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Problems of Practical Diagnostics of Induction Machines in Industry

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Summary: **There are many problems in practical diagnostics of high-power, squirrel-cage induction machines, operated in industrial conditions. These problems make the diagnostics a difficult matter. The problems appear already at the stage of gathering diagnostic signals. The only practically accessible signals are the currents on secondary sides of current transformers monitoring supply currents of separate machines. Due to the proximity of other conductors, carrying high currents, these signals are sometimes accompanied by heavy background noise. The next stage of the diagnostic procedure is off-line analysis of registered signals referring to investigated objects. The main problem at this stage is proper interpretation of gotten results, especially in the cases where determination of the cage state, of investigated machines, is difficult due to ambiguity of diagnostic signals. The ambiguities and doubts by taking diagnostic decision result from that the diagnostic-like signal could be generated not only by cage damage but also by slightly asymmetrically manufactured rotor cage. In such difficult cases, the many-year diagnosing experience is the indispensable precondition for proper diagnostic verdict.**

The present paper includes some reports on case studies encountered during practical diagnoses of high power, 6kV induction machines, operated in real industrial conditions.

Key words:
current measurement, diagnostic expert system, induction machine, squirrel cage motor

1. INTRODUCTION

Diagnosing of the cage state, of high-power, squirrel-cage induction machines, operated in real industrial conditions is confronted by numerous problems, causing the diagnostics a difficult matter. The problems appear already at the stage of gathering of diagnostic signals. The staff responsible for running the machines is not prone to allow for any, even temporary, changes in power supply configuration, of the machines under diagnostic survey. Hence, the only practically accessible signals are the currents of the secondary sides of current transformers monitoring supply currents of separate machines. The access to these currents is only allowed through current clips or current sensors, not requiring any disconnections in power supply circuitries. Due to the proximity of other conductors, carrying high currents, these signals are sometimes corrupted by heavy background noise. Normally, the current transformer secures good transfer capacity for 50Hz current. However, frequencies of diagnostic signals change, depending on current rotor speed, and can assume values far fetched from 50Hz. The same refers to passive-type current clips, used in the investigations the paper reports on. The problems become especially acute as the transfer capacity of current transformer diminishes drastically for low frequencies, being also of interest from diagnostic point of view. In practice, it was necessary to measure the frequency characteristic of the current clips. Of course, it was excluded to measure such characteristic with respect to current transformers installed on site. Hence, it was assumed that these characteristics coincide with those measured for the passive-type current clips. The product of these two characteristics was implemented as correction characteristic into the diagnostic software. It turned out that the measured transfer capacity of the current clips for 10Hz signal is 70%. Accounting also for a current transformer, the overall transfer factor for 10Hz component amounts to 0.5. Of course, this transfer factor falls down to zero for the constant signal, for which the frequency equals zero.

One of the interesting frequency ranges is just the vicinity of 10Hz, as during starting up the frequency of the diagnostic signal passes through this range. This frequency range is, for the one side, sufficiently lower than 50Hz, what allows to effectively damp the main current component, and for the other, is sufficiently high, to secure the overall transfer factor higher that 0.5. Acquisition of the currents was secured by a specially prepared measuring equipment, consisting of current clips, antialiazing filters, amplifiers and portable computer fitted with analog-digital converter. The specially prepared software allowed adjustment of sampling frequency. At earlier stages of investigations the frequency of about 4100Hz was assumed. Then, it turned out that the sampling frequency of about 6000Hz secured better insight in the current spectrums, facilitating better diagnoses.

The next stage of the diagnostic procedure is off-line analysis of registered signals, referring to investigated objects. Special, diagnostic oriented, software was made use of, for analysis of both the start up and steady state currents. The analysis of the start up currents was based on digital low pass filtering of these currents. The analysis of the steady state currents was based on FTT transform, of the minimum 20 seconds long current signals, multiplied by Hann window function. The main problem at this stage was proper interpretation of gotten results, especially in the cases where determination of the cage state, of investigated machines, is difficult due to ambiguity of diagnostic signals. The hardness and ambiguity of taking the diagnostic decision results from that a diagnostic-like signal could be generated not only by cage damage but also by slightly asymmetrically

manufactured rotor cage. In such difficult cases, the many-year diagnostic experience was the indispensable precondition for proper diagnoses.

The present paper includes reports on some case studies encountered during practical diagnoses of high power, 6kV, induction machines, operated in real, power plant, conditions. The cases posing difficulties are preceded and confronted by cases not rising any doubts.

