

A Novel Method for the Rotor Fault Detection in Small Inverter-Fed Induction Motors

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Abstract - It is known that when a rotor fault occurs, an induction machine draws an alternative power at twice the rotor frequency. In previous work the authors have shown how to employ this phenomenon in order to detect rotor faults in small inverter fed induction machines. In particular, a rotor fault index has been presented and tested supposing that the AC drive main supply is single phase. Starting from this approach, in the present paper two new rotor fault indexes suitable for three-phase input AC drives will be proposed. Furthermore, their capability to detect early rotor faults in different conditions has been evaluated through an extensive experimental activity. Some results will be presented.

I. Introduction

In a previous paper [1] the authors have shown that it is possible to combine diagnostic and monitoring operations on AC motor drives without installing dedicated sensors. In particular, in [2], [3], [4] and [5] the authors have demonstrated that it is possible to analyze the induction motor status from the analysis of the AC drive current draw. A new time domain algorithm for the rotor fault detection has been presented in [6] and [7]. Furthermore, the rotor fault condition has been summarized by means of a fault index; its capability to detect the fault severity has been shown, analyzed and finally discussed. Finally, it is important to highlight that the performed tests have confirmed the portability of the proposed index when different AC drives and control strategies are employed. Until now, only single-phase input AC drives have been considered. The aim of this paper is to extend this fault detection approach even to three-phase input AC drive systems.

II. Theoretical Considerations

Let's consider an n -phase linear and balanced load. Assuming steady state conditions, it is known that if a positive sequence voltage is applied, then a positive sequence current at the same frequency will flow through the phases. Otherwise, if the load is linear but unbalanced, when a positive sequence voltage is applied, the phase currents contains either positive, negative and zero sequence components. These simple considerations could be used to study the steady-state behavior of a faulted rotor induction machine. A positive sequence voltage at the angular frequency ω is supposed to be applied to the stator winding. Conventionally, an angular speed is considered positive if its direction is in agreement with that of the rotating magnetic field generated by a positive sequence stator current.

The electrical rotation speed ω_m is assumed to be almost constant. In many cases this is true with good accuracy thanks to the low-pass effect of the mechanical load. In addition, saturation and skin effect are neglected: thus, with reference to the classical Park d - q model of the induction machine, if the machine is balanced, all the electrical parameters are constant.

It is clear that in no fault condition, both the stator and the rotor windings are balanced, and the machine draws a positive sequence current at the line frequency ω . Thus, the instantaneous electrical power is constant.

When a rotor fault is taken into account, the rotor winding becomes an n -phase unbalanced load. If a rotor reference frame is considered, the d -axis and q -axis rotor parameters are constant but different. The space vector and the zero sequence rotor equations are mutually coupled. Using the relationship between the space vector and the symmetrical components, even the positive, the negative and the zero sequence rotor equations are coupled.

As usual, a positive sequence voltage applied to the stator windings generates a magnetic field which rotates in positive sense at the electrical angular speed $\omega - \omega_m$ with reference to the rotor frame. Because of the air gap field, a positive sequence *e.m.f.* at the frequency $\omega - \omega_m$ is induced in the rotor. In turn, the *e.m.f.* generates a positive, a negative and eventually a zero sequence rotor current at the same frequency $\omega - \omega_m$. The positive sequence rotor current is responsible of a positive sequence stator current at the supply frequency. The negative sequence rotor current generates a positive sequence stator current at the frequency $2\omega_m - \omega$. A component at twice the rotor frequency appears in the electrical power spectrum. The torque oscillates at the same frequency $2(\omega - \omega_m)$; however, in most cases the torque oscillation is damped by the mechanical load so that the rotor speed is almost constant. Considering an induction motor connected to a voltage source inverter, the low frequency power oscillation generates an alternative component (at twice the rotor frequency) in the DC-link voltage and in the rectified current. Both when the input stage is a single [7] or three phase rectifier, the oscillating effects can be easily detected by the analysis of the line current(s).

III. The Fault Detection Algorithms

It is clear that the average value I_{avg} of the rectified current is nearly proportional to the machine average power consumption. When a rotor fault occurs, a component at twice the rotor frequency appears in the rectified current; its peak to peak amplitude I_{fpp} is (almost) proportional to that of the alternative power draw generated by the fault. In turn, the strength of this power oscillation is strictly related to the rotor asymmetry and to the motor mechanical load. So, the amplitude of this low frequency rectified current component is a consistent indicator of the fault severity. It is important to stress that the rectified current can be easily computed from the line current(s) measurement. Starting from these considerations, an index useful to summarize the rotor fault severity of small inverter fed induction motors has been defined:

$$Index_1 = \frac{I_{fpp}}{I_{avg}} \quad (1)$$

Dividing I_{fpp} by I_{avg} allows to reduce the index sensitivity to the motor mechanical load.

