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Modified Rotor Flux Estimators for Stator-Fault-Tolerant Vector Controlled Induction Motor Drives

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Abstract: This paper deals with fault-tolerant control (FTC) of an induction motor (IM) drive. An inter-turn short circuit (ITSC) of the stator windings was taken into consideration, which is one of the most common internal faults of induction machines. The sensitivity of the classic, well-known voltage and current models to the stator winding faults was analyzed. It has been shown that these classical state variable estimators are sensitive to induction motor parameter changes during stator winding failure, which results in unstable operation of the direct field-oriented control (DFOC) drive. From a safety-critical applications point of view, it is vital to guarantee stable operation of the drive even during faults of the machine. Therefore, a new FTC system has been proposed, which consists of new modified rotor flux estimators, robust to stator winding faults. A detailed description of the proposed system is presented herein, as well as the results of simulation and experimental tests. Simulation analyses were performed using MATLAB/Simulink software. Experimental tests were carried out on the experimental test bench with a dSpace DS1103 card. The proposed solution could be applied as an alternative rotor flux estimation technique for the modern FTC drive.

Keywords: induction motor; stator fault; rotor flux estimator; current model; voltage model; DFOC; FTC

1. Introduction

Vector methods enable precise regulation of the electromagnetic torque or/and angular speed of induction machines; therefore, they are utilized in many practical applications [1,2]. These systems should be equipped with additional estimators of the induction motor (IM) state variables, such as a rotor or a stator electromagnetic flux [1,3]. One of the most popular types of estimators are those based on mathematical models of the machine. One such group of systems are the closed-loop estimators: observers [3], Kalman filters (KF) [4], model reference adaptive systems (MRAS) [5], and sliding mode observers (SMO) [6]. Open-loop estimators, which are based on the voltage model (VM) or the current model (CM) of the machine [1,3], are used as well. All these estimators are used in modern drive systems.

The main issue of machine-model-based estimators is related to a parameter mismatch between machine and estimator. Another problem relates to inexact mathematical models of the machine. Parameters such as rotor and stator resistance fluctuate during normal operation of the drive (heating process of the windings) [7]. These parameters vary as a results of internal faults of the machine as well. In general, faults can be categorized into mechanical and electrical [8–11]. Electrical faults in particular may led to changes of the parameters and model of the machine [12]. The most common electrical faults are related to stator windings. These are caused by insulation degradation inside the

machine [8,13,14]. The first stage of a stator winding fault is the inter-turn short circuit (ITSC) within a coil [8]. This results in stator resistance decrease and in asymmetry of the stator windings; therefore, the structure of the machine's mathematical model differs from the common model due to an increase in the state variable number [8].

Stator winding faults have negative impacts on IM properties. In comparison to rotor winding degradation, stator faults proceed relatively rapidly [8]. In extreme cases, they may lead to total failure of the IM, or even the entire drive system as well. Nevertheless, incipient detection of this type of fault is possible.

Many studies have focused on the incipient detection of ITSCs [10,11,14] for open-loop control schemes [15–18], as well as for closed-loop vector control structures of the IM. Field-oriented control (FOC) [19–22], direct torque control with switching table (DTC-ST) [23,24], and direct torque control with space-vector modulation (DTC-SVM) [21] structures have been considered.

In the abovementioned papers, the possibilities of utilizing signals from internal control scheme feedback, measured stator currents, and rotor speed in the incipient detection of ITSCs were studied. The main goals of this research were to identify the point at which the drive should be turned off and/or the staff should be informed about a failure.

Fault-tolerant control (FTC) systems have recently been developed for modern IM drives [9,10]. The FTC approach assumes the necessity for the stable operation of a drive even when faults with relatively heavy severity occur in machines [9], power electronics modules [25], and sensors [26]. The main goal of these systems, which are also known as drive systems with a high level of safety, is to enable the drive operation even after fault occurrence. It is assumed that after fault detection, a drive should be stopped or—if possible—it should operate until termination of the whole cycle of a process. In general, two main FTC approaches are used for internal machine faults: hardware (physical) or analytical redundancy [27].

In Reference [28], a hardware redundant FTC system was presented. The system is based on a setup with two coupled IMs (parallel or serial connection). During the healthy drive conditions, only one motor is utilized, but when a fault occurs, the motor is turned off. Due to the physical redundancy, the system can continue its operation as the second motor is started by a fault management unit. Another approach is to use multiphase motors with physical redundancy [29]. These types of machines allow for the acceptable operation of the drive after the stator windings lose a phase. The main drawbacks of FTC systems based on hardware redundancy are high costs and complexity [27,30].

Alternative solutions are FTC systems based on analytical redundancy. They may be a less expensive way of achieving fault tolerance of a drive. The hardware complexity of the system is also smaller [27,30,31]. Several approaches based on analytical redundancy have been developed for IM drives with internal faults. The first uses additional units in control structures, which inject additional control signals which compensate for the negative impact of the internal fault on the drive performance. A milestone in the research on this issue was Reference [32]. The authors of this paper utilized a feedback linear control (FLC) scheme with an additional embedded controller to compensate for the negative effects of broken rotor bars in a closed-loop control drive. Afterwards, several systems for ITSC effect compensation were developed based on the abovementioned paper. In Reference [33], an approach which deals with backstepping control was proposed, and it was then improved using additional schemes, such as the extended Kalman filter (EKF) [34] or the SMO [35] to estimate fault-related signals. Another technique is based on sliding mode control (SMC) [36,37] with an additional estimation unit—EKF [38]. It is important to point out that each of the presented FTC systems are based on sophisticated nonlinear control methods.

Nonetheless, other techniques for ITSC effect compensation in IMs have been considered in control schemes with classical (PI or hysteresis) controllers as well. In Reference [39], an extended state observer [40] was used to eliminate a decoupling between flux and torque control paths, caused by an ITSC in the FOC scheme. This method was based on the assumption that accurate estimation of the state variables of a machine during ITSCs enables precise control of the IM and ensures stable

operation of the drive. In Reference [41], a SMO was used as a subsystem of the FTC unit in the FOC structure of wind turbine with an induction generator.

In Reference [42], a modified stator winding resistance estimator based on an artificial neural network (ANN) was applied to counteract the negative effects of the ITSC in the DTC-ST scheme.

Another interesting technique which can be used at a later stage of fault counteraction is related to a control scheme with switched controllers, proposed in Reference [43] for sensor-fault-tolerant drives. In Reference [44], the same solution was developed for the internal faults of an IM. Furthermore, it is possible to reduce the value of a current in shorted circuits using the methods described in References [45,46]. Another advantage is the longer operation of the drive during ITSCs until the value of the stator current exceeds the permitted threshold or the drive is safely stopped by a control unit.

Based on the presented state of research, it can be concluded that fault-tolerant drives which are oriented to compensation for the negative effects of internal IM faults pertain to numerous research fields. It is necessary to point out that not all the scientific problems have been considered so far. For example, there are no papers in the literature with a comprehensive analysis of the impact of ITSCs on selected IM state variables' estimation accuracy, especially studies using well-known open-loop estimators of rotor flux (current and voltage model), which are still used in control schemes. The main contributions of this paper are:

- A comprehensive state of the art review about FTC systems for stator winding faults of induction machines;
- Detailed analysis of the impact of an ITSC on the accuracy of IM rotor flux estimation by open-loop estimators (analytical substantiation included);
- Analysis of an impact of an ITSC on the performance of a closed-loop control scheme (DFOC) with open-loop rotor flux estimators;
- A new FTC unit for ITSCs is proposed, based on modified rotor flux estimators.

The article is divided into several sections. Section 2 contains a mathematical model of an IM with faulted stator windings. Mathematical models of open-loop estimators of the rotor flux are then presented. Section 3 includes a description of open-loop (v/f) and closed-loop (DFOC) control structures. In Section 4, the results of simulations which illustrate the impact of an ITSC on drive properties and analytical substantiation of the obtained results are presented. In the next section, detailed descriptions of the proposed FTC unit, as well as the results of the simulation validation are shown. Section 6 includes experimental verification of the proposed system. Lastly, in Section 7, the conclusions are presented.

2. Mathematical Model of Induction Motor with Short Circuits in Stator Windings

To perform a computer simulation of an induction motor with faulty stator windings, a mathematical model was necessary. Therefore, in this paper, a model which was proposed in Reference [47] was used. The model enabled simulation of an ITSC in each phase of the IM. Figure 1 shows a schematic diagram of an IM with an ITSC in phase A.

In this paper, the following nomenclature is used to describe stator windings: N_s —number of turns per phase, N_{sh} —number of shorted turns in phase, η_f —fraction of shorted turns.

To simulate an ITSC in each phase of the machine, the additional vector fault $\mu_{\alpha\beta}$ was utilized. The components of $\mu_{\alpha\beta}$ represent the phase in which a fault occurs, and the modulus of $\mu_{\alpha\beta}$ represents the fraction of shorted turns. Fault vectors for each phase can be calculated by the Equations:

$$\mu_{\alpha\beta|A} = \eta_{fA} \begin{bmatrix} 1 & 0 \end{bmatrix}^T \quad (1)$$

$$\mu_{\alpha\beta|B} = \eta_{fB} \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} \end{bmatrix}^T \quad (2)$$

$$\mu_{\alpha\beta|C} = \eta_{fC} \begin{bmatrix} -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}^T \quad (3)$$

where η_{fA} , η_{fB} , η_{fC} —fractions of shorted turns in phases A, B, C of stator windings, respectively.

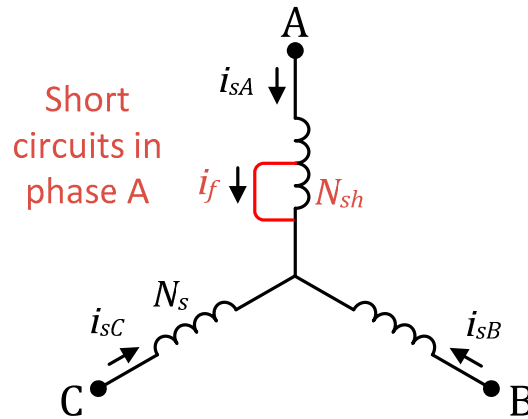


Figure 1. Schematic diagram of induction motor (IM) stator windings with short circuits in phase A.

