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Additional Losses by Magnetic Field Harmonics in the Rotor Bars of Asynchronous Machines and their Influence

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Summary: **Optimizing the efficiency of modern asynchronous machines requires the knowledge of the particular loss components. In this contribution a method shall be presented, where by the transient FEM-calculation the copper losses in the rotor bars by harmonic field effects and the consequential originating harmonic currents can be estimated. By this way the determination of the current density of the rotor current harmonics is carried out along the height of the rotor bar. The loss distribution from the bar bottom to the bar tip is derived from the effective current density and its spatial distribution. The calculation shows, that the additional losses represent a considerable quantum of the total losses, they are partly in the range of the fundamental copper losses and therewith they have a lasting effect on the efficiency of the machine. By convenient geometrical actions a reduction of the additional losses is possible.**

Key words:
induction motors, losses, additional losses, finite element method

1. INTRODUCTION

Losses in electrical machines can be determined both arithmetically and metrological relatively unproblematic, if they occur as winding losses or core losses as well as mechanical losses. Furthermore additional losses appear, which cannot be explained by the effect of the magnetic main-wave field. They are considered by a load-dependent coefficient and amounts to 0,5% of the input power up to 5% in unfavourable cases for squirrel cage induction machines.

The graduation into efficiency grades according to the European motor-challenge-program assumes an accurate arithmetically and metrological determination of the additional losses. The differences of EFF 1 and EFF 3 amounts to only 3% to 1% in the power range from 10 kW to 90 kW. In conformity with the IEC 61972 a value of 0,5% is valid for the additional losses in case of the metrological determination, in case of a general assignment to the rated power a higher value between 3% and 1% is valid [1].

Additional losses originate by leakage fluxes in inactive elements, by armature reaction of advanced type, current displacement in the stator winding and iron cross currents in squirrel cages with skewed, non-isolated bars. The additional losses include among others also the additional losses in the rotor bars by harmonic wave fields. This harmonic wave fields cause harmonic currents especially in the upper region of the rotor bar and affect a considerable increase of the copper losses.

Losses by harmonic currents in the rotor bar occur already in the idle run and are dependent on the load of the machine. How it will be exposed, in case of squirrel cage motors the additional copper losses are dominating compared with the iron losses.

2. FORMATION OF FIELD HARMONICS

The stator winding of the asynchronous machine evolves beside the main wave of the magnetic field a quite number of harmonic wave fields of different frequency, the amplitudes of which are dependent from their ordinal number and their winding factor. It is valid for the magnetomotive force wave for the case that the rotor winding iterates after one double pole pitch:

$$\Theta_{1,\nu} = k \cdot \xi_{1,\nu} \cdot \frac{1}{\nu} \cdot \hat{i}_1 \cdot cos\left(\lambda_1 \gamma_1 - \omega_1 t - \varphi_{i1}\right) \quad (1)$$

With $\nu = |\lambda_1|$ and $\lambda_1 = 3 \cdot g + 1;\ g = 0,\ \pm 1,\ \pm 2,$ .. there occur positive and negative rotating waves. Several harmonics eliminate themselves in the three-phase system respectively they disappear, since their winding factor amounts to $\xi_{1,\nu} = 0$. Particularly the slot harmonics are coined, since their winding factor is equal to whom of the main wave. The whole spectrum of the magnetomotive force distribution can be calculated in consideration of the winding factors as the sum of the harmonics.

$$\Theta_1(\gamma) = \sum \xi_\nu \cdot \hat{\Theta}_{1,\nu}(\gamma) \quad (2)$$

Each wave of the stator magnetomotive force (mmf) causes a sequence of rotor waves. These induce in the cage loop voltages, which drive harmonics of the rotor current. The strength of their occurrence can again be described with the coupling factor:

$$\xi_{k,\nu} = \frac{sin\frac{\nu \cdot \varepsilon}{2}}{\frac{\nu \cdot \varepsilon}{2}} \quad \text{with} \quad \varepsilon = \frac{p \cdot 2 \cdot \pi}{N_2} \quad (3)$$

where:
p — number of pole pairs,
N_2 — number of rotor slots,
or as leakage coefficient of the reactance of the actual harmonic [2].

