Rotor losses in a high speed synchronous generator with permanent magnet excitation and rectifier load

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Rotor Losses in a High Speed Synchronous Generator with Permanent Magnet Excitation and Rectifier Load

by
J.L.F. van der Veen
L.J.J. Offringa

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Trefw.: synchrone generatoren / harmonische analyse / elektrische machines ; verliezen / elektrische machines ; permanente magneten.
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Abstract - In an early stage of the development of a high speed synchronous generator with permanent magnet excitation it became apparent that rotor losses due to asynchronous components of the air-gap field, are a major problem. So, a model is needed which includes the effects of space harmonics and harmonics in the stator current caused by a rectifier load. An approximate solution for the rotor losses caused by the asynchronous components has been derived. The derived formulae show the effects of machine dimensions and harmonics. The main purpose of this study is to have a tool for making an early choice between several configurations. A modified 9 phase system, combined with a shield around the permanent magnet rotor, is a prospective option.

**keywords:** synchronous generators, permanent magnets, harmonic analysis, rotor losses, high speed, eddy current losses.

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List of symbols

<table>
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<tr>
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<th>Description</th>
<th>Unit</th>
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<tr>
<td>p</td>
<td>pole pair number</td>
<td></td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>fundamental frequency of the stator current</td>
<td>rad/s</td>
</tr>
<tr>
<td>$A_{n,q}$</td>
<td>surface current density due to the $n^{th}$ harmonic of the current and the $q^{th}$ space harmonic</td>
<td>A/m</td>
</tr>
<tr>
<td>$A_n$</td>
<td>surface current density on the conducting shield with radius $r_s$</td>
<td>A/m</td>
</tr>
<tr>
<td>$B_r, B_\theta$</td>
<td>radial resp. tangential component of the magnetic induction</td>
<td>T</td>
</tr>
<tr>
<td>$B_2$</td>
<td>radial component of magnetic induction at radius $r_2$</td>
<td>T</td>
</tr>
<tr>
<td>$E_2$</td>
<td>axial component of electric field strength at radius $r_2$</td>
<td>V/m</td>
</tr>
<tr>
<td>$J_{r_s}$</td>
<td>volume current density in the conducting layer</td>
<td>A/m²</td>
</tr>
<tr>
<td>$Q_{n,q}$</td>
<td>quality factor for component with order $n$ and $q$</td>
<td></td>
</tr>
<tr>
<td>$m$</td>
<td>number of phases</td>
<td></td>
</tr>
<tr>
<td>$l$</td>
<td>active length of the machine</td>
<td>m</td>
</tr>
<tr>
<td>$n$</td>
<td>order of the harmonic in the current</td>
<td></td>
</tr>
<tr>
<td>$q$</td>
<td>relative order of the space harmonic</td>
<td></td>
</tr>
<tr>
<td>$pq$</td>
<td>absolute order of the space harmonic</td>
<td></td>
</tr>
<tr>
<td>$I_n$</td>
<td>$n^{th}$ harmonic component in the phase current</td>
<td>A</td>
</tr>
<tr>
<td>$I_{dc}$</td>
<td>DC current</td>
<td>A</td>
</tr>
<tr>
<td>$I_{tl}$</td>
<td>total current in a slot</td>
<td>A</td>
</tr>
<tr>
<td>$Z_q$</td>
<td>winding density of the $q^{th}$ harmonic</td>
<td>m⁻¹</td>
</tr>
<tr>
<td>$t$</td>
<td>time</td>
<td>s</td>
</tr>
<tr>
<td>$\theta_s$</td>
<td>tangential coordinate in stator coordinates</td>
<td>rad</td>
</tr>
<tr>
<td>$\theta_r$</td>
<td>tangential coordinate in rotor coordinates</td>
<td>rad</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>( r, r_g, r_0 )</td>
<td>radial coordinate, radius of conducting layer in the rotor, reference radius</td>
<td>m</td>
</tr>
<tr>
<td>( r_1, r_2, r_3 )</td>
<td>radius of solid rotor iron, radius of conducting shield, radius of stator bore</td>
<td>m</td>
</tr>
<tr>
<td>( \omega_r )</td>
<td>electric frequency in rotor coordinates</td>
<td>rad/s</td>
</tr>
<tr>
<td>( \omega_m )</td>
<td>mechanical angular velocity of the rotor</td>
<td>rad/s</td>
</tr>
<tr>
<td>( i_{ij} )</td>
<td>integers</td>
<td></td>
</tr>
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<td>( k_1, k_2, k_3 )</td>
<td>integers</td>
<td></td>
</tr>
<tr>
<td>( k )</td>
<td>number of subsystems in the stator</td>
<td></td>
</tr>
<tr>
<td>( t_c )</td>
<td>commutation time</td>
<td>s</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>surface current density at stator bore</td>
<td>A/m</td>
</tr>
<tr>
<td>( d )</td>
<td>thickness of the conducting shield</td>
<td>m</td>
</tr>
<tr>
<td>( h_m )</td>
<td>height of the permanent magnet</td>
<td>sm</td>
</tr>
<tr>
<td>( d_{skin} )</td>
<td>skin depth</td>
<td>m</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>specific conductivity</td>
<td>((\Omega m)^{-1})</td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>permeability of vacuum ( 4 \pi \times 10^{-7} )</td>
<td>Vs/Am</td>
</tr>
<tr>
<td>( P_{ir} )</td>
<td>rotor loss due to one asynchronous component</td>
<td>W</td>
</tr>
<tr>
<td>( P_v )</td>
<td>total rotor loss</td>
<td>W</td>
</tr>
</tbody>
</table>
1. Introduction

