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The Origins of Shaft Currents in Squirrel-Cage Low-Voltage Induction Machines

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Original scientific paper

Possible origins of shaft currents in squirrel-cage low-voltage induction machines are analysed. The mechanism of generation of shaft currents fundamental frequency and slip frequency at 2-pole and 4-pole machines is explained, as well the influence of broken rotor bars or end rings on shaft currents.

Key words: AC machines, induction motors, diagnostics, measurements

1 INTRODUCTION

In a relatively early paper on origins of shaft currents in induction machines [1] it is stated that in induction machines with homogenous yokes fed from mains no significant shaft currents are generated. However, in [2] it is demonstrated that considerable shaft currents are present at motors with undamaged squirrel cages, and that broken rotor bars or end rings are reflected on shaft currents. Hence it is possible to detect cage damages by shaft current measurement. Therefore it was necessary to analyse once again the origins and mechanisms of shaft current generation.

2 ORIGINS OF SHAFT CURRENTS

A detailed analysis leads to the conclusion that at squirrel-cage low-voltage induction machines fed from mains [1, 2, 3] shaft currents can have three origins:

- eccentricity ($p = 1$) and oval shape of the stator or rotor ($p = 2$)
- other magnetic asymmetries (e.g. axial core ducts)
- broken rotor bars or end rings (rotor electrical asymmetry).

2.1 Eccentricity and oval shape of the stator or rotor

In [1] it is not noticed that the equations derived in that paper

$$\kappa = 2g\nu \quad \text{and} \quad \omega_0 = \omega_\kappa - 2g\omega_\nu \qquad (1)^*$$

$$g = \pm 1, \pm 2, \pm 3, \ldots$$

give the frequencies

$\omega_0 = \omega$ at static eccentricity,

$\omega_0 = s\omega$ at dynamic eccentricity

for the induction harmonics caused by permeance waves λ with numbers of pole pairs $\kappa = p \pm \lambda$ in the case of a 2-pole machine ($p = 1$, $\lambda = 1$, $\kappa = 2$) with the main induction harmonic ($\nu = p$ and $\omega_\nu = \omega$).

Similar frequencies are obtained at 4-pole machines ($p = 2$, $\lambda = 2$, $\kappa = 4$) in the case of an oval-shaped stator or rotor:

$\omega_0 = \omega$ at oval shape of the stator,

$\omega_0 = s\omega$ at oval shape of the rotor.

So, due to ever-present eccentricity and oval shape of the stator or the rotor shaft currents with fundamental frequency (f) and slip frequency (sf) are generated at 2-pole and 4-pole machines by complex mechanisms described in [1].

2.2 Other magnetic asymmetries

In [2] it is stated that considerable shaft current of fundamental frequency has been measured at 6-pole motor with undamaged squirrel cage.

According to [1] this current cannot occur at symmetric machine with homogenous yoke. The explanation is that it is caused by other asymmetries in the magnetic core (e.g. axial core ducts).

2.3 Broken rotor bars or end rings

Within the research of the effects of squirrel-cage damages, the shaft current was measured on motor 4AZ 250M-6. Measurements are described in [2].

* In (1) κ and ν are numbers of pole pairs of harmonics which together cause shaft current with frequency ω_0.

Data of tested motor are:

– rated power output	37	kW
– supply frequency	50	Hz
– rated line voltage	380	V
– rated current	72	A
– rated speed	978	1/min.

The waveforms and spectra of shaft currents in the cases of undamaged squirrel cage, two broken bars and a broken end ring are given in Figures 1, 2 and 3, resp. Laboratory tests are carried out at rated load.

An analysis of the phenomena in these figures shows that, in the case of broken bars or broken end rings, a current with frequencies

$$f_0 = (1 \pm 2s) f \qquad (2)$$

appears in the spectra, the same as in the stator current [4]. A multiple increase in the shaft current with slip frequency can be also seen.

