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CMCD OR CALCULATION VERSUS MEASUREMENT COMPARATIVE DIAGNOSIS

Abstract: In practice, the industry is ready to cover diagnostic costs only in case of big machines, operated in responsible drives. In case of big induction machines, their stators are, as a rule, fitted with windings with parallel branches. In that case, prediction of frequencies of the diagnostic signals is not that easy, as compared to the cases of small machines, without parallel branches in stator windings.
The contribution presents calculation results for a machine afflicted by eccentricities, as well as the results of industry measurements, and the comparison thereof. Both, the calculations and the measurements, refer to the same type, 6 kV, 3.15 MW rated power, squirrel-cage induction machines. The calculations are based on the dynamic diagnostic model with account for parallel branches, stator and rotor slotting, as well as for eccentricities. The measured quantities are two supply currents, then aggregated to Park's vector, which is FFT analyzed. The same, specially developed, dedicated informatics tool was used for analyses of both the calculated and measured currents. The proposed CMCD procedure, though requiring specialized calculations, seems to be justified for big power machines.

Streszczenie: W praktyce, przemysł jest gotowy pokrywać koszty diagnostyki tylko w odniesieniu do dużych maszyn, pracujących w odpowiedzialnych napędach. Stojany dużych maszyn elektrycznych często wyposażone są w uzwojenia z gałęziami równoległymi. W takich przypadkach, przewidzenie częstotliwości sygnałów diagnostycznych nie jest proste, w porównaniu do maszyn małej mocy, bez gałęzi równoległych w uzwojeniu stojana. Praca prezentuje wyniki obliczeń dla maszyny z ekscentrycznościami, a także wyniki pomiarów przemysłowych, oraz ich porównanie. Zarówno obliczenia jak i pomiary dotyczą takich samych maszyn o napięciu 6 kV i mocy 3.15 MW. Obliczenia bazują na dynamicznym modelu diagnostycznym, z uwzględnieniem gałęzi równoległych, użłobkowania stojana i wirnika, oraz ekscentryczności. Wielkościami pomiarowymi są dwa prądy, które są agregowane do wektora Parka i analizowane transformacją FFT. To samo, specjalnie opracowane dedykowane narzędzie informatyczne, było używane do analizy zarówno pomierzonych jak i obliczonych prądów. Zaproponowana procedura CMCD, chociaż wymaga specjalistycznych obliczeń, wydaje się być uzasadniona do maszyn dużych mocy.

Keywords: *cage induction machine, diagnosis, FFT analysis of complex signal*
Słowa kluczowe: *maszyna indukcyjna klatkowa, diagnostyka, analiza FFT sygnału zespolonego*

1. Introduction

The contribution refers to diagnosing of squirrel-cage induction machines. Typically, to diagnose the machine you register one of the supply currents and perform the FFT analysis of this current. Then, you check for presence or absence of harmonics characteristic for certain failures. For example, it is well known that the cage asymmetry is accompanied by frequency components spaced by multiples of $2sf_1$ to the right and left of the fundamental (50 Hz) harmonic, where s is the slip and f_1 is the supply frequency. In the case of eccentricities there are also some standard rules for frequencies expected in current spectra. For example, the mixed eccentricity is accompanied by the so called rotational harmonics, spaced up and down from the fundamental frequency by the rotor speed n_R, expressed in revolutions per second. For purely static eccentricity (s. ecc.), or for purely dynamic eccentricity (d. ecc.) these rotational harmonics do not appear. By registration of the currents in the industry, one of the constant problems is power system pollution. In particular, the supply grid is always polluted by the 3rd, 5th and 7th harmonics, the 5th of them rotating in the negative direction. Also they are asymmetric. The known rules, referring eccentricities to the harmonic spectrum, are established for the machines without parallel branches. Their correctness was checked in laboratories, for low power machines. However, in the industrial reality, machines undergoing diagnosis are of big power, hence often with parallel branches. The method proposed in the contribution is based on the FFT analysis of complex current being the Park's vector of supply currents. The FFT analysis always involves complex value calculations. However, typically, a sequence of

real samples is passed as an input for the FFT transform. Unlike this, here the complex value samples constitute the input signal. Hence, as a result, one receives not only the amplitudes of separate harmonics but also the direction of rotation, of separate harmonics. This, as will be seen, allows for much more accurate diagnosis. The same informatics tool will be used for complex-signal FFT analysis, of both the registered and calculated currents.
The registration of currents, of the two machines operated in the industry, was accomplished with the sampling frequency of almost 6 kHz.

