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Interharmonics Generated by Induction Machines

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***Summary*: The paper presents results of calculations of interharmonics generated by a squirrel cage induction machine, in both the healthy and faulty operating conditions. Two case studies refer to broken bars and clutch wobbling. The analyses were accomplished by a dedicated digital system for offline diagnosis of induction machines.**

Key words: *polyharmonic model, spectral composition of currents, interharmonics*

1. INTRODUCTION

The aim of the contribution is to present spectral compositions of stator currents received from simulations based on the specialized model. The supply voltage for simulations was assumed to contain not only the 50 cps fundamental component of 1000 $V_{rms, phase-to-phase}$ but also the 3rd, 5th and 7th harmonics. The rated power of the wye configured machine was P_N = 132 kW, the number of pole pairs $p = 2$, the speed $n = 1475$ r.p.m., the number of slots N_S/N_R = 72/56, the rotor inertia $J = 4.52$ kgm^2 and the inertia of the load J_L = 0.52 kgm^2. To prevent the torsions depending on the clutch stiffness from influencing the current spectra, the clutch was assumed to be perfectly stiff, except in paragraph 7 referring to clutch wobbling. The loading torque was assumed to depend on the square of the rotor speed and to amount to 841 Nm at synchronous speed. The rated torque is 855 Nm.

The case studies refer to 320 kW and 850/450 kW machines, operated in one of the power plants.

2. HEALTHY MACHINE

Figure 1 shows the starting current followed by the steady-state current, for the case of perfectly healthy machine.

The purposefully prolonged steady-state operation allowed to calculate spectral composition for the steady state segment of the current in Figure 1. It is presented in Figure 2.

The harmonic labeled with 50 is a fundamental harmonic, the steady state amplitude of which is 131.5 A_{max}, as already shown in Figure 1. The harmonics labeled as 150, 250 and 350 are the 3rd, 5th and 7th harmonics. The interharmonic labeled as 1433.8 is a main slot harmonic.

3. BROKEN BAR

Broken bar is modelled by 20 times magnified bar resistance [1]. Figure 3 presents spectrum of the steady state current segment, similar to that in Fig. 1 but for the rotor with one broken bar, out of 56 bars total.

The zoom around 50 cps shows up a pair of new interharmonics. Their frequencies are 48.788 and 51.212 cps, for the rotor speed resulting from full load of almost 841 Nm.

4. FREQUENCY OF DIAGNOSTIC COMPONENTS

The presence of diagnostic components in Figure 3b can be justified in the following manner [2]. For the machine operated in steady state the rotor angular speed ω can be expressed by:

$$\omega = (1-s)\frac{\Omega}{p} = (1-s)\frac{2\pi f_0}{p} \qquad (1)$$

where:

s — slip,
Ω — angular frequency of the supply voltages,
p — number of pole pairs,
f_0 — supply frequency.

The frequency f_r of the rotor currents is:

$$f_r = sf_0 \qquad (2)$$

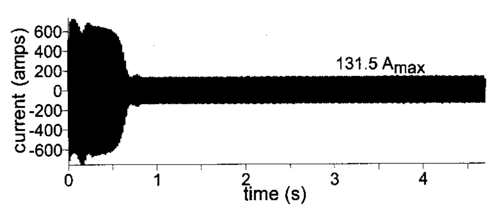

Fig. 1. Calculated start up and steady-state current for healthy machine. Sampling period T_S = 0.002 s.

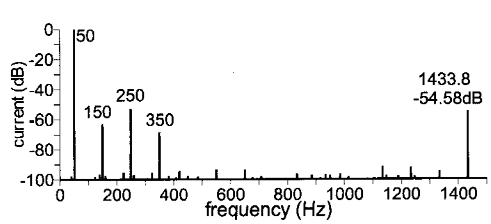

Fig. 2. Spectrum for calculated current segment between 1.5 and 4.7 s. Frequency resolution Δf = 0.3125 cps

