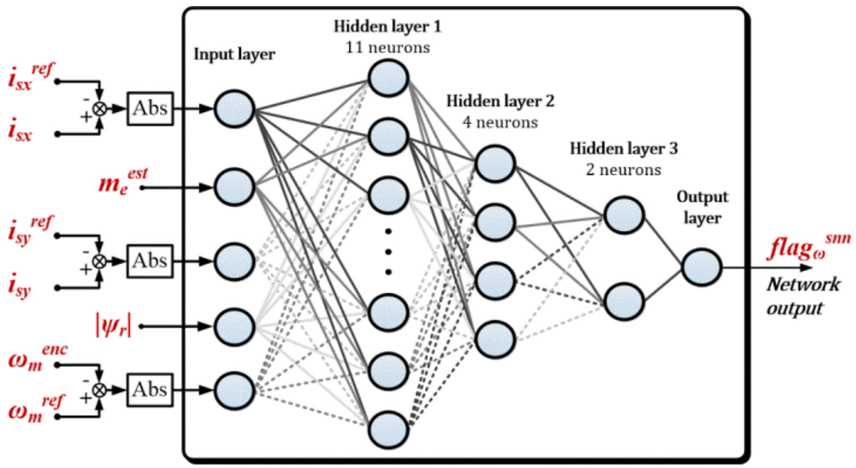

Fig. 8. Block diagram of the speed sensor fault detectors based on the neural network for the DFOC algorithm

As a result, three neural networks (one for incremental encoder, and two for stator current sensors) were designed. Detectors presented in Figs. 8 and 9 consist of three hidden layers in the configuration 5-11-4-2-1 (for speed sensor fault detection) and 6-13-4-2-1 (for stator current sensor fault detection). In the proposed systems, neurons with nonlinear activation functions were used. At the output of the NN detector there is a signal connected with the failures. It is possible to obtain the NN detectors with only two hidden layers, but complication of the system (numbers of neurons, learning process) is worse than for the system proposed.

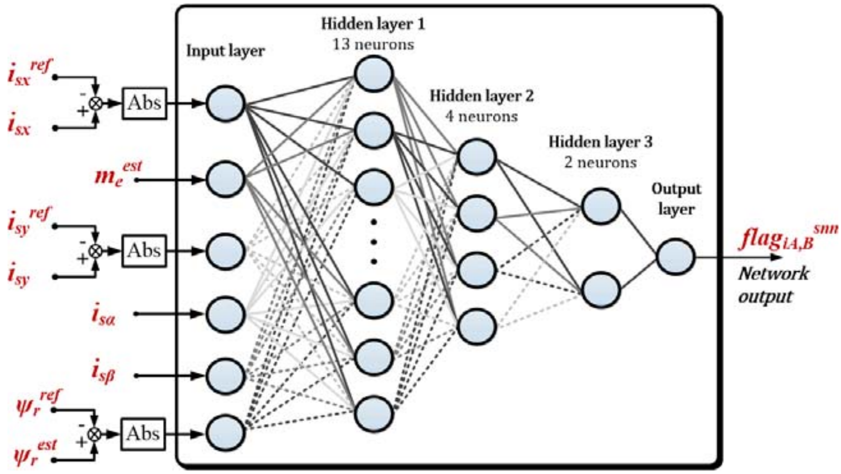

Fig. 9. Block diagrams of the current sensor fault detectors based on a neural network for the DFOC algorithm

For the closed loop scalar control structure, a simple algorithmic detector was used. Because of the lack of basic signals from internal loop, the only solution for speed sensor failure detection is to compare the output signal from the encoder and reference value of the speed, in the following way

$$\text{IF} \; |\, \omega_m^{\text{ref}} - \omega_m^{\text{enc}} \,| \geq \varepsilon_1 \quad \text{then} \quad \text{flag}_{\omega} = 1 \tag{1}$$

where ε_1 is the maximum speed error.

4. FAULT TOLERANT CONTROL SYSTEM ANALYSIS

In this part of the paper, the chosen simulation and experimental results of the fault tolerant induction motor drive system are presented. The general idea of the system proposed is based on the control algorithm redundancy depending on fault type occurrence. Experimental tests were performed using a laboratory set-up consisting of a 1.1 kW induction motor, a SVM voltage inverter and an incremental encoder to measure angular velocity (5000 imp/rev).