The application of a high speed generator with permanent magnet excitation in a generator set with a gas turbine has a potential advantage. The strong and simple construction enables operation at high speed and a direct coupling of the turbine with the generator (without a gearbox for reduction of the high speed of the turbine).

The important features of a high speed generator are a small volume, low weight and high efficiency.

A design of a high speed generator will be made for a NOVEM research and development project for application with a gas turbine with a rated power of 1400 kW and speed of 18000 rpm [4].

The frequency of the generator will be 600 Hz. The output will be rectified and the electric power will be available as DC power.

1.1. Construction

The generator is of the usual synchronous type with polyphase windings in the stator. The rotor will have permanent magnets for the excitation in stead of a field winding.

The design of the construction of the high speed generator has been drawn in fig.1. The permanent magnet segments are arranged on the surface of a solid iron core. The drawing shows a four pole generator. A carbon fibre will be wound around the permanent magnets to give the rotor sufficient strength at high speed.

Because of the permanent magnet excitation there is no need for a field winding and power supply for the excitation. This keeps the construction simple and has a positive effect on efficiency.
Fig. 1. Outline of the construction of the high speed generator.
1.2 Losses

For high power at high speed the power density should be as high as possible. The maximum admissible circumferential speed of the rotor and the possible diameter to length ratio set a limit to the dimensions. As a consequence it will be hard to cool the compact construction to a tolerable temperature level. A choice has been made for a cooling system with liquid cooling for the 1400 kW design. Special attention should be paid to the prediction of the losses, and it is necessary to find ways to decrease the losses by an adequate construction.

Brushless generators with a construction as given in fig.1 are available for a power up to 20 kW and a speed of 6000 rpm. The rotor has a layer of permanent magnet material, with carbon fibre wound around it, to withstand centrifugal forces.

The same construction for a 1400 kW generator would cause 2 problems:

1. The inductivity will be too high for commutation of a rectifier load at rated power.
2. Asynchronous components of the air gap field will induce eddy currents in the solid rotor iron, causing a dissipation too high for cooling at an acceptable temperature level.
1.3. Conducting shield and division of the stator circuit in subsystems

A conducting shield around the permanent magnets of the rotor offers a solution to both problems. The shielding effect of the conducting shield will decrease the inductances of the stator coils for fast changes in the current as these will cause mainly asynchronous components in the airgap field. A well conducting shield will have lower eddy current losses due to asynchronous field components than the solid iron in absence of a shield.

A further reduction of the rotor losses is possible with the use of a modified polyphase system in the stator circuit. The stator coils can be divided in several subsystems with a regular displacement in space. The number of possible asynchronous components in the airgap field will decrease in this way. This will ultimately result in a loss reduction.

The next chapters will include an analysis of possible components of airgap fields, the loss caused by such components and a comparison of the rotor losses for several configurations of the stator windings and with and without rotor shielding.
2. Analysis of harmonic components

In an electrical machine the effects of a non-sinusoidal current and a non-sinusoidal distribution of the windings can be described with Fourier series of the current in time and of the winding distribution in space.

