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DETERMINATION OF THE IRON LOSSES AND ROTOR ADDITIONAL LOSSES IN ELECTRIC MACHINES BY ADVANCED METHODS

ABSTRACT   *New demands of modern electric drives cause ever new machine designs. Simultaneous the utilization is increasing. This induces, that usual algorithms for the loss calculation are not valid any more in the full extent. The construction of prototypes should be dispensed with, so accurate calculation methods are necessary.*

In this contribution methods are presented for calculation of the iron losses of electrical machines. In addition to the short consideration of conventional analytical methods new procedures are regarded, with which both the losses through harmonics and the losses in the rotor and inactive parts of the magnetic circuit can be computed by utilization of the results of static or transient FEM computations.

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1. INTRODUCTION

The ever increasing utilization of modern electric drives, the thrust into new speed ranges at high speed machines and the operation in inverter mode also in the field weakening range results in the necessity of the accurate calculation of the iron losses. Losses originate in electrical machines by current flow in the windings, through effect of the temporally magnetic field changing as well as as mechanical losses.

While the winding losses in the stationary case are accessible easily for a calculation without regard of the current displacement, the connections are more complicated for the losses in the magnetic circuit. Calculation in particular runs into difficulties through the following factors:

- non-linear characteristics of the material depending on the field strength and the frequency
- sections of cross-section changing itself, different division of the magnetic circuit and the occurrence of litter courses
- harmonic appearances in the magnetic field
- different way of magnetization
- mechanical processing.

Therefore in the following novel calculation methods for the iron and stray losses is presented.

This method of the calculation of the losses und the representation of the loss distribution is carried out for different construction types of typical synchronous and asynchronous machines.

2. MATERIALS

Losses originate in all active and passive parts of the electrical machine. Whereas the losses in the laminated part are confessed by producer specification, they must be derived from the material properties in the compact parts.

2.1. Laminated iron - material characteristics

For calculation of the magnetic circuit with the aid of the reluctance, the process of the B-H-curve is from decisive importance. The same applies to calculation of the losses. The B-H-curve and the loss characteristic are both dependent on induction as the frequency.

The remagnetizing losses result through hysteresis and eddy currents. Losses due to hysteresis result by cycling the hysteresis loop with the frequency f. The face within the hysteresis loop is proportional to the square of induction and corresponds to the power dissipation. With it in the frequency range around $f = 50$ Hz after /1/ the specific loss part through hysteresis p_h and the loss part through eddy currents p_{wb} result in

$$p_h = \sigma_h \cdot k_h \frac{f}{50\,\mathrm{Hz}} \cdot \left(\frac{B}{T}\right)^2, \quad p_{wb} = \sigma_{wb} \cdot k_{wb} \left(\frac{f}{50\,\mathrm{Hz}}\right)^2 \cdot \left(\frac{B}{T}\right)^2 \tag{1}$$

The specific losses σ_h and σ_{wb} may be for $f = 50$ Hz and $B = 1$ T specified, in the case of great deviations from these values, other paired values are valid. The allowance factor k contains the higher losses during rotating magnetization and the processing allowances.

The entire hysteresis losses amount to

$$P_{Vfe} = (p_h + p_{wb}) \cdot m_{fe} \tag{2}$$

In addition to these closed loss functions, the representation of the material properties is possible with bisplines. Experimentally determined material characteristics with the functions for the magnetic field strength and the power dissipation

$$H = f(B, f) \quad \text{and} \quad P_V = f(B, f) \tag{3}$$

supply the material properties valid over a long frequency and induction range. The material characteristics form functional faces those can be described by means of 3rd order bisplines and its functional values are put down in the material file in the mentioned form. As plotted in Fig. 1 these material characteristics can be described normally over wide frequency ranges by the loss factors.
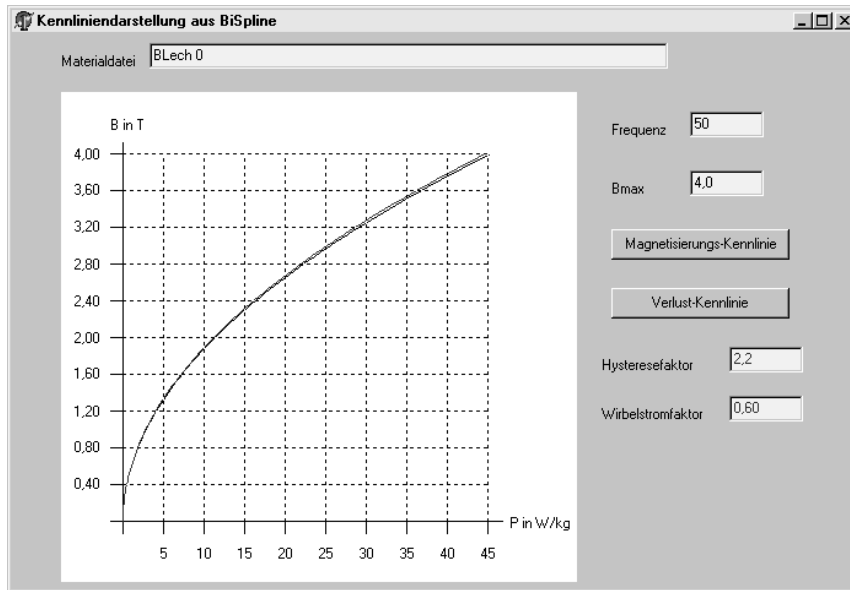
Fig. 1. Representation of characteristics with bisplines (black) und loss factors (red)