The control, detection and speed estimation algorithms were implemented using a MicroLabBox DS1202 card. The analyzed fault scenarios are presented in Fig. 10. The basic control structure in failure free operation of the drive is always the vector control algorithm. In the case of failure, the control structure topology can be changed to a scalar control system or a sensorless mode. The study involved faults of the speed sensor and the two stator current sensors during drive operation. In all the cases presented, the motor was loaded with half of the nominal torque value for 5 s starting from t = 2 s.

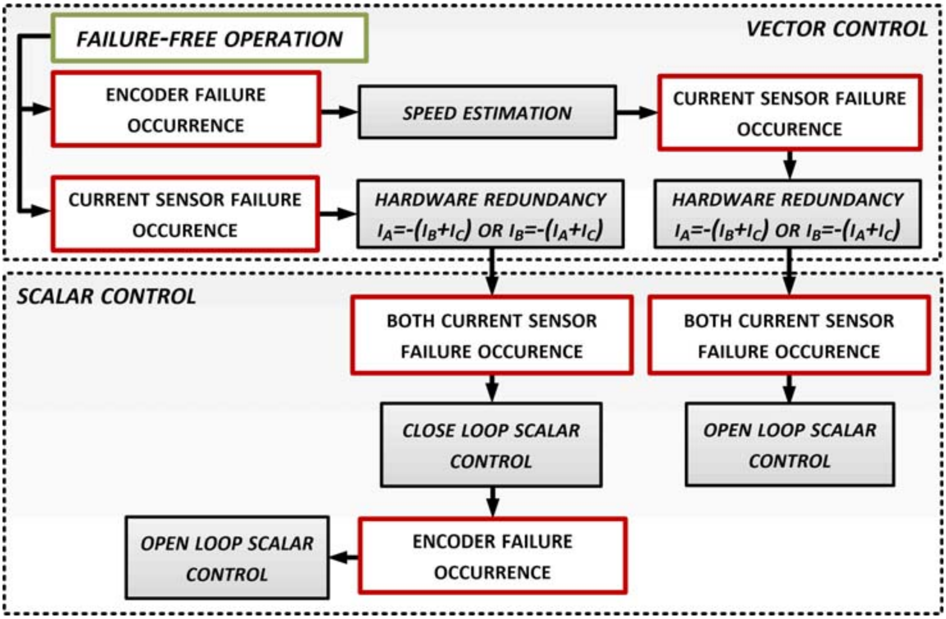

Fig. 10. Block diagram of the analyzed fault scenarios for a vector controlled motor drive

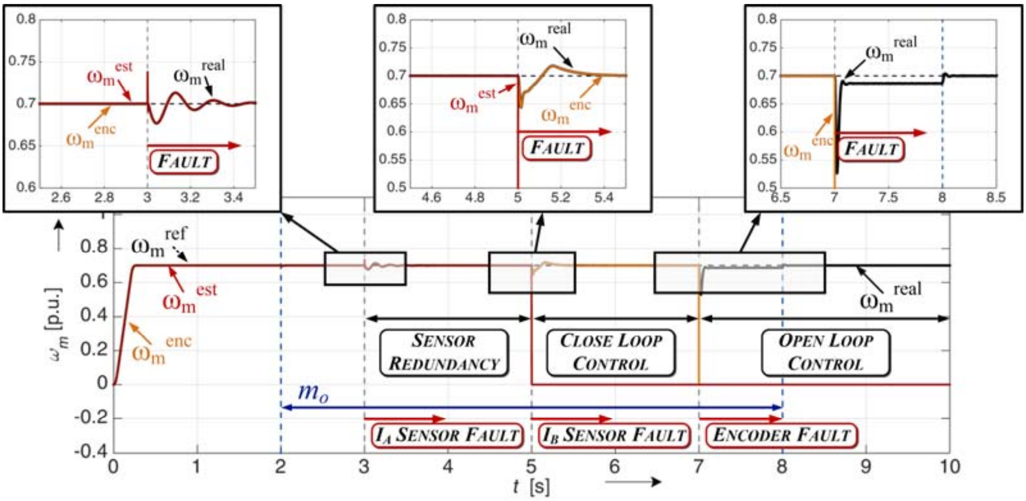

Fig. 11. The fault tolerant control system during faulted condition:
first scenario 1 – fault of the current sensor in phase A, 2 – fault of the current sensor in phase B,
3 – speed sensor fault (simulation results)