The current and the electromagnetic flux in the shorted circuit are described by:

$$i_f = \frac{\psi_f - \mu_{\alpha\beta}^T \psi_s}{\left(\frac{2}{3}|\mu_{\alpha\beta}|^2 - |\mu_{\alpha\beta}|\right)L_{\sigma s}} \quad (4)$$

$$\frac{d\psi_f}{dt} = -R_s \mu_{\alpha\beta}^T \mathbf{i}_s + (|\mu_{\alpha\beta}|R_s + R_f)i_f \quad (5)$$

where R_s —stator winding resistance, R_f —fault resistance, $L_{\sigma s}$ —stator winding leakage inductance. $\mathbf{i}_s$ —stator current, ψ_s —stator electromagnetic flux vectors.

The machine equations in the stationary reference frame (α – β) are expressed as:

$$\frac{d\psi_s}{dt} = \mathbf{u}_s - R_s \left(\mathbf{i}_s - \frac{2}{3} \mu_{\alpha\beta} i_f \right) \quad (6)$$

$$\frac{d\psi_r}{dt} = -R_r \mathbf{i}_r + j p_b \omega_m \psi_r \quad (7)$$

$$\mathbf{i}_s = \frac{L_r}{w} \psi_s - \frac{L_m}{w} \psi_r + \frac{2}{3} \mu_{\alpha\beta} i_f \quad (8)$$

$$\mathbf{i}_r = \frac{L_s}{w} \psi_r - \frac{L_m}{w} \psi_s \quad (9)$$

where R_r —rotor resistance, L_s , L_r , L_m —stator, rotor, magnetizing inductances, respectively, $\mathbf{u}_s$ —stator voltage, $\mathbf{i}_r$ —rotor current, ψ_r —rotor electromagnetic flux vectors, ω_m —rotor speed, $w = L_s L_r - L_m^2$.

The electromagnetic torque and mechanical dynamics are given by:

$$T_e = \frac{3}{2} p_b \text{Im} \left\{ \psi_s^* \left(\mathbf{i}_s - \frac{2}{3} \mu_{\alpha\beta} i_f \right) \right\} \quad (10)$$

$$\frac{d\omega_m}{dt} = \frac{1}{J} (T_e - T_l) \quad (11)$$

where p_b —number of pole pairs, J —inertia, T_l —load torque.

3. Mathematical Models of Rotor Flux Estimators

In this paper, two well-known estimators of rotor flux were tested, which are named the voltage and current models. Those estimators are based directly on the stator winding model and rotor winding model of the “healthy” machine [1,3]. In this model, the parameters of the IM are constant:

$$\frac{d\psi_s}{dt} = u_s - R_s i_s \quad (12)$$

$$\frac{d\psi_r}{dt} = -R_r i_r + j p_b \omega_m \psi_r \quad (13)$$

$$i_s = \frac{L_r}{w} \psi_s - \frac{L_m}{w} \psi_r \quad (14)$$

$$i_r = \frac{L_s}{w} \psi_r - \frac{L_m}{w} \psi_s \quad (15)$$

The first is the voltage model, which is based on the stator voltage (12) and current-flux (14) and (15) equations of the IM [3]:

$$\psi_r^v = \frac{L_r}{L_m} \int (u_s - R_s i_s) dt - \frac{w}{L_m} i_s \quad (16)$$

It can be observed that the presented model depends on motor parameters, especially on stator resistance, which varies depending on temperature and ITSC. This can result in inaccurate estimation of the rotor flux.

The second open-loop estimator is the current model, which is based on the rotor voltage (13) and the current-flux (14) and (15) equation of the IM [3]:

$$\psi_r^i = \int \left(\frac{R_r}{L_r} (L_m i_s - \psi_r^i) + j p_b \omega_m \psi_r^i \right) dt \quad (17)$$

As opposed to VM, the CM is independent of the stator winding model. Therefore, quite a common assumption is that CM is robust to ITSCs, due to its independence from stator resistance.

Nevertheless, there is some doubt with regards to this assumption. During an ITSC, asymmetry of the stator windings occurs, and the equations of the machine model are changed, which may result in the inaccurate estimation of rotor flux by CM and the deterioration of closed-loop drive performance as well. In the following sections of the paper, results and analytical substantiation are presented to confirm the proposed hypothesis.

4. Description of Control Structures of Induction Motor

In this paper, two types of control methods of IMs have been taken into consideration. The first is the open-loop scalar method, known as $v/f = \text{const}$, which is simple in implementation but does not ensure precise control of electromagnetic torque and rotor speed, especially during dynamic states. A detailed description of this scalar technique can be found in References [1–3], and in Figure 2, a schematic diagram of the control structure is shown. The main motivation for performing a test using this control structure was to eliminate the influence of the closed-loop control system, which can compensate negative effects of the faults. Rotor flux estimators work in open-loop mode, using only measured signals such as current, voltage, and rotor speed.

In the second case, the IM was operated in a closed-loop control scheme based on DFOC, which has been described accurately in the literature [2,3]. The main goal of this structure is to regulate the flux and the electromagnetic torque of the IM by separate control paths, which enables the achievement of a high dynamic and steady-state performance of the drive. A control path with a i_{sx} component of the stator current is responsible for stabilizing the rotor flux, whereas the second path, with a i_{sy} component, regulates the electromagnetic torque generated by the motor. If the machine is supplied by

the voltage source inverter (VSI) the stator voltage equations in a synchronous rotating reference frame $x - y$ are given by:

$$u_{sx}^{ref} = R_s(f_x^{ref} + e_x) \quad (18)$$

$$u_{sy}^{ref} = R_s(f_y^{ref} + e_y) \quad (19)$$

Signals $f_{x,y}^{ref}$ and $e_{x,y}$ are given by:

$$f_x^{ref} = i_{sx} + \frac{L_s \sigma}{R_s} \frac{di_{sx}}{dt} \quad (20)$$

$$f_y^{ref} = i_{sy} + \frac{L_s \sigma}{R_s} \frac{di_{sy}}{dt} \quad (21)$$

$$e_x = \frac{L_m}{R_s L_r} \frac{d\psi_r}{dt} - \frac{L_s \sigma}{R_s} \omega_{\psi r} i_{sy} \quad (22)$$

$$e_y = \frac{L_m}{R_s L_r} \omega_{\psi r} \psi_r + \frac{L_s \sigma}{R_s} \omega_{\psi r} i_{sx} \quad (23)$$

where $\omega_{\psi r}$ —synchronous angular speed of rotor flux, $\sigma = 1 - \frac{L_m^2}{L_s L_r}$.

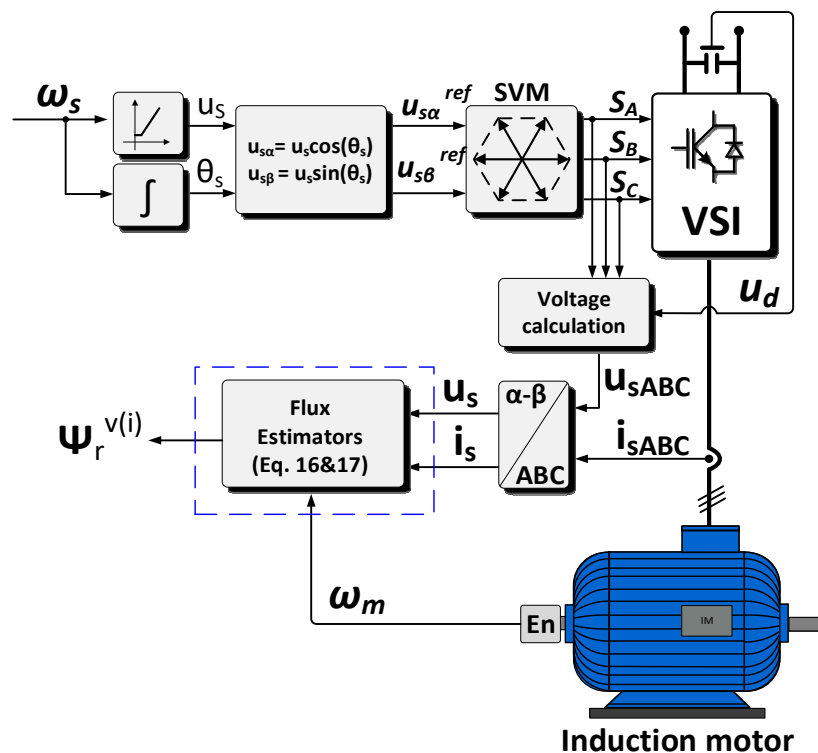


Figure 2. Schematic diagram of v/f control structure (open control loop).

It can be observed that both control paths are coupled (the i_{sx} component depends on the i_{sy} and vice versa). Therefore, to ensure independent control of both signals, an additional decoupling block was used in this control scheme. The decoupling block calculated signals e_x , e_y which were subtracted from the output reference signals (f_x^{ref} , f_y^{ref}) from the PI controllers of the stator current i_{sxy} components.

Figure 3 shows a block diagram of the DFOC with rotor flux estimator (CM or VM) as an integral part of whole system. In this control algorithm, accuracy of rotor flux estimation determines the

performance and properties of the drive. If the rotor flux estimator is unstable during IM parameter changes, the whole system will be unstable too.

