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Diagnosis of Mixed Eccentricity in 400 kW Induction Machine Based on Inspection of Stator Current Spectrums

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Abstract. This paper dealing with diagnosis of induction machines affected by combined eccentricity via analyzing the sator curents, inspection of the current spectrums and predict the harmonics that present in the spectrums and represent an indication for this ailment . The machine under invistigation is a 400 kW, four pole-pair, squarelcage induction machine. The current spectrums were calculated for the cases of full symmetry and mixed eccentricity. The calculations presented in this paper, are based on the poly-harmonic model that accounting for static and dynamic eccentricity, stator and rotor slotting, parallel branches as well as cage asymmetry. The calculations were followed by Fourier analysis of the stator currents in steady state operation.

The inspection of the current spectrums focusing on two main zones these are the 50 Hz fundamental harmonic zone and the main slot harmonic zone.

The paper will include the zooms of the above mentioned zones to demonstrate the harmonics presented in each zone.

The calculated spectrums will be compared with the spectrums of the real measured currents.

Key words

Diagnosis, Fundamental Harmonic, Slot Harmonic, Induction Machine, Current Spectrum, Zone.

1. Introduction

Generally, the rotating electrical machines play a very important role in the world industrial life. Among them, a three-phase induction machine is frequently used because of its relatively simple, robust construction and its low price.

Hence, it is natural that there is a strong industrial demand for reliable and safe operation of induction machines, as faults and failures of critical electromechanical parts can indeed lead to excessive downtimes and generate high costs in reduced output, emergency maintenance and lost revenues [1], [2].

That is why the industry is interested in adopting diagnosis techniques to assess and evaluate current condition of electrical machines .

Eccentricity related faults constitute one of major portions of the faults related to induction motors, even if they do not lead to immediate stoppage of the machine [3].

Faulty bearings, rotor ellipticity, misalignment of the shaft with the rotor, etc. might cause eccentricity that is, in most general terms, a non uniform air-gap between stator and rotor [4]. This paper dealing with the case of mixed eccentricity, where there is a composition of both static and dynamic eccentricities, which means that the rotor rotation axis does not match with neither the stator symmetry axis nor the rotor symmetry axis [5], [6], [7].

The calculations presented in this paper were performed with special software owned by the Chair of Electrical Machines, AGH University of Science and Technology. It consists of five programs [8]:

-Program Dpa1 calculates mainly leakage inductances.

-Program Din16 calculates self and mutual main inductances accounting for true stator winding configuration as well as for slotting and eccentricity.

-Program Dde18 calculates derivatives of the inductances, with respect to rotor angle.

-Program Ddy20 performs integration of differential equations using 3D matrices of inductances and their derivatives stored on the disk by program Dde18.

-Program Sp1 performs Fast Fourier Transform (FFT) as well as least squares approximation of the fundamental component of the currents.

The calculations performed refer to the 400 kW squirrel-cage induction machine, with 4-pole pairs (p=4) and N_S/N_R = 72/88 of stator/rotor slots.

All spectrums refer to steady state operation by full loading torque TL = 5162 Nm.

2. Healthy Machine

As a reference basis, the calculation of the stator current spectrum were performed for full symmetrical machine. As shown in fig.1, the spectrum does not contain any extraordinary harmonics. It only contains the 50 Hz fundamental harmonic, the main slot harmonic Slh [9], of the frequency of about 1139.7 Hz, and also, the second slot harmonic of the frequency of about 2129 Hz. The latter one falls out of our interest. The amplitude of the main slot harmonic is about -47 dB and its frequency can be predicted by the following formula [10], [11]:

$$\left| \; f_1 + h \cdot N_R(1-s)\; n_s \; \right| \qquad (1)$$

Where: the supply frequency f_1 = 50 Hz, the parameter h = 1 [12], the number of rotor slots N_R= 88, the slip s = 0.00935, and the synchronous speed $n_s = f_1/p$ = 12.5 revolutions per second.