It was assumed (Figs. 11 and 12) that after $t = 3$ s, the former current sensor (phase A) was broken, after 5 s from the start, the second one was destroyed (phase B). At $t = 7$ s, the rotor speed sensor was broken. After the first fault detection, the system was reconfigured. The redundant current sensor (in phase C) was used for the calculation of stator current components.

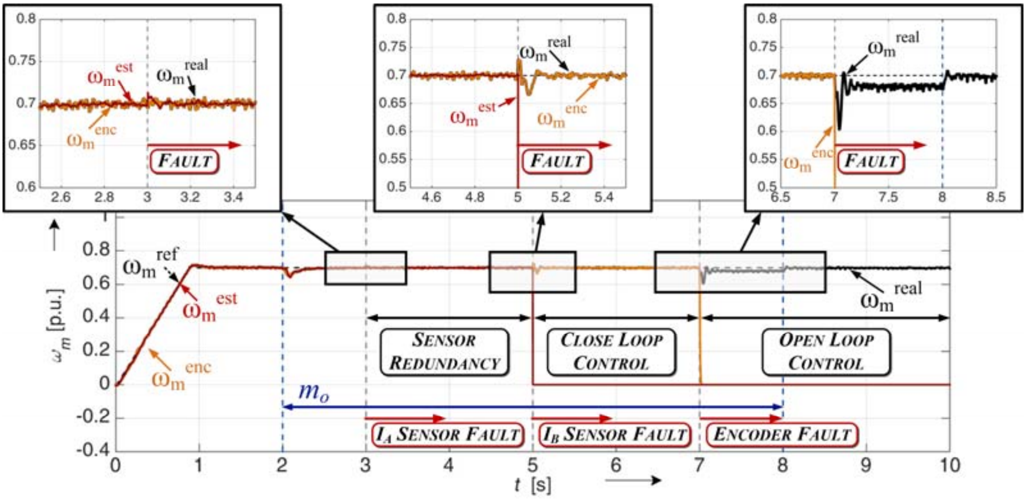

Fig. 12. The fault tolerant control system during faulted condition:
first scenario 1 – fault of the current sensor in phase A, 2 – fault of the current sensor in phase B, 3 – speed sensor fault (experimental results)

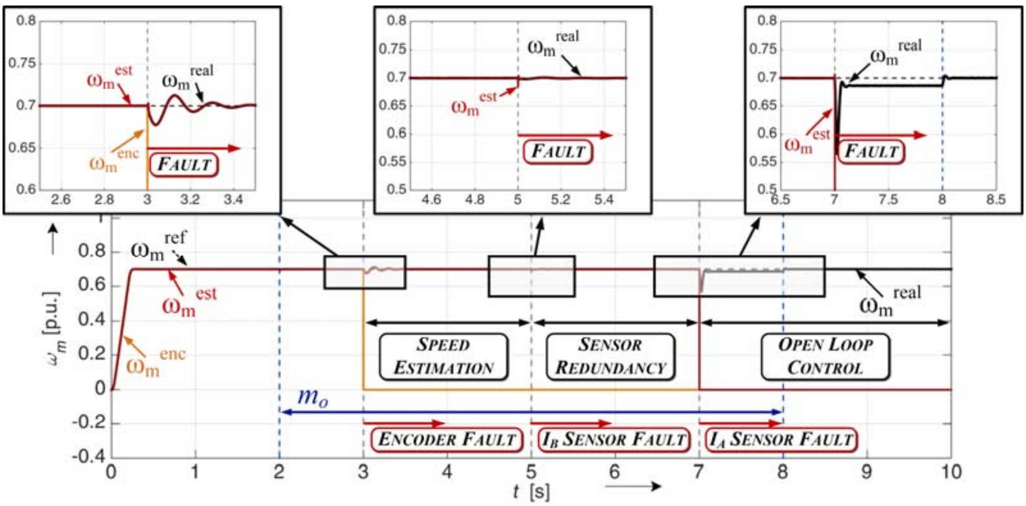

Fig. 13. The fault tolerant control system during faulted condition:
second scenario 1 – speed sensor fault, 2 – fault of the current sensor in phase B and 3 – fault of the current sensor in phase A, (simulation results)