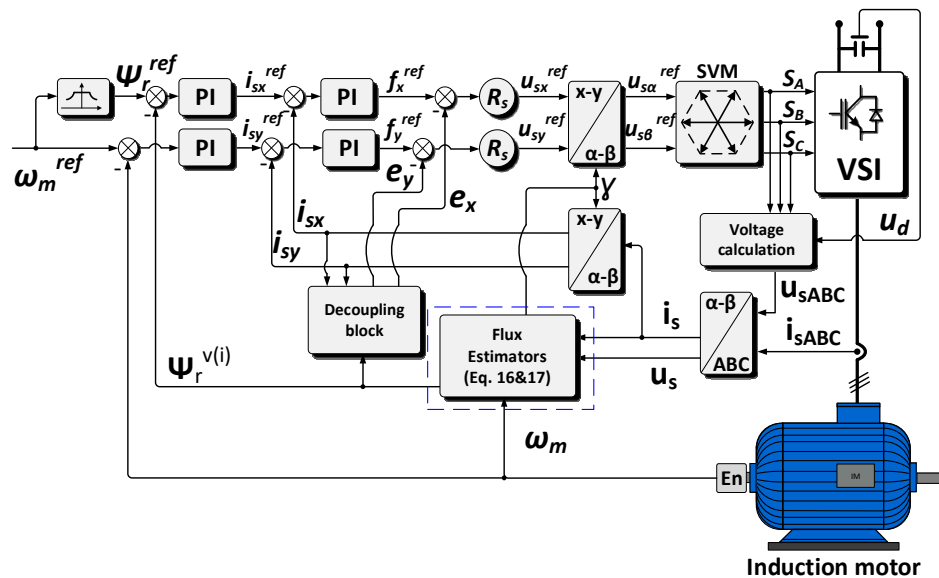


Figure 3. Direct field-oriented control structure.

5. Impact of Inter-Turn Short Circuits (ITSCs) on Rotor Flux Estimation Accuracy and Drive Performance

At first, computer simulations were conducted using MATLAB/Simulink software (2016a, MathWorks, Natick, MA, USA), during which two cases were studied: operation of the drive during ITSCs in open- (in scalar control) and closed-loop control structures (DFOC).

During the tests, the ITSC was simulated only in phase A, and the fraction of shorted turns was changed in accordance with the trajectory in Figure 4. The faulted condition was started at time $t = 4$ s, and the value of the fault fraction was increased linearly up to about 12%. This is quite a high severity of fault, but the main goal of the FTC system is the incipient detection of the ITSC, as well as compensation for its negative impact on the drive performance. Constant values of reference angular rotor speed and rotor torque were assumed during the tests. The switching frequency of the VSI control was 8 kHz. The specifications of the tested IM are summarized in Table A1 (Appendix A).

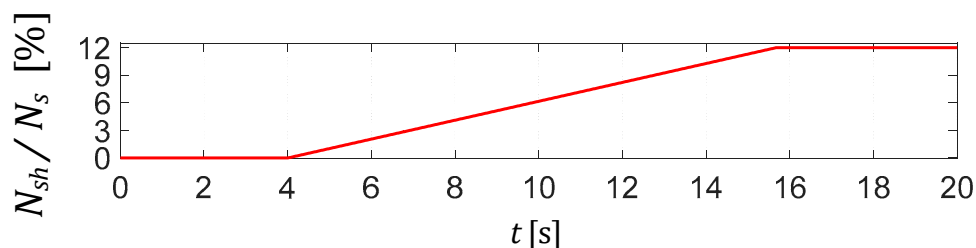


Figure 4. Trajectory of the fault fraction during tests.

To show the impact of ITSCs on the drive performance, the transients of the rotor angular speed, rotor flux, electromagnetic torque, and the current in phase A are shown. All the presented signals have been normalized with reference to their rated values.

(a) Performance of the CM and VM estimators in the open-loop control scheme

The results obtained for the scalar control are shown in Figure 5. An increase of shortened turns resulted in a rise of stator current amplitude, but an estimation error of the rotor flux was observed as well. In case of VM, these results were not surprising, because this estimator directly depends on stator resistance. However, although the CM is independent of the stator windings model, an estimation error of rotor flux occurred and was even greater than for VM. The explanation of this effect relates to the mathematical model of the machine, and it is described analytically at the end of this section of the paper.

(b) Performance of the CM and VM estimators in the closed-loop control scheme

Similar tests were performed for the DFOC scheme and two cases were taken into consideration: a control structure with the VM and CM. The transients of the rotor mechanical speed, rotor flux, electromagnetic torque, and the current in phase A are presented.

It can be observed that for the VM (Figure 6), the fault resulted in inaccurate estimation of the rotor flux, and consequently in the instability of the drive (for about 6% of shortened turns per phase).

Similar results were obtained for the CM (Figure 7). Due to the ITSC, an error of rotor flux was observed, and as a result, the control system was not able to regulate the speed (for about 10% of shortened turns). Furthermore, the value of the rotor flux estimation error was higher than for the VM.

It can be concluded that ITSCs had a negative impact on the drive performance for both cases. However, fault consequences were less harmful for control loop with the CM than when the VM was used. The closed-loop control system had the ability to compensate for the effects of the faults themselves, but only in a limited range. Therefore, with regards to FTC systems, it seems to be necessary to reduce the inaccuracy of rotor flux estimation during ITSCs to avoid the abrupt shutdown of the drive.

(c) Analytical substantiation of obtained results

Standard VM and CM Equations (16) and (17) are based on a healthy IM model, therefore they cannot ensure proper estimation during ITSCs. This can be proven analytically using the mathematical model of a faulted IM (Equations (6) and (11)). Based on Equations (6), (8), and (9), the real value of the rotor flux calculated by the VM is given by:

$$\psi_r^{vreal} = \frac{L_r}{L_m} \int (\mathbf{u}_s - R_s(\mathbf{i}_s - \frac{2}{3}\mu_{\alpha\beta}i_f))dt - \frac{w}{L_m}(\mathbf{i}_s - \frac{2}{3}\mu_{\alpha\beta}i_f) \quad (24)$$

whereas the real value of the rotor flux calculated by the CM, based on Equations (7)–(9), is given by:

$$\psi_r^{ireal} = \int \left(\frac{R_r}{L_r} \left(L_m(\mathbf{i}_s - \frac{2}{3}\mu_{\alpha\beta}i_f) - \psi_r^{ireal} \right) + jp_b\omega_m\psi_r^{ireal} \right) dt \quad (25)$$

It can be easily observed that in both equations, an additional factor: $\frac{2}{3}\mu_{\alpha\beta}i_f$ appears, which is strictly connected with the faulted conditions of the IM. In the following sections of the paper, the additional factor is considered as the fault factor.

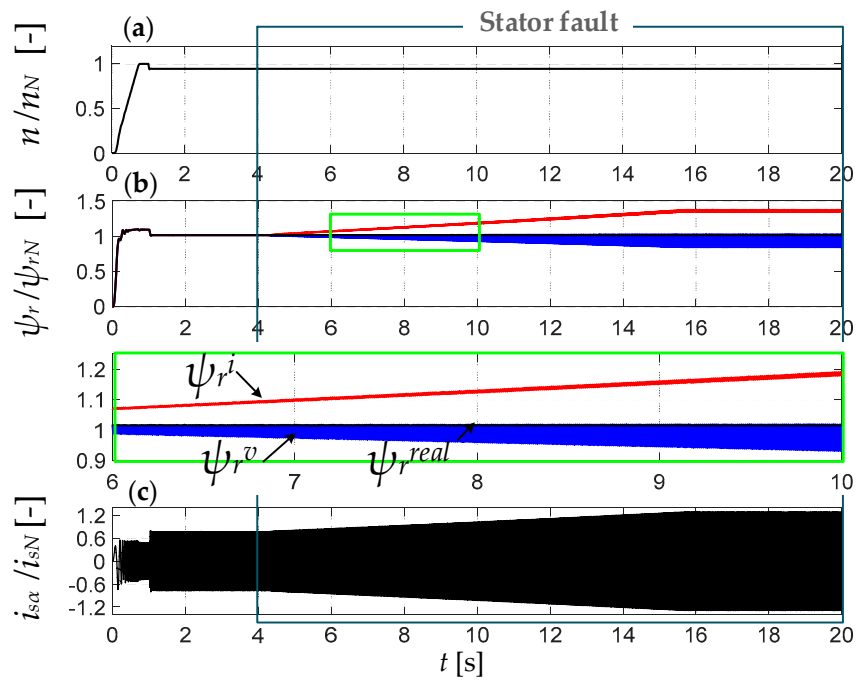


Figure 5. Operation of open-loop control scheme (v/f) during inter-turn short circuit (ITSC): (a) rotor speed, (b) estimated and real rotor flux, (c) stator current in phase A; (simulation results), ($n^{ref} = n_N$, $T_l = T_N$).

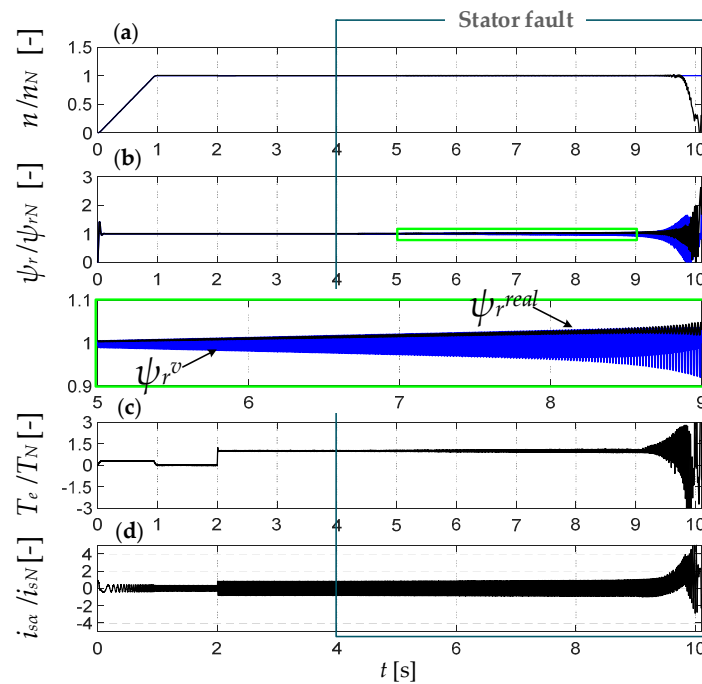


Figure 6. Operation of closed-loop control scheme (DFOC) during ITSC with the VM in the control structure: (a) reference and real rotor speed, (b) estimated and real rotor flux, (c) electromagnetic torque, (d) stator current in phase A; (simulation results), ($n^{ref} = n_N$, $T_l = T_N$).

