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On-Line Detection of High Resistance Connections with Negative-Sequence Regulators in Three Phase Induction Motor Drives

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Abstract—**High-resistance connections in electric drives can cause localized overheating and motor supply voltage unbalance, which degrade the performance, efficiency, and reliability of the system. An enhanced field oriented control scheme for induction machines that is capable of detecting resistive unbalance due to high resistance connections, and regulating the negative sequence current is proposed as the main contribution of this paper. Resistive unbalance is detected and located while maintaining the symmetric drive behavior both under transient and steady-state operating conditions. The negative-sequence regulator adopted in addition to the traditional current regulator for rotor field oriented control is used to compensate for the voltage unbalance caused by the inherent asymmetries in the cable and stator winding and by the poor contacts. A model that shows the relationship between the resistive unbalance and negative-sequence current components is derived from the analysis of the proposed scheme. The theoretical analysis and the validity of the detection technique are confirmed with a preliminary experimental study on a 4 kW induction motor drive.**

Keywords— *High-resistance connections, fault detection, fault-tolerant drive, induction motor drive*

I. INTRODUCTION

High resistance connections can be caused by a combination of poor workmanship, thermal cycling and vibration, or damage of the contact surfaces due to pitting,

corrosion or contamination. The increase in the resistance due to poor contacts can cause overheating to reach an unacceptable level, which can eventually cause open-circuit failures due to the melting of copper conductors, as shown in Fig. 1. Excessive overheating in the contact points can also deteriorate insulation and expose the copper conductor to serious damages such as short-circuit failures between conductors or to the ground. Localized temperature rise or arching due to poor or loose contacts can also initiate fire. In addition, the asymmetries of the stator voltage induced by poor contacts may cause negative sequence currents to circulate in the motor windings, thus reducing the motor output power, efficiency, and reliability [1]-[3]. If the evolution of this type of electrical fault is not detected at an early stage, its propagation can lead to more serious unexpected forced outages.

The traditional approach for the detection of high resistance connections include methods such as the offline resistive unbalance test, visual inspection, the voltage drop survey, and infrared thermography. To avoid specialized equipments, recently, sensorless on-line techniques based on the negative-sequence current and zero-sequence voltage have been proposed for three phase machines [4]-[5]. The main concept behind the detection of high-resistance connections is to monitor the asymmetry of the system. Therefore, the techniques developed to detect high resistance connections are based on indicators similar to the ones used to detect inter-turn faults or stator unbalances [6]-[9]. It is worth noting that high-resistance contacts do not usually require immediate shut down of the drive, since the problem may evolve very slowly unlike inter-turn stator turn failures.