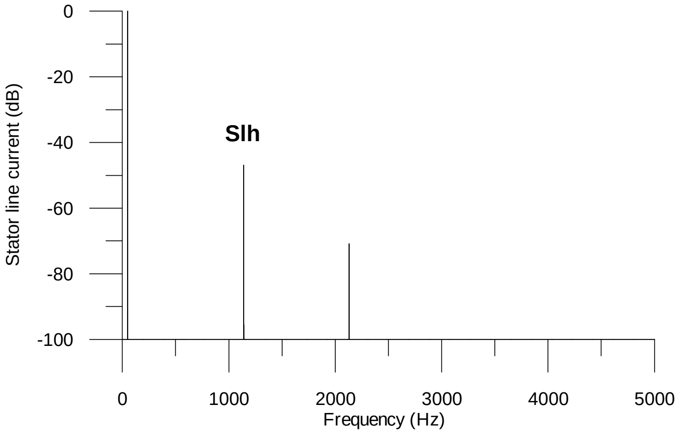

Fig. 1 Spectrum of the calculated stator current (Healthy Machine)

3. Mixed Eccentricity

In this case the calculations have been performed considering combination of both static and dynamic eccentricity [4], [6], [13].

The stator current spectrum shown in fig. 2a refers to the case of mixed eccentricity (20% static + 60% dynamic).

The spectrum contains many harmonics in the 50 Hz fundamental harmonic zone, as well as in the main slot harmonic zone.

The zoom of the fundamental harmonic zone is shown in fig. 2b. The rotational harmonics around the 50 Hz fundamental harmonic are clearly visible. They are spaced by ± $(1\text{-}s)nf_1/p$ above and below the 50 Hz harmonic. The most conspicuous rotational harmonics are the first order harmonics, of the frequencies of about 62.5 and 37.5 Hz, those are labeled as r_{+1} and r_{-1}. Their amplitudes reached the level of about -50 dB.

Similarly, in the main slot harmonic zone, as shown in fig. 2c, the first and second order mixed eccentricity harmonics are present around the main slot harmonic Slh. They are again spaced by $\pm(1\text{-}s)nf_1/p$ above and below the main slot harmonic, as shown in fig. 2d. The most conspicuous mixed eccentricity harmonics are the ones labeled as ms_{+1} and ms_{-1}, having the amplitudes of about -68 dB. These are the first order mixed eccentricity harmonics of the frequencies of about 1152 and 1127 Hz, respectively.

In addition, the main slot harmonic zone contains also a set of quite conspicuous harmonics, to the left of the potential twin harmonic, but they are of minor importance for diagnostic purposes. Also, the mixed eccentricity harmonics are present around the second slot harmonic, but they are out of our interest.

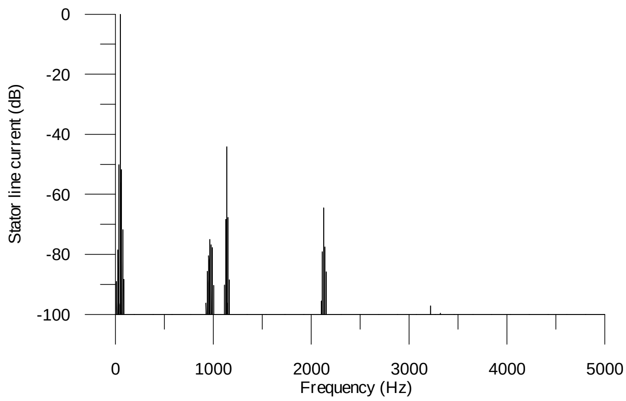

Fig. 2a Spectrum of the calculated stator current (20% static + 60% dynamic eccentricity)

