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Stator windings condition diagnosis of voltage inverter-fed induction motor in open and closed-loop control structures

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Abstract: This paper deals with detection of the stator windings shorted turns in an induction motor drive working under open (scalar) and closed loop (Direct Field Oriented DFO) control structures. In order to detect the early stage of stator winding fault, the analysis of symmetrical and principal components of stator voltages and currents is used. Experimental results obtained from a specially prepared induction motor are presented.

Key words: induction motor, shorted turns, scalar control, vector control DFOC

1. Introduction

Monitoring and detecting electrical and mechanical damages of induction motor drives became an important issue together with increasing popularity of the motors in industrial applications.

Modern induction motor drives, fed from the Voltage Source Inverters (VSIs) are required to operate safely and reliably. However, the number of the components that compose the drive is high and all of them can be the reason of the damage. All of the following: induction motor, supply and power electronics systems (PWM-VSI), measurement sensors and digital control system can be damaged and cause the unrequired perturbations in the drive operation. In such situation an adequate action must be taken by the control system.

According to [1], stator winding faults are one of the most common reasons of induction motor breakdowns and comprise about 36% of all failures. The stator winding damage begins with unnoticeable inter-turn short circuit, that eventually spread over the whole winding, causing main short circuit. It leads to an emergency stop of the motor and necessity of its immediate upgrade or repair, that often generates large costs.

Field Oriented Control (FOC) methods require that the rotor flux vector angle is precisely known, in order to make the transformation between stationary and synchronous frames.

When the stator winding damage occurs, the estimation of the rotor flux vector is erroneous, due to the unsymmetrical resistance of the stator windings [2]. As a consequence, the operation of the drive can become unstable when the damage process is uncontrolled and the proper action is not taken by the control system.

According to the above, it is important to detect the early stage of the stator winding damage. Currently applied protections do not react on small number of shorted turns, because they cause too low quantitative changes in phase currents. For that reason, other solutions, based on measurements and digital processing of diagnostic signals, are still looked for. They should allow on-line monitoring of the machine condition and alarm the user at the initial phase of the short circuit [1, 3, 4].

Early detection methods of the stator winding inter turns for the open-loop control of the IM are widely described in the literature, both for the net [5] and inverter fed drives [3, 4]. One of the few articles concerning the closed-loop control methods is the one that analyses the stator winding faults under the classical switching table DTC [6]. The diagnostic method is based on the stator current analysis in the frequency domain. The field oriented control of the IM under the stator winding damages is described in [7] and the stator winding monitoring is based on the symmetrical components analysis. In [8] another diagnostic method is proposed for the field oriented control of the IM, based on the stator resistance estimation using Extended Kalman Filter and Luenberger Observer.

In this paper two different diagnostic methods are considered. First one is the symmetrical components analysis method. The symmetrical components can be divided into positive and negative sequence components and both of them are calculated from stator phase currents and phase-to-phase voltages. The second method is the Principal Components Analysis (PCA), and similarly, the PCA components are calculated for both stator currents and voltages. The components are calculated for the damaged induction motor in function of the shorted turns number, load torque and speed of the drive. Usefulness for the failure diagnosis of the analysed components is finally evaluated.

The paper is organized as follows. First, the description of the experimental setup is presented. Then, the induction motor model is described. Next, the scalar and vector control methods are briefly presented, together with the block diagram of the DFOC method. Influence of the stator winding damages on the operation of mentioned control structures is the following part of the paper. Finally, the analysed symmetrical and principal component analysis methods are described and applied in diagnosis of the induction motor drive. They are illustrated using the experimental test results. The paper is shortly concluded at the end.

2. Description of experimental setup

In Figure 1 the whole experimental setup is presented. Experimental tests were conducted using 1.5 kW squirrel cage induction motor INDUKTA Sh 90L-4, coupled to another 1.5 kW induction machine, acting as an external load. Digital Signal Processor (dSpace DS 1103) was used to control the Voltage Source Inverter (VSI) of the tested machine. The control program was written in C language and consisted of data acquisition, non-measurable variables estimator, Space Vector Modulation (SVM) and two control methods: scalar U/f = const and DFOC method. The program took the advantage of three phase currents i_{sA}, i_{sB}, i_{sC}, DC voltage of the VSI u_d and angular speed of the drive ω_m. The control program defined the switching signals of the VSI transistors s_A, s_B, s_C and the reference value of the load torque m_o^{ref}, that was sent to the VSI of the load motor. In order to monitor the stator windings damages, a measurement-diagnostic computer system with a virtual measurement instrument was created in the LabView environment. The diagnostic program used three phase currents and phase to phase voltages u_{sAB}, u_{sBC}, u_{sAC}.