In this paper, an analytical model of a three-phase induction motor with unbalanced phase resistance is developed in terms of voltage and current space vectors under the assumption that the control system is capable of compensating for the effect of the three phase unbalance. Resistive unbalance in the three phases can be caused by
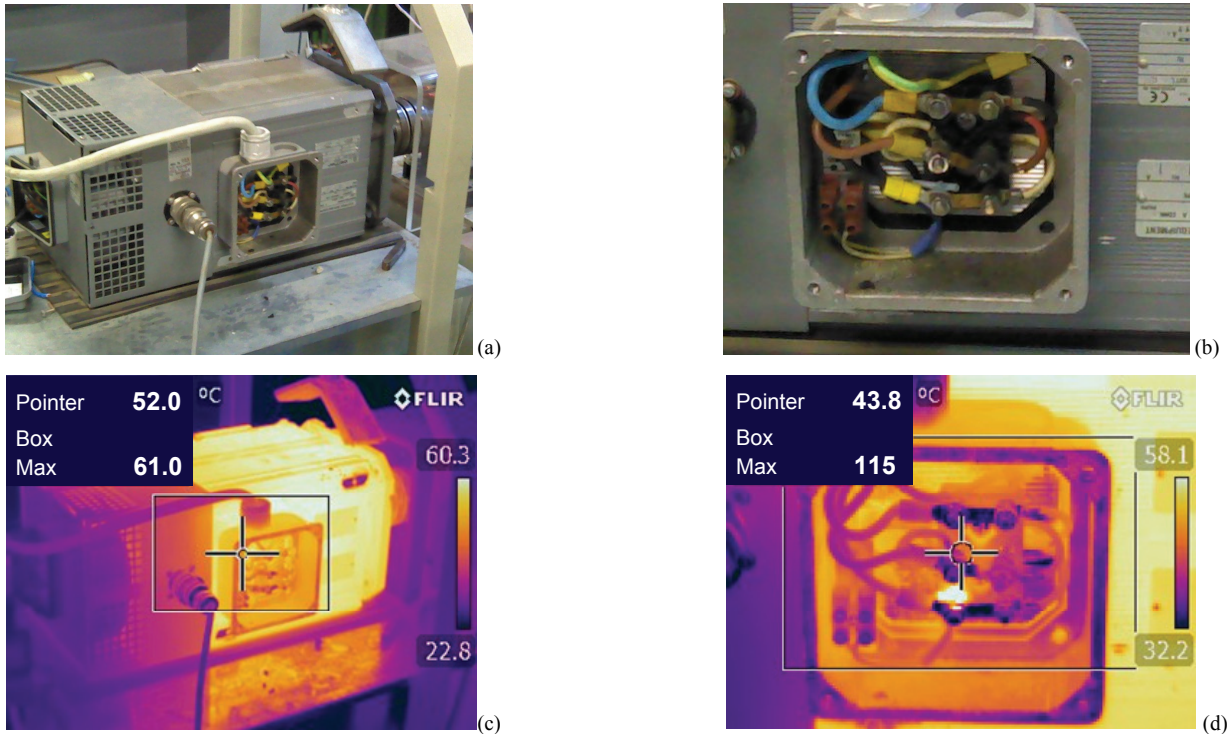
Fig. 1. Pictures of a laboratory prototype of induction motor drive for experimental tests on high-resistance connections. Figs. (a) and (b) show the induction motor and the detail of its terminal box, whereas Figs. (c) and (d) show the corresponding infra-red (IR) thermal images, which reveal the presence of a hot spot, artificially created. While the temperature of the motor case reaches 60°C at most, the temperature of the hot-spot is much higher.

inherent asymmetry in the stator winding (e.g. concentric windings) or cable (e.g. poor workmanship or high resistance contact). This analysis is in agreement with existing publications that investigate the use of the voltage and current negative sequence components [10]-[13]. However, the present paper differs from the previous studies in the fact that the analysis of the fault model is used to derive the design principles of a control scheme that is capable of detecting the unbalance of all phases simultaneously and identify the faulty phase(s), while keeping the drive operation unchanged. The key idea of this control scheme is to adopt multi-reference frame controllers to cancel the negative-sequence components of the stator currents. At the same time, the information generated by these regulators is used to detect the unbalance condition and identify the affected phase.

The use of resonant controllers to cancel the negative-sequence current or the use of controller implemented in counter-rotating reference frames is well-known for applications regarding the control of grid-connected converters and active filters [14]-[16]. However, this methodology is adopted here to tackle a totally different problem, i.e., the on-line fault diagnosis of induction machines.

The validity of the theoretical analysis and the feasibility of the control scheme are confirmed by experimental tests.

II. MOTOR DYNAMIC MODEL WITH ASYMMETRIC STATOR RESISTANCES

Let us consider a three-phase induction machine, where the resistances of the stator phases are not assumed equal to each other. The voltage equation of the kth phase can be expressed as

$$v_{Sk} = R_{Sk} i_{Sk} + \frac{d\varphi_{Sk}}{dt} \quad (k=1, 2, 3),$$ (1)

where, v_{Sk} is the voltage applied to the kth stator phase, R_{Sk} is its resistance, and φ_{Sk} is the stator flux linkage. The resistances can be expressed as the sum of two terms, i.e., the mean value R_S and the deviation ΔR_k from the mean value R_S.

$$R_{Sk} = R_S + \Delta R_k \quad (k=1, 2, 3).$$ (2)

As a consequence of (2), it is worth noting that the sum of the resistance deviations ΔR_k ($k=1,2,3$) must be zero.

$$\sum_{k=1}^{3} \Delta R_k = 0 \quad (k=1, 2, 3).$$ (3)

Equations (1), combined with (2), can be rewritten in the stator reference frame in terms of space vectors, which are

very useful for the field-oriented control of electric drives. It can be shown that that the final result can be derived as,

$$\bar{v}_S = R_S \bar{i}_S + \frac{d\overline{\varphi}_S}{dt} + \left(\frac{1}{3}\sum_{k=1}^{3}\Delta R_k \overline{\alpha}_k^*\right)\bar{i}_S^* \qquad (4)$$

where,

$$\overline{\alpha}_k = e^{j\frac{2\pi}{3}(k-1)} \quad (k=1,2,3), \qquad (5)$$

and the symbol "*" denotes the complex conjugate operator. Equation (4) is very similar to that of a balanced induction machine, except for the additional terms that are proportional to the resistance deviations ΔR_k (k=1,2,3) and to the current $\bar{i}_S^*$.