$$\sigma_{\sigma,\nu} = \frac{1}{\xi_{k,\nu}^2} - 1 \quad (4)$$

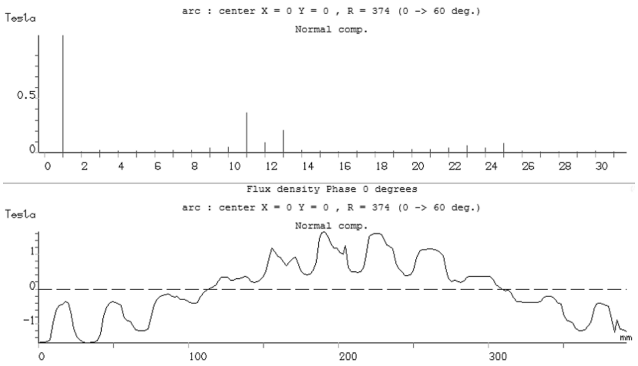

Fig. 1. Radial component of the air gap induction and its Fourier analysis

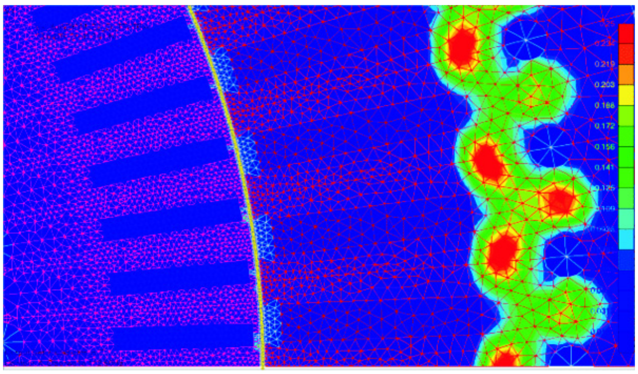

Fig. 2. Distribution of the flux density at 100% load, 5th harmonic, normalization 0..0.25 T

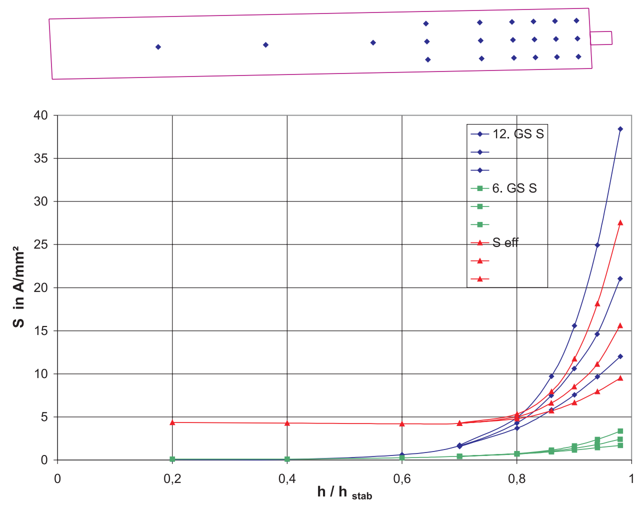

Fig. 3. Harmonic analysis of the current density $\hat{S}_\nu$ along the 1st rotor bar and calculation points in the rotor bar

The coupling of the particular harmonics is changing according to the choice of the rotor slot number N_2 very intensive. Contrariwise desired harmonics can be suppressed.

There are analytical approaches or programmes for the quantitative computation of the actual occurring field harmonics in the rotor region [3]. Thereby the accurate consideration of the real geometry and saturation conditions can be problematically. Accurate results there the method of numeric field calculation supplies, like it is applied in the following chapter.

3. FEM-METHOD OF LOSS DETERMINATION

3.1. Conditions for the FEM-calculation

The geometry of the regarded asynchronous machine consists of a stator with a chorded two-layer winding with open slots and a deep bar squirrel cage.

The stationary FEM-calculation supplies predications about the field distribution in the stator and the rotor as well as the air gap induction and the appearing winding harmonics, as Figure 1 shows. At the magnetodynamic calculation with complex vector potential approach also the frequency of the rotor quantities is known, with it already the current displacement in the rotor bars can be calculated.

