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INFLUENCE OF HIGHER HARMONICS ON LOSSES IN INDUCTION MACHINES

WPŁYW WYŻSZYCH HARMONICZNYCH NA STRATY W MASZYNIE INDUKCYJNEJ

A b s t r a c t

The paper summarizes the power loss results in induction machines supplied with distorted voltage. The voltage waveform contained the fifth and seventh harmonics components of adjustable level in the range of 0% to 30%. The influence of the harmonic content on the core and windings losses is of particular interest. The paper investigates the additive impacts of basic and additional losses resulting from distorted power supply conditions.

Keywords: induction machine losses, efficiency standards, power quality

S t r e s z c z e n i e

Artykuł przedstawia wyniki pomiarów strat silnika indukcyjnego zasilanego ze źródła napięcia odkształconego. Napięcie zawierało, prócz składowej podstawowej, także piątą i siódmą składową harmoniczną w zakresie od 0% do 30% w stosunku do składowej podstawowej. Badany był wpływ zawartości składowych na straty w rdzeniu i straty w wirniku silnika. Sprawdzono również czy straty powodowane zawartością poszczególnych składowych są addytywne.

Słowa kluczowe: maszyna indukcyjna, normy sprawności, jakość energii

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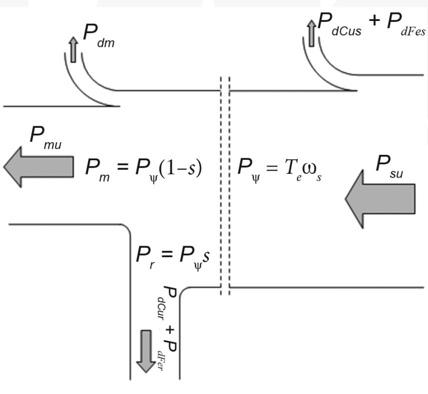
1. Introduction

The new standard IEC 60034–30 (International Electrotechnical Commission), published in 2011, introduces the method of assessing the efficiency ranges of all motors launched to the European market. In the light of the current standard, the class IE2 is required. Efficiency figures provided by manufacturers should be achieved at rated sinusoidal voltage supply conditions [1]. It can be expected that the declared standards may not be fulfilled when machines are supplied from poor–quality power sources. Efficiency standards may not be met by the very same machine operated in the conditions of poor–quality energy supply [2–4]. The quality of energy supply is a complex issue, beyond the scope of the present study, which focuses on the contribution of harmonics only.

The problem of iron losses and the impact of power quality on these losses have been discussed in a number of publications. The causes of losses in soft magnetic materials are described in the works [9, 10]; they also specified the methods of calculating these losses. The same author as in publication [3] describes the method of calculating the losses in rotating machines. The problem of losses increased due to the distorted power was discussed in work [12]. Modeling of losses in rotating machinery was also described in the works [2, 13]. All cited publications focus on modeling and calculating the iron losses caused by sinusoidal or distorted power. This article is a continuation of these studies, presenting the results of laboratory measurements of this problem.

2. Losses in Induction Machine

Typical energy flows and classes of energy losses of induction motors are well known [5, 6]. The flow of active power in an induction machine during a positive rotor slip, involving individual losses, is shown in the diagram in Fig. 1.



P_{su} – stator power; P_ψ – rotating field power; T_e – electromagnetic torque; ω_s – rotating field pulsation; P_m – mechanical power; P_{mu} – mechanical usable power; s – slip; P_r – rotor power (slip power); P_{dCus} – stator winding losses; P_{dCur} – rotor winding losses; P_{dFes} – stator core losses; P_{dFer} – rotor core losses; P_{dm} – mechanical losses

Fig. 1. The flow of active power in an induction machine

Harmonic distortions have a major impact on core and winding losses [6, 7]. The model of core losses is quite complicated and therefore loss prediction is not easy [8–15]. The Authors therefore undertook to directly measure the impacts of the higher harmonics on the loss results. This study is restricted to no–load tests and measurements were taken under varied conditions.