During the laboratory tests, a specially prepared induction motor was used, that enabled physical modelling of the stator winding inter-turns, independently for each of three motor phases. The maximum number of shorted turns is 8, that gives about 3% of the whole number of the winding turns. In order to ensure the real nature of the damage, there was no additional resistance placed in the short circuit.

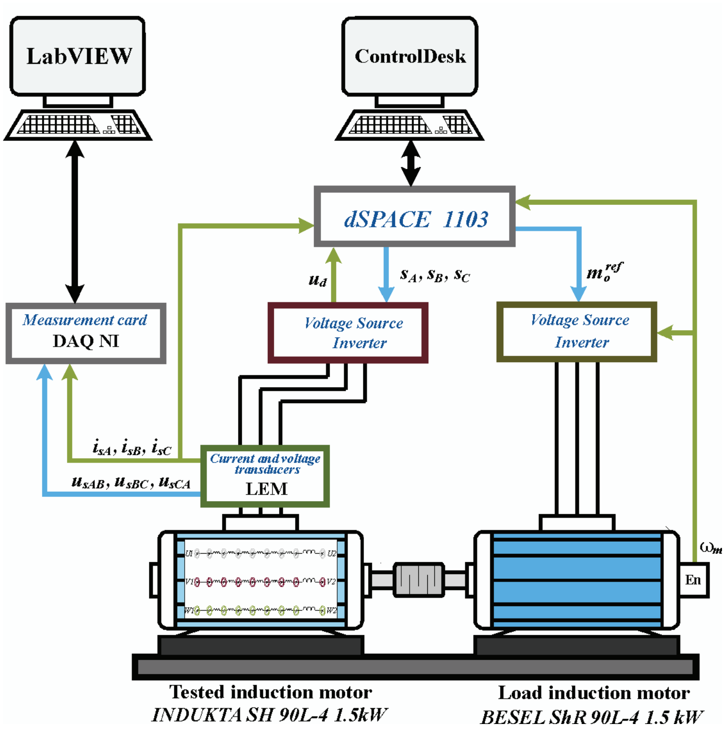

Fig. 1. Block diagram of experimental setup

3. Induction motor model

Mathematical model of a squirrel-cage induction motor can be derived using commonly known assumptions (symmetrical geometrical and electrical configuration, neglected: magnetic saturation, eddy currents, core loss, higher harmonics in stator and rotor voltages, currents and fluxes) in any *u*-*v* rotating frame using the following set of equations expressed in per unit [p.u.] system:

$$\mathbf{u}_\mathrm{s} = r_s \mathbf{i}_\mathrm{s} + T_N \frac{d}{dt} \boldsymbol{\psi}_\mathrm{s} + j\omega_k \boldsymbol{\psi}_\mathrm{s}, \tag{1}$$

$$0 = r_r \mathbf{i}_\mathbf{r} + T_N \frac{d}{dt} \boldsymbol{\psi}_\mathbf{r} + j(\omega_k - \omega_m)\boldsymbol{\psi}_\mathbf{r}, \tag{2}$$

$$\boldsymbol{\psi}_\mathbf{s} = x_s \mathbf{i}_\mathrm{s} + x_M \mathbf{i}_\mathbf{r}, \tag{3}$$

$$\boldsymbol{\psi}_\mathbf{r} = x_r \mathbf{i}_\mathbf{r} + x_M \mathbf{i}_\mathrm{s}, \tag{4}$$

$$\frac{d\omega_m}{dt} = \frac{1}{T_M}(m_e - m_o), \tag{5}$$

$$m_e = \mathrm{Im}\left(\boldsymbol{\psi}_s^* \mathbf{i}_s\right) \tag{6}$$

where: $\mathbf{u}_\mathbf{s} = u_{su} + ju_{sv}$, $\mathbf{i}_\mathbf{s} = i_{su} + ji_{sv}$, $\mathbf{i}_\mathbf{r} = i_{ru} + ji_{rv}$, $\boldsymbol{\psi}_\mathbf{s} = \psi_{su} + j\psi_{sv}$, $\boldsymbol{\psi}_\mathrm{r} = \psi_{ru} + j\psi_{rv}$ – space vectors of stator voltage and current, rotor current, stator and rotor fluxes. Parameters of induction motor: r_s, r_r, x_M, $x_s = x_M + x_{s\sigma}$, $x_r = x_M + x_{r\sigma}$ – stator and rotor winding resistances, main, stator and rotor reactances; $x_{s\sigma}$, $x_{r\sigma}$ – leakage reactances. Angular frequencies: ω_k – of chosen frame, ω_m – mechanical. Torques: m_e – electromagnetic and m_o – load. Time constants: mechanical T_M and $T_N = 1/\Omega_\mathrm{b} = 1/(2\pi f_{sN})$.