By the transient calculation especially the harmonic wave effects by the slotting of the stator and the rotor and the consequential originating losses can be estimated. The rotor drives with a speed corresponding to the slip, the stator winding is fed with a sinusoidal voltage at the rated frequency. The rotation is carried out with a step width, which allows the registration of the essential harmonics.

The rotation of the motor is carried out over a double pole pitch. Therewith not all states are realized the registration of the harmonics of the rotor current and the losses is guaranteed.

3.2. Calculation of the iron losses

The calculation of the stator and rotor losses is carried out according to [4] from the transient calculation with the really occurring harmonics and subharmonics of each element by the harmonic analysis of the time course and following the loss calculation from the value of the harmonics summarized over all elements of the regarded section. Figure 2 shows exemplary the formation of the 5th harmonic in the stator.

Well to be seen is the concentration of the 5th harmonic to the areas between the stator teeth and the stator yoke, which causes there exalted iron losses. The slotting harmonics are reflected marked in the tooth tip area of the rotor. Asymmetries in the evaluation caused by the fact, that the rotation over the period of a original winding ensures that all harmonics are captured, though due to the existing slip not all appearing states can be realized.

3.3. Computation of the rotor bar additional losses

In the area of the tooth tip considerable differences of the harmonic effects occur in accordance with the magnetic field course. The calculation therefore is carried out in the upper range of the rotor bar in three areas with the plotted calculation points.

Figure 3 shows the course of the current density across the whole rotor bar for the 6th (6. GS S) and the 12th (12. GS S) harmonic of the fundamental of the stator and its effective value. Thereby in the tooth bottom the same current density takes effect as in the stationary calculation, whereas in the tooth tip especially the slotting harmonics 1st order referred to the fundamental of the stator take effect. The effective current density S_{eff} is calculated with:

$$S_{eff} = \sqrt{S_0^2 + \frac{1}{2} \cdot \sum_{\nu} \hat{S}_\nu^2} \qquad (5)$$

Since the harmonics don't occur spatially und with it also temporally with the same amplitude, the area of the tooth tip must be investigated for every bar like shown in Figure 4.

From the effective value of the spatial distribution the effective current density of the several harmonics and the effective value of the responsible for the copper losses total value can be calculated.

From the effective current density the loss distribution along a rotor bar from the bar bottom to the bar tip can be calculated. From the loss distribution in the three ranges by summation under consideration of the width of the ranges a loss coating P_V^* as a function of the bar height can be determined. The loss coating contains a constant quota and a quota by current harmonics, which permit the following proximity:

$$P_V^* = S_{eff}^2 \cdot l_{stab} \cdot b_{stab} \cdot \rho \qquad (6)$$

where:

l_{stab} — bar length,
b_{stab} — bar width.

$$P_{cu2,stab} = P_{V,0} + P_{V,zus} \qquad (7)$$

$$P_{cu2,stab} = N_2 \cdot \left(\int_0^{h_{stab}} p_0^* \, dh + \int_{h_x}^{h_{stab}} p_{zus}^* \cdot \left(\frac{h - h_{stab}}{[mm]} \right)^3 dh \right) [W]$$

Thereby the 2nd quota $P_{V,zus}$ represents the additional losses. The range $h_x \leq h \leq h_{stab}$ comprises circa 25% of the bar height in the investigated example.

4. CALCULATION RESULTS

Figure 5 shows the distribution of the loss density by the effect of the harmonic wave fields in the rotor bar and in the iron. It follows the dominating quota of the copper losses compared with the iron losses.

The described losses must be associated to the additional losses. Normally these are estimated as percentage of the absorbed active power. In the available cases these loss percentages amounts to 2.3% of the absorbed active power. There the other additional losses come along anymore. With it for unfavourable slot number combinations the assumed factor between 0.5% to 1% is to be rated as not sufficient for the calculation.

The losses by current harmonics in the rotor bars occur already in the idle run and are dependent of the load of the machine.

Figure 6 shows the dependence of the additional losses of the machine. Since the harmonics occur always in the idle run, the losses in the rotor bars occur likewise always in the idle run. At measurements often these are imputed by mistake exalting iron losses. For the calculation of the additional losses a constant quota should complete the current- or torque-dependent quota more right.