2. SIMPLE CASES OF DIAGNOSTICS OF INDUCTION MACHINES

2.1. Motor without damage

Two diagnostic reports for two similar induction machines have been presented in Figures 1 and 2. Figure 1 refers to diagnosis based on start up current, whereas figure 2 to the one based on steady state current. The only restriction for the usability of the start up current for diagnostic purposes is its length of minimum half a second. That is due to the fact that right after switching on the diagnostic signal is corrupted by transient current components. It follows from the experience that the start up time higher than half a second secures damping of these corrupting components. Though, in some critical cases, only the second half of the diagnostic signal is valuable, that is the half referring to the rotor speed higher than 50% of the synchronous speed. In Figure 1 the start up time of about six seconds fulfills in excess this requirement. It follows from the Figure 1 that the level of diagnostic signal reaches 0.083%. It is well below 0.5%, being the threshold for damaged/non-damaged cage. This threshold was established through experience gathered from numerous diagnoses of both the real industrial machines and laboratory experiments on machines with purposefully cut-through cage bars.

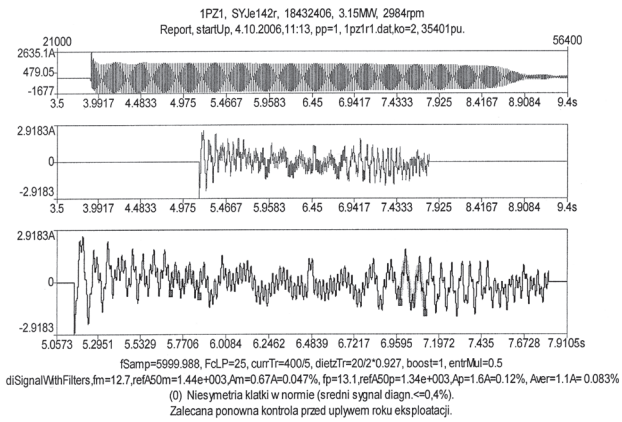

Fig. 1. Diagnostic report for induction motor without damages – start-up

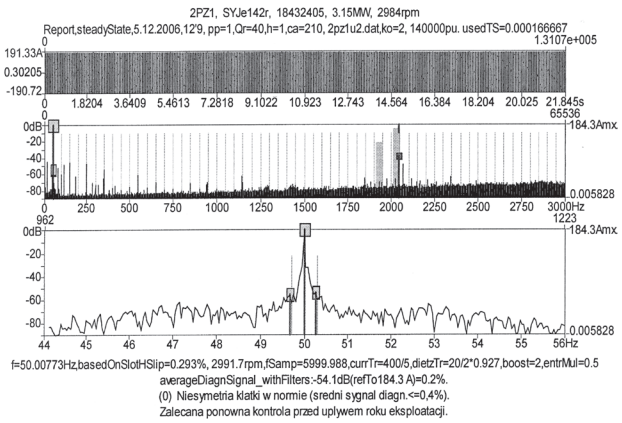

Fig. 2. Diagnostic report for induction motor without damages – steady state

The condition for the diagnostic value of the steady state currents is that they refer to the loaded machine, minimum 50% of the rated power. This secures sufficiently high currents flowing though the cage elements. Broken bars do not allow the currents to flow, to their full extents, through the damaged bars. This provokes air gap flux disturbances, as compared to the healthy case, resulting finally in diagnostic components in stator currents. Too small loading would provoke too small rotor currents and hence too small flux disturbance to induce discernible diagnostic signals in stator currents. However, there is one more, not less important, reason for the requirement of minimum 50% load. The diagnostic components in normal steady state are close to the 50Hz fundamental component. The smaller the slip the closer these components are to the fundamental or 50Hz component. Of course, the vicinity of the 50Hz fundamental component corrupts the diagnostic components, resulting in overestimation their amplitudes. Only big enough slip, following big enough loading, secures big enough separation of diagnostic components from the 50Hz component, thus preventing false assessment of their amplitudes. Hereby, it should be remembered that the bigger the machine the smaller the rated slip. In consequence, the just mentioned problem of identification of the amplitudes of the diagnostic components becomes extremely serious in case of big machines. And, in practice, exclusively the big machines are commissioned for diagnostics. In figure 2 the slip of 0.293% secured big enough distance of diagnostic components from the 50Hz one. The diagnostic signal amplitude of 0.2% falls well below the 0.5% threshold. Hence, the diagnostic verdict is that the rotor cage remains healthy.