4. Basics of scalar and vector control methods of induction motor drives

In the paper two different control structures for induction motor drives are compared – scalar and vector control methods.

When the drive is controlled using the scalar control method, the control algorithm has to keep the *U/f* ratio at constant level. It means that the supply amplitude of the supply voltage *U* is changed according to its frequency *f* variations. If there is no closed loop control, speed of the drive depends on the frequency and load torque value. This control method ensures proper operation only during the steady-states, however it is still commonly applied in industrial frequency inverters.

The block diagram of vector control method is shown in Figure 2. The Direct Field Oriented Control (DFOC) method is chosen to control the induction motor. Two separated control paths can be distinguished: rotor flux amplitude stabilization and mechanical speed control path. The control paths are separated and decoupled as a result of the decoupling block usage. The four PI regulators work in *x*-*y* frame, rotating synchronously with rotor flux vector. Reference values of voltage are transferred to the stationary *α*-*β* frame and then are used by the Space Vector Modulation (SVM) block. In order to regulate the flux and make the transformation between synchronous and stationary frames, it is necessary to estimate the rotor flux vector amplitude and its angle. Therefore, proper flux estimator must be applied. The choice of the estimator is a crucial issue, in terms of the diagnosis of the stator windings damages. One of the estimators that allows monitoring the damages effectively is a simple rotor flux simulator called the voltage simulator. It was chosen for the further tests. The estimator can be described by the following equations:

$$\hat{\psi}_{r\alpha} = \frac{x_r}{x_M}\left(\hat{\psi}_{s\alpha} - \sigma x_s i_{s\alpha}\right), \tag{7}$$

$$\hat{\psi}_{r\beta} = \frac{x_r}{x_M}\left(\hat{\psi}_{s\beta} - \sigma x_s i_{s\beta}\right), \tag{8}$$

where calculated stator flux vector components:

$$T_N \frac{d\hat{\psi}_{s\alpha}}{dt} = u_{s\alpha} - r_s i_{s\alpha}, \tag{9}$$

$$T_N \frac{d\hat{\psi}_{s\beta}}{dt} = u_{s\beta} - r_s i_{s\beta}, \tag{10}$$

Sensitivity of the estimator to the stator windings damage is connected with stator flux components calculations in (9) and (10). Both stator currents and voltages are taken into account, and the only parameter used in these equations is stator resistance, that becomes unsymmetrical (between motor phases) and changes its value during the damage.

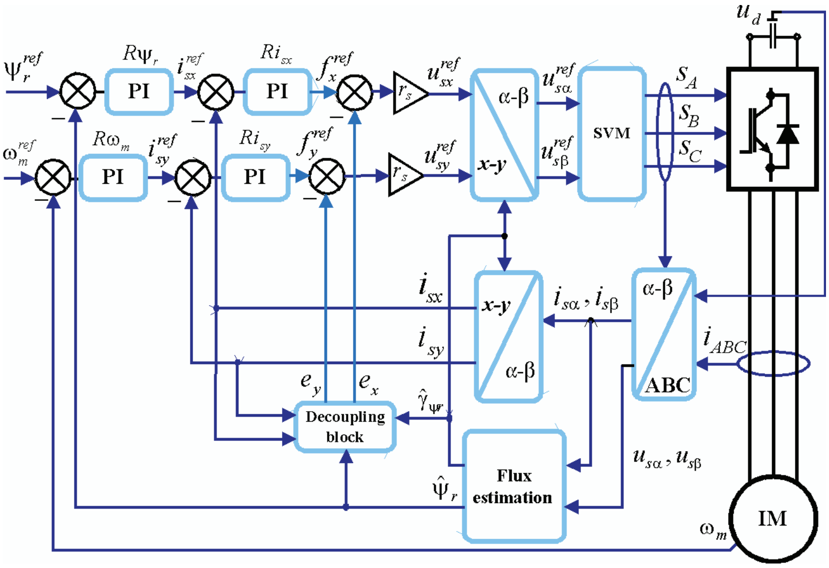

Fig. 2. Block diagram of Direct Field Oriented Control (DFOC) method

5. Influence of the stator winding damage on scalar and vector control methods operation

Figures 3 and 4 show the comparison of the analysed control methods operation: scalar (Fig. 3) and vector (Fig. 4) during the A phase winding damage. In both cases, the drive accelerate to a fixed speed (half of the nominal frequency in case of the scalar control; reference speed equal to 0.5 in case of the vector control). Next, the nominal load torque appears (after about 7 s), that takes effect in speed reduction – permanent in case of the scalar control method (Fig. 3a) and transient in case of the vector control (Fig. 4a).