To avoid potential problems with aliasing, the calculations, involving integration of differential equations, were carried out with the integration step equivalent to about 30 kHz. The electrical part of the equations accounts for all linearly independent circuits of the stator, for all peripheral meshes of the cage, and for the circuit of one cage end ring. The mechanical part is described by four equations, referring to speed and angle of two inertias, one of the machine and the other of the load.

2. FFT analysis of measured currents

2.1 First industrial machine

Figures 1a and 1b refer to the industrial machine, referred to in the contribution as the 1st one. System pollution by the 3rd, 5th and 7th harmonics is visible. Also the 2nd harmonic is visible. Its origin may be the supply system or, as it will be shown later, it may be caused by the machine itself, if the latter suffers from the mixed eccentricity. The forward rotating harmonics are displayed upwards, and the backward rotating downwards.

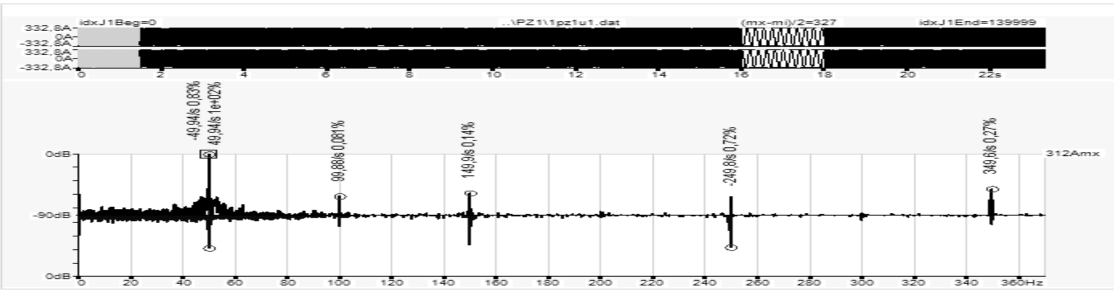

Fig.1a. First industrial machine. Spectrum within the fundamental harmonic zone.

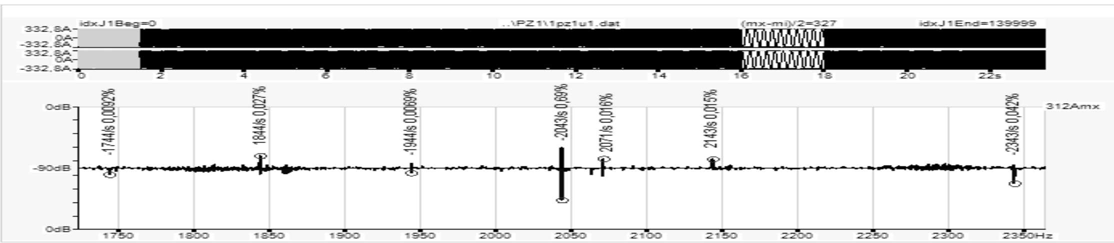

Fig.1b. First industrial machine. Spectrum within the slot harmonic zone.

In all figures, the currents in intervals used for FFT analyses are drawn in full black. In Fig 1a the frequency of the fundamental harmonic amounts to 49.94/s. The accuracy of this value is limited by the frequency resolution amounting to 1/22.5 Hz, as the interval of the black drawn current is about 22.5 seconds. Figure 1a contains also a negative sequence of the fundamental frequency. Identification of this sequence was only possible thanks to the complex-signal FFT analysis.

2.1 Second industrial machine

Figures 2a and 2b refer to the 2nd industrial machine. Though the ratings of this machine are exactly the same as those of the 1st machine, its spectrum is different. The first difference is the background noise, now much heavier. The reason for this may be the reciprocating compressor of the air. It can be active or not, depending on the pressure in its receptacle. In real industrial conditions, you can hardly require to have it switched off. The other difference is the pair of harmonics of the frequency of 2070 Hz. Its origin remains unknown. The amplitude of the positive sequence is 0.074 % of the fundamental.