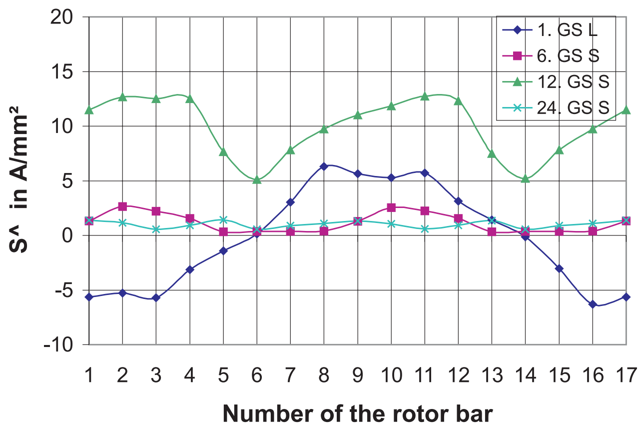

Fig. 4. Distribution of the harmonics (amplitude)

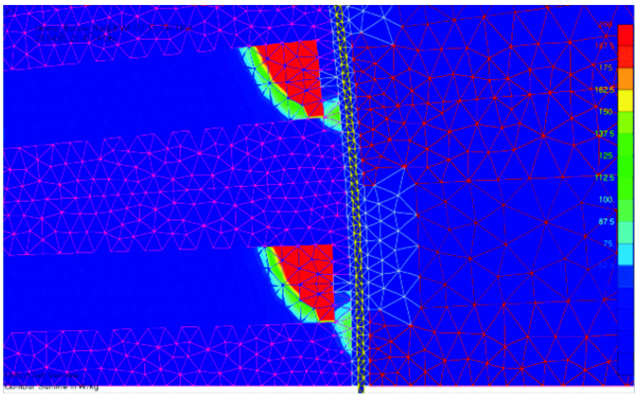

Fig. 5. Loss density sum by the harmonics in copper and iron, normalization 0..200 W/kg

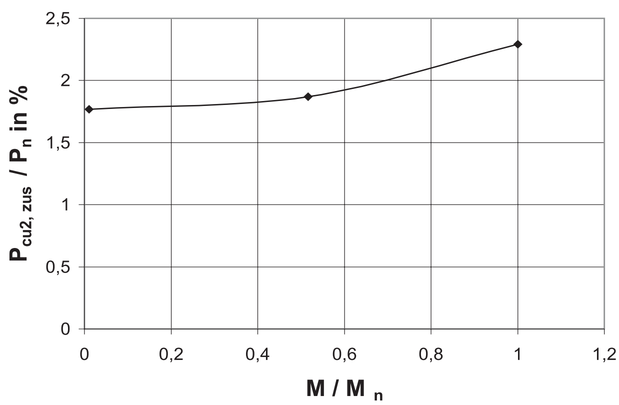

Fig. 6. Additional losses $P_{cu2,zus}$ as a function of the load

$$P_{Vzus} = P_{vzus0} + P_{1n} \cdot \left(\frac{I_1}{I_{1n}} \right)^2 \qquad (8)$$

The additional losses by harmonics in the rotor bars can be explained by the effect of harmonic wave fields of the stator mmf. Their propagation can be antagonized by two different ways:

— the variation of the effective leakage reactance for the concerning harmonic be changing the rotor geometry in the tooth tip area;
— the variation of the coupling of the rotor winding with the harmonic wave fields by suitable slot number ratios.