3. Measurements

During the idle run, all energy that is supplied becomes wasted on losses. The supplied energy is quite easy to measure. Voltage and currents are sampled and measured by an analog to digital (A/D) converter card. Voltage is supplied from a programmable AC source, allowing almost any shape of voltage waveform to be generated. A diagram of the measurement system is shown in Fig. 2. For each operating point of the machine, the waveform portion was recorded, with a 20 kHz sampling frequency, and calculations of the active power were performed accordingly [16]. For each case, the full 'no load test' was performed, involving power measurements for voltage being varied from 0.2 to 1.2 Un. All testing was done on a wound–rotor induction machine type SUDg 132M-4A, $U_N = 400$ V, $I_N = 13.0$ A, $n = 1400$ rpm, $P_N = 6.3$ kW.

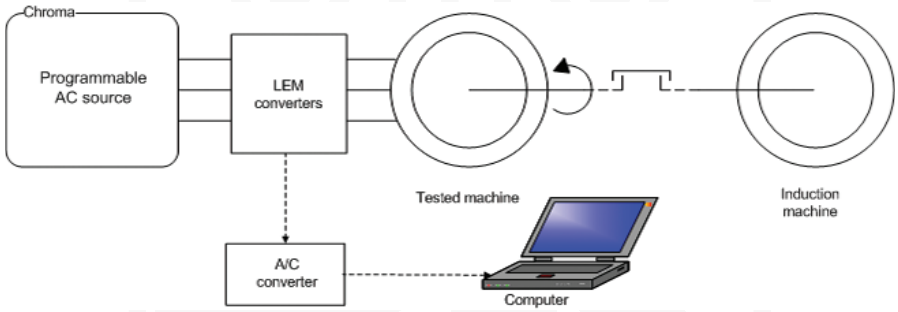


Fig. 2. Diagram of the measurement system

Four cases were considered in the test:
Case 1: rotor windings are open and rotor is immobile, the fifth harmonic is added
Case 2: rotor windings are open and rotor is immobile, the seventh harmonic is added
Case 3: rotor windings are shorted, rotor is in motion, the fifth harmonic is added
Case 4: rotor windings are shorted, rotor is in motion, the seventh harmonic is added

Seven tests were performed in each case, for 0, 5, 10, 15, 20, 25, 30% of added harmonics amplitude.

3.1. Case 1

The first set of tests was performed on a machine with open rotors windings and with the contribution of the fifth harmonic. Under these conditions, the active power of the supply source is wasted on stator winding losses and iron losses. Figure 3 shows iron losses only. It can be seen that there is a set of characteristic curves for different levels of harmonics contribution. In the range of 0.2–1 Un, the differences between curves are very small, indicating that the influence of the fifth harmonic on iron losses is rather minor. Fig. 4 shows a zoomed section of Fig. 3. It appears that the losses are even smaller for higher harmonic contents, which may be because the harmonic component changes the total RMS voltage value. Fluctuations of RMS value of voltage are therefore bigger than loss variations. One has to bear in mind, however, that the chart shows only the loss results obtained for the total RMS value of voltage.

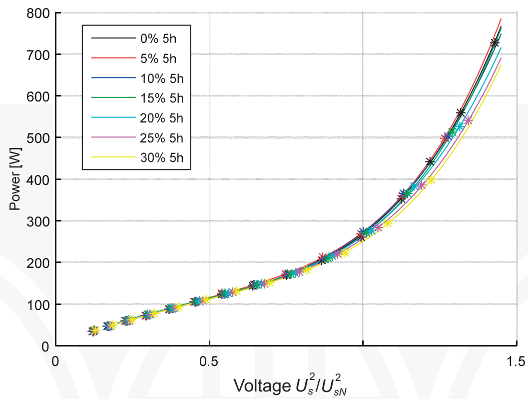


Fig. 3. Iron losses, for voltage with various amount of 5 harmonic added (with winding losses subtracted), open rotor

3.2. Case 2

The results of measurements taken for Case 2 and involving the seventh harmonic contribution were very similar. The zoomed section of the graph near the nominal voltage value is shown in Fig. 5. The losses turned out to be similar to those reported in Case 1.