That is caused by two different mechanisms of generation of slip frequency shaft current:

a) Damaged squirrel cage, e. g. a broken bar, can be replaced with symmetrical system of currents of undamaged cage and additional current of opposite sign in broken bar, so that resultant current in the broken bar is zero. Additional current causes bar voltage, which produces current through parallel impedance of part of the shaft in laminated core and impedance of the rest of shaft, bearings, end shields and stator frame.
b) Another component of shaft current of slip frequency is generated by complicate mechanism

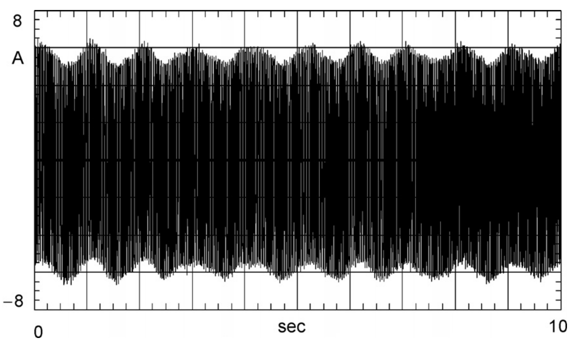

Fig. 1a Shaft current waveform – undamaged rotor cage

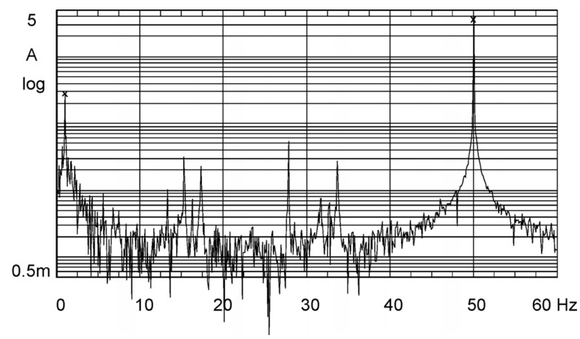

Fig. 1b Shaft current spectrum – undamaged rotor cage

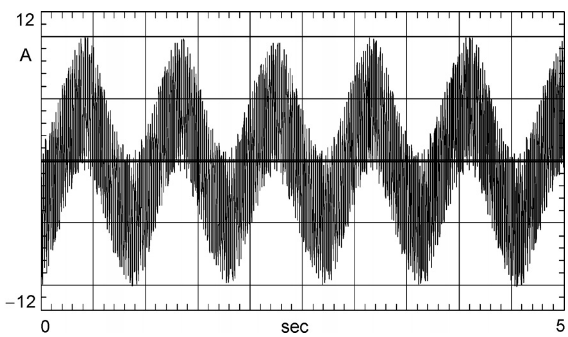

Fig. 2a Shaft current waveform – two broken bars

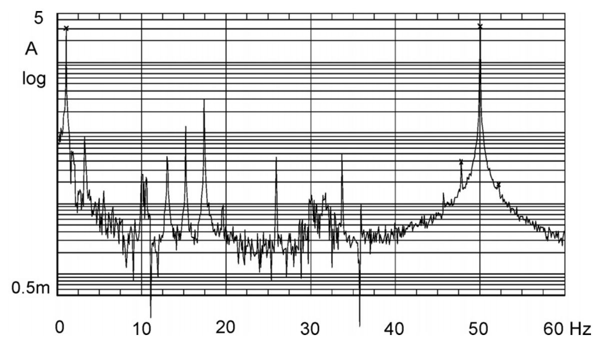

Fig. 2b Shaft current spectrum – two broken bars

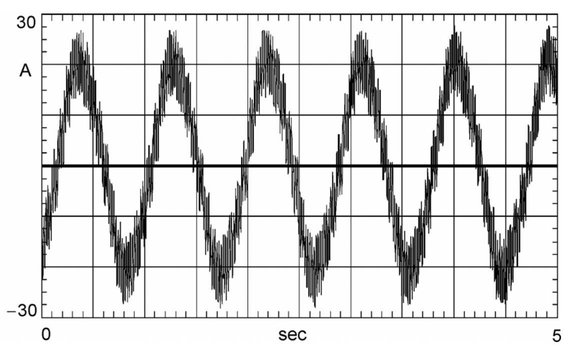

Fig. 3a Shaft current vaweform – broken end-ring segment

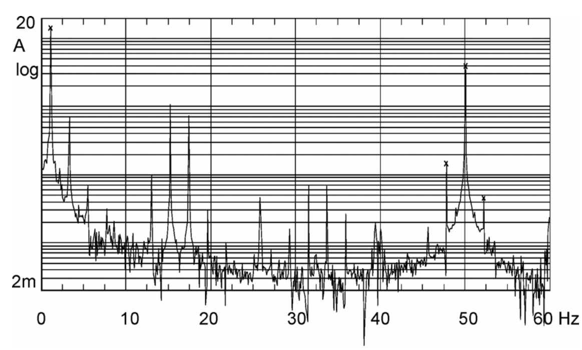

Fig. 3b Shaft current spectrum – broken end-ring segment

described in [1]. If one takes into consideration the case of broken bar, additional magnetomotive force is

$$\vartheta_{r\mu k} = \Theta_{\mu k} \sin\left(\mu x_r + \mu \frac{\pi}{Q_r}\right) \cos(ks\omega t + \varphi_k) \quad (3)$$

$\mu = 1, 2, 3, ...$

where are:

- $\Theta_{\mu k}$ – amplitude of magnetomotive force for harmonic of μ pole-pairs,
- μ – pole-pairs,
- x_r – rotor co-ordinate, measured from center of first loop with broken bar,
- Q_r – number of rotor slots,
- $k = 1$ for main harmonic ($\nu = p$),
- $k = 3$ for harmonic due to saturation ($\nu = 3p$),
- φ_k – phase angle of additional current due to main harmonic ($\nu = p$) or harmonic due to saturation ($\nu = 3p$).

After multiplication of magnetomotive force according to (3) with average permeance of air gap, the induction for harmonic of μ pole-pairs is derived. Using the trigonometric relation

$$\sin\alpha \cos\beta = 0.5[\sin(\alpha - \beta) + \sin(\alpha + \beta)]$$