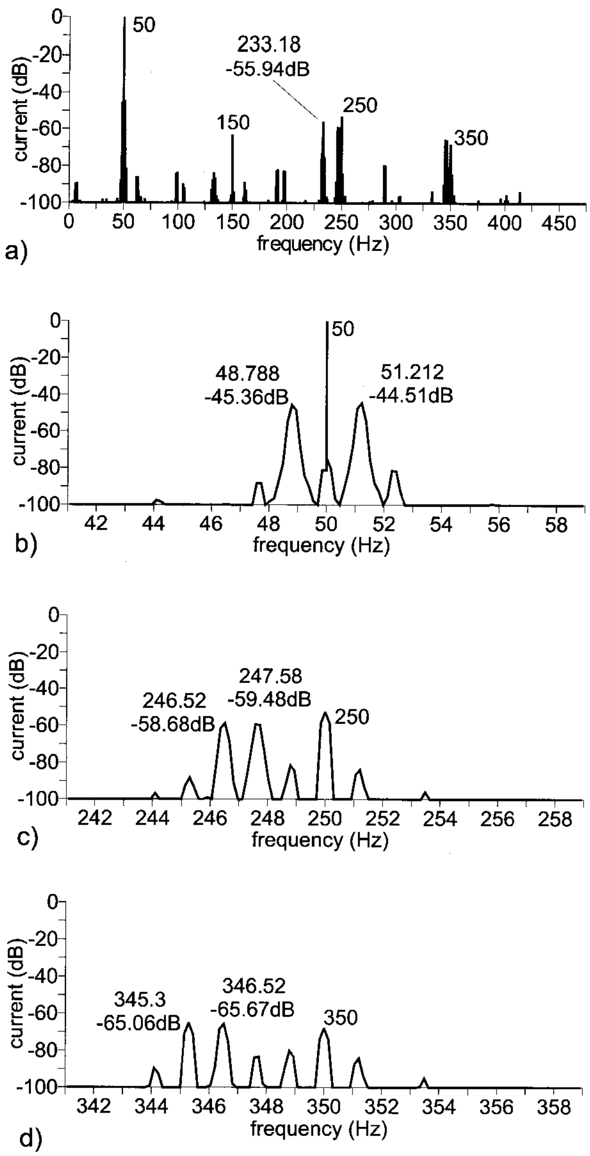

Fig. 3. a) Spectrum for calculated curent segment between 1.5 and 8.1 s. Resolution Δf = 0.151515 cps; b, c, d) zooms around 50, 250 and 350 cps; Resistance of one bar multiplied by 20

Broken bar can be modeled by artificial current counter balancing the real one. This current will produce a number of pulsating flux components. The wave of the air gap magnetic flux density of p pole pairs can be expressed qualitatively by:

$$B_{Add,R}(y,t) = I_{Add,mx}\,cos(s\Omega t) \quad \Lambda\, sin(py) \tag{3}$$

or by:

$$B_{Add,R}(y,t) = \\ = B_{Add,mx}[sin(py - s\Omega t) + sin(py + s\Omega t)] \tag{4}$$

where Λ is a proportionality coefficient between the current and the magnetic flux density, and y is a rotor referred circumferential coordinate starting at broken bar.

It follows from (4) that the additional flux can be interpreted as a superposition of two flux waves rotating with the rotor referred angular speed of (5) and (6).

$$\omega_{R1} = s\frac{\Omega}{p} \tag{5}$$

$$\omega_{R2} = -s\frac{\Omega}{p} \tag{6}$$

Considering the angular speed of the rotor itself, the speeds (5) and (6) are equivalent to the stator referred speeds of (7) and (8):

$$\omega_{S1} = \omega + \omega_{R1} = \frac{\Omega}{p} \tag{7}$$

$$\omega_{S2} = \omega + \omega_{R2} = (1-2s)\frac{\Omega}{p} \tag{8}$$

Considering that the stator winding has p pole pairs, the wave of the angular frequency (8) will induce in the stator winding the current component of the frequency (9):

$$f_{S2} = (1-2s)\cdot f_0 \tag{9}$$

However, in practice, the stator currents also contain the harmonic of the angular frequency of(10):

$$f_{S3} = (1+2s)\cdot f_0 \tag{10}$$

Frequencies (9) and (10) are just the ones seen in Figure 3b to the left and right of the fundamental or 50 cps component. Their frequencies are 48.788 and 51.212 cps.

5. BROKEN SEGMENT IN ONE CAGE END RING

Figure 4 presents the spectrum for one broken segment (200 times magnified resistance) in one end ring.

6. STATIC AND DYNAMIC ECCENTRICITY

The spectrum in Figure 5 refers to the steady state interval from 1.5 to 4.7 s, by mixed eccentricity of 30% static plus 30% dynamic ones.

It follows from Figure 5 that the mixed eccentricity is accompanied by a pair of interharmonics around the 50 cps fundamental harmonic. The distance of these harmonics from the fundamental one is the same and amounts to the rotor speed expressed in revolutions per second. The steady state speed varies between 155.262 and 155.267 rad/s. Thus the middle steady state speed is 155.2645 rad/s, what is tantamount to 24.71 rev/s. The predicted frequencies of the above mentioned pair of rotational interharmonics are 50 - 24.71 = 25.29 and 50 + 24.71 = 74.71 cps. Considering the frequency resolution of 0.3125 cps, these frequencies coincide with those of 25.314 and 74.688 cps seen in Figure 5.