Next, from about 11 s to 17 s, 5 shorted turns in A phase of the motor are physically modelled. Presented enlargements of the time courses show that the appearing short circuit does not practically influence the speed of the motor. When the nominal load torque occurs, phase currents of the motor (Fig. 3b, 4b) rise to their nominal values (amplitudes are equal to 1 in p.u. system). At the moment of the damage, an increase of the stator phase currents is also visible. This change is insignificant and equal to about 5%.

The amplitude of the estimated rotor flux (obtained using the simple voltage simulator, (7-10)) is actually constant in case of the scalar control (Fig. 3c) and is stabilized exactly on the nominal value by the vector control structure DFOC (Fig. 4c). Variation of the estimated flux during the damage is quite small in case of the scalar control, and practically invisible in case of the DFOC.

Due to the speed stabilization at the fixed level in the DFOC structure, the output value of the speed regulator changes, and consequently actual torque component of the stator current vector, i_{sy}, changes its value (Fig. 4d). However, this change is too small to utilize it in the diagnostic process of the damage, especially as this component varies significantly with the load torque. Second component of the stator current vector, i_{sx}, is shown in Figure 4f. Also in this case, the value of the component changes slightly and cannot be used in shorted turns diagnosis.

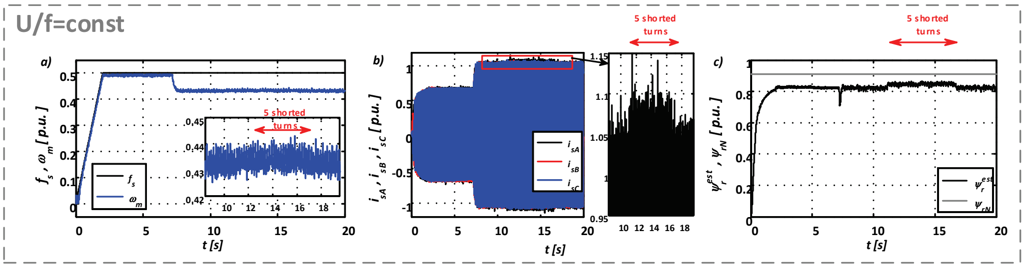

Fig. 3. Scalar control method operation during the start-up of the induction motor, for nominal load appearance (after 7 s) and physical modelling of 5 shorted turns in A phase of the motor (from about 11 s to 17 s): a) supply frequency and angular speed, b) stator phase currents and zoom of A phase, c) estimated and nominal rotor flux amplitudes

According to the presented results, it is impossible to detect the early stage of the winding damage, depending only on the quantitative changes in the analysed time signals, because they are simply too small. Therefore other solutions, based on digital signal processing of the diagnostic signals, must be taken into account. These methods should allow an on-line monitoring and diagnosis of the machine and alarm the user in even initial phase of the fault. In the further part of the article two different methods are analysed: symmetrical components analysis and principle components analysis of the stator voltage and current.

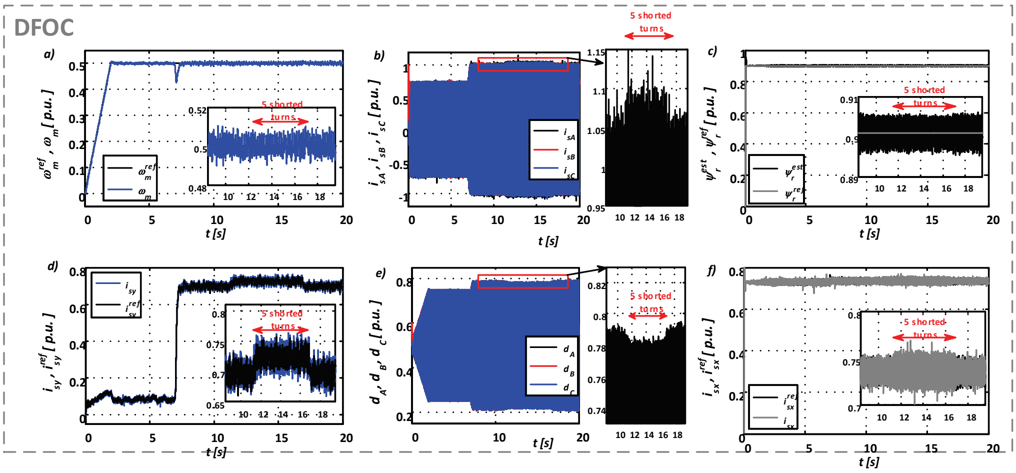

Fig. 4. DFOC operation during the start-up of the induction motor, for nominal load appearance (after 7 s) and physical modelling of 5 shorted turns in A phase of the motor (from about 11 s to 17 s): a) reference and actual speed, b) stator phase currents, c) reference and estimated amplitude of rotor flux, d) i_{sy} component of the stator vector, e) control signals, f) i_{sx} component of the stator vector

6. Monitoring of the stator windings condition using symmetrical components method

6.1. Experimental tests methodology

Supplying induction motors from a frequency converter introduces a large number of higher harmonics in currents and voltages, causing their deformation from sinusoidal signals. In such situation it is necessary to make an additional analysis of mentioned signals, in order to isolate the symptoms of the damage.