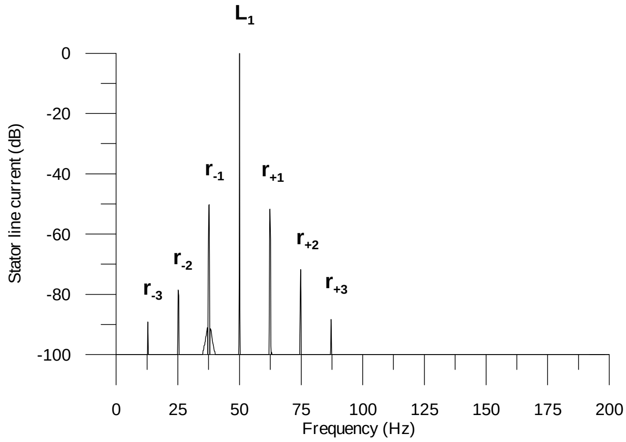

Fig. 2b Zoom around 50 Hz of the calculated stator current (20% static + 60% dynamic eccentricity)

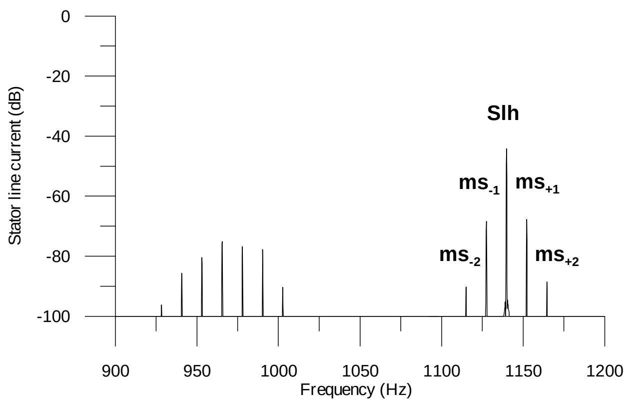

Fig. 2c Zoom of the main slot harmonic zone of the calculated stator current (20% static + 60% dynamic eccentricity)

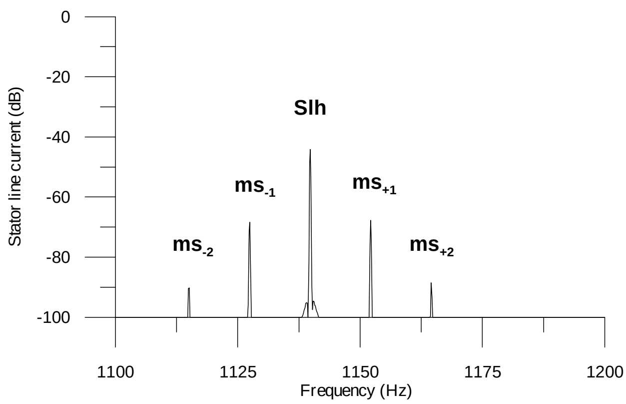

Fig. 2d Zoom around the main slot harmonic of the calculated stator current (20% static + 60% dynamic eccentricity)

The next spectrum of the mixed eccentricity cases, shown in fig. 3a, refers to the case of mixed eccentricity (40% static + 40% dynamic). The zoom of fig. 3a around the 50 Hz fundamental harmonic is shown in fig. 3b. The rotational harmonics around the 50 Hz harmonic are present practically in the same manner as in fig. 2b, which referred to the case of mixed eccentricity (20% static + 60% dynamic). The rotational harmonics are spaced, again, by $\pm\ (1\text{-}s)nf_1/p$ above and below the 50 Hz harmonic.

The zoom of the main slot harmonic zone is shown in fig. 3c. It contains practically the same mixed eccentricity harmonics as in fig. 2c, which referred to the previous case of mixed eccentricity (20% static + 60% dynamic). They are again spaced by $\pm (1\text{-}s)nf_1/p$ above and below the main slot harmonic. It should be noted again, that the most conspicuous mixed eccentricity harmonics, are the first order ones ms_{+1} and ms_{-1}. They are having practically the same amplitudes as in the previous case of 20% static plus 60% dynamic eccentricity.

Also, it should be noted that the twin harmonic **tw**, of the frequency of about 1039.7 Hz, is present with practically negligible amplitude, due to the small degree of static eccentricity [14] in this case (40%).