7. CLUTCH WOBBLING

In was assumed that the wobbling torque amounts to 2% of the clutch nominal torque of 2565 Nm. The latter value amounts to three rated torques of the motor. Here the clutch was assumed to possess the limited stiffness of $9 \cdot 10^4$ Nm/rad and the nonlinearity factor of 0.9, what causes the clutch characteristic to be parabolic. Figure 6 shows the spectrum of the steady state current interval of 1.5 to 4.7 s.

The spectrum in Figure 6 is, qualitatively, very close to that in Figure 5. The most conspicuous quantitative difference between these spectra is the magnitude of the 99.375 cps interharmonic. In Figure 5 its magnitude is comparable with that of the 74.688 cps interharmonic, whereas in Figure 6 it is much smaller.

8. VIBRATION OF BEARINGS

It was assumed that each full rotor revolution is accompanied by eight radial vibrations of the amplitude of 40% of the geometrical air gap. The spectrum of the steady state current is given in Figure 7.

It follows from Figure 7 that the vibrations of the rotor produce two additional harmonics, the frequencies of which are 345.31 and 445.31 cps, of the amplitude of –74.46 and –75.07 dB with respect to 50 cps fundamental harmonic.

9. CASE STUDY – BROKEN BARS

Figure 8 presents a diagnostic report for a 320 kW machine operated in steady state conditions at partial load. The report is produced automatically by a diagnostic system making use of the pre-registered currents [3]. Actually the current in a secondary side of a current transformer has been registered via current clips. The analog-to-digit converting card onboard of a portable computer performed the registration. The thus registered currents were offline loaded by the diagnostic system. The presence of the additional components around the 50 cps fundamental component is clearly visible. Figure 8 confirms that broken bars cause

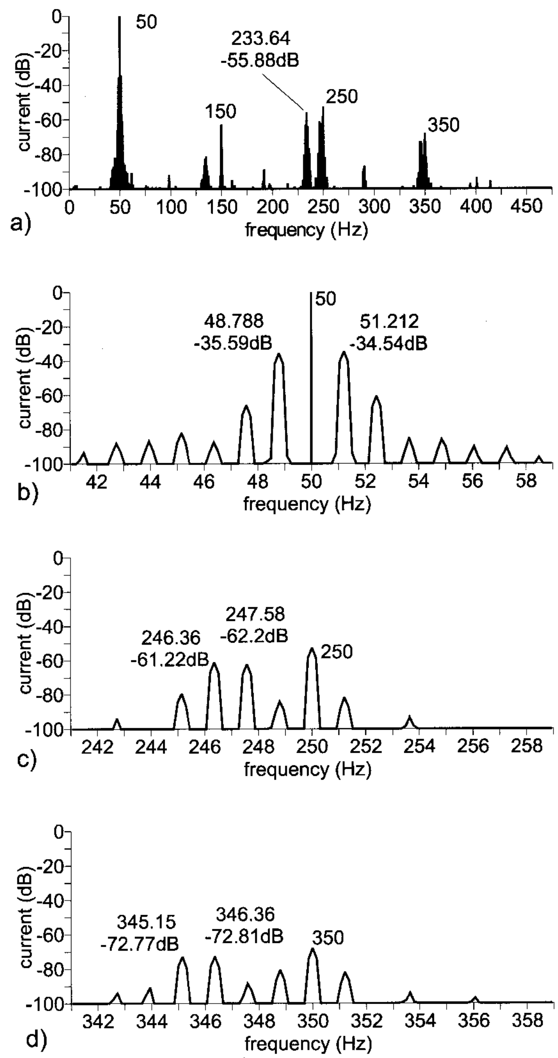

Fig. 4. a) Spectrum for the calculated current segment between 1.5 and 8.1 s; Resolution Δf = 0.151515 cps; b, c, d) zooms around 50, 250 and 350 cps; resistance of one segment multiplied by 200

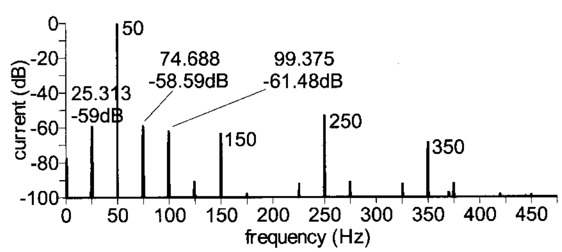

Fig. 5. Spectrum for the calculated current segment between 1.5 and 4.7 s; resolution Δf = 0.3125 cps; both static and dynamic eccentricities amount to 30% of geometrical air gap length

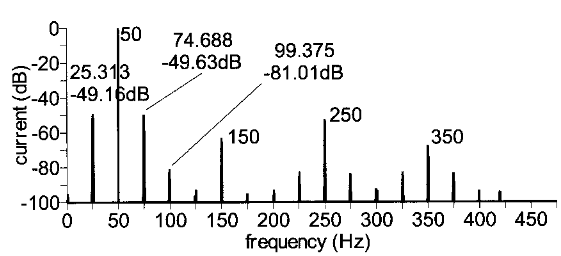

Fig. 6. Spectrum for the calculated current segment between 1.5 and 4.7 s; resolution Δf = 0.3125 cps; the clutch wobbling amounts to 2% of the clutch nominal torque of 2565 Nm