With the iron fill factor which must consider both the lamination and perhaps available cooling ducts, acceptance is valid under that $\mu_{rel} \gg 1$

$$B_{fe} = \frac{B}{\varphi_{fe}} \tag{4}$$

2.2. Losses in not ferromagnetic parts of the magnetic circuit

These losses originate through eddy currents in the conducting parts of the magnetic circuits interspersed by alternating fields. That essentially concerns the magnets and the basic body of the rotor and conducting structural elements in the stator. The eddy currents engender even a magnetic field and affect field replacing back to the primary field. According to /2/ is the depth d, with that the electric or magnetic field strength below the influence of the eddy currents has decreased to e^{-1} of their surface value, designated as penetration measure δ.

$$\delta = \frac{1}{\beta} = \frac{1}{\sqrt{\pi \cdot f \cdot \kappa \cdot \mu}} \tag{5}$$

with: $\mu = \mu_0 \cdot \mu_{rel}$ - permeability.

Consequently, the penetration measure depends on the electric conductivity κ and of the relative permeability μ_{rel} of the material. The skin depth of the field amounts to 4 .. 8 δ. The limit, above that due to field displacement a considerable attenuation of the field occurs, is the limiting frequency f_g. For fields with the thickness d is

$$f_g = \frac{1}{\pi \cdot \kappa \cdot \mu \cdot d^2} \tag{6}$$

After this the reactions through eddy currents in the iron because of use of sheet steel and in the magnet because of small conductance are lower, however, are to consider in the aluminium body of the rotor for the special construction. The specific dissipation factor for iron losses amounts to

$$\sigma_{wb} = \frac{1}{24} \cdot \frac{\kappa}{\rho} \cdot d^2 \cdot \omega^2 \cdot \hat{B}^2 \cdot F(x) \tag{7}$$

with $\quad F(x) = \frac{3}{x} \cdot \frac{\sinh x - \sin x}{\cosh x - \cos x} \quad$ and $\quad x = d \cdot \beta = d \cdot \sqrt{\pi \cdot f \cdot \kappa \cdot \mu}$

$F(x) \approx 1$ is valid for small values of x and the equation for the dissipation factor goes over in

$$\sigma_{wb} = \frac{1}{24} \cdot \frac{\kappa}{\rho} \cdot d^2 \cdot \omega^2 \cdot \hat{B}^2 \tag{8}$$

TABLE 1
Specific dissipation factors of different materials according to (8) for f = 50 Hz, B = 1 T

	thickness d mm	specific gravity ρ kg/cm³	conductance κ S·m/mm²	dissipation factor σ_{wb} W/kg
iron	1	7,8	10	5,272
copper	1	8,9	58	26,799
aluminium	1	2,9	37	52,468
magnet	1	7,6	0,625	0,338

The dissipation factors computed in TABLE 1 apply to sheet steels supposing that the thickness d is less than the other dimensions and are possibly too high with increasing material thickness. Nevertheless, it is normal to determine the losses in this way in compact parts. These can take considerable values at high frequencies in compact material, for example the losses in surface-mounted magnets in around setting converter fed synchronous machines /3/ or induction machines /4/. A decreased skin depth through eddy currents is to be considered as described above.

The specific dissipation factor p_{wb} through eddy currents and the entire iron losses result in analogue mode with (2) and (3) at the iron losses.

3. OVERVIEW ABOUT CALCULATION METHODS FOR LOSS CALCULATION

Losses originate in electrical machines by current flow in the windings, through effect of the temporally magnetic field changing as well as as mechanical losses. While the winding losses in the stationary case are accessible easily for a calculation without regard of the current displacement, the connections are more complicated for the losses in the magnetic circuit.

Therefore in the following different calculation methods for the iron and stray losses are presented and compared. In this case, there are differences in addition to the method and the results too in the requirements to the calculation software and the compute time. There are presented

- model 1: analytical calculation of the iron losses from the induction maximum in the sections of the magnetic circuit in the draft programme
- model 2: Calculation of the stator losses of the stationary FEM computation with the ascertaining of the highest burdened tooth sections and the loss calculation of these maximum as a effect of the fundamental wave
- model 3: Calculation of the stator and rotor losses of the transient FEM computation with the field harmonics and subharmonics occurring in actual fact of every element; harmonic analysis of the temporal field profile and of loss calculation from the size of the harmonic ones summed up over all elements of the considered section
- model 4: Calculation of the rotor losses of the stationary FEM computation with ascertaining the field waves of the rotor; the harmonic analysis of local field distribution in the air gap including the determination of the rotational motion direction and loss calculation from its effect in consideration of penetration depth.

