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Reliable stator fault detection based on the induction motor negative sequence current compensation

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ABSTRACT

The objective of this work is the compensation of the negative sequence current of the faulty induction motor in the aim to increase the accuracy and the sensitivity of the incipient stator fault detection under different disturbances. This is because, the negative sequence current generated in a faulty machine is the superposition of the different negative sequences current generated by the fault and others disturbances, which are the inherent asymmetry in the machine, the unbalanced supply voltage and the sensor inaccuracy. Thus, this paper proposes an efficient experimental method that allows the compensation of the negative sequence current of the faulty machine, by subtracting the negative sequence current of the different disturbances from the total negative sequence current of the faulty machine to isolate the negative sequence current due to the fault. Thus, the negative sequence currents of the different disturbances are isolated using an original experimental technique. The efficiency of the proposed method is validated experimentally on a 1.1 kW motor under inter-turns short circuit faults and phase to phase faults.

1. Introduction

The induction motor (IM) is the fundamental machine in various industrial processes and plants. Therefore, early and accurate incipient faults detection into this machine is crucial to avoid unexpected and catastrophic failures and ensure the continuity and the safety of the machine [1,2].

As it has been reported in [3–6], the most relevant electrical faults occurring into IM are stator winding faults. Inter-turns short circuit (ITSC) fault has specifically attracted much significant attention. This is due to the fact that the worst stator faults, as phase to phase fault and phase to ground fault start generally by an ITSC fault caused by an undetectable insulation failure between adjacent turns [7–10]. Consequently, various methods are developed to detect this type of fault over the past decade or so. The most prominent methods are those using techniques based on the monitoring of one or more variables of the machine and the use of advanced signal processing. Review of these techniques is reported in detail in [11–38], where an ITSC can be detected via: vibration analysis [11,12], thermal monitoring [13], time-frequency domain [14–16], parameter estimations [17], phase shift monitoring [18], axial flux analysis [19,20], stator current Park's vector approach analysis [21], instantaneous active and reactive power analysis [22], magnetic pendulous oscillation technique [23], motor current signature analysis (MCSA) [24,25] and symmetrical components analysis [26–38]. Among these methods, the negative sequence current based method seems to be the most promising, since it is simple, fast, non-invasive and highly sensitive to any asymmetry in the machine [31]. But, despite its efficiency, the negative sequence current (NSC) based method presents a limit. This limit is resumed in the fact that the NSC generated in the faulty machine does not represent only the asymmetry introduced by the fault, but also by others superposed asymmetries, such as the voltage unbalance, the inherent asymmetry in the machine and the sensors inaccuracy. Therefore, this aspect makes very difficult the achievement of accurate incipient faults detection and explains the limited number of developed methods to compensate the NSC of the faulty machine. In fact, in [32,33] the authors are focused on the compensation of the voltage unbalance effect, where an effective model and a lookup table for the negative sequence impedance Z_2 as well as the voltage are used in [32] and [33] respectively. In [34–36], the authors are interested on the compensation of the voltage unbalance and the machine inherent asymmetry effects. However, an effective phase and an artificial neural network are used in [34,35] and [36] respectively. In [38], the effects of voltage unbalance, load conditions and machine inherent asymmetry are

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Nomenclature

$\bar{a}$	complex operator	N	total turns number of a stator winding
F_{1a}, F_{1b}, and F_{1c}	inter-turns fault in phase a, b and c	N_a, N_b, and N_c	shorted turns number on phase a, b and c
F_{2bc}	short circuit fault between b and c	R_1	stator resistance
$\bar{I}_a$, $\bar{I}_b$ and $\bar{I}_c$	three line currents of the induction motor	R'_2	rotor resistance
$\bar{I}_1$, $\bar{I}_2$ and $\bar{I}_0$	positive, negative and zero sequence current	S_1, S_2 and S_3	sensor$_1$, sensor$_2$ and sensor$_3$
$\bar{I}_{2asy}$	negative sequence current generated by the inherent asymmetry in the machine	s	slip of the machine
$\bar{I}_{2f}$	negative sequence current generated by the fault.	$U_{V\text{-b}}$	unbalanced voltage on phase b
$\bar{I}_{2f\_calc}$	negative sequence current generated by the fault calculated theoretically	$U_{V\text{-bc}}$	unbalanced voltage on phase b and c
$\bar{I}_{2s}$	negative sequence current generated by the sensors inaccuracy	$\bar{V}_1$, $\bar{V}_2$ and $\bar{V}_0$	positive, negative and zero sequence voltages
$\bar{I}_{2t}$	total negative sequence current of the motor	$\bar{V}_{2s}$	negative sequence voltage generated by the sensor inaccuracy
$\bar{I}_{1v}$	positive sequence current generated by the voltage unbalance	$\bar{V}_{2v}$	negative sequence voltage generated by the unbalanced voltage
$\bar{I}_{2v}$	negative sequence current generated by the voltage unbalance	$\bar{V}_{2v\text{-}inv}$	negative sequence voltage generated by the unbalanced voltage of the inverter
$\bar{I}_{2v\text{-}inv}$	negative sequence current generated by the unbalanced voltage of the inverter	$x_a = N_a/N$	relative fault quantity on phase a
k and α	gain and phase shift errors of the sensor	$x_b = N_b/N$	relative fault quantity on phase b
		$x_c = N_c/N$	relative fault quantity on phase c
		X_m	magnetizing reactance
		X_1	stator leakage reactance
		X'_2	rotor leakage reactance