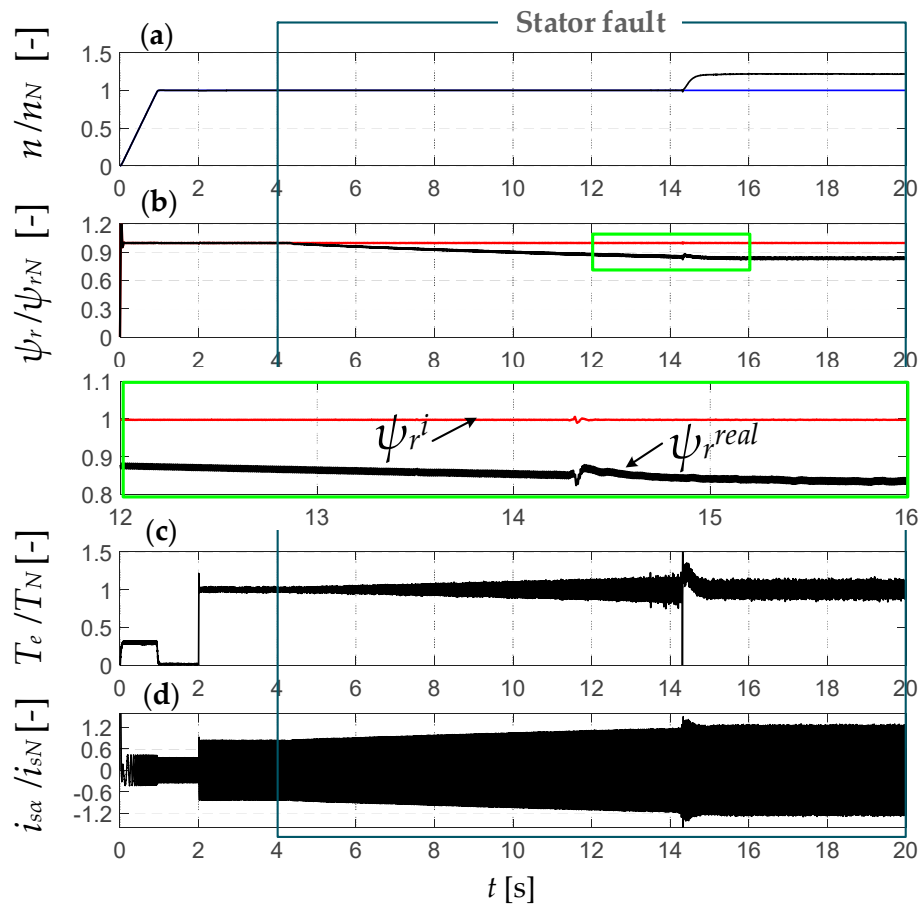


Figure 7. Operation of closed-loop control scheme (DFOC) during ITSC with the CM in the control structure: (a) reference and real rotor speed, (b) estimated and real rotor flux, (c) electromagnetic torque, (d) stator current in phase A; (simulation results), ($n^{ref} = n_N$, $T_l = T_N$).

6. Improvement of the Drive Performance during ITSC by an FTC Unit with Modified Rotor Flux Estimators

To improve the accuracy of rotor flux estimation during ITSCs using the voltage and current models, a suitable model of the machine was necessary. The VM and CM represented by Equations (24) and (25) can estimate the rotor flux correctly during the faulted and non-faulted conditions of the machine. These models are a new concept for rotor flux estimation. Therefore, based on the hypothesis that accurate estimation of the state variables of the machine during a faulted condition enables stable operation of the drive in faulted mode, these models can be used in the new FTC unit.

The main problem is that the components of the fault factor, such as $\mu_{\alpha\beta}$ and i_f , cannot be measured in practice. Therefore, the only way to achieve actual information about the fault factor value is its estimation. To achieve this goal, a method based on a stator current observer can be utilized [40,47]. This idea relies on calculation of the error between the estimated and measured stator current. The estimated stator current is given by:

$$\mathbf{i}_s^{est} = \frac{L_r}{w} \psi_s^{est} - \frac{L_m}{w} \psi_r^{est} \quad (26)$$

where ψ_s^{est} and ψ_r^{est} can be calculated by:

$$\psi_s^{est} = \int (\mathbf{u}_s - R_s \mathbf{i}_s^{est}) dt \quad (27)$$

$$\psi_r^{est} = \int \left(\frac{R_r}{L_r} (L_m \mathbf{i}_s^{est} - \psi_r^{est}) + j p_b \omega_m \psi_r^{est} \right) dt \quad (28)$$

where $\mathbf{i}_s^{est}$ is defined by:

$$\mathbf{i}_s^{est} = \mathbf{i}_s - \frac{2}{3} \mu_{\alpha\beta} i_f \quad (29)$$

the real (measured) value of the stator current is:

$$\mathbf{i}_s = \frac{L_r}{w} \psi_s - \frac{L_m}{w} \psi_r + \frac{2}{3} \mu_{\alpha\beta} i_f \quad (30)$$

and the estimation error of the stator current is expressed as:

$$\mathbf{i}_s - \mathbf{i}_s^{est} = \frac{2}{3} \mu_{\alpha\beta} i_f \quad (31)$$

which is exactly equal to the fault factor.

The calculated factor can be used to adjust the voltage and current model with the aim of accurate estimation of the rotor flux, and consequently can ensure stability of the drive during ITSCs. This is not obvious for the classical CM and VM. The adjusted estimators are called the modified voltage model (MVM) and the modified current model (MCM), and the estimated rotor fluxes by them are marked respectively by ψ_r^{vm} and ψ_r^{im} . The MVM is based on Equation (24) and the MCM on Equation (25). Figure 8 illustrates the structure of proposed FTC system.

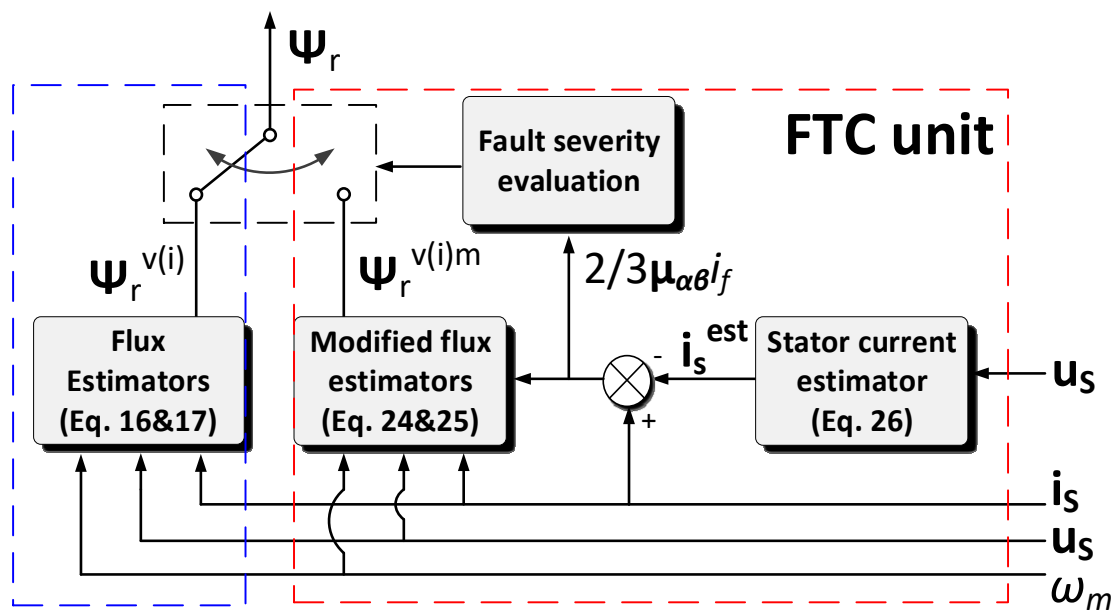


Figure 8. Schematic diagram of proposed new fault-tolerant control (FTC) system.

It is important to point out that Equation (31) is true when the parameters of the stator current estimator and the IM are matched. To eliminate a parameter mismatch problem, the estimation error decomposition technique can be used [47], as well as other methods which enable the identification of machine parameters [7,48,49]. In this paper, problems related to parameter mismatch were not considered.

Computer simulations were performed to validate the proposed FTC unit. The conditions of the test were the same as in the previous section. Open-loop and closed-loop control structures for the IM were tested.

(a) Performance of the open-loop control system with FTC unit

Results for the v/f control structure are shown in Figure 9. The FTC unit was activated at $t = 10$ s. Rotor flux estimated by both modified estimators covered the real value of the flux. A difference between estimated and real value of the stator current was observed, and therefore the fault factor could be calculated.