First of all, the index computation requires the measurement of the AC mains current(s) for a sufficiently long observation period T_o (several cycles at twice the rotor frequency) with an adequate sampling rate. Then, the rectified current signal i_r and its average value I_{avg} have to be evaluated. The angular frequency $2(\omega - \omega_m)$ is very low with respect to that of the other rectified current components. Thus, the spectral component due to the rotor fault can be easily extracted employing a properly tuned low pass filter. The filter cutoff frequency must be significantly greater than twice the rotor frequency in every motor working condition. The maximum rotor frequency can be calculated considering the maximum inverter output frequency and the maximum mechanical load. Finally, the value I_{fpp} have to be assessed.

The observation time window T_o must be divided into N (for example 10) time slots. Each time slot must be longer than a period at $2(\omega - \omega_m)$ angular frequency. The minimum rotor frequency in every motor working condition (thus considering the minimum load and inverter output frequency) must be evaluated in order to choose the minimum time slot length. Then, the peak to peak values of the filtered rectified current in each time slot (I_{fppj} with j integer between 1 and N) can be extracted, and I_{fpp} is the arithmetic mean of these values. This averaging process allows a good rejection of the effects due to the disturbances.

Another rotor fault index can be proposed as the extension of that presented in [7] when three phase input AC drives are considered. As known, the rectified current is a sequence of peaks, and it can be shown that their amplitude is strictly related to the instantaneous machine power draw. In particular, the average peaks amplitude is related to the average power draw. When a rotor fault occurs, the low frequency power component modulates the height of the peaks. The amplitude of this modulation is

related to the fault level and to the mechanical load.

Starting from these considerations, a second rotor fault index can be proposed:

$$Index_2 = \frac{I_{pp}}{I_{pavg}} \quad (2)$$

$$I_{pp} = I_{pmax} - I_{pmin} \quad (3)$$

where I_{pmax} , I_{pmin} and I_{pavg} are the maximum, the minimum and the average amplitude of the current peaks respectively. The index computation requires the line current acquisition with a proper sampling rate. Obviously, the observation time T_o must be several times longer than the rotor frequency period. Then, the rectified current peaks values have to be extracted. In order to reject the effect of the 3-phase AC mains asymmetry, the current peak values are collected in blocks of six (there are six peaks in an AC supply period) and the signal $i_{pm}(k)$ contains the average values of each block. This operation can be easily performed by using the line voltage signal as a trigger. I_{pavg} is evaluated as the $i_{pm}(k)$ mean value. As before, the observation period T_o has to be divided into N time slots, longer than a period at twice the rotor frequency. The difference between the maximum and minimum values of $i_{pm}(k)$ in each time slot has to be computed; let's call these values I_{ppj} where j is an integer between 0 and N . Finally, I_{pp} is the average of these values.

IV. Experimental set-up

In order to test and to compare the performances of the proposed indexes an experimental set-up has been employed as shown in Fig. 1. The most of the induction machines are squirrel cage type, thus the most common rotor fault is the bar breakage. It is possible to simulate this fault employing a wound rotor, slip ring induction machine (2 poles, 750 W rated power, 5.2% nominal slip) with a resistance R_{fault} connected in series to a rotor phase. The mechanical load is provided by a DC generator. The main features of the employed AC drive are summarized in TABLE 1; constant V/f control mode has been selected.

The line currents has been acquired using three closed-loop Hall effect transducers, while the line voltage signal (which provides the trigger for the current peak detection) has been measured employing a voltage divider and an isolation amplifier [8].

The signals have been acquired with a National Instruments PCI 6143 data acquisition board (DAQ) and elaborated by means of a Virtual Instrument developed in LabView environment.

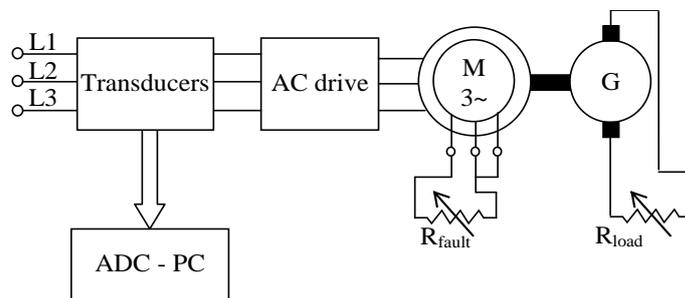


Fig. 1– Experimental set-up employed to compare the proposed indexes

TABLE 1 - Inverter specifications

Type	ACS350-03E-05A6-4
Input type	3-phase
Input voltage	380-480V
Rated input current	9.6 A
Output type	3-phase
Rated output current (4 kHz switching frequency)	5.6 A
Control mode	scalar, vector torque, vector speed
Switching frequency (scalar control)	4, 8, 12 or 16 kHz
Output frequency	0-500 Hz (scalar control) 0-150 Hz recommended (vector control)

V. Experimental results

In [7] the authors have shown how the index based on the current peaks amplitude can follow the rotor fault evolution considering single phase input AC drives. In the present paper, the indexes described in paragraph III are analysed and compared in order to evaluate their sensitivity and repeatability in rotor fault detection; in particular, low fault levels (thus low series resistance) are considered. The capability to detect incipient rotor faults is mandatory when an advanced maintenance strategy is employed.