4. ANALYTICAL CALCULATIONS OF THE LOSSES IN THE DRAFT PROGRAMME

For the calculation of the losses with the draft programme the iron losses in the stator are considered. The maximum induction values in the teeth and the stator back result directly from air gap induction.

For calculation of the iron losses, the specific dissipation factor is determined from the induction values depending on the frequency for the teeth and the stator back from the loss characteristic. In this way, the iron losses in the individual sections can be computed. The entire iron losses P_{Vfe} compute themselves from the sum of the iron losses in the individual sections of the magnetic circuit in the stator

$$P_{VfeS} = k_z \cdot \left(P_{VR1} + P_{VZ1} + P_{VO} \right) \tag{9}$$

with: k_z – allowance factor, P_{VR1} - back losses, P_{VZ1} - tooth losses, P_{VO} - surface losses.

The allowance factor k_z comprises from the stator factor k_S that considers the influence of the harmonic ones as well as the technological influences like cutting edges and pressure and a rotor factor k_L, with that the rotor losses proportional to the stator losses may be estimated.

Since calculation is constituent of the draft programme, its advantage lies in the possible calculation of the losses already in the design phase. In this way, a fast machine draft is possible where a real material characteristic represented with bisplines is already considered. The disadvantage lies in a whole series of simplifications as

- summarizing calculation of the induction for typical fields of the magnetic circuit
- only partial regard for saturation conditions and the dispersion
- no regard for harmonic appearances
- summary of supplementary security in allowance factors

As the machine calculation for a detailed design itself should be checked for specific operating points and operating cases through a FEM computation, is to be defined also loss calculation through the results of the FEM computation.

5. CALCULATION OF THE LOSSES BY STATIC FEM COMPUTATION

In Flux2D /5/ the calculation of induction for every element in post-processing as a internal function or its harmonic analysis along a curve $B(x)$ and in transient computation in addition a harmonic analysis of the induction B(t) are possible. However, this method is for different reasons (selection of the elements, unacceptable CPU time, result format) not practical for loss calculation. The potentials on the nodal points are only output to the result file after a FEM computation with Flux2D. The losses must be determined from it. For the determination of the losses, the flux density B must be confessed. It is computed from the vector potential $\vec{V}$:

$$\vec{B} = rot\left(\vec{V}\right) = \vec{B_x} + \vec{B_y} \tag{10}$$

For loss calculation, a higher flux density will be decisive because of the iron fill factor $\varphi_{fe} < 1$. The specific losses in every stator element are determined with the induction values computed in such a way with the frequency

$$p_{fe,e} = f\left(B_{fe,e}, f\right) \tag{11}$$

and with the face dissipation factor

$$c_V = l_{fe} \cdot \varphi_{fe} \cdot \rho_{fe} \tag{12}$$

and the element face A_e the losses in every element

$$P_{fe,e} = p_{fe,e} \cdot A_e \cdot c_V \tag{13}$$

The elements are first combined into loss regions, which contain for every tooth the ranges of
- the tooth tip (within the radius of the interior winding limitation)
- the tooth surface (at the face that is included by the winding radii)
- the yoke (outside of the radius of the external winding limitation including the stator back).

The maximum of the ranges are combined into maximum tooth losses.

$$P_{Vfe,Z} = \sum_{e(Z)} P_{fe,e} \qquad (14)$$

With the ranges with the highest losses the maximum losses that can occur in the machine are registered. That corresponds to the value that is registered with the maximum induction values in the described manner as in chapter 4.

The described method is implemented from the programme *FLUXauswertung* and its results processed in Excel for the total losses.

Precondition of use method is the existence of one static FEM computation. In this way, the computing time in this connection is relatively small. The advantage of the technique lies in the simplicity of its use and of its evaluation. The induction maxima occurring in actual fact are registered in every element of the magnetic circuit sufficiently precisely.

Disadvantages of method are
- only a moment value of the induction amplitude is registered, the actual maximum can be higher
- harmonic appearances are indeed registered in computation, in evaluation however, they only suppress themselves tendentially at the mean value of induction and this is always assigned to the fundamental wave
- rotor evaluation would supply only a statement about the amount of induction, not however about its change, because the fundamental can not be parted by the harmonics as a DC component; a calculation of the rotor losses is further possible only by a factor proportionally to the stator losses
- eddy currents and its reaction receive no regard in the FEM computation
- harmonic oscillations in feeding and supplementary effects like cutting edge influence must further considered in allowance factors

There the real, represented with bisplines one, material characteristic is considered. Therefore, a quite precise statement is possible about the iron losses in the stator. By classification in loss regions, a differentiation of the losses for specific ranges and processing with differentiated allowance factors is at least tendentially possible.

6. CALCULATION Of THE LOSSES
BY TRANSIENT FEM COMPUTATION

While up to now it was gone out by the loss calculation from effect of a fundamental (analytical) or FEM calculation (statically) and the losses resultant from it, that the fundamental manufactures, on the one hand deposits a transient computation precise statements about occurring harmonic in every element. If moreover the turn more than one entire original winding occurred, on the other hand, every possible state of an element is registered during sufficiently fine decomposition and therefore a more precise statement about the maximum compared to the selected state of static computation is possible. By harmonic analysis induction can be split in every element into its frequency components and correspondingly the losses can be computed for the correct frequency.