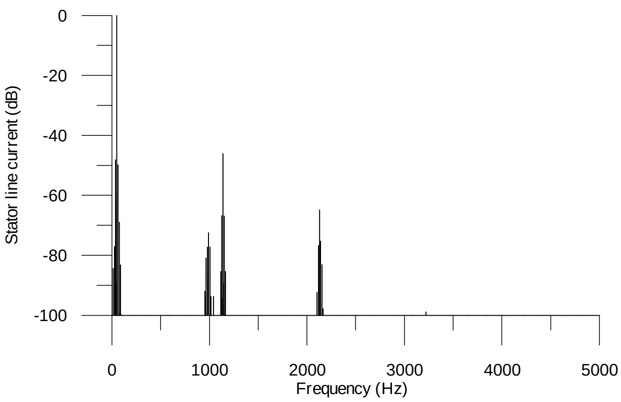

Fig. 3a Spectrum of the calculated stator current (40% static + 40% dynamic eccentricity)

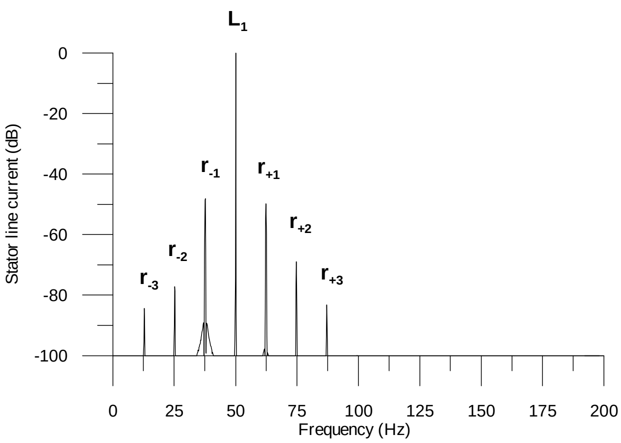

Fig. 3b Zoom around 50 Hz of the calculated stator current (40% static + 40% dynamic eccentricity)

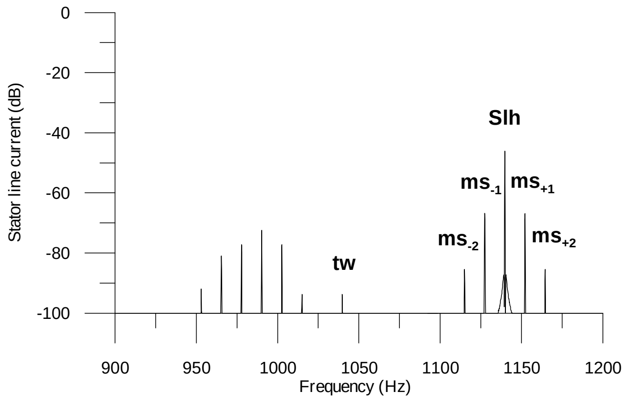

Fig. 3c Zoom of the main slot harmonic zone of the calculated stator current (40% static + 40% dynamic eccentricity)

The stator current spectrum of fig. 4a refers to the case of mixed eccentricity (60% static + 20% dynamic). The zoom around the 50 Hz fundamental harmonic is shown in fig. 4b. Practically there is no change as for the rotational harmonics around the 50 Hz fundamental harmonic, as compared to the previous cases of mixed eccentricity. That proves that the rotational harmonics, around the 50 Hz fundamental harmonic, are good indication for the existence of mixed eccentricity.

Similarly, in fig. 4c, which is the zoom of the main slot harmonic zone, the mixed eccentricity harmonics around the main slot harmonic are present in practically the same manner as in the previous cases of the mixed eccentricity. Hence, we could conclude that both the rotational harmonics around the 50 Hz fundamental harmonic, and the mixed eccentricity harmonics around the main slot harmonic, deliver clear evidence for mixed eccentricity.

However, the harmonics to the left of the twin harmonic are of minor importance for diagnosing the mixed eccentricity.