To analyze (4) further, it is necessary to consider the behavior of the rotor currents. The stator flux vector in (4) can be expressed as a function of the stator current and rotor flux vectors as,

$$\overline{\varphi}_S = \sigma L_S \bar{i}_S + \frac{M}{L_R}\overline{\varphi}_R, \qquad (6)$$

where σL_S, M and L_R are the total leakage inductance, the mutual inductance, and the rotor self inductance, respectively. Finally, $\overline{\varphi}_R$ is the space vector of the rotor flux. It is well-known that the rotor flux $\overline{\varphi}_R$ can be related to the stator current vector $\bar{i}_S$ by the following first-order differential equation:

$$\tau_R \frac{d\overline{\varphi}_R}{dt} + \left(1 - j\omega_m \tau_R\right)\overline{\varphi}_R = M\bar{i}_S, \qquad (7)$$

where j represents the imaginary unit, ω_m is the rotor speed in electrical radians per second, and τ_R is the rotor time constant defined as the ratio between the rotor self-inductance L_R and the rotor resistance R_R.

Equations (4)-(7) fully describe the behavior of the induction motor with unequal stator resistances. The schematic circuit of the induction motor, in terms of space vectors, is shown in Fig. 2.

III. Steady State Solution Under Resistance Unbalance

Let us suppose that the electric drive is in steady-state operating conditions and that the control system is able to feed the machine in such a way that $\bar{i}_S$ perfectly tracks the reference current vector $\bar{i}_{S,ref}^{(p)}$, rotating at constant angular frequency ω with constant magnitude.
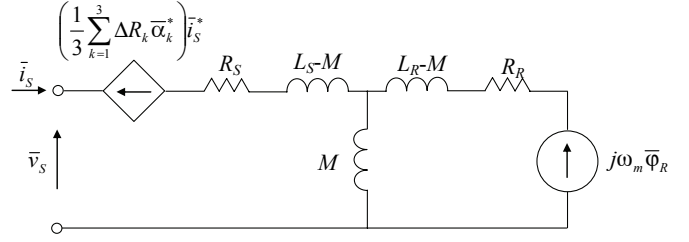
Fig. 2 - Schematic circuit of the induction motor with unbalanced resistances in terms of space vectors.

$$\bar{i}_S = \bar{i}_{S,ref}^{(p)}. \qquad (8)$$

All the electrical quantities in (4)-(7) can be re-written as linear combinations of vectors rotating in counter-clockwise direction, with angular frequency ω, or in clockwise direction, with angular frequency $-\omega$. The counter-clockwise direction is usually referred to as "positive", whereas the clockwise direction as "negative". Hence, to distinguish between these two directions, the letters "p" and "n" will be used hereafter.

The stator voltage becomes

$$\bar{v}_S = \bar{v}_S^{(p)} + \bar{v}_S^{(n)}. \qquad (9)$$

Since the only non-zero stator current vector is $\bar{i}_S^{(p)}$, the rotor flux vector $\overline{\varphi}_R$ can be can be calculated by substituting (8) in (7). Since the rotor flux depends only on the stator current vector, it turns out that it is not affected by an unbalance in the stator resistances as long as the control system is able to track perfectly the reference currents. As a consequence, the rotor flux does not present any negative-sequence component.

$$\overline{\varphi}_R = \overline{\varphi}_R^{(p)} = \frac{M\bar{i}_{S,ref}^{(p)}}{1 + j(\omega - \omega_m)\tau_R}. \qquad (10)$$

Similarly, the stator flux can be found by substituting (10) in (6).

$$\overline{\varphi}_S = \overline{\varphi}_S^{(p)} = \left[\sigma L_S + \frac{M^2/L_R}{1 + j(\omega - \omega_m)\tau_R}\right]\bar{i}_{S,ref}^{(p)}. \qquad (11)$$