Summing up, the magnitude of the diagnostic signal at a startup is 0.083% and at steady-state 0.2%. As these magnitudes are smaller than 0.5% the machines are diagnosed as not damaged.

2.2. Motor with damage symptoms

The reports presented in Figures 3 and 4 refer to one and the same machine. Figure 3 refers to the current registered on October 6th, 2006 and figure 4 on October 4th, 2006. As the dates of start up and steady state measurements are close to each other, it could be assumed that the cage state did not change. However, the amplitude of the diagnostic signal in Figure 3 amounts to 0.1% whereas that in figure 4 to 0.51%. The explanation for this discrepancy is that the results in Figures 3 and 4 refer to different regimes of operation. In Figure 3 the frequencies at which the amplitudes of the diagnostic component were identified were 11.3Hz and 9.8Hz. The frequency of the rotor currents, when these frequencies were identified, was around 25 Hz. Current distribution over separate cage bars depends on both the bar resistance and bar leakage reactance. Damaged cage bar only effects increase of bar resistance, and not bar reactance. The higher

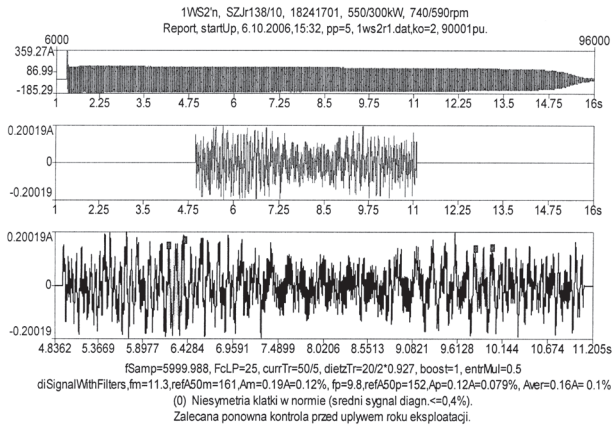

Fig. 3. Diagnostic report for induction motor with damage symptoms – start-up

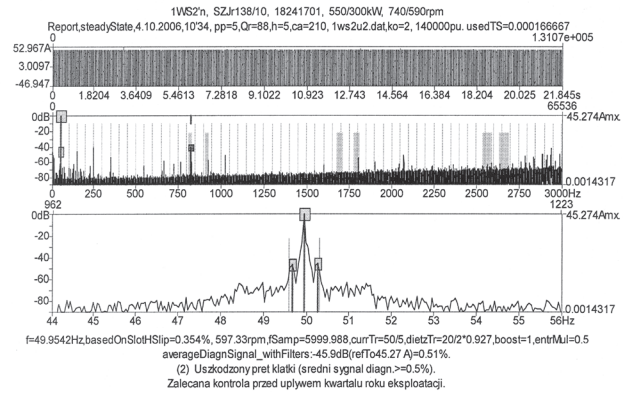

Fig. 4. Diagnostic report for induction motor with damage symptoms– steady state

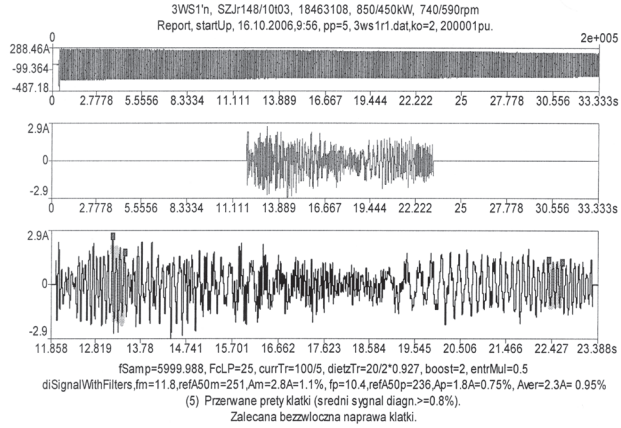

Fig. 5. Diagnostic report for induction motor with stable cage asymmetry – start-up