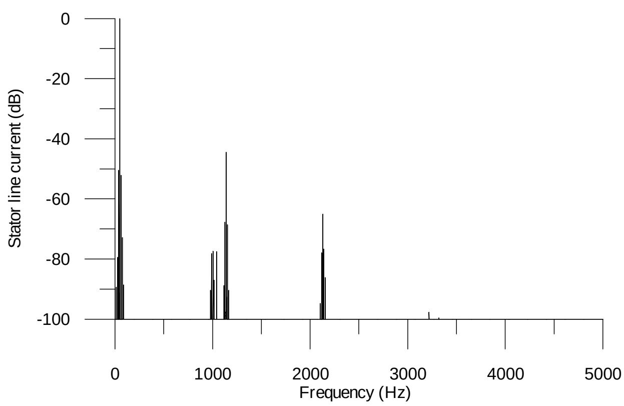

Fig. 4a Spectrum of the calculated stator current (60% static + 20% dynamic eccentricity)

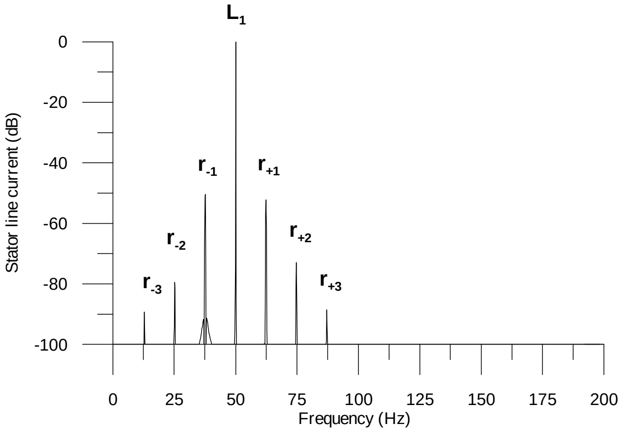

Fig. 4b Zoom around 50 Hz of the calculated stator current (60% static + 20% dynamic eccentricity)

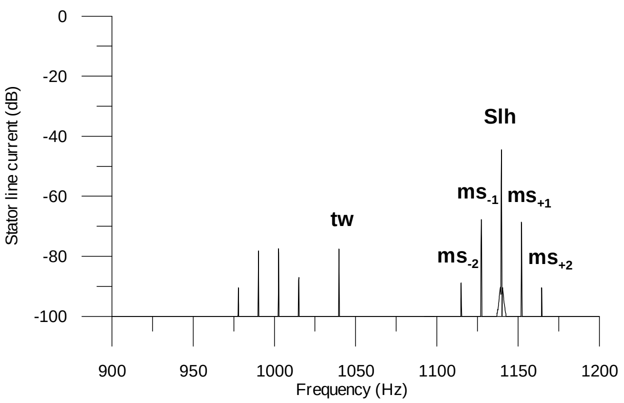

Fig. 4c Zoom of the main slot harmonic zone of the calculated stator current (60% static + 20% dynamic eccentricity)

4. Cases Study

Spectral analyses have been performed for a number of currents really registered in the industry.
The analyzed currents are referred to four pole pair, 400 kW, induction machines, labeled in the industry as WP.
Among all the analyzed cases, there were some cases found with mixed eccentricity.
In the following there are three examples of the real measured currents, referring to the 400 kW, WP machines, (files names 3WP1U1, 4WP1U1 and 4WP1obc2).
These three cases were classified as showing up mixed eccentricity, due to the following reasons:

1. The presence of the 1st, 2nd and 3rd order, rotational harmonics, around the 50 Hz fundamental harmonic, as shown in figs. 5 b, 6 b and 7 b. This gives good indication for the mixed eccentricity in theses cases.
2. The presence of the twin harmonic tw, to the left of the main slot harmonic Slh, as shown in figs. 5 c, 6 c and 7 c, delivers clear evidence for the static eccentricity in all these cases.
3. The presence of the mixed eccentricity harmonics, ms_{+1} and $ms_{-1,}$ around the main slot harmonic Slh, as shown in figs, 5 d, 6 d and 7 d, gives clear indication for the mixed eccentricity, especially that these harmonics were present in addition to the multi-order rotational harmonics around the 50 Hz fundamental harmonic L_1.
4. The high level of the back ground, in the first and second examples, did not allow identifying the second order mixed eccentricity harmonics which will, additionally, confirm the presence of mixed eccentricity in these cases. Whereas the lower level of the first order mixed eccentricity harmonics (about -80 dB), in the third example, suggest that the second order ones would be of practically negligible amplitudes.