The aforementioned indexes have been evaluated in different working conditions. In particular, 35 Hz, 40 Hz, 45 Hz, 50 Hz inverter output frequencies and 0 Ω (no fault), 1 Ω , 2 Ω , 3 Ω series resistance values have been considered. Notice that the rotor resistance of the employed machine is 4.7 Ω . Furthermore, the same tests have been repeated with different mechanical loading (30%, 40%, 60% and 100% of the nominal torque). For each test condition 16 acquisitions have been performed in order to evaluate the repeatability. Assuming these test conditions, the minimum rotor frequency is about 0.6 Hz, while the maximum rotor frequency is approximately 2.6 Hz (see section III). According to these values, a one second long time slot is adequate for the I_{fppj} and I_{ppi} computation. In addition, a 10 s observation time has been chosen. A Butterworth 5th order low pass filter with 10 Hz cutoff frequency has been employed for the extraction of the rectified current component at $2(\omega - \omega_m)$ angular frequency.

It is important to stress that the two indexes shown a low sensitivity to the inverter output frequency. In addition, when the load torque is greater than 20-30% of the rated value, both indexes shown only a slight dependence on the mechanical load. Thus, for sake of clearness only few meaningful experimental results are reported. In particular, Fig. 2 and TABLE 2 show the measured fault indexes values versus R_{fault} for 50 Hz inverter output frequency and 40% of the rated mechanical load.

TABLE 2 – Fault indexes average values and three times their sample standard deviation evaluated for different rotor fault levels.

R_{fault} [Ω]	$Index_1$		$Index_2$	
	Avg	3 \cdot s	Avg	3 \cdot s
0	0,0202	0,0091	0,039	0,023
1	0,0718	0,0020	0,072	0,013
2	0,1475	0,0035	0,120	0,012
3	0,2350	0,0042	0,177	0,016

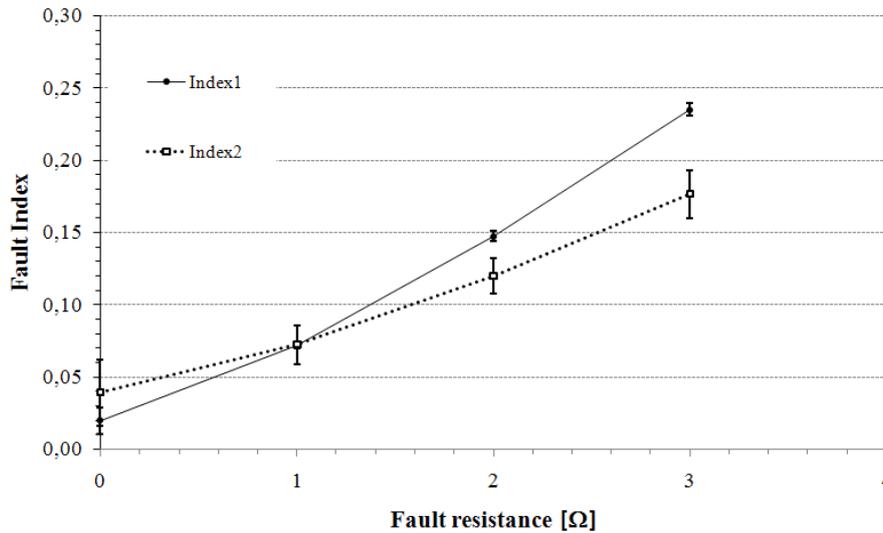


Fig. 2 – Indexes average values vs R_{fault} ; motor fed with a 50 Hz positive sequence voltage, 40% of the rated mechanical load. The vertical bars reports three times the sample standard deviation

The experimental results confirm the strong correlation between the fault level and the values of the two indexes. As discussed before, the amplitude of the $2(\omega - \omega_m)$ rectified current component is almost proportional to the amplitude of the machine power draw oscillation due to the rotor fault (see section III). It can be shown that the amplitude of the rectified current peak modulation is less than proportional to the magnitude of the machine power draw ripple. This explains why the first proposed index features an higher sensitivity. It can be noticed that the first index shows also a much better repeatability, because of the employment of a low-pass filter with a very low cut-off frequency which assures a very good disturbance rejection. As a matter of fact, the first index permits to clearly distinguish the different rotor fault levels. In addition, the evaluation of the first proposed index is simpler and does not require a triggering system.

VI. Conclusions

Two different rotor fault indexes have been defined and their performances has been evaluated by means of a proper experimental set-up. In particular, their capability to detect the fault severity has been tested in term of sensitivity and repeatability. A comparative analysis has been performer in order to choose the index that allows a better detection of incipient rotor faults. The experimental results show that the first proposed index features an higher sensitivity and repeatability. Furthermore, its computation very simple. It is important to highlight that the behavior of the first index at low fault levels makes it suitable for a cost-effective implementation of advanced maintenance strategies. This permits to improve the system dependability.

The authors will investigate the feasibility to detect incipient rotor faults from the analysis of a single line current in order to simplify further the index computation. Other types of fault will be considered (in particular stator inter-turn short circuit) and new *ad-hoc* fault indexes will be proposed.

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