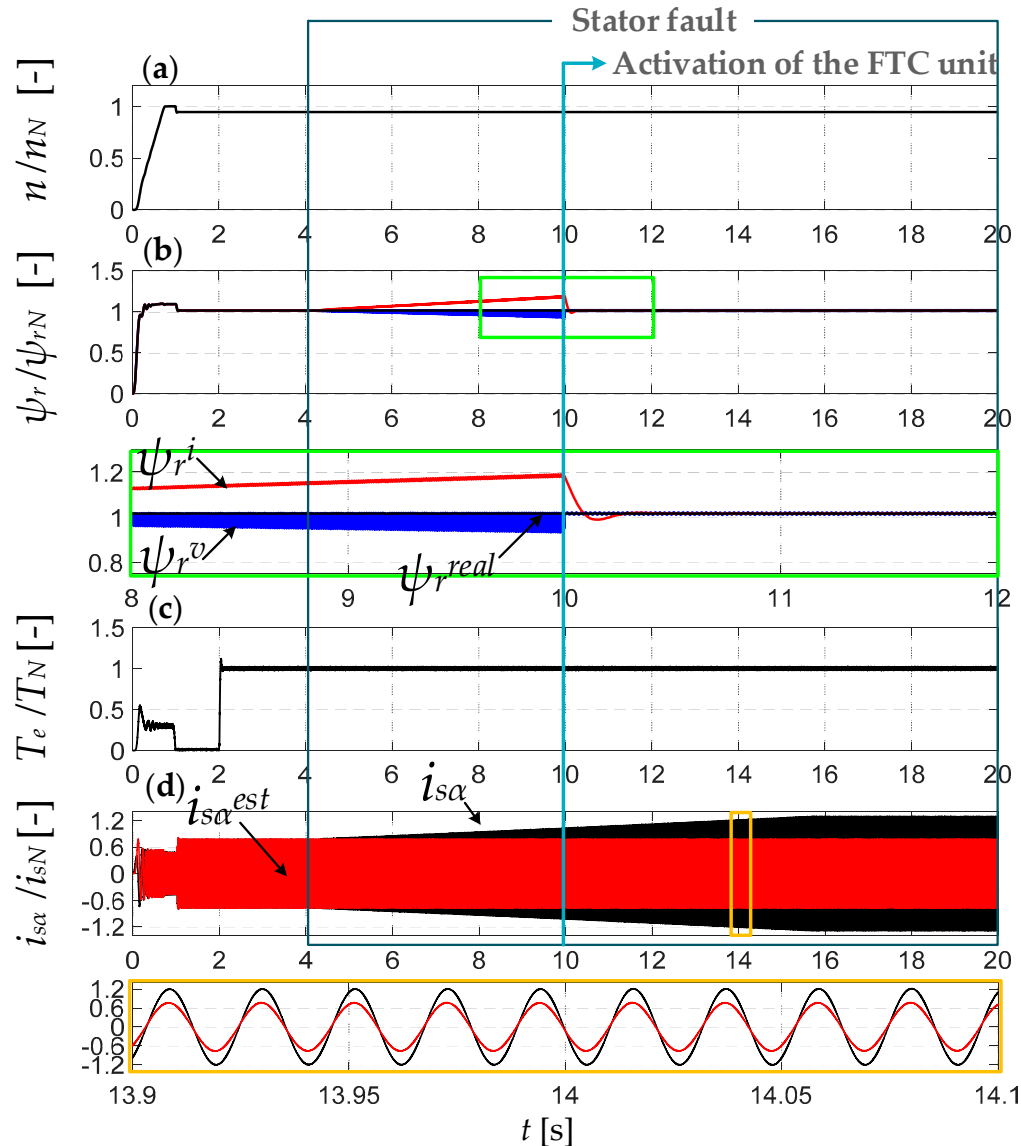


Figure 9. Operation of open-loop control scheme (v/f) during ITSC with FTC unit: (a) rotor speed, (b) estimated and real rotor flux, (c) electromagnetic torque, (d) estimated and real stator current in phase A; (simulation results), ($n^{ref} = n_N$, $T_l = T_N$).

(b) Performance of the closed-loop control system with FTC unit

The DFOC control structure was tested as well. Two cases were considered, proceeding according to the following scenario: the VM (or CM) was used to estimate rotor flux until time $t = 8$ s was reached, when the FTC unit switched on the MVM (or MCM) to reduce the estimation error of the rotor flux.

The results obtained for the modified voltage and current models during the tests are presented in Figures 10 and 11, respectively. It can be easily observed that the inaccuracy in the rotor flux calculation was successfully reduced in both cases, which resulted in the stable operation of the drive. Due to the ITSC, an estimation error of the stator current occurred, and therefore a fault factor could be calculated. The amplitude of the stator current did not increase heavily. However, a strong deformation of the

stator current waveform occurred, which resulted in quite high ripples of the electromagnetic torque. Nevertheless, the main goal of the proposed system was to enable the stable operation of the drive until the machine reached a safe (controlled) stop.

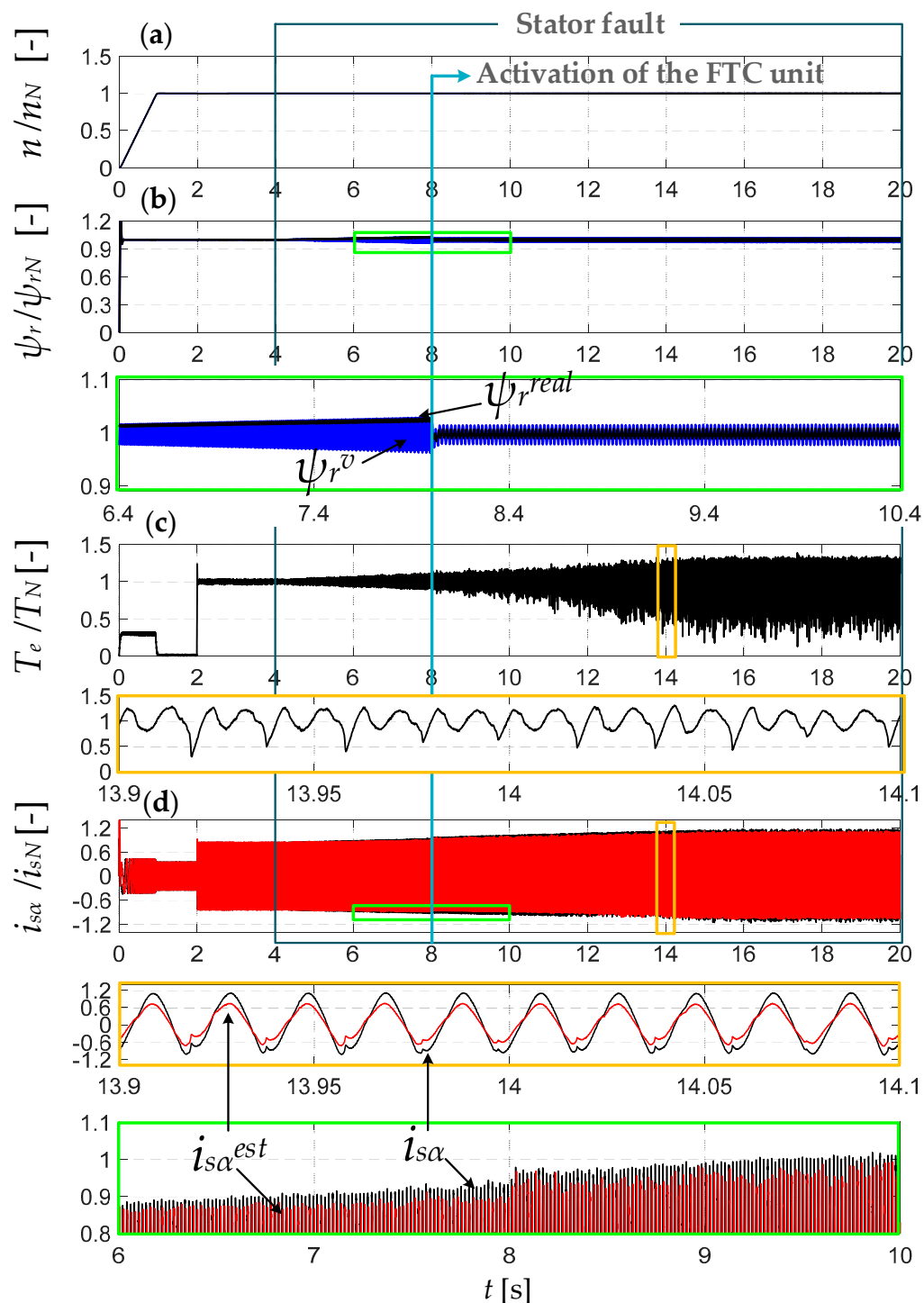


Figure 10. Operation of closed-loop control scheme (DFOC) during ITSC with the modified voltage model (MVM) in the control structure: (a) reference and real rotor speed, (b) estimated and real rotor flux, (c) electromagnetic torque, (d) estimated and real stator current in phase A; (simulation results), ($n^{ref} = n_N$, $T_l = T_N$).

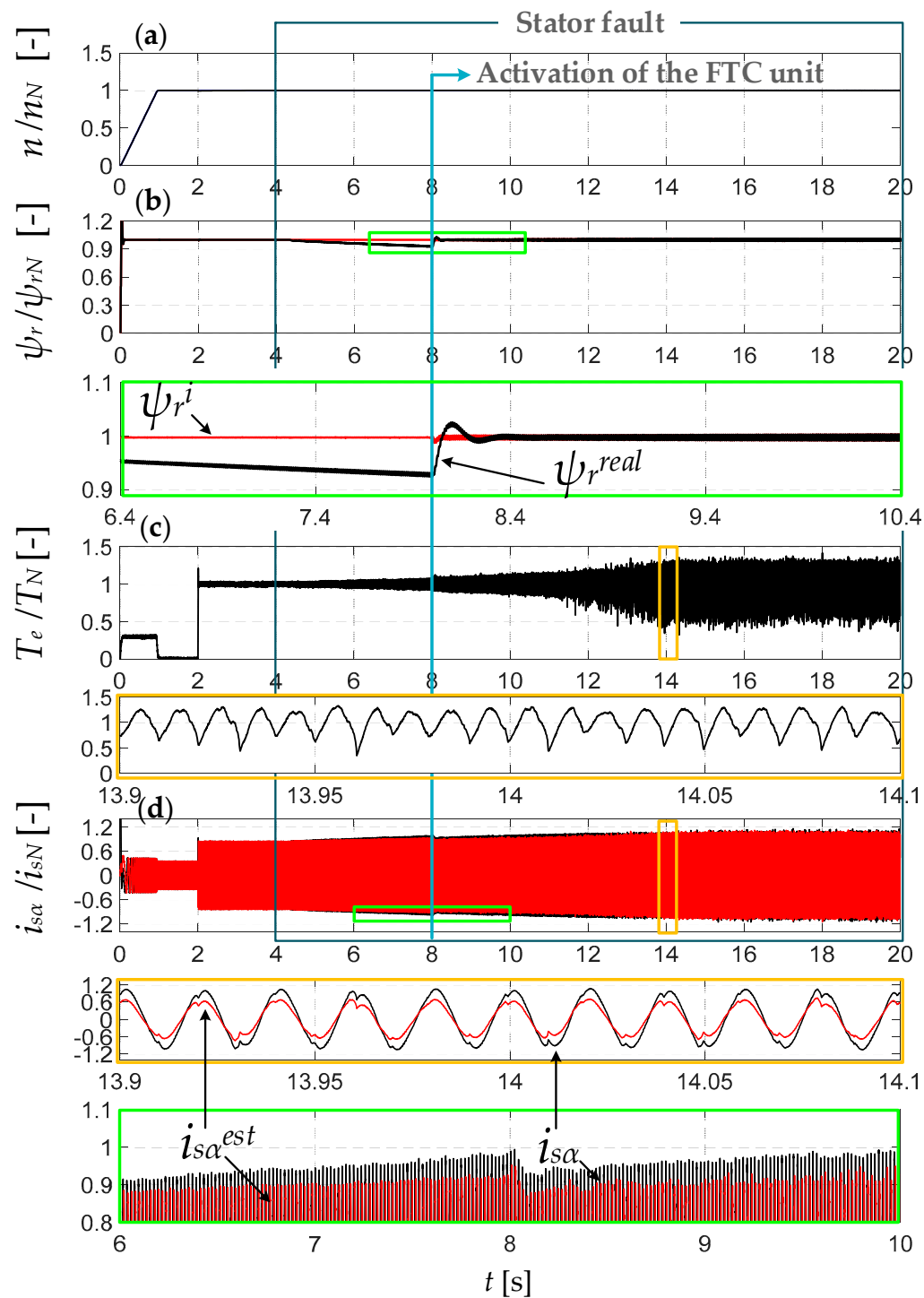


Figure 11. Operation of closed-loop control scheme (DFOC) during ITSC with the modified current model (MCM) in the control structure: (a) reference and real rotor speed, (b) estimated and real rotor flux, (c) electromagnetic torque, (d) estimated and real stator current in phase A; (simulation results), ($n^{ref} = n_N$, $T_l = T_N$).