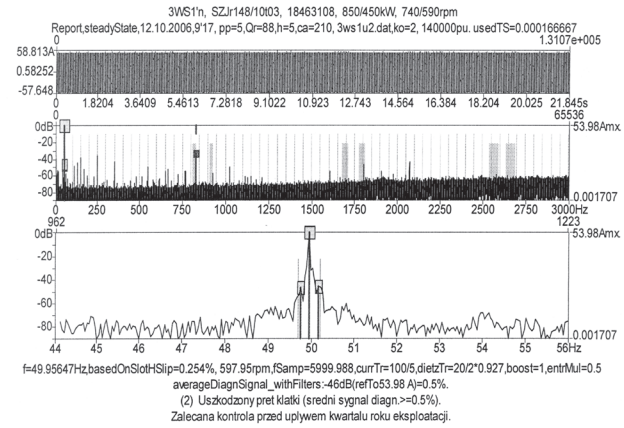

Fig. 6. Diagnostic report for induction motor with stable cage asymmetry – steady state

the rotor currents' frequency the higher the bar's reactance, and hence the lower the effect of increased bar's resistance on the result bar's impedance. In consequence, the disturbance in current distribution, followed by the disturbance in air gap flux, is small. Thus, small is also the diagnostic signal in Figure 3. To the contrary, by full speed the frequency of the rotor currents is very low. Low in then also the bar's reactance. In consequence, the bar's impedance is determined practically by bar's resistance. Hence, the disturbance in bar resistances carries to comparatively high disturbances of the air gap flux and thus to higher diagnostic signal. This explains the elevated (up to 0.51%) magnitude of the diagnostic signal in steady state. All this reasoning is valid only if the cage bar is not totally broken. Thus the ultimate diagnosis, resulting jointly from the Figure 3 and 4 is that the cage damage still remains in the incipient stage. It is expressed in diagnostic report as "symptoms of damaged cage".

3. SPECIAL CASES OF DIAGNOSTICS OF INDUCTION MACHINES

3.1. Big, but stable, start-up signal.

Figures 5 and 6 refer to one and the same machine. The amplitude of the diagnostic signal in Figure 5 amounts to 0.95%, thus well trespassing the half percent threshold for the cage to be diagnosed as damaged. The amplitude of the steady state signal in Figure 6, amounting to 0.5%, also confirms cage asymmetry. However, the diagnostic measurements performed in three previous years delivered practically exactly the same values. This allows to conclude that the cage asymmetry, though not rising any doubts, is stable and does not show up the tendency to magnify. One of the possible explanations for elevated, though stable, asymmetry could be that the end rings are of bended slabs of copper, welded together. The welding seam would surely introduce some magnified resistance of one end ring segment, resulting in overall cage asymmetry. The ultimate diagnosis, accounting also for three years old history, was that the cage, though asymmetric, was healthy.

3.2. Interrupted bar after certain heating

Figure 7 presents the diagnostic signal during starting up. The peculiarity of this signal lies in that after about 8 seconds from switching on, its amplitude magnifies in a step wise manner. The waveform shown in Figure 7 refers to measurements performed on October 31, 2006. Exactly the same signal envelope behavior was registered one year earlier. This seems to justify the supposition that after heavy heating of the cage, resulting from heat development during 8 seconds of start up, one of the cage bars looses its contact with one of the end rings. However, in steady state, that is when the cage cools down again to normal operating

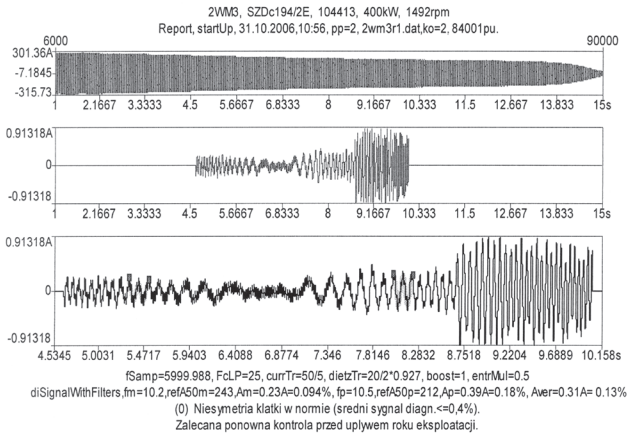

Fig. 7. Diagnostic report for induction motor with interrupted bar after certain heating – start-up