Hence, these cases were classified as showing up mixed eccentricity.

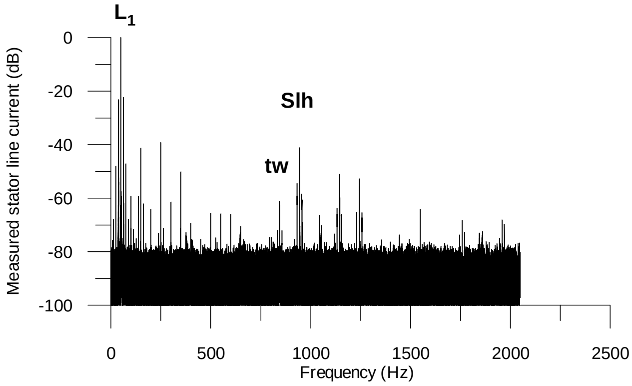

Fig. 5 a Spectrum of the measured stator current (3WP1U1)

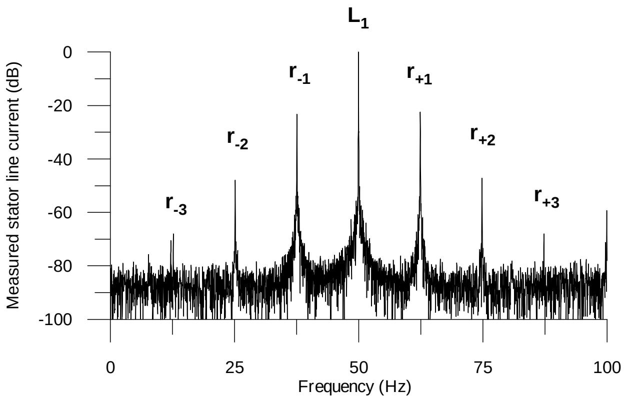

Fig.5 b Zoom around 50 Hz of the measured stator current (3WP1U1)

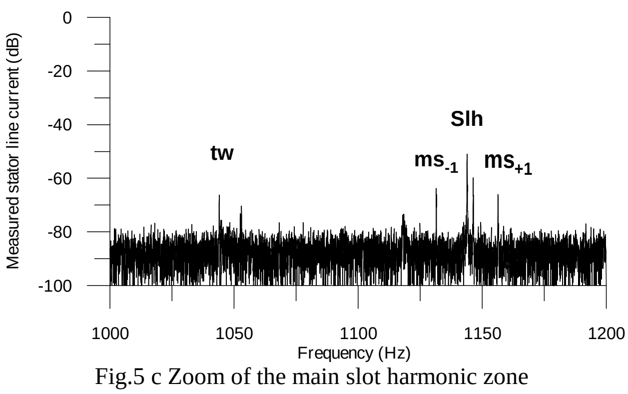

Fig.5 c Zoom of the main slot harmonic zone of the measured stator current (3WP1U1)

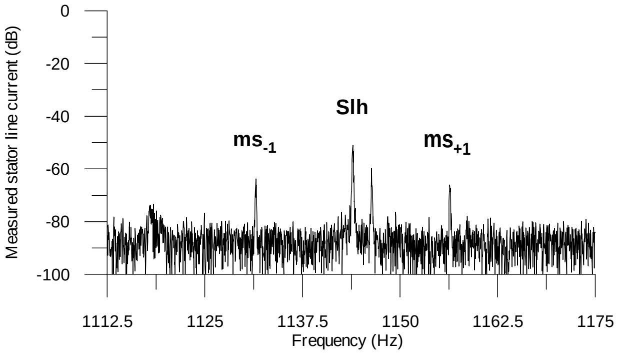

Fig. 5 d Zoom around the main slot harmonic of the measured stator current (3WP1U1)

