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Research Article

Comparative investigation of diagnosis media for induction machine mechanical unbalance fault

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A B S T R A C T

For an induction machine, we suggest a theoretical development of the mechanical unbalance effect on the analytical expressions of radial vibration and stator current. Related spectra are described and characteristic defect frequencies are determined. Moreover, the stray flux expressions are developed for both axial and radial sensor coil positions and a substitute diagnosis technique is proposed. In addition, the load torque effect on the detection efficiency of these diagnosis media is discussed and a comparative investigation is performed. The decisive factor of comparison is the fault sensitivity. Experimental results show that spectral analysis of the axial stray flux can be an alternative solution to cover effectiveness limitation of the traditional stator current technique and to substitute the classical vibration practice.

1. Introduction

In large variety of industrial processes, online monitoring of electrical machinery is a challenging task for early detection of possible failures occurrence. Nowadays, to avoid unexpected faults which can cause high cost damages, intensive attention is given to predictive maintenance and to the development of new diagnosis media.

Process efficiencies can be affected by diverse fault sources. Besides electrical troubles like winding faults [1], voltage unbalance [2], and broken rotor bars [3], induction machines are threatened with several mechanical faults. Serious problems include bearing defects [4,6], eccentricities [5], shaft misalignment [6], gearbox [7], and mechanical unbalances [8].

Particularly for dusty industrial environment, careful check of the induction machine fans is often required to avoid mechanical unbalance conditions due to a probable matter deposit. Yet, without the employing of an online diagnosis technique, such operation cannot be carried out while the driven process is in action.

Traditionally, mechanical unbalances are monitored by spectral analysis of vibration data [9]. Unfortunately, this practice is costly and cannot always be achieved. More recently, many research works were focused on the exploitation of the stator current data for the implementation of alternative online diagnosis media.

In the presence of a mechanical unbalance fault, an additional undesirable torque will be superposed to the load one, and rotor currents will be affected. Consequently, by reaction principle, stator current will undergo an amplitude modulation at the rotational speed. Hence, spectrum related to the motor current signature analysis (MCSA) will be characterized by the apparition of two sidebands around the main supply frequency. Unluckily, in the presence of other mechanical defects related to the load condition and coupled to the rotational speed (rotor position varying torque, eccentricity, etc.), the same spectral effect is observed. Characteristic sidebands are overlapped and the distinction of the failure source becomes, practically, impossible.

This major drawback of MCSA, for the distinction of motor faults from other similar mechanical load abnormalities, was extremely discussed in the scientific community and several alternative schemes were proposed.

Because torque oscillations have the particularity to involve phase modulation of the stator current, time–frequency approach based on Wigner distribution allows discerning these related load faults from rotor abnormalities [10,11]. Moreover, examination of the simultaneous behavior of the three stator line currents, while the machine operates under faulty conditions, can be useful for distinguishing the defect cause. In fact, through Park vector approach, it

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has been shown that the phase displacement between active and reactive components is a fundamental parameter to discern rotor faults from external torque ripple [12]. In addition, the stator current space vector can be decomposed into positive and negative sequence information and, while rotor asymmetries generate negative sequence harmonics, load oscillations have the particularity to produce only the positive ones. Hence, by consideration of the interaction between these sequences, a rotor fault indicator can be obtained [13].

On the other hand, power media has proven their efficiency for fault source distinction. Indeed, using spectral analysis of instantaneous active and reactive power components and their derived signals (power factor and its phase angle), it is possible to distinguish between the presence of broken rotor bar, air-gap eccentricity and load torque oscillation [14,15]. In addition, by considering the modulus of the active and reactive Park′s vectors obtained from the instantaneous powers, broken bars and load oscillations can be discerned [16].

Numerous other diagnosis techniques based on the machine′s model were, also, suggested. In Ref. [17], the Vienna monitoring method (VMM) has shown its effectiveness for the discrimination of rotor faults and low frequency load torque modulation.

In this paper, we are going to suggest a theoretical development of the mechanical unbalance effects on the radial vibration, the stator current, and the stray flux expressions. Experimental related spectra will be analyzed and characteristic defect frequencies will be determined. By magnitude comparison of these frequency components with respect to their initial values (related to the healthy condition), fault sensitivity will be calculated for several load levels and diagnosis media efficiencies will be compared. Accordingly, a new online monitoring technique will be proposed.

2. Basic theories of mechanical unbalance diagnosis media

In the following, all machine parameters are referred to stator. "p" denotes the number of the induction machine pole pairs, "ω_r" represents the rotor angular speed, "ω_s" the supply voltage frequency, and "m" is the total machine mass. Mechanical unbalance is represented by a mass "μ" rigid at a distance "r" from the rotor axis center.