and using the connection between stator and rotor co-ordinate system

$$x = x_r + \frac{\omega}{p}(1-s)t, \quad (4)$$

the equation for induction harmonic of μ pole-pairs in stator in stator co-ordinate system can be derived

$$b_{s\mu k} = B_{\mu k} \sin\left\{\mu x - \left[\frac{\mu}{p}(1-s) + ks\right]\omega t + \varphi_\mu - \varphi_k\right\} \quad (5)$$

$\mu = \pm 1, \pm 2, \pm 3, ...$

If rotor harmonic of induction $\mu = \kappa = 2p$ is observed, it, together with the main harmonic of induction $\nu = p$, according to (1), produces in saturated stator yoke the magnetomotive force and flux with frequency

$$\omega_0 = \left[\frac{\kappa}{p}(1-s) + ks - 2\right]\omega. \quad (6)$$

For $k = 1$, it follows:

$$|\omega_0| = |2(1-s) + s - 2|\omega = s\omega. \quad (7)$$

So, regardless of the number of poles p, the shaft current of slip frequency is always obtained in the case of damaged cage (for $\mu = \kappa = 2p$ and $k = 1$) in accordance with (6).

Equation (6) gives the slip frequency also for $\mu = \kappa = 2p$ and $k = 3$, so that the shaft current of slip frequency is caused also by the saturation harmonic ($\nu = 3p$).

3 CONCLUSIONS

Possible causes of shaft currents in LV squirrel-cage induction motors with homogenous yokes (in the 1st approximation) are analysed. Generation of shaft currents in 2-pole and 4-pole machines (eccentricity and ovality), and increase of shaft current of slip frequency in the case of broken bars or rings in relation to undamaged squirrel cage are explained. In that way, the results of attached measurements are explained.

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Uzroci osovinskih struja kod niskonaponskih kaveznih asinkronih strojeva. Analizirani su mogući uzroci osovinskih struja kod niskonaponskih kaveznih asinkronih strojeva. Objašnjen je mehanizam nastajanja osovinskih struja frekvencije napajanja i frekvencije klizanja kod dvopolnih i četveropolnih strojeva i utjecaji prekida štapova ili prstena rotorskog kaveza.

Ključne riječi: izmjenični strojevi, asinkroni motori, dijagnostika, mjerenja

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