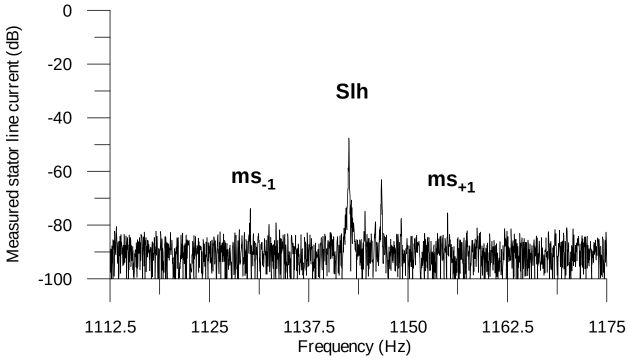

Fig. 6d Zoom around the main slot harmonic of the measured stator current (4WP1U1)

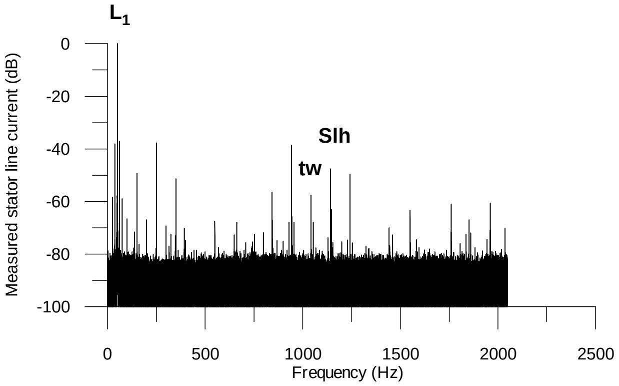

Fig. 6a Spectrum of the measured stator current (4WP1U1)

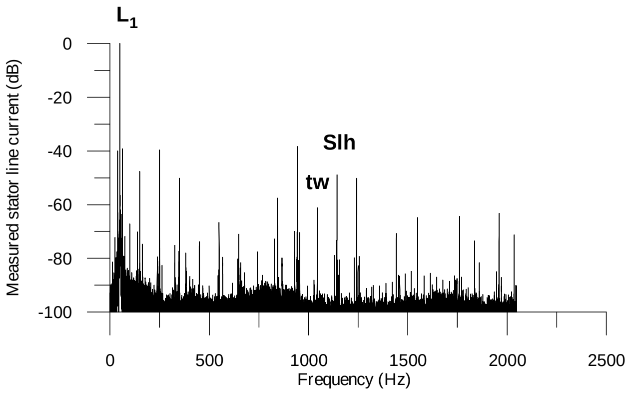

Fig. 7 a Spectrum of the measured stator current (4WP1obc2)

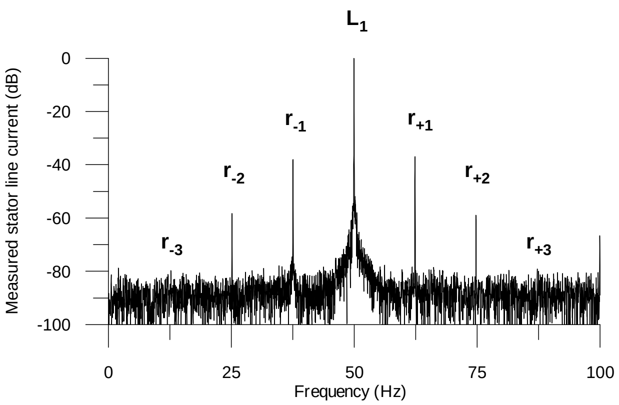

Fig. 6b Zoom around 50 Hz of the measured stator current (4WP1U1)