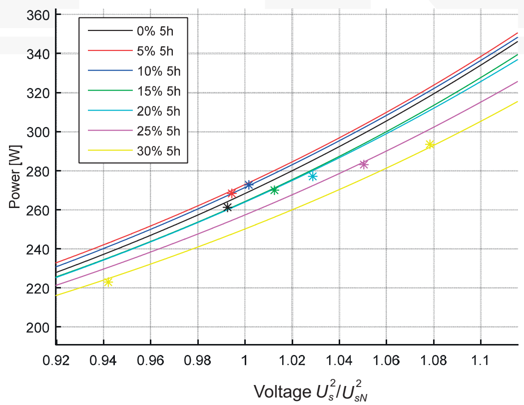


Fig. 4. Iron losses, for voltage with various amount of 5 harmonic added (with winding losses subtracted), zoomed section

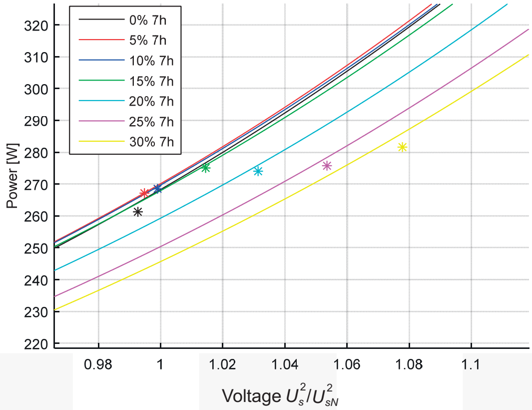


Fig. 5. Iron losses, for voltage with various amount of 7 harmonic added (with winding losses subtracted), zoomed section

3.3. Case 3

During this test, the rotor windings were shorted so the total losses of the machine should involve the core losses and rotor winding losses. Mechanical losses and stator winding losses were subtracted after the measurements. The resistance of the stator windings was measured by the technical method, the same for all tests. It is worthwhile to mention that, in the first and second case, the magnetic field pulsation in the stator and rotor remained the same. Now, when the rotor speed is nearing the synchronous speed, the magnetic field pulsation of the rotor caused by fundamental harmonic is close to zero, whilst the pulsation due to higher harmonics will be nonzero. The fifth harmonic is a positive sequence component and therefore the rotor's magnetic field pulsation due to this component is increased by the rotational speed, giving the rotor current a frequency of 300 Hz. Waveform measurement data seem to corroborate this view (Fig. 6). Fig. 7 shows the characteristics obtained for the

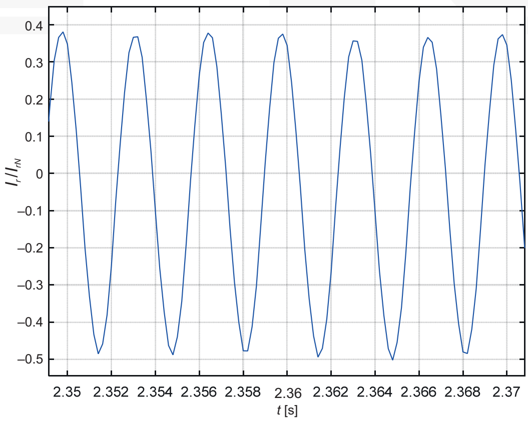


Fig. 6. Rotor current waveform

fifth harmonic contribution. In contrast to Case 1, the losses are clearly dependent on the harmonic contribution. It can be assumed that it is so because of the losses from the rotor's current. The loss increase can be well seen in Fig. 8.