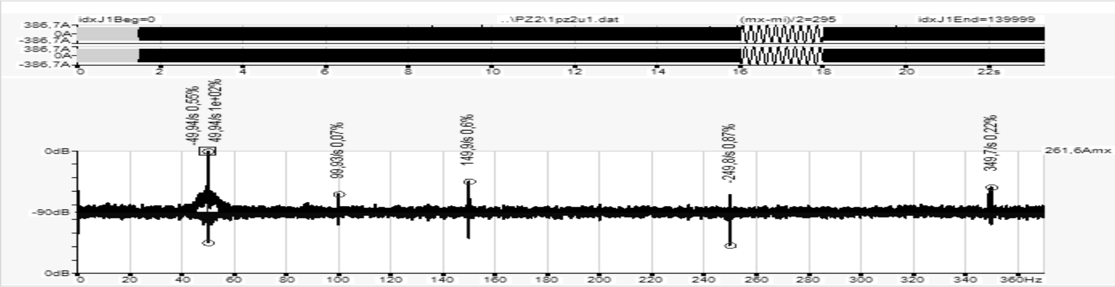

Fig.2a. Second industrial machine. Spectrum within the fundamental harmonic zone.

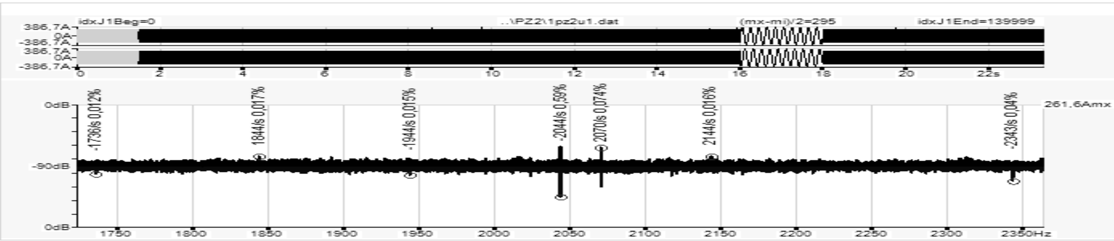

Fig.2b. Second industrial machine. Spectrum within the slot harmonic zone.

The spectra in figures 1a and 2a reveal that the forward rotating fundamental harmonic is accompanied by its twin harmonic rotating in opposite direction. Its amplitude amounts to 0.83 %, for the first machine, and 0.55 %, for the second machine.

3. FFT analysis of calculated currents

3.1 Sound machine plus system pollution

Figure 3 shows the spectrum of the 3.15 MW machine, fed from the power system with symmetrical fundamental voltages, plus asymmetrical 3rd, 5th and 7th harmonics [1]. In details, the supply voltage amplitudes (phase values), and their phase shifts (in degrees), were assumed as follows:

50 Hz:
4899, +30;
4899,-90;
4899, -210;.

150 Hz:
15, 0
20,-120;
20, +120;

250 Hz:
41, 0;
55, +120;
55, -120;

350 Hz:
23, 0;
30, -120;
30, +120;

In accordance to the above shown values, every supply-voltage phase consists of four connected in series electromotive forces, the frequencies of which are 50, 150, 250 and 350 Hz, appropriately phase shifted with respect to one another. These supply conditions were assumed for all calculations. The machine possesses two branches in each phase. The number of pole pairs is p = 1, and the number of rotor slots is N_R = 40. Figures 3a and 3b show the spectrum of the machine with centrically suspended rotor, within the stator hole.

A polluted system was assumed, as literally every industrial measurement reveals the presence of these harmonics. Of course the power system is polluted also by other harmonics, but their amplitudes are much smaller. The phase shift assumed for the 5th harmonic was 0, +120, -120 degrees. This means that the sequence of the 5th harmonic is negative, i.e. contrary to the sequences of all other harmonics. The only consequence of accounting for system pollution is that the spectra from calculations are more realistic, that is they are closer to the spectra of the registered currents. The amplitudes of pollution harmonics are too small to result in any measurable diagnostic signal. Let us repeat that the presence of these harmonics in the calculated current spectra is a result of the assumed power supply, and not of any damage of the machine.

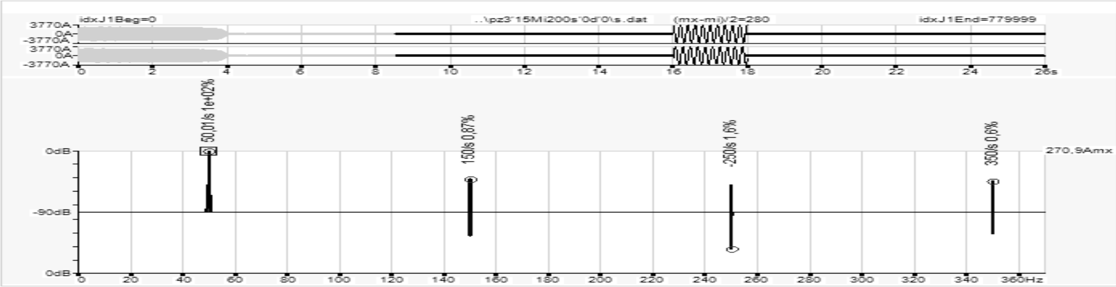

Fig.3a. Calculations. Fundamental harmonic zone. Eccentricity: static = 0, dynamic = 0.