Starting point of loss calculation is the FEM computation and the evaluation of the vector potential for ascertaining induction from the results in the elements as in chapter 5. There are N Solutions of a transient computation with an increment φ_{step}, so that with

$$N \cdot \varphi_{step} = p^* \cdot \tau_p \tag{15}$$

with: p^*- pole pair number of the original winding, τ_p- pole pitch the range of one original winding is seized as a result of which all subharmonics of the winding are registered.

The evaluation of the vector potential from the FEM computation is used for calculation again.

The difference lies in it that the results of every time step are read, processed and internally. The spectrum of the frequencies with which the frequency individual losses for each is determined results from the time steps. The Fourier analysis occurs with these converted values. In this way, induction is available for every element e in the form $\sum \hat{B}_{e,\nu'}$.

The frequency of the first harmonic results from the period of transient computation or expressed with the rotation speed n

$$f_0 = \frac{1}{T_0} = \frac{2 \cdot \pi \cdot n}{N \cdot \varphi_{step}} \tag{16}$$

The ordinal number and the frequency of the fundamental are

$$\nu = p^* \qquad \text{and} \qquad f_1 = f_0 \cdot p^* \tag{17}$$

The summary of the losses to loss regions occurs for every harmonic one like the evaluation of the static computation. For the total losses, these element losses may be added simply so that final results

$$P_{fe,\nu'} = \sum_e P_{fe,\nu',e} \tag{18}$$

The sum

$$P_{Vfe} = \sum_{\nu'} P_{fe,\nu'} \tag{19}$$

is valid for the partial losses as well as for the entire range of the motor geometry contained in the FEM computation.

In this way the losses are computed separate in the stator and in the rotor. The loss sums received in such a way contain the influence of the harmonics resulting through the winding and the slotting and of the subharmonics. For the losses occurring in actual fact, the processing allowances must only be added and the allowances during not sinusoidal supply, if these were not already considered by correspondingly not sinusoidal feeding in the transient computation.

The described method is computed by the programme *VerlustScan*.

Precondition of use of the method is the existence of a transient FEM computation. This ought itself spatial more than at least one original winding may extend - with sufficiently fine increment in order to be able to register precisely the harmonics. In this way, the computing time in this connection is very high. The advantage of the technique lies in the registration of the upper and sub-waves, so that both the iron losses in the stator and rotor and the losses in the magnets and the aluminium body can be computed. Because of with the turn around one original winding all possible moment values are computed, the actual induction maximum of every element is also registered. Too harmonic oscillations in feeding can possibly be considered.

Restrictions and disadvantages of the technique are

- eddy currents and its reaction are not regarded in the FEM computation
- magnetic and aluminium losses depend on dissipation factors whose ascertaining is difficult, with them the reaction by eddy currents affect especially aggravating because of the missing lamination
- allowance factors are valid for mechanical factors furthermore
- that draft- and above all computing time required as well as the amounts of data are enormous so that the computation can not always be executed

The real, represented with bisplines one, material characteristic is regarded. Therefore, a quite precise statement is possible over the iron losses in the stator and the rotor.

7. EVALUATION OF AIR GAP INDUCTION OF STATIC COMPUTATIONS

It is a main problem of static computation that no specifications of the rotor losses can be made since the amounts of the computed induction values in the rotor of the fundamental rotary with the rotor are dominated. As a result, these appear in the rotor as a DC component of magnetization and cause no losses.
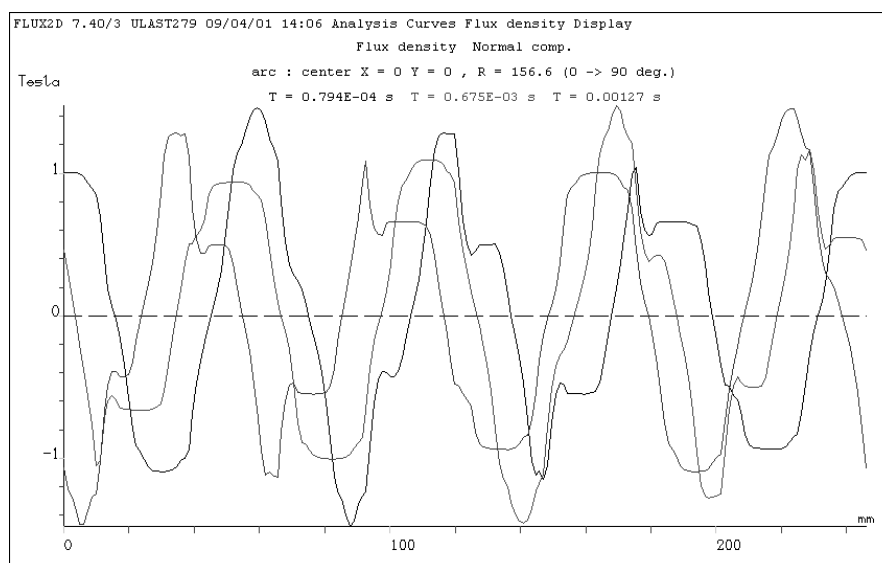

Fig. 2. Air gap induction in the dimensioning point for three different time points

The calculation of the losses (above all in the rotor) would be desirable when inferences are pulled out of the harmonic analysis of air gap induction (Fig. 2) onto the occurring harmonic in the rotor, with the aim to register tendentially the occurring upper and sub-waves correctly.