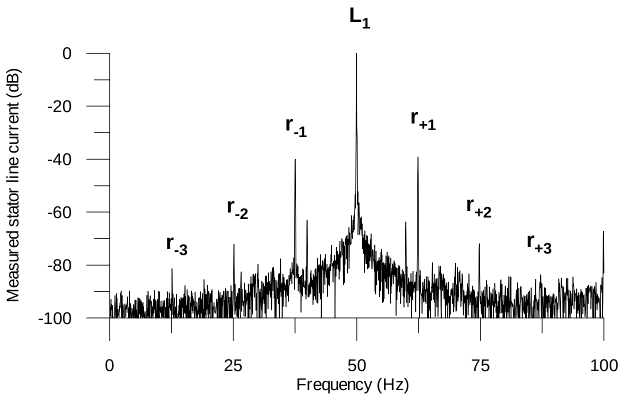

Fig. 7 b Zoom around 50 Hz of the measured stator current (4WP1obc2)

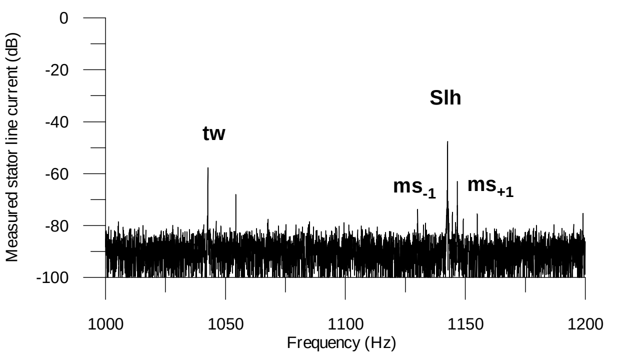

Fig. 6c Zoom of the main slot harmonic zone of the measured stator current (4WP1U1)

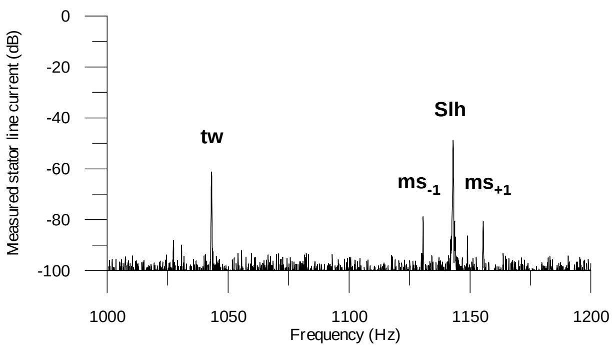

Fig. 7 c Zoom of the main slot harmonic zone of the measured stator current (4WP1obc2)

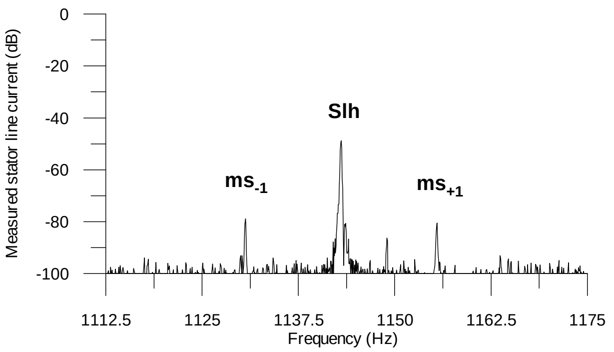

Fig. 7 d Zoom around the main slot harmonic of the measured stator current (4WP1obc2)

5. Conclusion

1. The mixed eccentricity is, generally, characterized by a set of harmonics around the 50 Hz fundamental harmonic, around the main slot harmonic. These harmonics are always spaced by multiples of rotational speed, above and below the fundamental, the slot harmonics, appropriately.
2. The first order harmonics are always the most conspicuous ones, either around the 50 Hz fundamental harmonic or around the main slot harmonic.
3. The calculations proved that the fundamental harmonic and the main slot harmonic zones are, from diagnostic point of view, the most important ones, as they contain diagnostic information, in form of the most important diagnostic harmonics. In addition, the slot harmonic zone is cleaner as compared to the fundamental harmonic zone, normally polluted by many other harmonics like higher harmonics of the supply system and the harmonics related to the cage asymmetry.
4. Coincidence of the spectrums of the registered and calculated currents proved the effectivness of the diagnostic procedure for diagnosing mixed eccentricity.

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