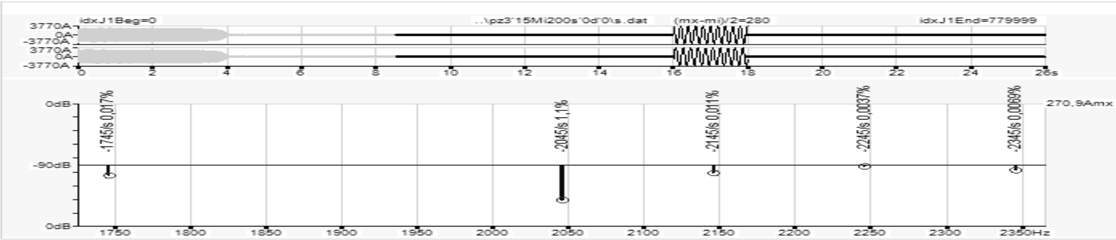

Fig.3b. Calculations. Slot harmonic zone. Eccentricity: static=0, dynamic=0.

The spectrum in figure 3a contains a fundamental harmonic, serving as amplitude reference. Hence, its amplitude is described as 100 %. Figure 3a contains also harmonics of the frequencies of 150, 250 and 350 Hz. All the frequencies are approximate values, due to finite frequency resolution. The 3rd, 5th and 7th harmonics have both the positive and negative sequences. This results from the asymmetrical electromotive forces assumed in the supply. Figure 3b contains the main slot harmonic, rotating in negative direction. This coincides with the particular harmonic balance model [2]. For p = 1, and N_R = 40, the main slot harmonic index *mShi* = 1, and the sequence index *Si* = 210. Hence, the frequency f_S of the main slot harmonic is $f_S = f_1 + f_1\,(1\text{-}s)/\mathrm{p}\, N_R\, h$, where s is a slip, and h is a slot harmonic zone index. For h = *mShi* = 1, and for small slips the f_S is a bit smaller than 2050 Hz. As *Si* = 210 the main slot harmonic belongs to negative sequence, hence, it should rotate in negative direction. Just this confirms figure 3b. The harmonics of the frequencies to the left of 1750, 2150 and 2250 Hz are of much smaller amplitudes.

3.2 Machine with static eccentricity

Figure 4 shows the spectrum of the 3.15 MW machine, for the case of static eccentricity of 0.8 of the geometrical air gap.

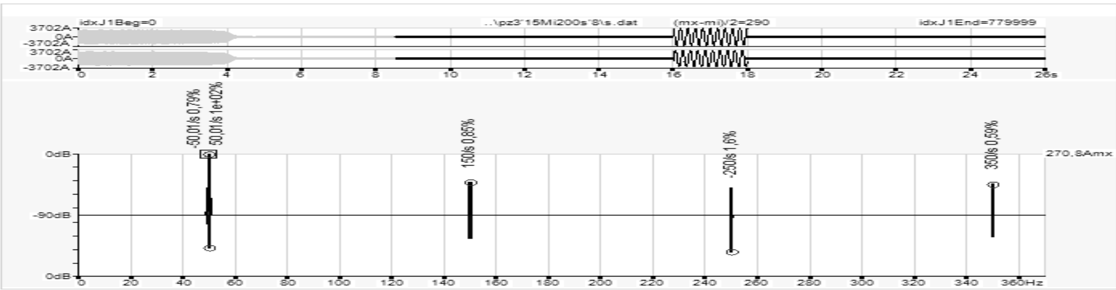

Fig.4a. Calculations. Fundamental harmonic zone. Eccentricity: static = 0.8, dynamic = 0.