Once it is clear that the stator flux has no negative component, it is straightforward to decouple the positive and negative components $\bar{v}_S^{(p)}$ and $\bar{v}_S^{(n)}$ in (9) and to find their explicit expressions:

$$\bar{v}_S^{(p)} = R_S \bar{i}_S^{(p)} + j\omega\overline{\varphi}_S^{(p)} \qquad (12)$$

$$\overline{v}_S^{(n)} = \frac{1}{3}\left(\sum_{k=1}^{3} \Delta R_k \overline{\alpha}_k^* \right) \overline{i}_{S,ref}^{(p)*} . \tag{13}$$

By analyzing (12) and (13), one comes to the conclusion that the effect of the stator unbalance can be cancelled if the control system feeds the motor by adding a negative-sequence component (13) that balances the terms in (4) due to the resistance asymmetry. This result is particularly interesting because it correlates the asymmetry of the stator resistances with the behavior of the control system, and can be used for the detection of stator unbalances.

IV. CONTROL SYSTEM WITH UNBALANCE DETECTION

The most common control scheme for three-phase induction motor drives is the rotor field-oriented control, which uses two PI regulators, implemented in a reference frame synchronized to the rotor flux vector, to track the current references.

It would be desirable that the machine operation were not influenced by the stator unbalance due to high-resistance connections. At the same time, this kind of operating condition should be detected as soon as possible.

A control scheme for three phase induction motor drives with these capabilities is shown in Fig. 3. The currents i_{Sd}^{sync} and i_{Sq}^{sync} are controlled by the PI regulators (a) and (b) implemented in the rotor-flux oriented d-q reference frame, identified by the superscript "sync". The behavior of the current control is improved by the compensation of the stator back electromotive forces. The angle θ is the phase angle of the rotor flux vector in the stationary reference frame and it can be determined by a suitable observer. For sake of completeness, the current-speed observer is recalled in Section IV-(D). The reference value of i_{Sd}^{sync} in Fig. 3 is equal to the rated magnetizing current of the machine, whereas the reference value of i_{Sq}^{sync} is calculated by the PI regulator (c) on the basis of the speed error.

A. Fault Tolerance

When the motor resistances are balanced, the negative component $\overline{i}_S^{(n)}$ is theoretically zero. However, when a resistance unbalance arises, the current vector contains not only a positive but also a negative component. Simple PI regulators implemented in the stationary reference frame are insufficient to ensure zero error at steady-state, and the same is true for regulators implemented in the synchronous reference frame with the rotor flux.

The solution adopted to control these current components in the scheme of Fig. 3 is to implement another pair of PI regulators (d) in a reference frame rotating in the opposite direction of the field-oriented reference frame. This reference frame is synchronous with the negative components of the stator currents at steady-state, and is identified by the superscript "neg". The current error, expressed in the reference frame that is synchronous to the rotor flux vector, has the following expression:

$$\Delta \overline{i}_S^{sync} = \left[\overline{i}_{S,ref}^{(p)} - \overline{i}_S \right] e^{-j\theta} . \tag{14}$$

Similarly, the expression of the current error in the negative-sequence reference frame is as follows:

$$\Delta \overline{i}_S^{neg} = \left[\overline{i}_{S,ref}^{(p)} - \overline{i}_S \right] e^{j\theta} . \tag{15}$$

By combining (14) and (15), it results that the calculation of the current error in the negative-sequence reference frame is very simple if the expression of the current error is already known in the positive-sequence reference frame:

$$\Delta \overline{i}_S^{neg} = \Delta \overline{i}_S^{sync} e^{2j\theta} . \tag{16}$$

Equation (16) has been used in Fig. 3 for the calculation of the current error in the negative-sequence reference frame, at the input of the PI regulator (d).

Finally, to understand the behavior of the control system, it

Fig. 3 - Block diagram of the proposed control scheme, with the capability to detect and compensate for the phase unbalance.

is sufficient to note that the regulators in the positive field-oriented reference frame drive the positive components of the current error to zero whereas the regulators in the negative reference frame cancel the negative components.

Since the reference output voltage vector is obtained by summing the outputs of all regulators, according to the superposition principle it can drive the total current tracking error to zero, thus keeping the stator currents perfectly sinusoidal even in case of resistance unbalance.

B. Unbalance Detection and Localization

As long as the regulators perform correctly, i.e., the negative sequence of the current is cancelled, the output signals of the negative-sequence PI regulators can be used to detect the resistance unbalance and identify the faulty phases.