It is readily apparent that the contribution of 30% of the fifth harmonic produces a 30% increase of the losses in relation to those registered for the clear sine waveform.

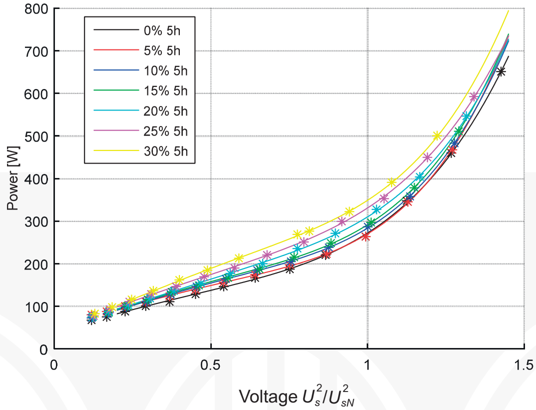


Fig. 7. Idle run losses, for voltage with various amount of 5 harmonic added (with winding and mechanical losses subtracted) shorted rotor

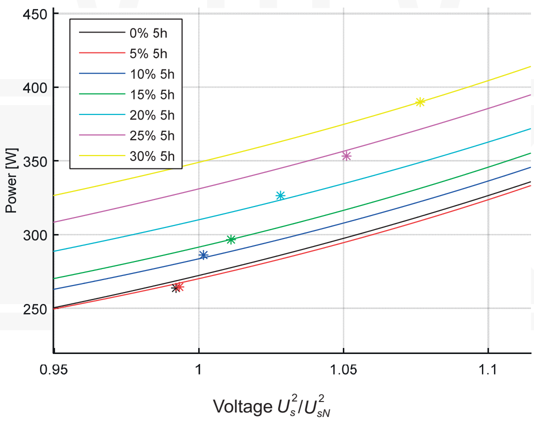


Fig. 8. Idle run losses, for voltage with various amount of 5 harmonic added (with winding and mechanical losses subtracted) shorted rotor, zoomed section

3.4. Case 4

Similar measurements taken for the seventh harmonic reveal a decidedly smaller increase of rotor winding and rotor core losses. It may seem unexpected, as the magnetic field pulsation in the rotor was identical. One has to bear in mind, however, that pulsation is the same because the seventh harmonic is a negative sequence component, and therefore the magnetic field pulsation in the rotor due to this component is decreased by the rotational speed. Fig. 9 gives a zoomed section of the characteristic showing the contribution of the seventh harmonic.

In the case of the seventh harmonic, the maximal loss increase is about 12% compared to the purely sine waveform supply conditions. The difference between losses registered with the fifth and seventh harmonic contribution is attributable to the damping of higher frequencies by the stator windings.

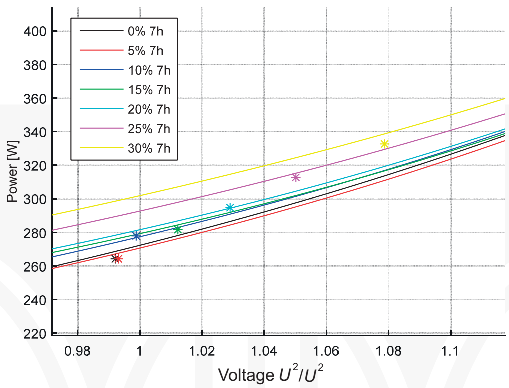


Fig. 9. Idle run losses, for voltage with various amount of 7 harmonic added (with winding and mechanical losses subtracted) shorted rotor, zoomed section

For clarity of presentation, let us consider another characteristic. Fig. 10 plots the losses under nominal voltage versus the level of harmonic contribution. In Case 1 and Case 2, (open rotor) we only obtain iron losses, whereas in Case 3 and Case 4 (shorted rotor), the rotor winding losses are also involved.