The air gap field is reproduced along path x within one original winding with p^* poles or the motor size at p pole pairs. It has the form

$$B'_{v'} = \hat{B}'_{v'} \cdot \cos v'\left(\gamma' - \gamma'_{B_{v'}}\right)$$ (20)

with the related coordinates

$$\gamma' = \frac{2\pi}{2p \cdot \tau_p} x$$ (21)

For the dominant wave with $v' = p$ is:

$$\gamma = \frac{\pi}{\tau_p} \cdot x = p \cdot \gamma' \quad \text{and} \quad B_1 = \hat{B}_1 \cdot \cos\left(\gamma - \gamma_1\right)$$ (22)

The Fourier analysis of every step permits a statement about amplitude and the phase of a harmonic, however not about its rotational motion direction. The separate synthesis of the individual harmonic in Fig. 2 shows advance of the individual waves.
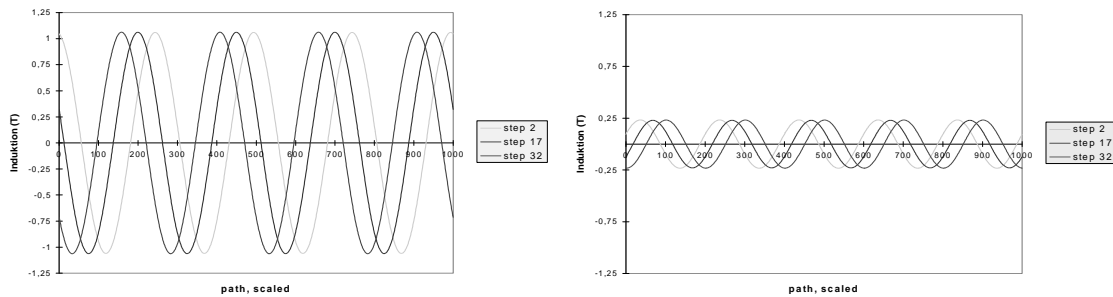

Fig. 3. Air gap induction 4th harmonic (fundamental) and 5th harmonic

Therefore, a further step must at least be analysed in order to gain a statement about the rotational motion direction of the wave. However, this

further step can be carried out into Flux2D as a static computation with the corresponding rotor position and the corresponding current angle. The frequencies of the harmonic one, which work in the stator with the frequency

$$f_{v'} = v' \cdot \frac{f_1}{p} \tag{23}$$

and for that in the step *k*+1 the operational sign of phase displacement in relation to phase displacement the fundamental can be determined, come in the rotor with the frequency

$$f_L(v') = \frac{v'}{p} - \mathrm{sgn}\left(\frac{\varphi_{v'}(k+1) - \varphi_{v'}(k)}{\varphi_1(k+1) - \varphi_1(k)} \right) \cdot f_1 \tag{24}$$

in appearance. In this way, a statement can be made both about amplitude and the frequency of the occurring field waves in the rotor.

A harmonic one the air gap field has the wavelength

$$\lambda_{v'} = \frac{2 \cdot \pi \cdot D}{v'} \tag{25}$$

Spreading of the upper wave field depends on subdivision of the air gap limitation faces in rotational direction. If the limitation face is considerably longer than the wavelength of the harmonics, the upper wave closes densely below these surfaces. If the limitation face is shorter than the wavelength, the harmonic wave closes over the yoke. In the rotor no closed back exists so that the upper wave field pattern closes via the magnets and the key field. Because of the large key width with $b_K \gg \delta$ there is valid for these waves no more the air gap conductance Λ_δ but a considerably less conductance $\Lambda_{K\delta}$ so that these waves hardly appear with their amplitudes $\hat{B}(v') = \Lambda_{K\delta} \cdot \hat{\Theta}(v')$. That is the case during this construction in the case of all subharmonics that are in a remote manner from the fundamental far enough.

Supposing a circular spreading of the lines of magnetic flux of the harmonic between the poles the spreading depth in the static case amounts to $h_\lambda = \lambda/4$. The spreading depth is not to be confused with the penetration measure δ and the penetration deep of chapter 2 those result from the eddy current reaction. The actual skin depth is greater since the field waves extend

purely into the infinite. The induction of the harmonic is largest in its poles, in the iron occurs a relatively uniform load below the rotor surface that decreases approximately to the centre according to an e-function. Therefore, the depth is approximated as spreading depth that results from a face like a rectangle registered by the induction wave. From these considerations a value results of

$$h_\lambda = \frac{\lambda}{\pi} \qquad\qquad (26)$$

The course of the upper wave field in the iron is used for the verification of the simplified model. The spreading depth of the air gap harmonics was checked with specific FEM computations.

With the field curves impressed in such a way, the field distribution and the skin depth can be determined concretely for each harmonic one if the real saturation conditions are neglected.