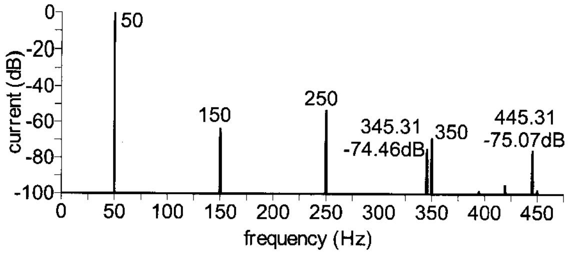

Fig. 7. Spectrum for the calculated current segment between 1.5 and 4.7 s; resolution Δf = 0.3125 cps; eight radial swings of the rotor, of the amplitude of 40% of air gap length, per one rotor revolution

that a pair of twin harmonics is injected into power supply system. In the case presented in Figure 8, the amplitudes of these harmonics amount to 1.5% by 49.16 cps and 0.85% by 50.72 cps of the fundamental component, whose amplitude is 36.2 Amx by 49.95 cps. The slip of 0.778% was established relying on a slot harmonic marked with a square in the vicinity of 900 cps in plot number two of Figure 8. The distance of both diagnostic components from the fundamental one is $2 \cdot s \cdot f_0 = 2 \cdot 0.778/100 \cdot 49.95 = 0.777$ cps. This theoretical distance is confirmed in Figure 8 with satisfactory accuracy.

10. CASE STYDY – CLUTCH WOBBLING

Figure 9 refers to a double speed machine of 850/450 kW rated power, operated at lower speed that is by 5 pole pairs. It drives a flue gas exhauster in one of the power plant. The analysis was done with the diagnostic system for the pre-registered supply current [3]. Irregular load, caused for example by nonalignment of motor and exhauster axes, or by non-uniform sediments on exhauster's blades, referred to as clutch wobbling, will cause generation of twin rotational harmonics. In the case presented in Figure 9 their amplitudes are 5.58% by 40 cps and 5.12% by 59.94 cps, with respect to the fundamental component of 53 Amx by 49.97 cps. Comparing Figures 8 and 9 it can be concluded that clutch wobbling will be accompanied by much higher harmonics injected into power supply system than broken bars.

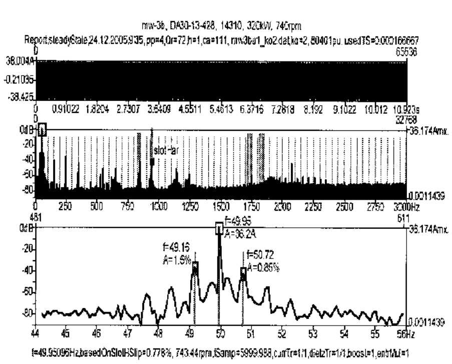

Fig. 8. Diagnostic interharmonics around the 50 cps fundamental component, due to broken bars in the Industrial machine

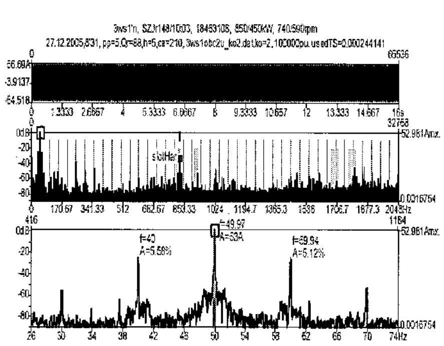

Fig. 9. Rotational interharmonics around the 50 cps fundamental component, due to clutch wobbling in the industrial machine

11. CONCLUSIONS

Calculated spectra confirm that the squirrel cage induction machine generates interharmonics. In healthy conditions the most important interharmonic is the so called slot harmonic. In faulty conditions additional interharmonics pop up, especially in lower frequency range. Though in some cases their amplitude may reach –35 dB (e.g. in Figure 4), usually their amplitude is smaller than –50 dB. However, in the case of bigger machines their amplitudes expressed in amperes can achieve the values being able to deform the grid voltage, resulting in that the polluted voltage would be delivered to other recipients.

The developed and implemented "diagnostic model" proved to be capable to properly simulate various ailments in squirrel cage induction machines. It was indispensable that the model accounted for higher harmonics of the stator and rotor self and mutual inductances.

Qualitative and quantitative results of calculations remain in good coincidence with those obtained from case study analyses, performed for industrial machines.

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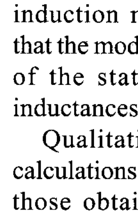

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