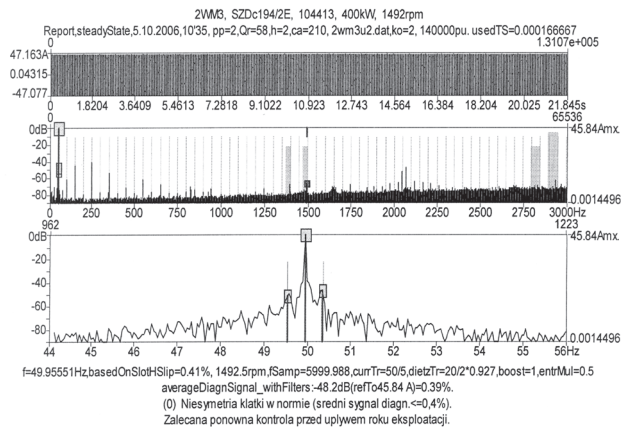

Fig. 8. Diagnostic report for induction motor with interrupted bar after certain heating – steady state

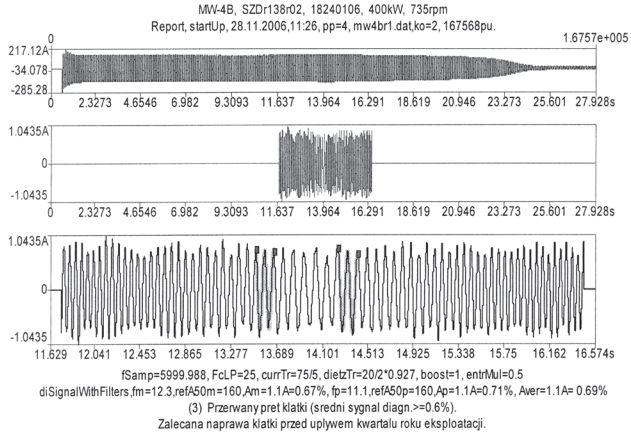

Fig. 9. Diagnostic report for induction motor with non-diagnostic signal – start-up

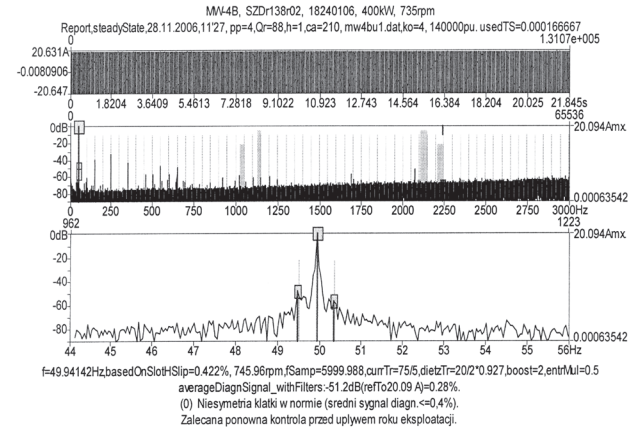

Fig. 10. Diagnostic report for induction motor with non-diagnostic signal – steady state

temperature of the cage, the bar regains its contact with the end ring, as the amplitude of the diagnostic signal in figure 8 amounts to 0.39%, that is, it does not trespasses the half percent threshold.

3.3. Non-diagnostic signal

Figure 9 contains the waveform of the diagnostic-like signal. When the speed approaches half of the synchronous one, the frequency of the signal diminishes. Then, above half of the synchronous speed, the frequency of the signal magnifies. These are features characteristic for diagnostic signal. However, for the signal to be recognized as diagnostic one, its amplitude by half of the synchronous speed had to fell down to zero. This is but not the case in Figure 9. Hence the only conclusion must be that this is not the diagnostic signal. The explanation of the nature and origin of this signal still remains unknown. The level of the diagnostic signal in figure 10 is 0.28%, confirming that the cage is healthy.

3.4. High level of background

Figures 11 and 12 refer to one and the same machine. Figure 11 refers to start up current. The start up time is rather short. The first half of the start up time is useless for the diagnostic purposes as the diagnostic signal is corrupted by the transient current components. But the second half of the start up current delivers clear diagnostic signal, amounting 0.23%. Thus, the cage is diagnosed as healthy. Figure 12 shows the spectrum referring to the steady state current. It contains heavy background, hardly allowing for sturdy identification of diagnostic components. In fact, the placements of these components was identified on the basis of current signal after notch-filter suppression of the 50Hz component. This technique of current registration, to be presented in a separate paper, proved to be priceless in cases like the one of Figure 12. The reason for heavy background is that the machine in Figure 12 drives the coal mill, accompanied by stochastic loading torque.