The dashed lines in Fig. 10 denote core losses in the rotor and stator due to the fifth and seventh harmonics. Solid lines denote losses registered in Case 3 and Case 4, when the losses

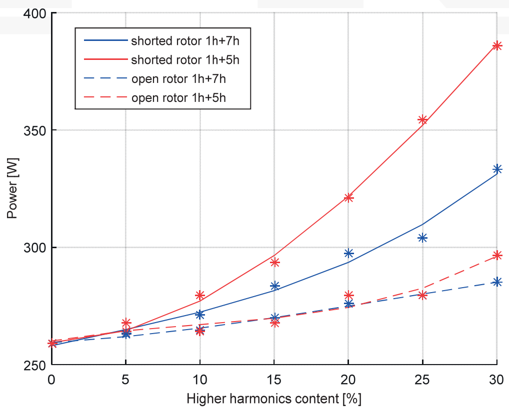


Fig. 10. Losses under idle run, with open and shorted rotor

are further increased by rotor currents. For practical purposes, only the results obtained for harmonic contribution of up to 15% will be relevant. Higher harmonics contributions are rather unusual in real–life conditions, which is why the measurements taken of higher harmonics provide the framework for comparison only. Test results reveal that major loss increases are caused only by the rotor current. Iron losses are increased slightly, and in the same extent for both harmonics (the fifth and seventh).

4. Additivity of losses

Further experiments were performed to check whether the losses due to the fundamental harmonic and higher harmonics would simply add up. Having already measured the loss due to the pure fundamental harmonic, we proceeded to measure losses due to higher harmonics only. The frequency of the applied voltage supply was 250 Hz as well as 350 Hz and the amplitude fell in the range of 0–30% of the nominal value.

As in the previous cases (Case 1 and Case 2), we measured losses while rotor windings were open and the rotor was stalled, and while rotor windings are shorted and the rotor was rotating (Case 3 and 4). To ensure the required rotating speed, the rotor was driven by another induction machine (Fig. 2).

Figure 11 shows experimental results obtained when the rotor windings were open. Upper lines denote results for the distorted supply conditions (fundamental and higher harmonics); lower lines denote the power supply conditions with the contribution of higher harmonics only. The graph reveals the power after deducting losses in stator windings, so iron losses can be clearly seen.

When the losses due to the contribution of fundamental harmonic and higher harmonics are simply added (dashed line in Fig. 12), we obtain values nearing those obtained for the distorted supply conditions (solid lines in Fig. 12).

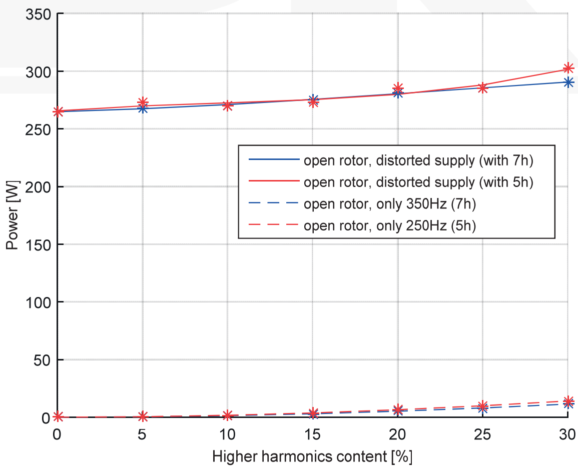


Fig. 11. Study of the additivity of losses. Iron losses

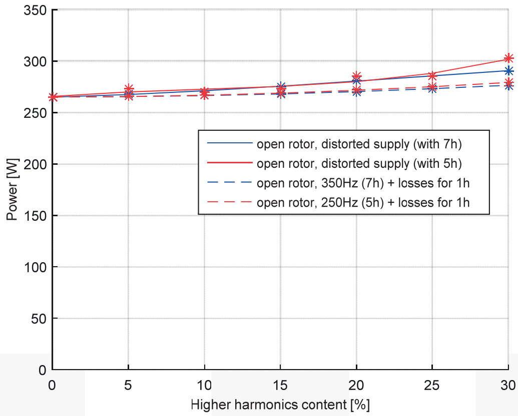


Fig. 12. Study of the additivity of losses. Iron losses, comparison

For a harmonics contribution of 15% or less, the values are very close, while for higher harmonics contributions, the power values tend to differ slightly because of the saturation effect. In other words: voltage supply conditions with higher harmonics contribution tend to shift to the nonlinear area on the iron core magnetization curve.