The voltage in the negative-sequence reference frame,

$$\overline{v}_{S,ref}^{(n),neg} = \frac{1}{3}\left(\sum_{k=1}^{3} \Delta R_k \overline{\alpha}_k^*\right)\left(\overline{i}_{S,ref}^{sync}\right)^* \tag{17}$$

can be found by multiplying both sides of (13) by $e^{j\theta}$. The voltage $\overline{v}_{S,ref}^{(i),neg}$ contains information regarding the unbalance of the three phases. It is possible to calculate the resistance deviations ΔR_k by solving (3) and (17), which form a set of three linear and independent equations.

$$\Delta R_k = 2 \frac{\overline{v}_{S,ref}^{(n),neg}}{\left(\overline{i}_{S,ref}^{sync}\right)^*} \cdot \overline{\alpha}_k^* \quad (k=1,2,3) \tag{18}$$

It is worth noting that the quantities $\overline{i}_{S,ref}^{sync}$ and $\overline{v}_{S,ref}^{(n),neg}$ become constant in steady state operating conditions. According to (18), it is possible to detect the deviation of all the stator resistances, but it is not possible to determine the mean value R_S. In practical applications, this is actually an advantage. In fact, variations of the stator resistances are normally caused by changes in the winding temperatures. As long as the temperature distribution is uniform in the three stator phases, and the resulting variations of the resistances can be assumed to be symmetric, the developed algorithm does not detect appreciable deviations of the stator resistances and deems the machine behavior as healthy.

Equations (13) or (17) show that the voltage at the output of PI (d) does not depend only on the resistance unbalance, but also on the current reference. In the rated operating conditions, the voltage drop on the stator resistances is typically a few percents of the nominal voltage (independently of the machine size), and it exhibits less variability (in proportion of the nominal voltage) than the other variables alone. Consequently, although the stator resistances may be very small in high power machine, the resistance unbalance can be detected if the stator current is sufficiently high.

As regards the gains of PI (d), different tunings may affect the behavior of the estimation technique, but not the final value of the estimated unbalance resistances. In fact, the resistance variations are calculated from the steady-state output voltage (17) of the regulator, which is independent of the regulator static gain, since the PI controller always cancels the dc-component of the input error.

The parameters of the controller can affect the bandwidth of the negative-sequence current loop, and therefore they can change the settling time of the transient. However, this aspect does not seem particularly relevant, since the evolution of the resistances in the connections is hopefully slow-varying. The bandwidth of the current loop may be important for the rejection of the noise on the measurement of the stator currents. However, this analysis is rather complex, since it involves the values of the switching frequency, the quantization effect, the bandwidth of the current sensors, and it has been omitted in this paper.

C. Effect of the Unbalance on the Electric Drive

The algorithm proposed is based on the capability of the control system to cancel the negative sequence currents. However, this goal can be reached only if the dc-link voltage is sufficient to compensate the back electromotive force produced by the resistance unbalance.

This assumption is usually acceptable if the resistance variation is limited and a voltage margin is present. If the resistance variation is large, the dc-link voltage may not be sufficient, depending on the speed of the machine and the entity of the back electromotive forces. If this happens, the output voltage of the PI controllers saturates and the fault-tolerant control is not possible.

The magnitude of the negative component of the stator voltage can be calculated starting from (13).

$$\left|\overline{v}_S^{(n)}\right| = \sqrt{\frac{1}{6}\left(\sum_{k=1}^{3} \Delta R_k^2\right)}\left|\overline{i}_{S,ref}^{(p)}\right| \tag{19}$$

If the nominal stator resistance is R_{nom}, and the resistance of phase 1 increases by a small quantity r, then the stator resistances of the phases can be written as follows

$$R_1 = R_{nom} + r \tag{20}$$

$$R_2 = R_3 = R_{nom} \tag{21}$$

The average resistance is

$$R_{avr} = \frac{1}{3}\left(R_1 + R_2 + R_3\right) = R_{nom} + \frac{r}{3} \tag{22}$$

and the resistance variations become

$$\Delta R_1 = R_1 - R_{avr} = \frac{2}{3}r \tag{23}$$

$$\Delta R_2 = R_2 - R_{avr} = -\frac{1}{3}r \qquad (24)$$

$$\Delta R_3 = R_3 - R_{avr} = -\frac{1}{3}r \; . \qquad (25)$$

Substituting (23)-(25) in (19) leads to the following result

$$\left|\overline{v}_S^{(n)}\right| = \frac{|r|}{3}\left|\overline{i}_{S,ref}^{(p)}\right| . \qquad (26)$$

Equation (26) shows that the inverse voltage depends on the product between the resistance variation r and the magnitude of the stator current.