For this purpose, the symmetrical components method can be used. Method shown in [3, 9] is based on filtering all of the higher harmonics and analysing only the fundamental harmonic of the supply voltage. To isolate fundamental frequency signals, so called instantaneous symmetrical components were calculated, replacing the imaginary rotation operator j with 90 degrees rotation operator in time domain.

According to this, it is possible to filter only the fundamental frequency component f_s of the signal, e.g. using spectral analysis, and monitoring changes of its amplitude. Positive and negative sequence components of supply voltages and currents, determined in the described way are used to evaluate the condition of the induction motor stator windings. Successive stages of the diagnostic signals processing are shown in Figure 5.

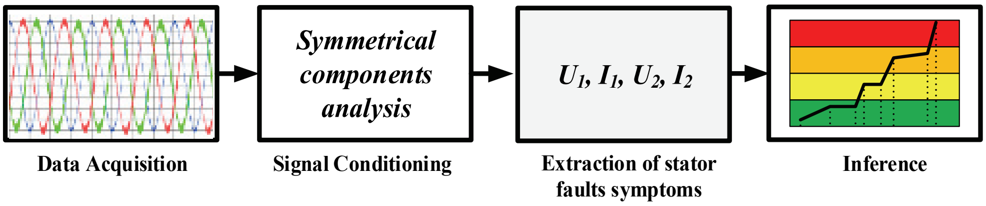

Fig. 5. Diagnostic signals processing using the symmetrical components analysis

In order to verify the influence of the stator windings asymmetry on the stator currents and voltages, it is also possible to make use of vector hodograph changes in stationary reference frame *α-β*. As shown in [10], in case of the stator winding damage, the hodograph becomes deformed, and the level of the deformation increases with progressive damage. The circular hodograph becomes elliptical when the damage occurs.

To calculate quantitative changes of the hodograph, evoked by the shorted turns, a statistical data analysis method, called the Principal Component Analysis (PCA) can be applied [10, 11].

In Figure 6 stages of the diagnostic data processing is shown, when the PCA method is used. First, the stator currents and voltages are measured, then they are transformed to the stationary *α-β* frame. Next step is to calculate the principal components from the stator current and voltage vectors. Finally, the principal components variation indexes λ_{PCA} are determined, and on the grounds of these, the stator winding condition is inferred.

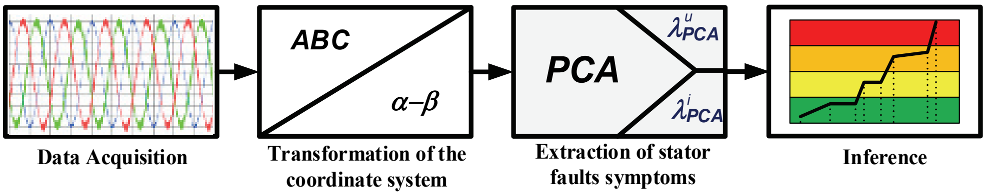

Fig. 6. Diagnostic data processing stages using the PCA method

6.2. Experimental tests results

In Figure 7 comparison of results obtained for the symmetrical components analysis of stator current – positive sequence (Fig. 7a) and negative sequence (Fig. 7b) is presented, for both control structures analysed in this paper (scalar U/f = const, f = 50 Hz and vector *DFOC* for nominal speed $\omega_m = \omega_n$). Additionally, these results are compared for no load and nominal load operation. For both control structures, short circuit of even high number of turns in one coil does not practically change the positive sequence component value (Fig. 7a). A slight change is visible for nominal load operation (for 5 shorted turns about 5%).

It can be noticed that the short circuit of even 1 or 2 turns in A phase of the motor causes a significant increase of the negative sequence component. Monitoring of this component, for both scalar and vector control structures, allows to detect the initial phase of the damage. Additionally, the load torque has almost no influence on the negative sequence component value $I_2^{(fs)}$.