2.1. Vibration technique

A rotating machine can be modeled on a spring of stiffness "K" with a damping viscous csoefficient "F_v". The considered fault is supposed to begin at a time "$t=0$" (Fig. 1).

If we assume that the machine body has a single degree of freedom and constrained to move vertically, equation of the displacement "$y(t)$" which results from the mass unbalance gets

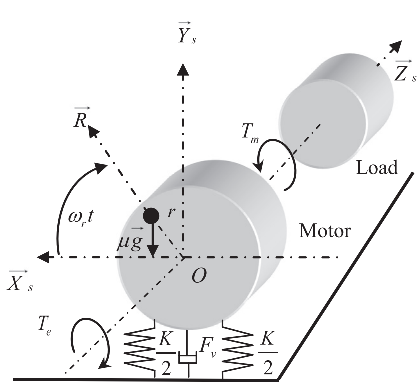

Fig. 1. The mechanical model of an unbalanced machine.

$$m\frac{d^2y(t)}{dt^2}+F_v\frac{dy(t)}{dt}+Ky(t)=\mu r\omega_r^2\sin(\omega_r t) \quad (1)$$

At steady state, solution of previous equation gives

$$y(t)=Y\sin(\omega_r t-\delta) \quad (2)$$

where

$$\begin{cases} Y=\frac{\mu r\omega_r^2}{\sqrt{(K-m\omega_r^2)^2+(F_v\omega_r)^2}} \\ \tan(\delta)=\frac{F_v\omega_r}{K-m\omega_r^2} \end{cases} \quad (3)$$

Eq. (3) shows that mechanical unbalance will involve a small radial vibration of the stator structure. This vibratory signal will oscillate at the rotational frequency and can be sensed by a suitable transducer (accelerometer) fixed on the machine body. In addition, the vibration level will take its maximum "Y_m" when rotational speed equals the system natural frequency defined by $\omega_0=\sqrt{K/m}$ (resonance phenomenon). This maximal magnitude will be given by

$$Y_m=\mu r\omega_0/F_v \quad (4)$$

It is important to report that, far from this natural frequency, vibration magnitude can be approximated by

$$Y_\infty=\mu r/m \quad (5)$$

In practice, for standard induction machines, the previous condition ($\omega_r \gg \omega_0$) is always factual. Eq. (5) proves that vibration level will be independent of the load torque level. Therefore monitoring of mechanical unbalance faults through vibration analysis is an efficient technique for all levels of the driven load.

2.2. MCSA technique

Assuming that the shape of the steady state torque–speed curve is approximately linear and disregarding the stator resistance and leakage reactance, for small variations of "ω_r" the usual equivalent circuit of an induction machine allows writing [18]

$$\begin{cases} \Delta T_e(t)=-C\Delta\omega_r(t) \\ C=\frac{3p^2V_s^2}{2\omega_s^2R_r^s} \end{cases} \quad (6)$$

where "R_r^s" denotes the rotor resistance referred to stator and ″V_s″ the supply voltage maximal amplitude.

Eq. (6) shows that any oscillation of rotational speed will induce an electromagnetic torque oscillation at the same frequency.

Taking into account previous relation, mechanical behavior can be described by

$$J\frac{d\Delta T_e}{dt}+(F+C)\Delta T_e(t)\approx C\mu gr\cos(\omega_r t) \quad (7)$$

with coefficient "J" the inertia of revolving system part, "F" its damping factor, and "g" the gravitational acceleration.

At steady state, solution of Eq. (7) is given by

$$\Delta T_e(t)=\frac{C\mu gr}{\sqrt{(F+C)^2+(J\omega_r)^2}}\cos\left[\omega_r t-\text{arc }tg\left(\frac{J\omega_r}{F+C}\right)\right] \quad (8)$$

Hence, mechanical unbalance will lead to electromagnetic torque oscillation at the rotational frequency.

On the other hand, electromagnetic torque can be viewed as the interaction result of the stator flux with the stator current:

$$T_e=\frac{3}{2}p\left(\det\left|\overrightarrow{\Phi_{sdq}}\,\vdots\,\overrightarrow{I_{sdq}}\right|\right) \quad (9)$$

when flux linkage is purely sinusoidal and unaffected, differentiation of (9) gives

$$\Delta T_e(t)=(3/2)p\left[\varphi_{ds}(t)\Delta i_{qs}(t)-\varphi_{qs}(t)\Delta i_{ds}(t)\right] \quad (10)$$