(c) Fault severity evaluation

In this paper, the switching between CM (VM) and MCM (MVM) was performed manually. It is obvious that in practical implementation, this procedure should be automatic. Figure 12 shows the change of the fault factor modulus due to an ITSC. An increase in its value was noticeable, which could be used as a fault severity indicator. Therefore, a fault severity evaluation procedure in the FTC

unit may rely on comparison of the fault factor modulus with a fixed threshold which indicates the stator fault. Furthermore, it was observed that for the non-faulted condition of the motor, the fault factor modulus equaled zero. The fault factor disappeared for these conditions, which resulted in the fact that the equations of the modified flux estimators (24) and (25) look the same as the equations of the standard estimators (16) and (17). Therefore, it can be concluded that the proposed modified flux estimators can be used during non-faulted conditions as well as faulted conditions of the motors. Nevertheless, it is important to point out that in this paper, a parameter mismatch between motor and estimators was not considered. Parameter mismatch may result in stator current estimation error, and consequently, a fault threshold may be exceeded. In practical implementation, to improve the robustness of the proposed FTC technique, an additional system for parameter identification should be used as well as an external unit for fault detection and identification. In the literature [10,11,13–15], a variety of techniques for incipient ITSC detection have been described.

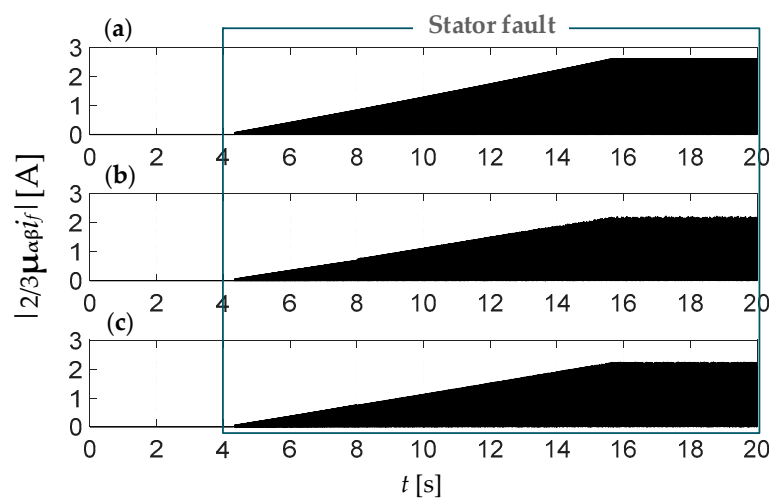


Figure 12. Modulus of the fault factor during ITSC: (a) *v/f* control structure (with the MVM and MCM), (b) DFOC control structure with the MVM, (c) DFOC control structure with the MCM.

7. Experimental Verification

Experimental tests of the proposed FTC unit were carried out using a laboratory setup (Figure 13) which was equipped with a special IM able to induce ITSCs in each phase of the stator windings. The IM was supplied by the VSI (power module) and the control algorithm was implemented using a dSPACE rapid prototyping card DS1103. The IM was coupled with another machine which was operating as a load. During testing, the rotor speed was measured by incremental encoder and two phase currents (i_{sA} , i_{sB}) were measured by LEM transducers. To calculate the stator voltage vector, the DC voltage (u_d) of the inverter was measured as well.

During experimental testing, ITSCs were induced only in phase A, and the fraction of shorted turns was equal to 1.7%, 3.4%, or 5.2%. Only the *v/f* control structure was tested for constant rotor speed ($n_{ref} = 0.5n_N$) and constant load torque ($T_l = 0.5T_N$).

In Figure 14, results for *v/f* control structure without the FTC unit are presented. It was observed that the behavior of the drive was like the simulation test (Figure 5): estimated rotor flux increased for CM and decreased for VM. Figure 15 shows the performance of the drive with an FTC unit. Activation of the FTC unit resulted in alignment of the values of estimated rotor fluxes by both estimators. During ITSCs, an estimation error of the stator current was observed; therefore, the fault factor can be calculated in real time and injected into the modified rotor flux estimators.

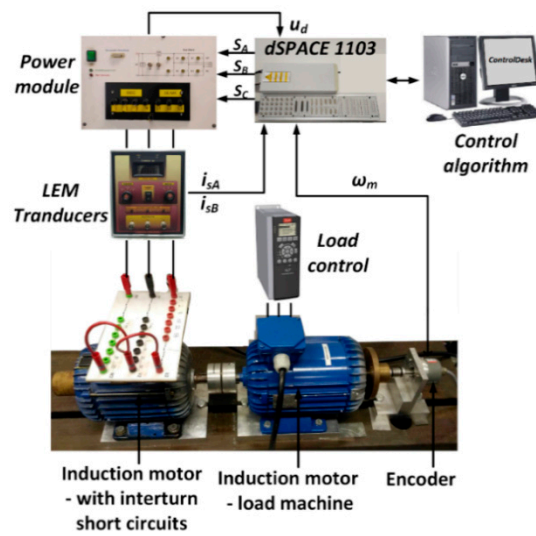


Figure 13. Schematic diagram of experimental setup.

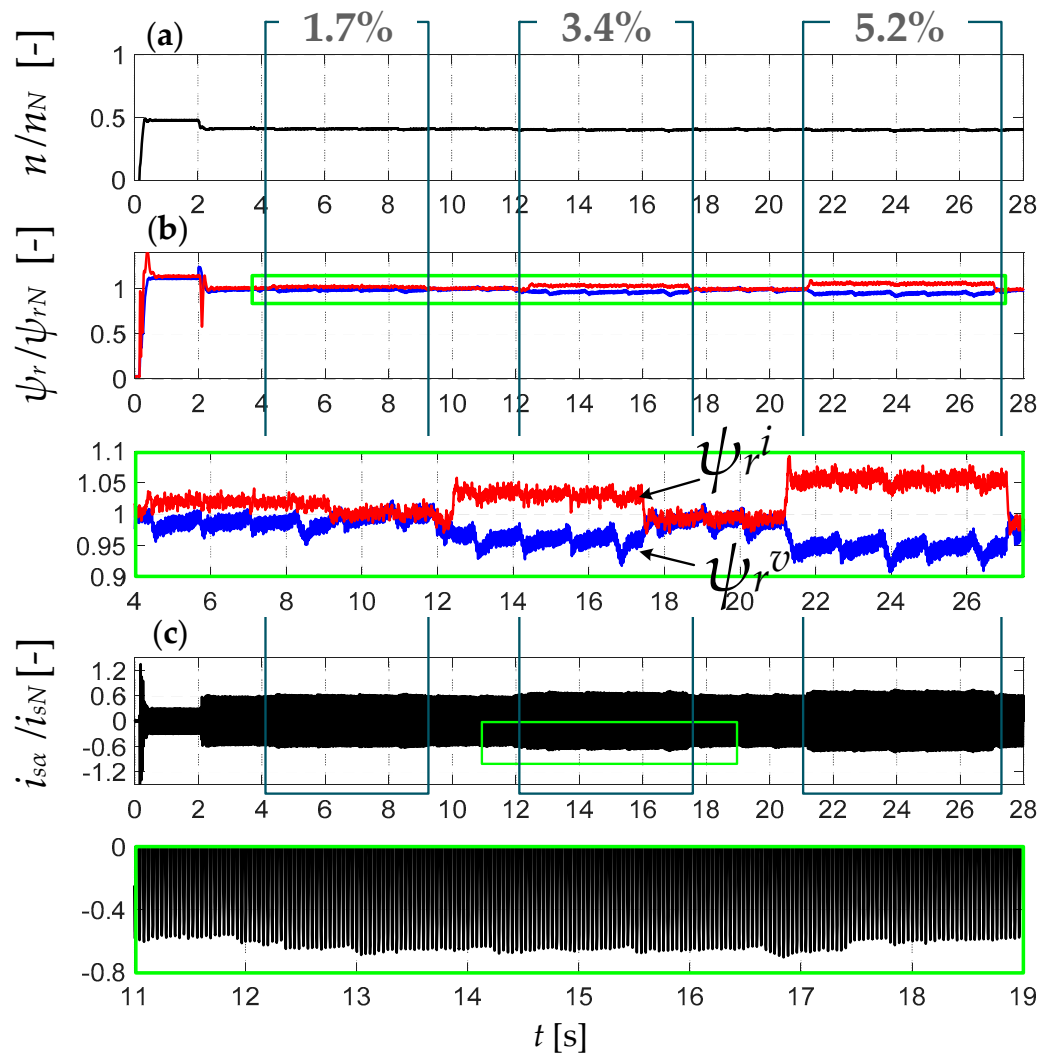


Figure 14. Operation of open-loop control scheme (v/f) during ITSC: (a) measured rotor speed, (b) estimated rotor flux, (c) measured stator current in phase A; (experimental results), ($n^{ref} = 0.5n_N$, $T_l = 0.5T_N$).