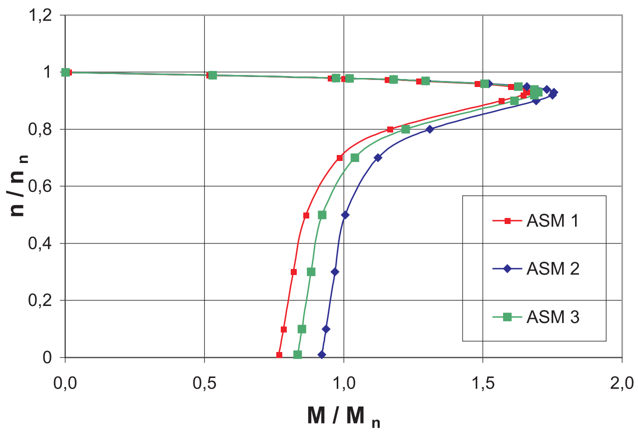

Fig. 7. Speed as a function of the torque, related to the rated values

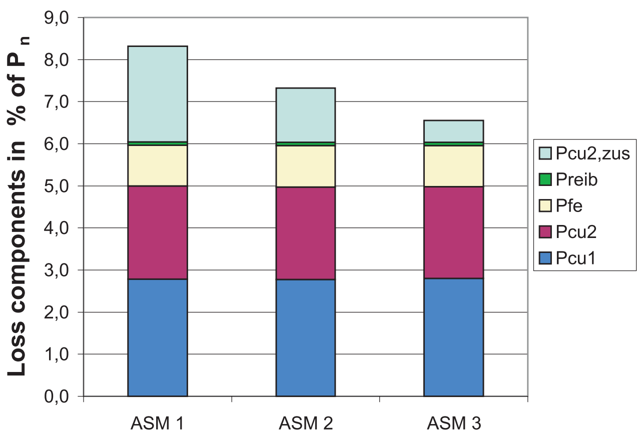

Fig. 8. Loss components in the analysed machines

The second measure shall be tried at further computations. By the decrease of the slot number in the rotor the coupling of the slot harmonics 1st order shall be reduced. Thereby is valid in the investigated example:

$$N_{2,ASM\,1} > N_{2,ASM\,2} > N_{2,ASM\,3} \qquad (9)$$

The operating parameters of the machine are not changed by it. Minor deviations results however by the modified leakage to the breakdown torque, the initial torque and the short-circuit currents of the machine. Figure 7 shows the characteristics of the so modified machines.

In addition to the additional losses the other loss components are computed and compared with.

$$P_{V,ges} = P_{V,cu1} + P_{V,cu2} + P_{V,fe} + P_{V,reib} + P_{V,zus} \qquad (10)$$

where:

$P_{V,cu}$ — copper losses,
$P_{V,fe}$ — iron losses,
$P_{V,reib}$ — friction losses

Like presented in Figure 8, in the rotor the great loss component of the copper losses by current harmonics $P_{cu2,zus}$ is revealed caused especially by the dominating harmonics of the rotor mmf.

The additional losses calculated that way amounts at the regarded machines at the rated point between 0.6% and 2.3% of the absorbed power and are with it partially in the range of the main wave copper losses of the rotor.

Since the other parts are unchanged, the efficiency of the machine improves from $\eta = 92.3\%$ to $\eta = 93.2\%$ respectively $\eta = 93.8\%$.

5. CONCLUSIONS

Additional losses at asynchronous machines play a important role especially at unfavourable conditions and can influence the efficiency considerable. There is described a method, by with these losses can be calculated quite accurate. However by suitable geometric measures these loss components can be reduced considerable. This is possible without influencing the other parameters of the machine adversarial.

In the available cases this loss parts amounts from 0.6% to 2.3% of the absorbed active power consisting of an idle run component and a component increasing quadratic with the load. Therewith for unfavourable slot number ratios an assumed factor between 0.5% and 1% of the absorbed effective value of the machine is to be estimated as insufficient.

REFERENCES

1. Hartnuß H.: *Vergleich genormter Verfahren zur Bestimmung des Wirkungsgrades von Induktionsmaschinen*. Electrical Engineering 81 (1998) 281, Springer-Verlag 1998.
2. Müller G.: *Betriebsverhalten rotierender elektrischer Maschinen*. Verlag Technik Berlin 1985.
3. Janssen W.: *Analytische Berechnung von Stromwärmeverlusten in Käfigläufermotoren unter Einschluß der Ankerrückwirkung zweiter Art und der Ständernutung*. Elektrie, Band 56 (2002) Heft 1–4, Berlin 2002.
4. Schuffenhauer U., Kuß H.: *A novel method for the determination of the iron losses and the rotor additional losses in electric rotating field machines*. XLI Symposium on Electrical machines SME 2005, Opole 2005.

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