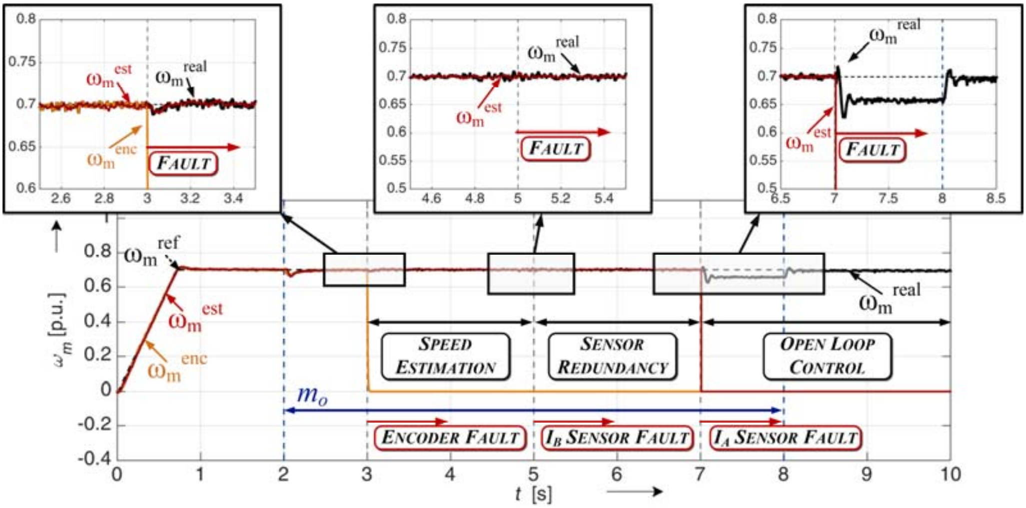

Fig. 14. The fault tolerant control system during faulted condition:
second scenario 1 – speed sensor fault, 2 – fault of the current sensor in phase B and
3 – fault of the current sensor in phase A, (experimental results)

The failure of the latter current sensor made impossible proper estimation of basic state variables used in the control loop determined due to the change of the whole control structure. The topology is changed from the vector control algorithm (DFOC) to the scalar control with the speed control loop. The rotor speed estimation is not possible, so after the speed sensor fault, the control algorithm must be changed to the scalar control without feedback.The other scenario, presented in Figs. 13 and14 and analyzed in this section, is based on the assumption that the rotor speed sensor was broken first. Afterwards the current sensors were faulted (for $t = 5$ s in phase B and for $t = 7$ s in phase A).

After the first fault detection, the topology of the drive was changed to the speed sensorless drive (with MRAS type estimator [19]). During the topology changes, small oscillations are visible in the measured and estimated state variables. First current sensor occurrence was detected by the detection system, and an additional sensor was used for hardware redundancy. During the current sensor changes, abnormal behaviors are not observed. After the next fault, the drive is switched to the scalar control with an open loop due to the lack of any properly operating sensor.

5. CONCLUSION

Mathematical models of detection algorithms for rotor speed and stator current sensors have been presented and. The solution proposed is based on three neural networks (one for each sensor used in the system) with three hidden layers and different input signals. A compensation algorithm of faulted sensors based on drive system control topology changes was described. Moreover, in the paper, the results of the fault-tolerant motor drive operation during different fault scenarios have been presented.

It was proved that the proposed complete fault-tolerant algorithm is able to identify a faulted sensor and to compensate failure providing further stable operation of the drive. The system presented is able to ensure the continuation of the process even in the case of failure occurrence of all measurement sensors in a short period of time.

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