D. Flux Observer

The machine is controlled according to the principle of rotor field-oriented vector control, i.e., the control system is implemented in a reference frame that is aligned with the rotor flux vector. This vector can be estimated by integrating the rotor equation (current-speed flux observer). The equation of the flux estimator is as follows:

$$\frac{d\widetilde{\overline{\varphi}}_R}{dt} + \left(\frac{1}{\tau_R} - j\omega_m\right)\widetilde{\overline{\varphi}}_R = \frac{M}{\tau_R}\overline{i}_S \qquad (27)$$

where $\widetilde{\overline{\varphi}}_R$ is the estimated rotor flux vector, expressed in the stator reference frame, τ_r and M are, respectively, the rotor time constant and the mutual inductance between stator and rotor, and the motor speed is supposed to be measured by an encoder. Finally, the angle θ is the phase angle of the vector $\widetilde{\overline{\varphi}}_R$.

V. EXPERIMENTAL RESULTS

A complete drive system has been built and an experimental study has been carried out to verify the theoretical analysis. The experimental set-up consists of a 4 kW, 4-pole squirrel cage induction machine fed by a 3-phase IGBT inverter. The parameters of the electric drive are shown in Table I.

During the experimental tests, two external resistors have been added in series with the stator phases to reproduce an unbalance or a fault condition. The nominal value of the stator resistance at room temperature is 0.45 Ω. The resistances can be inserted or removed from the circuit by acting on suitable potentiometers. Therefore, the insertion of the resistances is not instantaneous and the estimated resistance variations exhibit a brief transient before reaching the steady-state condition, but the control system is fast enough to keep the stator currents unchanged. It is worth noting that the evolution of resistance in motor connections is usually quite slow and consequently the duration of the insertion transients should not be a problem.

TABLE I.		MOTOR PARAMETERS			
P_{rated}	=	4	kW	R_s	= 0.45Ω
$I_{s,rated}$	=	16	A_{rms}	R_r	= 0.44Ω
$V_{s,rated}$	=	110	$V_{phase,rms}$	L_s	= 56 mH
ω_s	=	$2\pi50$	rad/s	L_r	= 56 mH
T_{rated}	=	26	Nm	M	= 53 mH
n_{rated}	=	1480	rpm	p	= 2
J	=	0.03	Kg m^2	J_{tot}	= 0.22 Kg m^2

A. Steady-State and Transient Operation

Fig. 4 shows the behavior of the control system when the additional resistor of the first phase is increased from zero to 0.1 Ω. Initially the resistance deviation ΔR_1 and the voltages generated by the negative-sequence regulator are zero. As soon as the unbalance takes place, $v_d^{(n),neg}$ and $v_q^{(n),neg}$ change to avoid that the stator is affected by the phase asymmetry. As can be seen, the waveform of the stator current does not show any particular variation. At the same time, the estimation of the resistance deviation ΔR_1 change from 0 to about 0.08 Ω. This result is in good agreement with the theoretical analysis. In fact, the mean value of the phase resistances becomes (0.55+0.45+045)/3 $\cong$ 0.48 Ω. The theoretical value of ΔR_1 is 0.55-0.48 $\cong$ 0.07 Ω, whereas ΔR_2 and ΔR_3 are respectively 0.45-0.48 = -0.03 Ω.

The behavior of all the resistance deviations is shown in detail in Fig. 5. As can be noted, ΔR_1, ΔR_2 and ΔR_3 become equal to the expected values and their sum is always zero.

Fig. 6 shows the behavior of the machine when two phases are unbalanced. Initially, the resistance of phase 1 is increased by 0.1 Ω. Then, the resistance of phase 2 is increased by 0.18 Ω. At the end of the test the mean value of the phase resistances is (0.55 + 0.63 + 0.45)/3 $\cong$ 0.543 Ω and the expected values of ΔR_1, ΔR_2 and ΔR_3 are respectively nearly
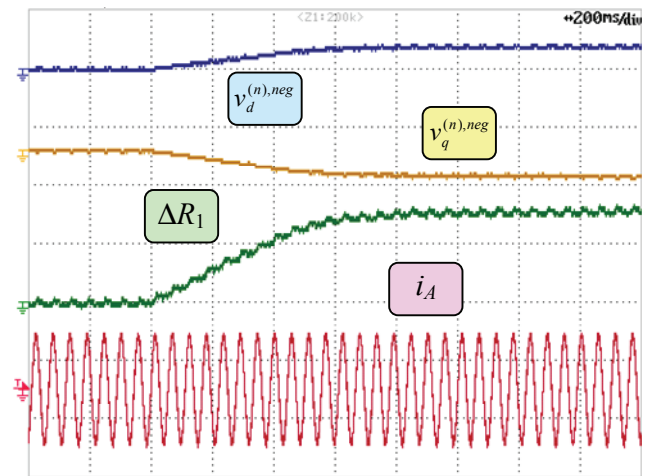