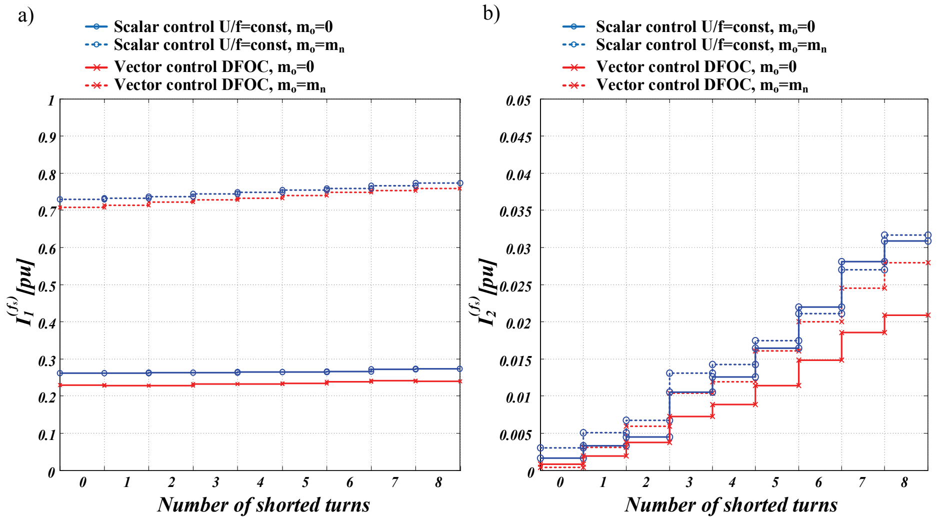

Fig. 7. Symmetrical components of stator current: a) positive sequence $I_1^{(fs)}$, b) negative sequence $I_2^{(fs)}$ for no load and nominal load operation and different levels of damage

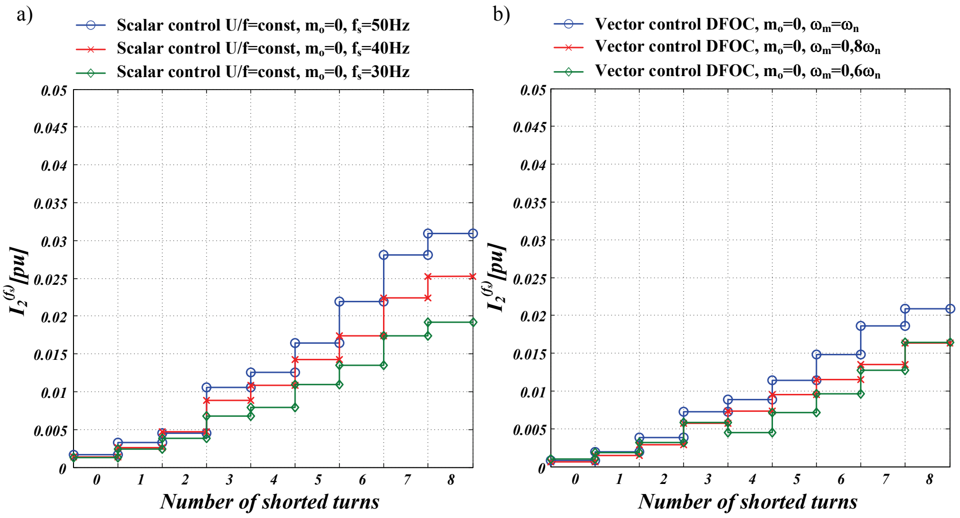

Fig. 8. Negative sequence component variations for different levels of damage and speed, no load operation

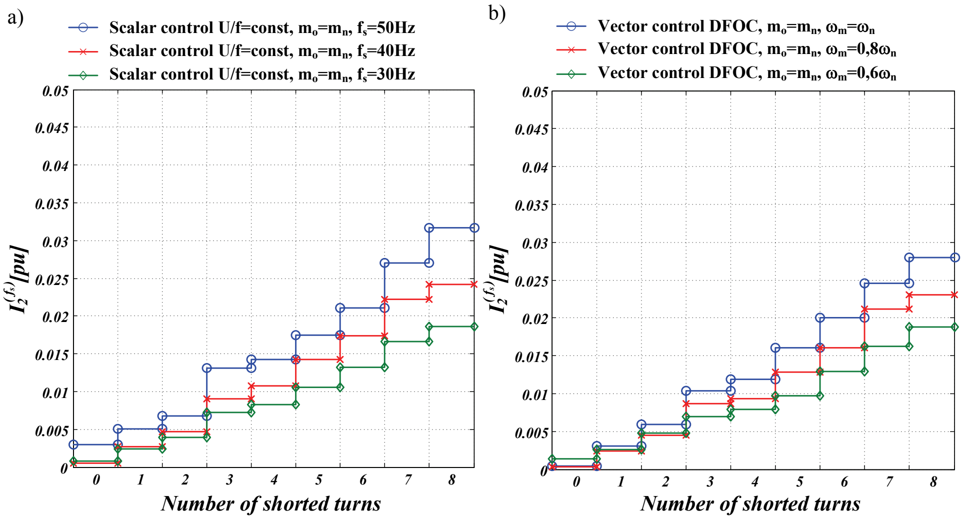

Fig. 9. Negative sequence component variations for different levels of damage and speed, nominal load operation

Variations of the negative sequence component amplitudes of the stator current, calculated for the fundamental frequency, for different values of frequencies and reference speeds are shown in Figure 8 (no load operation) and 9 (nominal load). It can be seen that the lower the speed of the drive, the lower the variation intensity of the analysed component. However, detection of even 1 shorted turn is still possible.