Figure 4 shows besides the supposed curve the normal and tangential components of the induction in the tooth centre along a course times as a function of the distance of the air gap. The ordinal number of the harmonic is applied to the reproduced geometry section of an original winding.
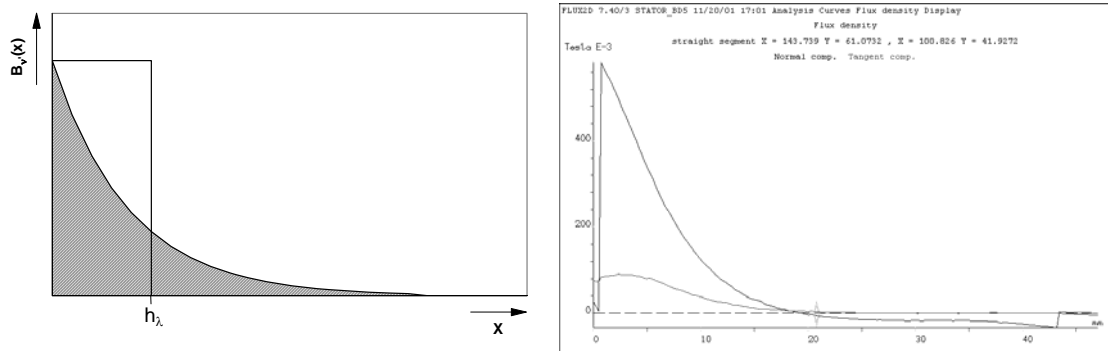

Fig. 4. Supposed spreading depth of the harmonics in the iron and calculated induction in the case of stamped 5th harmonic at B = 0.4 T in centre 3. tooth

The entire calculation and evaluation occurs in the programme *VerlustBd*.

Precondition of use of this method is the existence of at least two steps of a transient FEM computation or two static computations with different original angles. These should be in a separated manner from each other so far that one can conclude without problems from the air gap analysis to the direction of the circulating fields.

In this way, the computing time in this connection is very short and is only secondarily above that of static computation. The advantage of the method lies in the registration of the air gap harmonic and subharmonic waves, so that through the conclusion onto the induction waves in the rotor both the iron losses and the losses in the magnets and the aluminium body can be compute.

Restrictions and disadvantages of the technique are
- the used skin depth states nothing about the real saturation conditions
- the induction values in the magnets and aluminium can only be approximated with flow concentration
- eddy currents and its reaction find in the FEM computation no regard
- magnetic and aluminium losses depend on dissipation factors whose ascertaining is difficult, with them the reaction by eddy currents affect especially aggravating because of the missing lamination
- allowance factors are valid for mechanical factors furthermore
- the loss calculation with evaluation of the induction in the element is more precise, therefore, the method with flux evaluation is further used for the losses in the stator

With evaluation of the air gap harmonics, a statement about the losses in the rotor is at least tendentially possible. The losses in the magnets and aluminium need a further study and a measure technical inspection.

8. USE OF LOSS CALCULATION

8.1. Permanent-magnet machine of novel construction

A high-pole synchronous machine of novel construction with a power of $P = 80$ kW at a speed of $n = 1050$/min is to be investigated. The presented methods of the computation of the iron losses in the stator and the determination of the losses in the rotor were applied to the permanent excited synchronous machines.

Figure 5 shows the propagation of the main wave in the stator, that causes there the main wave losses. In the rotor the main wave acts as absolute direct component of the magnetization and doesn't cause losses.
Spreading of the upper wave field depends on subdivision of the air gap limitation faces in rotational direction. If the limitation face is considerably longer

than the wavelength of the harmonics, the upper wave closes densely below these surfaces. If the limitation face is shorter than the wavelength, the harmonic wave closes over the yoke. So the field of the 9th harmonic in Fig. 6 closes partially via the whole rotor construction and causes losses also in the there existing not ferromagnetic construction elements.
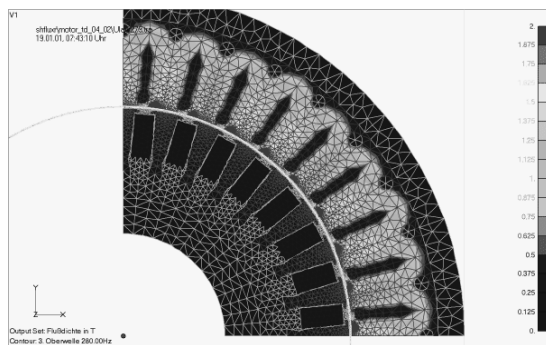

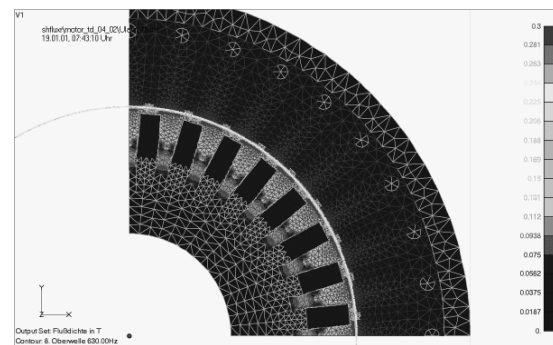**Fig. 5. Induction for the 4th harmonic (main wave) with f = 280 Hz, scaling B = 0 T .. 2,0 T**