Fig. 4 - Behavior of the electric drive when the resistance of phase 1 is increased by 0.1 Ω. From top to bottom: waveforms of the voltage $v_d^{(n),neg}$ (40 mV/div), waveform of the voltage $v_q^{(n),neg}$ (40 mV/div), resistance deviation ΔR_1 (40 mΩ/div), phase current (10 A/div).
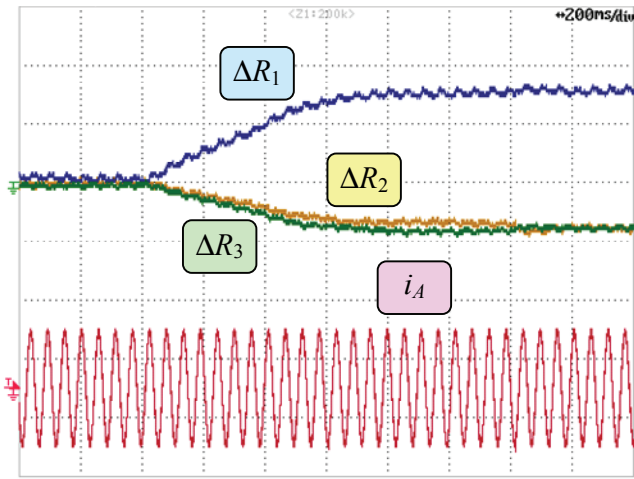
Fig. 5 - Behavior of the electric drive when the resistance of phase 1 is increased by 0.1 Ω. From top to bottom: waveforms of the resistance deviations ΔR_k (40 mΩ/div), phase current (10 A/div).
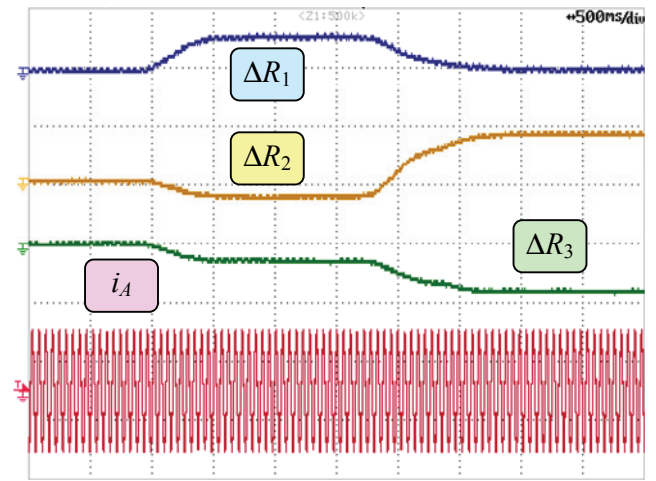

Fig. 6 - Behavior of the electric drive when the resistance of phase 1 is increased by 0.1 Ω, and then the resistance of phase 2 is increased by 0.18 Ω. From top to bottom: waveforms of the resistance deviations ΔR_k (0.1 Ω/div), phase current (10 A/div).

0.007 Ω, 0.087 Ω and -0.093 Ω, respectively, which are in good agreement with the experimental results.

Finally, Fig. 7 shows the behavior of the electric drive during a speed transient from 40% to 90% of the base speed after the resistance of the first phase has been increased by 0.1 Ω. The aim of the test is to verify the robustness of the estimation technique in case of transient operating conditions. As can be seen, the waveform of ΔR_1 is almost constant during the speed transient and is quite insensitive to torque and current variations.

B. Resolution of the Developed Method

Some tests have been carried out to determine the resolution of the developed method, i.e., the smallest change in the stator resistance that it can measure.

It was found that variations of about 5% of the stator resistance, which correspond to about 20 mΩ, are still detectable (owing to the difficulty to achieve adequate accuracy, it was not possible to test lower values than these).