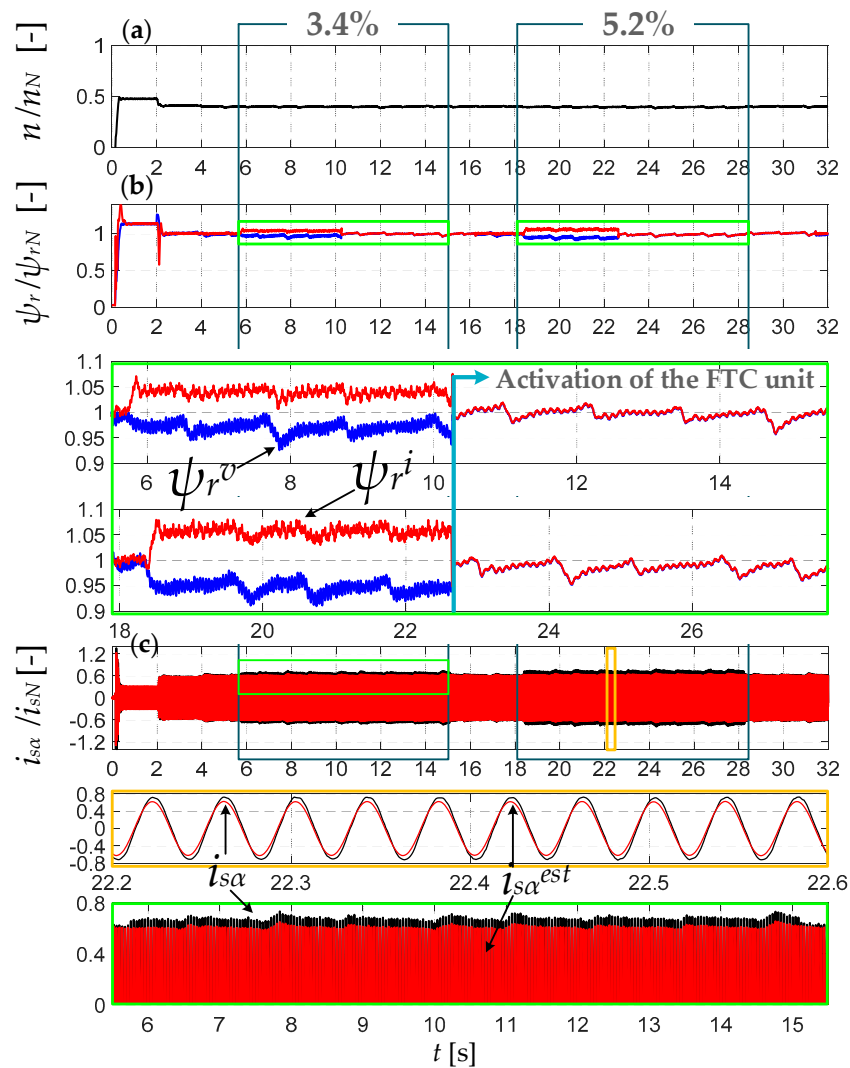


Figure 15. Operation of open-loop control scheme (v/f) during ITSC with FTC unit: (a) measured rotor speed, (b) estimated rotor flux, (c) estimated and measured stator current in phase A; (experimental results), ($n^{ref} = 0.5n_N$, $T_I = 0.5T_N$).

Figure 16 shows the change of the fault factor modulus due to ITSCs during experiments. An increase in its value is visible. However, due to the parameter mismatch and measurement noise, the stator current estimation error occurred during non-faulted conditions as well.

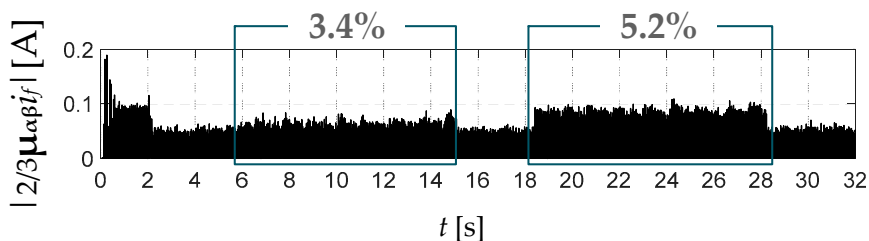


Figure 16. Modulus of the fault factor during ITSC (experimental results).

It is important to point out that the rotor flux calculated by the voltage models (MV as well as MVM) was obtained by pure integration of stator voltage equations. This method is difficult to realize in practical implementations due to offset and drift effects of the measured current and voltage, which are inevitable in experiments. Even minor DC offset or drift of the signals accumulates and results

in unstable operation of the estimator, because there is no feedback from output to the input of the integrator. To improve performance of this estimator, several methods can be used. One common technique is based on replacing the pure integrator with a low-pass filter [3]. This technique was used in this paper to perform experimental tests. Other methods rely on programmable cascaded low-pass filters [50] or other modified integration algorithms [51]. In estimators based on the current model of the flux, the mentioned issue does not occur.

8. Conclusions

This paper was concerned with fault-tolerant control of the induction motor during internal faults of the induction machines. In particular, an inter-turn short circuit of stator windings was considered. A detailed analysis of the impact of the ITSC on the rotor flux estimation process and performance of the drive has been provided. Based on the analysis, an FTC unit has been proposed to compensate for the negative effects of the ITSC, which have been confirmed by simulation and experimental results.

It is important to point out that the drive operated with quite a high value of the fault fraction. However, there is some doubt with regards to the considered assumption because ITSCs are a fault which spreads quickly, which may be dangerous to the machine. Nevertheless, the main goal of the FTC systems is to enable the stable operation of the drive until a point is reached when the machine can be safely stopped. This is a crucial issue in safety-critical applications where an abrupt shutdown of the drive is unacceptable.

The main advantages of the proposed FTC unit are relatively simple implementation; the algorithm is based on measurable signals and no adaptation mechanism is required. Potential problems are related to a parameter mismatch, but these can be solved using existing parameter estimation algorithms, which will be a contribution of further work. This paper clearly shows that the application of classical simulators in electrical drives (in open or closed loop) can lead to their loss of stability under stator winding faults. A full model of the induction machine should be taken into account in the equations of estimators.

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Appendix A

Table A1. IM data.

Symbol	Rated Data	Value	Unit
P_N	Power	1.5	kW
U_N	Stator voltage	220/380	V
I_N	Stator current	5.0/2.9	A
n_N	Mechanical speed	1400	rpm
T_N	Torque	7.5	Nm
R_s	Stator resistance	5.9	Ω
R_r	Rotor resistance	4.6	Ω
L_s	Stator inductance	417.3	mH
L_r	Rotor inductance	417.3	mH
L_m	Magnetizing inductance	392.5	mH
p_b	Pole pairs	2	-
N_s	Turns per phase	292	-

References

1. Bose, B.K. *Power Electronics and Motor Drives: Advances and Trends*, 1st ed.; Academic Press: Cambridge, MA, USA, 2006.
2. Kazmierkowski, M.P.; Krishann, F.; Blabjerg, F. *Control in Power Electronics: Selected Problems*, 1st ed.; Academic Press: San Diego, CA, USA, 2002.
3. Holtz, J. Sensorless Control of Induction Motor Drives. *Proc. IEEE* **2002**, *90*, 1359–1394. [[CrossRef](#)]
4. Barut, M.; Demir, R.; Zerdali, E.; Inan, R. Real-time implementation Speed-sensorless, of bi input-extended Kalman filter-based estimator for control of induction motors. *IEEE Trans. Ind. Electron.* **2012**, *59*, 4197–4206. [[CrossRef](#)]
5. Syam, P.; Kumar, R.; Das, S.; Chattopadhyay, A.K. Review on model reference adaptive system for sensorless vector control of induction motor drives. *IET Electr. Power Appl.* **2015**, *9*, 496–511. [[CrossRef](#)]
6. Lascu, C.; Boldea, I.; Blaabjerg, F. A class of speed-sensorless sliding-mode observers for high-performance induction motor drives. *IEEE Trans. Ind. Electron.* **2009**, *56*, 3394–3403. [[CrossRef](#)]
7. Toliyat, H.A.; Levi, E.; Raina, M. A review of RFO induction motor parameter estimation techniques. *IEEE Trans. Energy Convers.* **2003**, *18*, 271–283. [[CrossRef](#)]
8. Bellini, A.; Filippetti, F.; Tassoni, C.; Capolino, G.A. Advances in Diagnostic Techniques for Induction Machines. *IEEE Trans. Ind. Electron.* **2008**, *55*, 4109–4126. [[CrossRef](#)]
9. Campos-Delgado, D.U.; Espinoza-Trejo, D.R.; Palacios, E. Fault-tolerant control in variable speed drives: A survey. *IET Electr. Power Appl.* **2008**, *2*, 121–134. [[CrossRef](#)]
10. Riera-Guasp, M.; Antonino-Daviu, J.A.; Capolino, G.A. Advances in Electrical Machine, Power Electronic, and Drive Condition Monitoring and Fault Detection: State of the Art. *IEEE Trans. Ind. Electron.* **2015**, *62*, 1746–1759. [[CrossRef](#)]
11. Merizalde, Y.; Hernández-Callejo, L.; Duque-Perez, O. State of the art and trends in the monitoring, detection and diagnosis of failures in electric induction motors. *Energies* **2017**, *10*, 1056. [[CrossRef](#)]
12. Bednarsz, S.A.; Dybkowski, M. Induction Motor Windings Faults Detection Using Flux-error Based MRAS Estimators. *Diagnostyka* **2019**, *20*, 87–92. [[CrossRef](#)]
13. Zhang, P.; Du, P.; Habetler, T.G.; Lu, B. A Survey of Condition Monitoring and Protection Methods for Medium-Voltage Induction Motors. *IEEE Trans. Ind. Appl.* **2011**, *47*, 34–46. [[CrossRef](#)]
14. Gandhi, A.; Corrigan, T.; Parsa, L. Recent Advances in Modeling and Online Detection of Stator Interturn Faults in Electrical Motors. *IEEE Trans. Ind. Electron.* **2011**, *58*, 1564–1575. [[CrossRef](#)]
15. Maraaba, L.; Al-Hamouz, Z.; Abido, M. An Efficient Stator Inter-Turn Fault Diagnosis Tool for Induction Motors. *Energies* **2018**, *11*, 653. [[CrossRef](#)]
16. Bazan, G.H.; Scalassara, P.R.; Endo, W.; Goedtel, A.; Palacios, R.H.C.; Godoy, W.F. Stator Short-Circuit Diagnosis in Induction Motors Using Mutual Information and Intelligent Systems. *IEEE Trans. Ind. Electron.* **2019**, *66*, 3237–3246. [[CrossRef](#)]
17. Zamudio-Ramirez, I.; Osornio-Rios, R.A.; Trejo-Hernandez, M.; Romero-Troncoso, R.D.J.; Antonino-Daviu, J.A. Smart-Sensors to Estimate Insulation Health in Induction Motors via Analysis of Stray Flux. *Energies* **2019**, *12*, 1658. [[CrossRef](#)]
18. Skowron, M.; Wolkiewicz, M.; Orłowska-Kowalska, T.; Kowalski, C.T. Application of Self-Organizing Neural Networks to Electrical Fault Classification in Induction Motors. *Appl. Sci.* **2019**, *9*, 616. [[CrossRef](#)]
19. Tallam, R.M.; Habetler, T.G.; Harley, R.G. Stator winding turn-fault detection for closed-loop induction motor drives. *IEEE Trans. Ind. Appl.* **2003**, *39*, 1553–1557. [[CrossRef](#)]
20. Cheng, S.; Zhang, P.; Habetler, T.G. An impedance identification approach to sensitive detection and location of stator turn-to-turn faults in a closed-loop multiple-motor drive. *IEEE Trans. Ind. Electron.* **2011**, *58*, 1545–1554. [[CrossRef](#)]
21. Wolkiewicz, M.; Tarchała, G.; Kowalski, C.T.; Orłowska-Kowalska, T. Stator Faults Monitoring and Detection in Vector Controlled Induction Motor Drives—Comparative Study. In *Advanced Control of Electrical Drives and Power Electronic Converters*; Kabziński, J., Ed.; Springer: Berlin/Heidelberg, Germany, 2017.
22. Tarchała, G.; Wolkiewicz, M. Performance of the Stator Winding Fault Diagnosis in Sensorless Induction Motor Drive. *Energies* **2019**, *12*, 1507. [[CrossRef](#)]
23. Cruz, S.M.A.; Cardoso, A.J.M. Diagnosis of Stator Inter-Turn Short Circuits in DTC Induction Motor Drives. *IEEE Trans. Ind. Appl.* **2004**, *40*, 1349–1360. [[CrossRef](#)]