The results of experiments with shorted rotor windings are presented in Fig. 13. To ensure the same test conditions as in Case 3 and 4, the rotor had to be driven by an additional machine. Therefore, pulsation of higher flux density harmonics in the rotor was the same as in the previous tests. The results are represented by a dashed line in Fig. 13, providing the comparison to Case 3 and 4 (solid lines).

Loss increase is more considerable than in the tests with open rotor windings because of additional losses in rotor windings. Higher harmonics contribution causes the current flow at a frequency of 300 Hz in the rotor windings, as it was discussed before.

The summarized results (see Fig. 14) reveal that losses due to distorted supply conditions are quite similar to those registered for the contributing fundamental harmonic summed with higher harmonics.

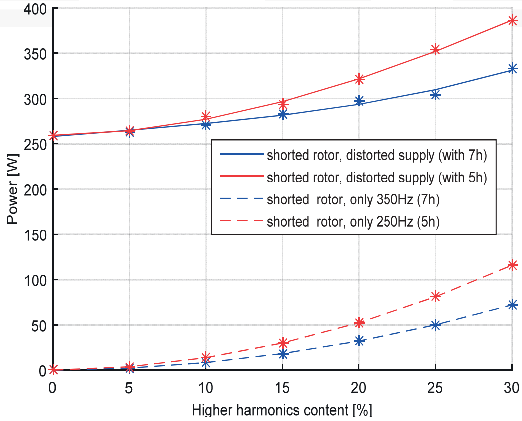


Fig. 13. Study of the additivity of losses. Losses under idle run (P–Pdcu–Pdm)

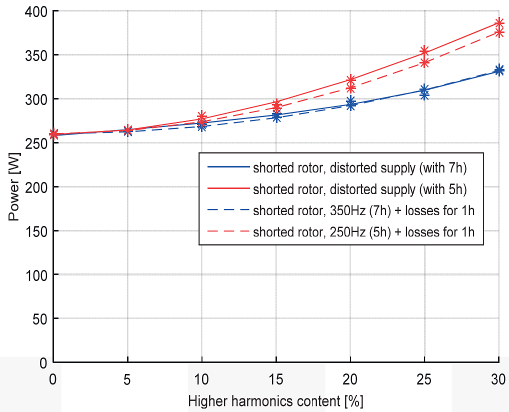


Fig. 14. Study of the additivity of losses. Losses under idle run (P–Pdcu–Pdm), comparison

5. Conclusion

Iron losses depend on higher harmonics in a minor degree only. For harmonics contribution of up to 15%, they practically remain on the same level and they are nearly the same for both the fifth and seventh harmonics.

The loss increased during the tests with shorted rotor windings. This is a normal state of work for the induction machine. Higher losses are attributable to currents induced by higher harmonics in the rotor windings. Here, the fifth harmonic gives rise to higher losses due to the damping of the seventh (and higher) harmonic in stator windings. Besides, it appears that losses due to higher harmonics and the fundamental harmonic tend to add up. The effects they produce in the core and windings of machines are the same, no matter whether contributing jointly or separately.

However, losses caused by higher harmonics seem not to be comparable, almost all of them affect the rotor, not the stator. In some cases, it could be a problem, because of the fact that heat transfer from the rotor is much more difficult than from the stator.

The investigations presented in the article do not cover work under the load, and the influence of the higher harmonics on the rated parameters of the machines was not tested as well.

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