Fig. 8 shows the estimated deviations of the phase resistances while the resistance of phase 2 is increased by 20 mΩ. As can be seen, the deviation of all resistances is zero at the beginning of the test. After the unbalance, the mean value of the resistances is theoretically 0.456 Ω, and the resistance deviations are ΔR_1=-6 mΩ, ΔR_2=13 mΩ, ΔR_3= -6mΩ. The results of Fig. 8 show that the measurement error is about 4 mΩ, which may depend on the inverter non-linear behavior (dead times, voltage drop of the switches) or on the contact resistance.
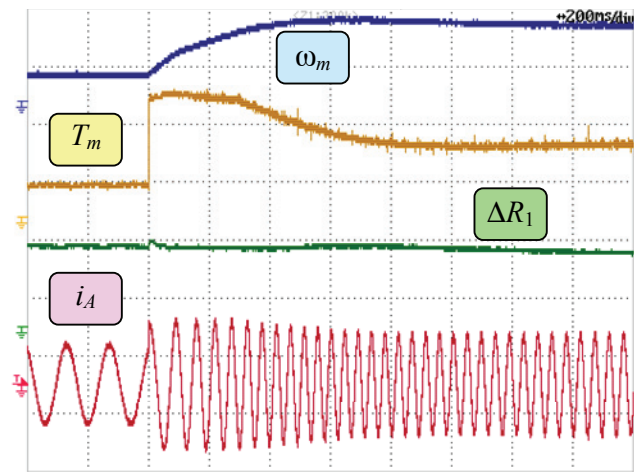

Fig. 7 - Behavior of the electric drive during a speed transient from 40% to 90% of the base speed, when the resistance of phase 1 is increased by 0.1 Ω. From top to bottom: waveforms of the rotor speed (500 rpm/div), motor torque (10 Nm/div), resistance deviation ΔR_1 (40 mΩ/div), phase current (10 A/div).
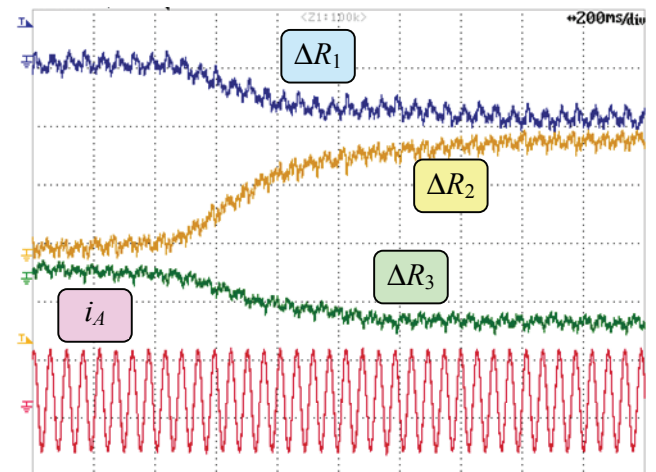

Fig. 8 - Behavior of the electric drive when the resistance of phase 2 is increased by 20 mΩ. From top to bottom: waveforms of the resistance deviations ΔR_k (10 mΩ/div), phase current (10 A/div).

VI. Conclusions

An improvement in the traditional field-oriented control scheme for induction machine is proposed in this paper. The basic idea is to include additional PI controllers in the control scheme to cancel the negative-sequence component of the stator current vector caused by inherent asymmetries or faults in the cable and stator winding. The purpose is to prevent the degradation in the performance, efficiency, and reliability of the induction motor drive system due to the asymmetry between the three phases. By means of a suitable mathematical model, the voltage component that is necessary to obtain this result has been related to the resistive unbalance of the stator phases due to high resistance contacts. This method can be used to detect high-resistance connections in industrial applications, or in civil applications, such as home appliances. Its main advantages are:

i. Scarce dependence on temperature variations that may affect the phase resistances during the normal operation of the machine, since they do not cause notable stator asymmetries;

ii. Capability of detecting the unbalance of all phases simultaneously.

Experimental tests have been performed to verify the effectiveness of the proposed technique, both in steady-state and transient operating conditions. It was shown that the proposed method is capable of detecting resistance deviations as low as 5% of the stator resistance.

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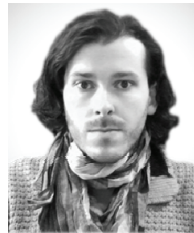
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