Fig. 6. Induction for the 9th harmonic with f = 630 Hz, scaling B = 0 T .. 0,3 T

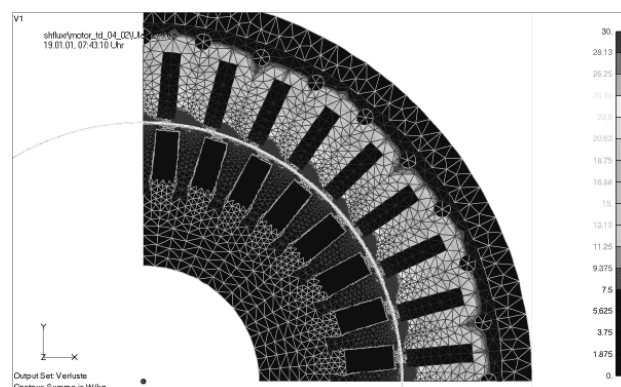Figure 7 shows the loss distribution of the Stator.

Fig. 7. Loss density as the sum of all harmonics, scaling P_V = 0 W/kg .. 30 W/kg

A short summary of the calculated results of FEM evaluation shows TABLE 2.

TABLE 2
Summary of the loss calculation for the synchronous machine

	model 2 analytical calculation	model 3 novel method by static FEM	model 4 novel method by transient FEM
stator	823,9 W	---	843,0 W
stator, fundamental	---	---	795,0 W
rotor, iron	---	15,0 W	18,4 W
rotor, magnet	---	103,3 W	86,9 W
rotor, aluminium	---	172,6 W	91,1 W

These values are valid with acceptances that feeding the winding occurs with purely sinusoidal currents and tensions and in the FEM the reduction of the skin depth is not considered by eddy currents.

For the stator, the transient computation certainly reflects the real conditions best. The losses of stationary computation are under it since the effect of the harmonics is not sufficiently considered. Nevertheless, these results are sufficient for the draft of the machine, the effect of the harmonics is to where appropriate be considered by a higher allowance factor. An allowance factor is always necessary because of the usually not sinusoidal feeding and the processing allowances.

The immense draft and computing time and also memory requirement for the carrying out of the transient computation is to be considered. Therefore, the represented course of calculation of the rotor losses supplies usable results from stationary computation quite. In the result of transient computation of these computations and of the comparison with the rotor losses, it results that the pure iron losses are very small. However, the eddy current losses bring further loss quota in the magnet and the aluminium body so that in total a loss part of 30 % of the stator losses results in the rotor.

8.2. Calculations of the losses for an asynchronous machine

An asynchronous machine with squirrel cage with a power of $P = 630$ kW at a speed of $n = 994$/min is to be investigated.

The analytic calculation of the losses is carried out for the areas of the back iron and the stator teeth according to the chapter 4.

At the asynchronous machine the pulsation losses are opeative for the surface losses by eddy currents, if both the stator and the rotor are slotted. Those can be estimated for the rotor

$$P_{Vp2} = 8{,}3 \cdot \sigma_{wb} \cdot \left(\frac{N_1 \cdot n}{10000 / \min}\right)^{1,5} \left(\frac{\hat{B}_{p2} \cdot \tau_n}{T \cdot mm}\right)^2 \cdot m_{z2} \qquad (27)$$

with

$$\hat{B}_{p2} = \frac{\tau_{n1} \cdot n}{2 \cdot \tau_{n2}} \cdot k_{c2} \cdot (k_{c1} - 1) \cdot B_{z2m} \qquad (28)$$
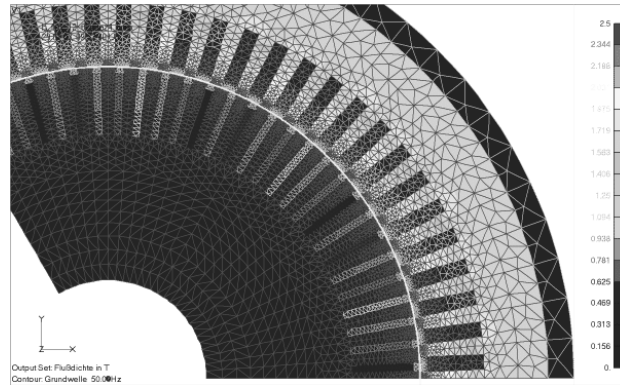
with:

k_c — Carter's coefficient,

B_{z2m} — induction in the middle of the tooth,

σ_{wb} — eddy current loss factor.

Analogue relations are valid for the pulsation losses in the stator teeth.

Common the pulsation losses aren't calculated directly, but specified by means of a factor of 0,5 .. 1 % of the feeding power.

Next is carried out the transient FEM-Calculation.

Figure 8 shows the propagation of the main wave in the stator in the rated point.