4. SUMMARY AND CONCLUSIONS

Normally, diagnostics of the state of the induction machine rotor cage is based on a well established theory relating the existence of the $(1\pm2s)f_0$ current components with the degree of cage asymmetry (s – slip, f_0 – supply frequency). In the case of steady state operated machine, both components are identifiable through FFT algorithms. During starting up, the $(1-2s)f_0$ component is identifiable through digital low pass filtering. However, in practice, both of these possibilities face sometimes serious problems, causing the diagnosis a difficult matter.

At steady state, especially by big machines, the diagnostic harmonics are very close to the fundamental one, causing the latter to corrupt the former ones. The situation worsens if the machine is only partially loaded, what result in operation

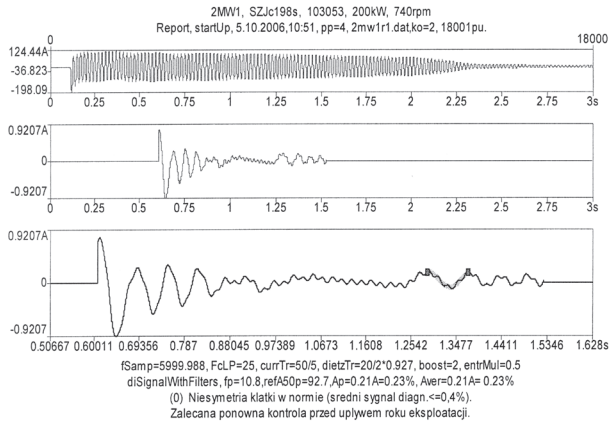

Fig. 11. Diagnostic report for induction motor with high background signal of measurements – start-up

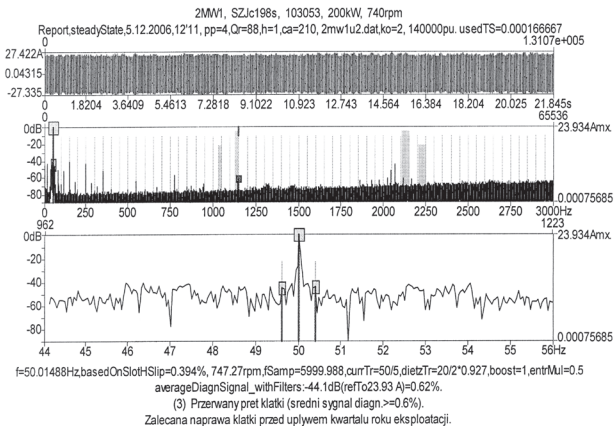

Fig. 12. Diagnostic report for induction motor with high background signal of measurements – steady state

at still smaller slip. At least 50% load could be treated as a general guide for loading conditions, to make the FFT based algorithm viable. Theoretically, it should be possible to magnify the time of current acquisition in order to enhance the frequency resolution. This, however, crushes in practice due to changing load conditions. It follows from many measurements that the acquisition time between 20 and 30 seconds turned out to be a good compromise securing big enough frequency resolution and sharp enough spectral plot.

During starting up, the critical problem for diagnosis could be the short starting up time. That is due to the fact that the start up current, apart of 50Hz fundamental, contains not only the diagnostic component but also transient components. The latter ones undergo damping, whereby the damping degree is higher for the higher rotor speed. By short startup times only the second half of the start up current could present diagnostic value. In practice, this problem was faced when the start up times were smaller than about 1 second.

The other group of problems are those resulting from that the current signals are always contaminated by the noise. It causes that the spectrums of the measured signals include high level of background (chapter 3.4). It happened to identify a non-diagnostic signal, remaining the diagnostic one (chapter 3.3). As it repeated itself in two successive years, the phenomenon must be recognizes as really existing, with respect to the investigated machine, though not explained thus far. In other case, sudden increase of diagnostic signal during start-up was identified. It causes some interpretation difficulties (chapter 3.2), even if not so serious as in the previous case. Many cases have been identified where the cages showed up some asymmetries, though not suffering from any ailments. The most probable reason was the technology of production, especially of the end rings, as welding of the end rings could introduce some additional resistance to one of the end ring segments (chapter 3.1). Drawing of these conclusions was possible thanks to performing measurements over several successive years. If the signal remains on constant level, over several last diagnostic periods, then the machine can be left in operation, despite of not fully symmetrical layout of the cage.

The problems mentioned above constitute only a small fraction of problems encountered during diagnostic activities in real industrial conditions. Estimating of conditions of induction motors requires often detailed analysis and the authors remain skeptical whether it would be possible to fully automatize the diagnostic procedures.

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