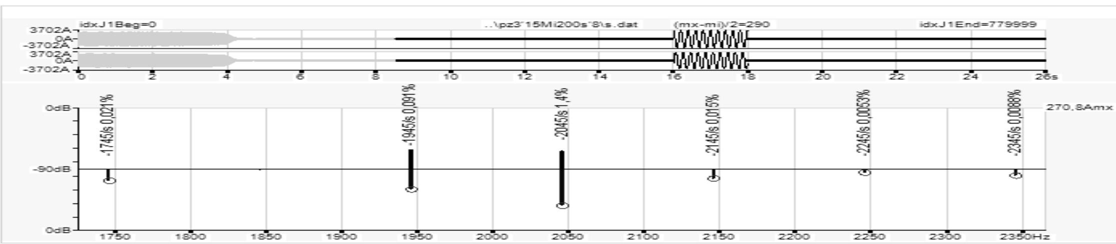

Fig.4b. Calculations. Slot harmonic zone. Eccentricity: static = 0.8, dynamic = 0.

In figure 4a a negative sequence of the fundamental harmonic appeared, though amounting to only 0.79 % of its positive sequence counterpart. As this harmonic did not exist for centric rotor suspension, this negative sequence can be considered as the **1st** symptom of static eccentricity. In figure 4b, the slot harmonic, the one below 2050 Hz, possesses not only the negative but also a positive sequence, albeit of much smaller amplitude. That is the **2nd** symptom of static eccentricity. In figure 4b, below 1950 Hz, there appeared also the twin slot harmonic. It follows from the particular harmonic balance model [2] that each slot zone contains a pair of slot harmonics spaced by 100 Hz (i.e. double the supply frequency). However, for the machines for which the sequence indices *Si* are 210 or 012, and not 111, only one of them is really present, provided the machine is centrically suspended. If, like in figure 4, the machine is afflicted by static eccentricity the missing counterpart of the pair, i.e. the twin harmonic, in the first slot zone, which coincides here with the main slot zone, appears. This was discovered already in [3], and can be considered as the **3rd** symptom of static eccentricity. What more, this twin harmonic contains not only the negative sequence, i.e. the same as the main slot harmonic, but also a positive sequence, of the same frequency, i.e. a bit smaller than 1950 Hz. This can be considered as the **4th** symptom of static eccentricity.

3.3 Machine with dynamic eccentricity

Figure 5 shows the spectrum of the 3.15 MW machine, for the case of dynamic eccentricity of 0.7 of the geometrical air gap.

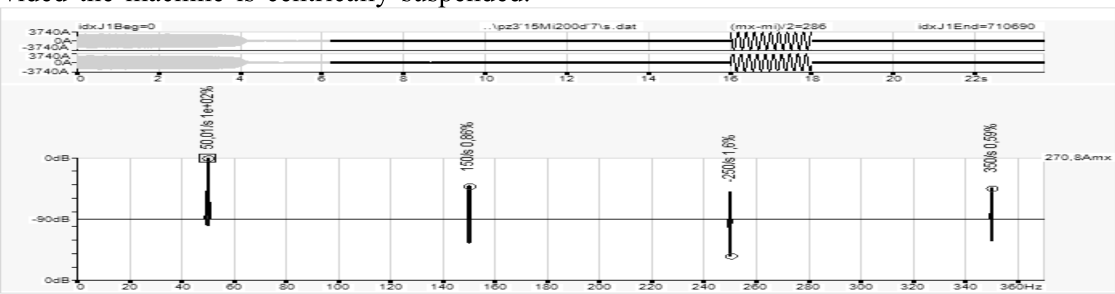

Fig.5a. Calculations. Fundamental harmonic zone. Eccentricity: static = 0, dynamic = 0.7.

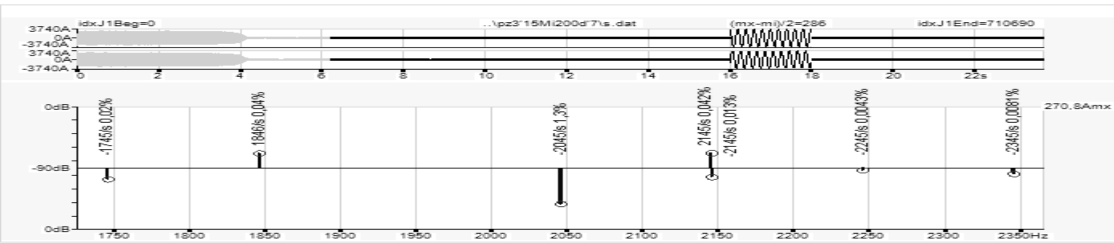

Fig.5b. Calculations. Slot harmonic zone. Eccentricity: static = 0, dynamic = 0.7.