**Fig. 8. induction for the 1st harmonic (main wave)
with f = 50 Hz, scaling B = 0 T .. 2,5 T**

Harmonics of lower frequency propagates in the stator first of all in the area of the tooth tip and parts of the back iron. Partially there a rotating magnetization occurs, that is considered in the analytical calculation by allowance factors.

Figure 9 shows exemplary propagation of the 5th harmonic. Harmonics of higher frequency propagates in the stator and the rotor along the tooth tip as shown in Fig. 10 the represented induction caused by slotting pulsation.
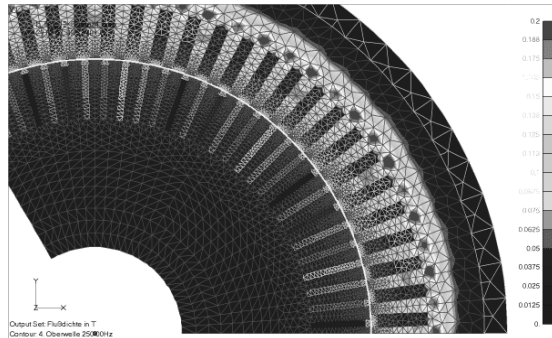

Fig. 9. Induction for the 5th harmonic f = 250 Hz, scaling B = 0 T .. 0,2 T

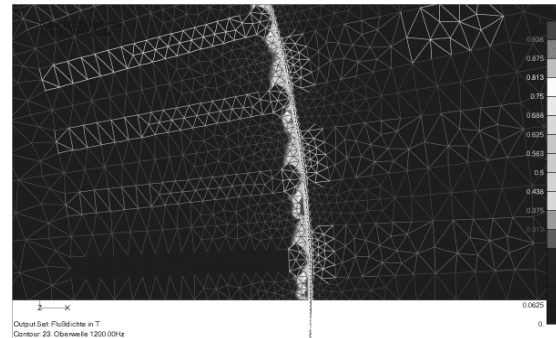**Fig. 10. Induction for the 24th harmonic f = 1200 Hz, scaling B = 0 T .. 1,0 T**

The evaluation of the induction results in the loss distribution in Fig. 11.

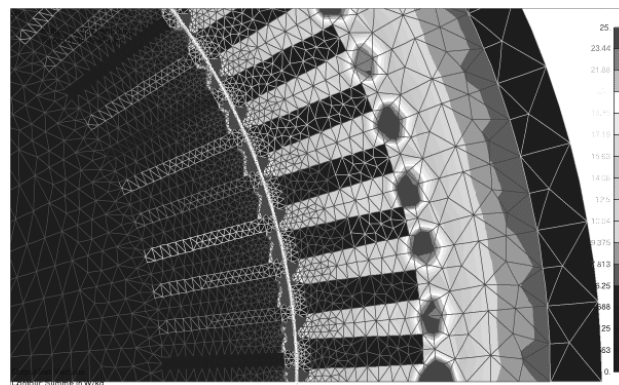**Fig. 11. Loss density as the sum of all harmonics, scaling P_V = 0 W/kg .. 25 W/kg**

The iron losses are concentrated to the area of the tooth tips of the stator and the rotor caused by the pulsation losses and the transition from the teeth to the back iron.

TABLE 3
Results of the loss calculation for the asynchronous machine

	model 2 analytical calculation	model 4 novel method by transient FEM
main wave losses	4302 W	5282 W
harmonic losses	---	3079 W
pulsation losses stator	623 W	661 W*
pulsation losses rotor	1103 W	1081 W**

* only consideration of the 29th harmonic

** only consideration of the 24th harmonic

9. CONCLUSION

The draft of novel electro drives requires modern design processes. In this case, the effectiveness and the accuracy of the draft plays equally a role as the shortening of development time by increase of security of calculation and the saving of prototype studies by expanded simulation studies.

The developed methods for loss calculation both the iron losses through the fundamental and the losses through harmonics and the losses in the rotor and inactive parts of the magnetic circuit by utilization of the results of static or transient FEM computations have itself proved already in the case of the development of innovative permanent excited motors and generators.

The resulted development instruments are prepared for different machine types.

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WYZNACZENIE ZAWANSOWANYMI METODAMI STRAT W RDZENIU I STRAT DODATKOWYCH W WIRNIKU W MASZYNACH ELEKTRYCZNYCH

Uwe SCHUFFENHAUER, Hans Kuß

STRESZCZENIE   *Nowe wymagania stawiane napędom elektrycznym powodują, że zachodzi potrzeba wykonywania nowych projektów. Jednocześnie zwiększa się stosowanie procesów symulacyjnych. To sprawia, że zwykłe algorytmy obliczające straty nie są wystarczające. Względy oszczędnościowe powodują, że wskazane jest obywanie się bez konstrukcji prototypów dlatego też dokładne metody obliczeń są konieczne.*

W artykule przedstawiono metody obliczające straty w rdzeniu maszyn elektrycznych. Dodatkowo wzięto pod uwagę klasyczne metody analityczne oraz nowe procedury, w których straty od harmonicznych i straty w wirniku oraz w elementach nieaktywnych obwodu magnetycznego mogą być obliczane przy zastosowaniu metody elementów skończonych.