24. Berzoy, A.; Mohammed, O.A.; Restrepo, J. Analysis of the Impact of Stator Interturn Short-Circuit Faults on Induction Machines Driven by Direct Torque Control. *IEEE Trans. Energy Convers.* **2018**, *33*, 1463–1474. [[CrossRef](#)]
25. Sobański, P.; Orłowska-Kowalska, T. IGBT Open-Circuit Fault Diagnostic Methods for SVM-VSI Vector-Controlled Induction Motor Drives. In *Advanced Control of Electrical Drives and Power Electronic Converters*; Kabziński, J., Ed.; Springer: Berlin/Heidelberg, Germany, 2017.
26. Dybkowski, M.; Klimkowski, K. Fault Tolerant Control Structure for Induction Motor Drive System. *Automatika* **2016**, *57*, 638–647. [[CrossRef](#)]
27. Isermann, R. *Fault-Diagnosis Applications, Model-Based Condition Monitoring: Actuators, Drives, Machinery, Plants, Sensors, and Fault-tolerant Systems*, 1st ed.; Springer: Berlin/Heidelberg, Germany, 2011.
28. Muenchhof, M.; Beck, M.; Isermann, R. Fault Diagnosis and Fault Tolerance of Drive Systems: Status and Research. *Eur. J. Control* **2009**, *15*, 370–388. [[CrossRef](#)]
29. Levi, E. Multiphase electric machines for variable-speed applications. *IEEE Trans. Ind. Electron.* **2008**, *55*, 1893–1909. [[CrossRef](#)]
30. Blanke, M.; Kinnaert, M.; Lunze, J.; Staroswiecki, M. *Diagnosis and Fault-Tolerant Control*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2016.
31. Jiang, J.; Yu, X. Fault-tolerant control systems: A comparative study between active and passive approaches. *Annu. Rev. Control* **2012**, *36*, 60–72. [[CrossRef](#)]
32. Bonivento, C.; Isidori, A.; Marconi, L.; Paoli, A. Implicit fault-tolerant control: Application to induction motors. *Automatica* **2004**, *40*, 355–371. [[CrossRef](#)]
33. Roubache, T.; Chaouch, S.; Naït Saïd, M.S. Backstepping fault tolerant control for induction motor. In Proceedings of the International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Ischia, Italy, 18–20 June 2014.
34. Roubache, T.; Chaouch, S.; Naït Saïd, M.S. Backstepping design for fault detection and FTC of an induction motor drives-based EVs. *Automatika* **2017**, *57*, 736–748. [[CrossRef](#)]
35. Djeghali, N.; Ghanes, N.; Djennoune, S.; Barbot, J.P.; Tadjine, M. Fault tolerant control for induction motors using sliding mode observers. In Proceedings of the 11th International Workshop on Variable Structure Systems (VSS), Mexico City, Mexico, 26–28 June 2010.
36. Kouchih, D.; Hachelaf, R.; Boumalha, N.; Tadjine, M.; Boucherit, M.S. Vector fault tolerant control of induction motor drives subject to stator interturn faults. In Proceedings of the 16th International Power Electronics and Motion Control Conference and Exposition (PEMC), Antalya, Turkey, 21–24 September 2014.
37. Abdelmajid, G.; Ahmed, S.; Mohamed, B.S.; Mohamed, T. Sliding mode observer for fault tolerant control of induction motor. In Proceedings of the 2nd International Symposium On Environment Friendly Energies And Applications, Newcastle, UK, 25–27 June 2012.
38. Roubache, T.; Chaouch, S.; Naït Saïd, M.S. Sensorless Fault-Tolerant Control of an Induction Motor Based Electric Vehicle. *J. Electr. Eng. Technol.* **2016**, *11*, 1423–1432. [[CrossRef](#)]
39. Toumi, D.; Boucherit, M.; Tadjine, M. Observer-based fault diagnosis and field oriented fault tolerant control of induction motor with stator inter-turn fault. *Arch. Electr. Eng.* **2012**, *61*, 165–188. [[CrossRef](#)]
40. Kallesøe, C.S.; Izadi-Zamanabadi, R.; Vadstrup, P.P.; Rasmussen, H. Observer-based estimation of stator-winding faults in delta-connected induction motors: A linear matrix inequality approach. *IEEE Trans. Ind. Appl.* **2007**, *43*, 1022–1031. [[CrossRef](#)]
41. Sellami, T.; Berriri, H.; Jelassi, S.; Darcherif, A.M.; Mimouni, M.F. Short-Circuit Fault Tolerant Control of a Wind Turbine Driven Induction Generator Based on Sliding Mode Observers. *Energies* **2017**, *10*, 1611. [[CrossRef](#)]
42. Refaat, S.S.; Abu-Rub, H.; Iqbal, A. ANN-based system for inter-turn stator winding fault tolerant DTC for induction motor drives. In Proceedings of the 17th European Conference on Power Electronics and Applications (EPE'15 ECCE-Europe), Geneva, Switzerland, 8–10 September 2015.
43. Diallo, D.; Benbouzid, M.E.H.; Makouf, A. A Fault-Tolerant Control Architecture for Induction Motor Drives in Automotive Applications. *IEEE Trans. Veh. Technol.* **2004**, *53*, 1847–1855. [[CrossRef](#)]
44. Gaeid, K.S.; Ping, H.W.; Khalid, M.; Masaoud, A. Sensor and sensorless fault tolerant control for induction motors using a wavelet index. *Sensors* **2012**, *12*, 4031–4050. [[CrossRef](#)] [[PubMed](#)]

45. Youngkook, L.; Habetler, T.G. A Stator Turn Fault Tolerant Strategy for Induction Motor Drives in Safety Critical Applications. In Proceedings of the 37th IEEE Power Electronics Specialists Conference, Jeju, Korea, 18–22 June 2006.
46. Refaat, S.S.; Abu-Rub, H.; Saad, M.S.; Aboul-Zahab, M.S.; Iqbal, A. Fault tolerance of stator turn fault for three phase induction motors star-connected using artificial neural network. In Proceedings of the IEEE Applied Power Electronics Conference and Exposition (APEC), Long Beach, CA, USA, 17–21 March 2013.
47. De Angelo, C.H.; Bossio, G.R.; Giaccone, S.J.; Valla, M.I.; Solsona, J.A.; Garcia, G.O. Online Model-Based Stator-Fault Detection and Identification in Induction Motors. *IEEE Trans. Ind. Electron.* **2009**, *56*, 4671–4680. [[CrossRef](#)]
48. Rasmussen, H.; Knudsen, M.; Tonnes, M. Parameter estimation of inverter and motor model at standstill using measured currents only. In Proceedings of the IEEE International Symposium on Industrial Electronics (ISIE), Warsaw, Poland, 17–20 June 1996.
49. Dybkowski, M.; Orłowska-Kowalska, T.; Wierzbicki, R. Self-commissioning sensorless induction motor drive with new MRAS estimator: Experimental tests. *Pozn. Univ. Technol. Acad. J. Electr. Eng.* **2007**, *55*, 59–71.
50. Zorgrani, Y.A.; Jouili, M.; Koubaa, Y.; Boussak, M. A very-low speed sensorless control induction motor drive with online rotor resistance tuning by using MRAS scheme. *Power Electron. Drives*. **2018**, *3*, 171–186. [[CrossRef](#)]
51. Hu, J.; Wu, B. New integration algorithms for estimating flux over a wide speed range. *IEEE Trans. Power. Electron.* **1998**, *13*, 969–977. [[CrossRef](#)]



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