In figure 5a, unlike in figure 4a, the fundamental harmonic consists practically of only the positive sequence. In figure 5b, unlike in figure 4b, the slot harmonic of the frequency a bit smaller than 2050 Hz consists of only a negative sequence. In figure 5b two new harmonics appeared which are characteristic for the dynamic eccentricity. The frequency of the first one is a bit smaller than 2150 Hz. It is shifted by $2n_R$ to the right of the slot harmonic, where n_R is the rotor speed expressed in revolutions per second. Unlike the slot harmonic, it rotates here in positive direction. The frequency of the second harmonic is a bit smaller than 1850 Hz. It is shifted by $2n_R$ to the left of the here not visible twin slot harmonic. The twin slot harmonic is not visible, as the static eccentricity is now zero. But its frequency is well defined (a bit smaller than 1950 Hz) and, here, is smaller by 100 Hz ($2f_1$) from the slot harmonic. The presence of these two characteristic harmonics can be considered as the symptom of dynamic eccentricity.

3.4 Machine with mixed eccentricity

Figure 6 shows the spectrum of the 3.15 MW machine, for the case of mixed eccentricity, static 0.5, and dynamic 0.1, both of geometrical air gap.

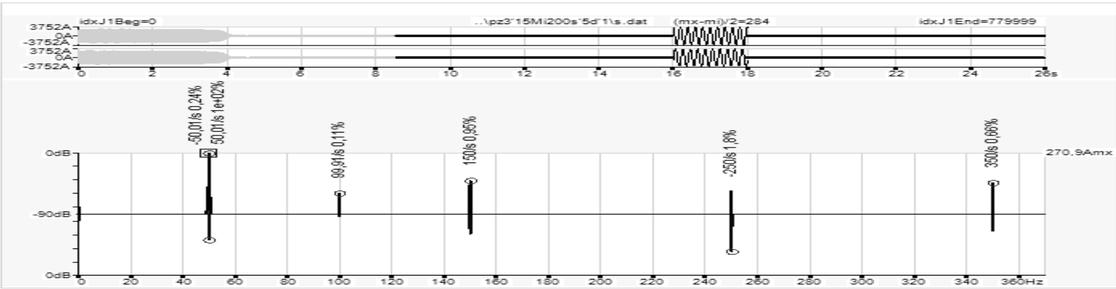

Fig.6a. Calculations. Fundamental harmonic zone. Eccentricity: static = 0.5, dynamic = 0.1.

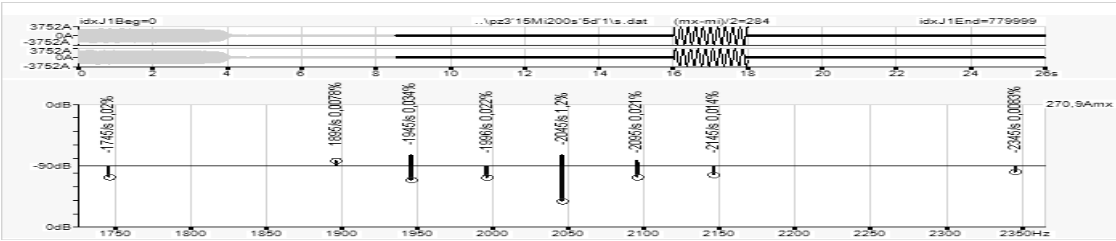

Fig.6b. Calculations. Slot harmonic zone. Eccentricity: static = 0.5, dynamic = 0.1.

The aim of this section is to compare the spectra shown in figures 6a and 6b with those shown in figures 1 and 2. In figure 6a the negative sequence of the fundamental harmonic is present (1st symptom of s. ecc.). In figure 6b the negative main slot harmonic is accompanied by its positive sequence counterpart (2nd symptom of s. ecc.). In figure 6b the negative twin harmonic (below 1950 Hz) is present (3rd symptom of s. ecc.). In figure 6b the twin harmonic also possesses its positive sequence counterpart (4th symptom of s. ecc.). It turns out that the 10 % dynamic eccentricity does not produce big enough harmonics being symptoms of dynamic eccentricity. However, in figure 6a the 100 Hz harmonic is present, what is symptom of mixed eccentricity. This was the reason for accounting for 10 % dynamic eccentricity in calculations.

4. Conclusions

1. The developed, and in C++ implemented dynamical model proved to be useful to perform calculations at the level of accuracy required by diagnostic investigations.
2. The developed, and in C# implemented diagnostic tool, based on complex-signal FFT analysis, allowed to reveal new symptoms of static eccentricity.
3. Both investigated industrial machines show symptoms of static eccentricity. They probably suffer also of minute dynamic eccentricity.

5. References

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Reviewer

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