On the basis of the analysis of the results shown in Figure 10, it can be stated that the positive and negative sequence components of the supply voltage are not dependent on the damage level, when the damage is caused by the shorted turns within one coil of the stator winding.

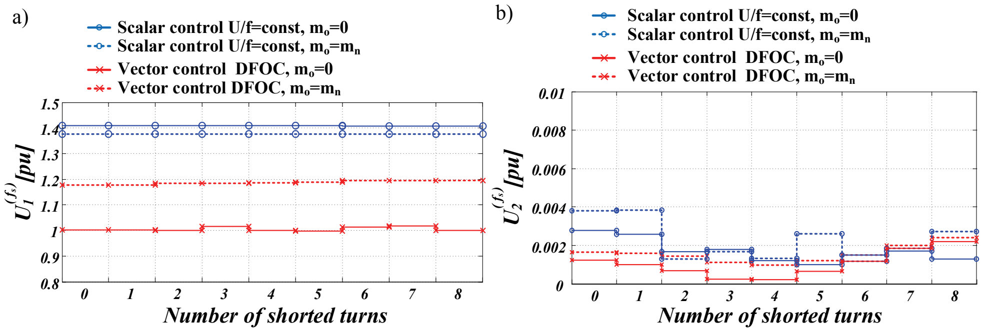

Fig. 10. Symmetrical components of supply voltage: a) positive sequence $U_1^{(fs)}$, b) negative sequence $U_2^{(fs)}$ for no load and nominal load operation, different levels of damage in A phase of the motor and different control structures

As was proved before, stator winding damage makes changes in phase currents of the stator. These changes can be observed also in the hodograph of stator current vector, expressed in a stationary coordinate frame α-β [10].

Figure 11a shows the dependence of the stator voltage intensity index λ_{PCA} on the number of the shorted turns and load torque value for both scalar and vector control methods. It can be noticed, that for both damaged and undamaged windings, the analysed factor is practically invariable. Similarly, as for the symmetrical components analysis, the voltage signal cannot be used to detect the damage.

In Figure 11b intensity index λ_{PCA} calculated from the stator currents is shown. For the undamaged motor value of the index is almost zero. Together with the increasing level of the damage, the index λ_{PCA} also rises. It can be seen, that similarly to the negative sequence component, the intensity of λ_{PCA} changes is smaller for vector control. However, it is possible to detect several shorted turns.

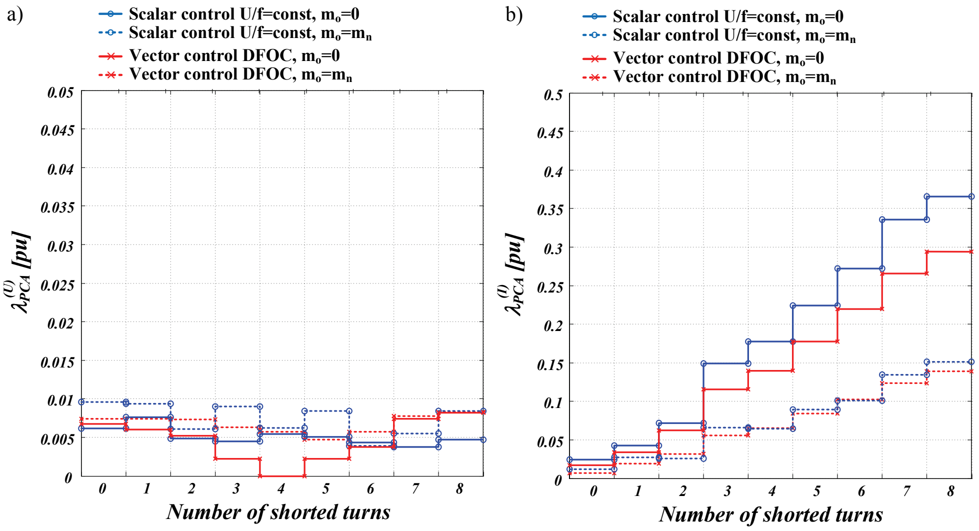

Fig. 11. Variation of λ_{PCA} of: a) stator voltage, b) stator current, for no load and nominal load operation for different levels of damage and various control structures

Figures 12 and 13 show variation of the λ_{PCA} index in case of different frequencies and reference speeds for no load and nominal load operation. It can be seen that the lower the speed the lower the intensity of the analysed PCA index changes. However, it is possible to detect even 1 shorted turn for both control structures.