compensated based on the estimation of the negative sequence impedance of the healthy motor using empirical formulas. Therefore, there is no until now, available method that allows the determination of the correct NSC representing the fault under different disturbances.

Thereby, this paper proposes an efficient method able to compensate the effect of the different considered disturbances through experimental technique having the originality to isolate the NSC of each disturbance. Hence, experimental tests are performed on two steps. In the first step, tests are achieved on the healthy machine supplied by a balanced voltage where a new experimental technique is employed to determine separately the NSC of the inherent asymmetry in the machine and the NSC due to the sensors inaccuracy. In the second step, tests are carried out on a faulty machine supplied by unbalanced voltage to determine the total NSC of the faulty machine and the NSC due to the unbalanced voltage. The NSC due to the voltage unbalance is extracted using an adequate model. Once the different NSCs of each disturbance are isolated, the NSC representing the fault is extracted by subtracting the NSC of each disturbance, from the total NSC of the faulty IM. This compensated component is the one which must be monitored to ensure accurate incipient stator faults detection. In this way, the proposed method can intensively contribute to enhance the accuracy and the sensitivity of the NSC-based method towards incipient stator faults.

The effectiveness of the proposed method is validated experimentally on a 1.1 kW IM under different cases of inter-turns short circuit and phase to phase faults with different cases of unbalanced voltage.

2. Principal of the proposed method

As it is well kwon, the symmetrical component methodology is very used to analyse the unbalanced three systems. Based on this method, any unbalanced three-phase system can be decomposed on three balanced systems: positive, negative and zero ones. For a three-phase current system, the expressions of the NSC and the positive sequence current (PSC) are given respectively by (1) and (2).

$$\bar{I}_1 = \frac{1}{3}(\bar{I}_a + \bar{a}\cdot\bar{I}_b + \bar{a}^2\cdot\bar{I}_c) \quad (1)$$

$$\bar{I}_2 = \frac{1}{3}(\bar{I}_a + \bar{a}^2\cdot\bar{I}_b + \bar{a}\cdot\bar{I}_c) \quad (2)$$

With $\bar{a} = e^{j2\pi/3}$ and $\bar{a}^2 = e^{j4\pi/3}$.

In previous recent published works [29,30], we have demonstrated that the tracking change of the magnitude and the phase angle of the NSC is an efficient method to detect stator faults. In fact, it has been proved that the magnitude of the NSC informs about the importance of the stator faults and its phase angle indicates the location of the fault. But unfortunately, the value of the NSC generated in a faulty IM does not represent only the effect of the fault but also of others superposed asymmetries.

In fact, the IM can be affected by several types of internal or external disturbances. The internal disturbances are the inherent asymmetry in the machine and the asymmetry introduced by the fault. The external disturbances are the voltage unbalance and the sensor inaccuracy. Each of these disturbances generates its own NSC and the total NSC $\bar{I}_{2t}$ generated in a faulty IM is the result of the superposition of these different negative sequence currents.

As it is shown in Fig. 1, the total NSC $\bar{I}_{2t}$ of a faulty IM can be expressed as a vector sum of four separate NSC due to the fault $\bar{I}_{2f}$ the voltage unbalance $\bar{I}_{2v}$ the inherent machine asymmetry $\bar{I}_{2asy}$ and the sensor inaccuracy $\bar{I}_{2s}$ as it is expressed by (3).

$$\bar{I}_{2t} = \bar{I}_{2f} + \bar{I}_{2v} + \bar{I}_{2asy} + \bar{I}_{2s} \quad (3)$$

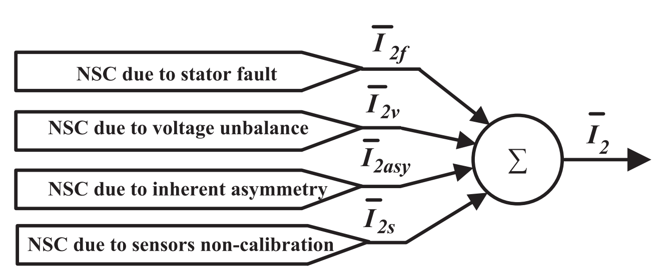

Fig. 1. Composition of the total NSC generated in an IM.