Analysing the above results, it can be stated that generally the closed-loop speed control structure lowers slightly the intensity of the damage symptoms, that appear in directly available signals of the motor (in case of the presented research – in stator currents), in contradiction to scalar control methods (in this case U/f = const).

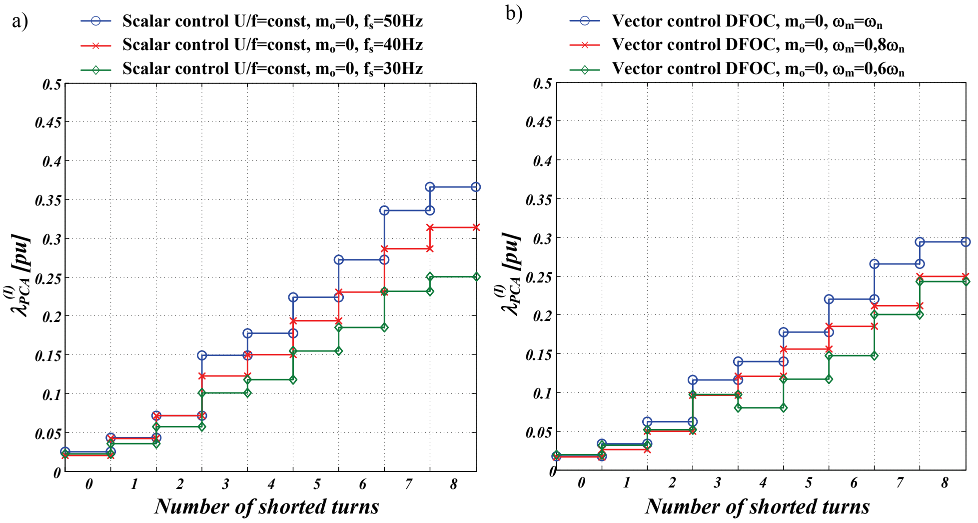

Fig. 12. Variations of the PCA index calculated from stator current for different levels of the damage under no load for: a) scalar and b) vector control structure

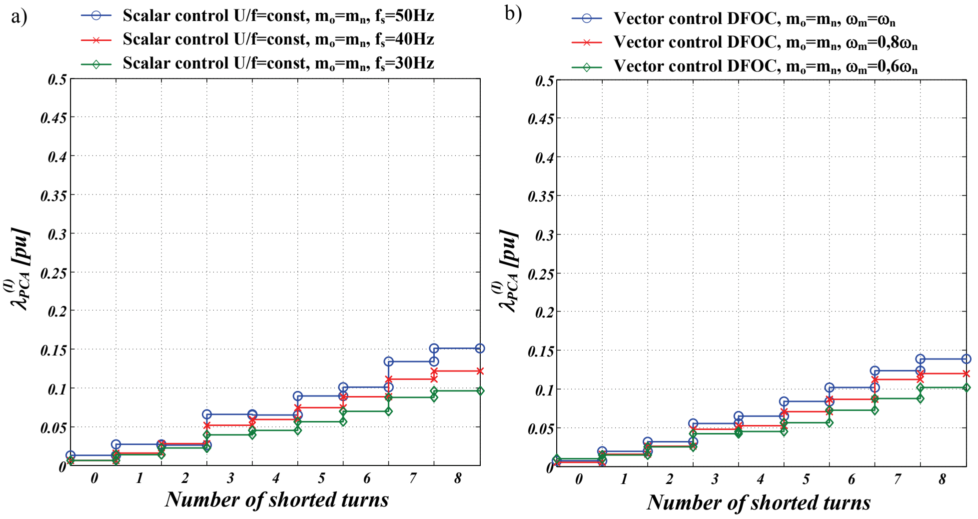

Fig. 13. Variations of the PCA index calculated from stator current for different level of the damage under nominal load for: a) scalar and b) vector control structure

7. Conclusions

According to the presented experimental results, obtained using specially prepared induction motor, it can be concluded that there is a possibility of monitoring the inter turns of the stator windings in both scalar and vector control methods. Despite of the compensating effect of the closed-loop control structure on the damage symptoms, they are visible in the positive sequence symmetrical component and the PCA index of stator currents. The symptoms are visible even for single shorted turns, therefore it is possible to detect the damage in its early stage and react properly.

Presented methods of stator windings monitoring, taking the advantage of the proposed damage estimation indexes, extended with a neural or fuzzy detector can allow to create a diagnostic system working in open (scalar) or close (vector) control structure.

Practical realization of the monitoring system is connected with implementation of some additional diagnostic procedures in the control system software of the induction motor drive. However, the implementation should not be problematic in case of most modern microprocessors.

Acknowledgements

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