2.1 Three phase winding

As a first step in the analysis the well known case of a three phase machine will be taken. In a machine with pole pair number \( p \) and a phase current with fundamental frequency \( \omega_s \), each phase will have a shift in space of \( \frac{2\pi}{3p} \) and the phase current a shift in time of \( \frac{2\pi}{3\omega_s} \). With \( n \) as the order of the harmonics in the current and \( q \) as the order of the harmonics in space, relative to the pole pair number, the surface current density at the stator bore can be written as:

\[
A_{n,q} = \sum_{i=1}^{3} I_i \cos(n\omega_i(t-(i-1)\frac{2\pi}{3\omega_s}))Z_q \cos(qp\theta-(i-1)\frac{2\pi}{3p}) + \cos(n\omega_i(t+qp\theta-(n+q)(i-1)\frac{2\pi}{3}))
\]

With \( (n-q) = \ldots \), -9, -6, -3, 0, 3, 6, 9, etc.:

equation (2.1) becomes:

\[
A_{n,q} = \frac{3}{2} I_q Z_q \cos(n\omega_i t - qp\theta)
\]

and these components have a positive angular velocity: \( \frac{n\omega_s}{qp} \)

With \( (n+q) = 3, 6, 9, \ldots \), etc.:

equation (2.1) becomes:

\[
A_{n,q} = \frac{3}{2} I_q Z_q \cos(n\omega_i t + qp\theta)
\]

and these components have a negative angular velocity: \( -\frac{n\omega_s}{qp} \)

Other combinations of \( n \) and \( q \) do not have a resulting current density component.

*) The main interest is in the losses, so the phase angle of these components can be ignored.
2.2. Simple elimination of harmonic components

As most of these components do not run synchronously with the rotor, the elimination of these asynchronous components might improve the behaviour of the machine. The next measures will in a simple way eliminate a lot of these components.

First, make the windings symmetrical in space so that the space distribution of the windings become $Z(p\theta_j) = -Z(p\theta_j - \pi)$, and only odd harmonics exist.

Second make the sum of the phase currents $\sum_{i=1}^{3} I_{1,i} = 0$, and components with order $n = 3, 6, 9, \ldots$ become $I_n = 0$.

Third make the electrical load (or supply) symmetric with $I_y(\omega_2 t) = -I_y(\omega_2 t - \pi)$, so only odd harmonics will exist.

As a result the remaining harmonics have the order:

\begin{align*}
n &= 6k_y \pm 1 \\
q &= 2k_2 - 1
\end{align*}

Only combinations with $|n-q| = 0, 6, 12, \ldots$ and $n+q = 6, 12, 18, \ldots$ remain.

For the following calculations it will be taken for granted that the three conditions have been fulfilled.
2.3. Transformation to rotor coordinates

For the calculation of the losses in the rotor a transformation to rotor coordinates is necessary. The transformation has been carried out with:

\[ \theta_r = \theta_s - \omega_m t \text{ and } p \omega_m = \omega_s \]  \hspace{1cm} (2.4)

a. With \(|n-q| = 0, 6, 12, \ldots \text{ etc.}\)

the transformation of (2.2) results in:

\[ A_{n,q} = \frac{3}{2} Z_q \cos((n-q)\omega_s t - q\theta_s) \]

a.1. Components with \(n-q = 0\):

run synchronously with the rotor, and these can contribute to the torque.

a.2. Components with \(|n-q| = 6, 12, 18, \ldots \text{ etc.}\)

cause rotating fields with rotor frequencies \((n-q)\omega_s\) and pole pair number \(pq\),
relative to the rotor.

b. Substitution in eq.(2.3) with \(n+q = 6, 12, 18, \ldots \text{ etc.}\) results in:

\[ A_{n,q} = \frac{3}{2} Z_q \cos((n+q)\omega_s t + q\theta_s) \]

These components have a rotor frequency \((n+q)\omega_s\) and pole pair number \(pq\),
relative to the rotor.

The rotor frequencies of the asynchronous components are multiples of \(\pm 6 \, k_s \omega_s\) with \(k_s = 1, 2, 3, \ldots \text{ etc.}\)

These frequencies are in agreement with a direct deduction from eq. (2.4) as in a time shift
\(\Delta t = \frac{\pi}{3 \omega_s}\) and a rotor displacement \(\Delta \theta_s = \frac{\pi}{3 p}\) both stator currents and the rotor have been rotated
over an angle \(\Delta \Theta_s = \frac{\pi}{3 p}\).
2.4. Division of the stator phase windings in subsystems

A subdivision of each phase of the three phase system in $k$ parts which have a shift in space of

\[ \frac{\pi}{3pk} \]

makes it possible to realise $k$ three phase subsystems with a shift in time of \( \frac{\pi}{3 \omega k} \) for the currents.

To make the subsystems as symmetrical as possible the subsystems can be connected as given for $k=3$ in fig.2. Each subsystem is star connected, and the DC sides of the rectifiers are in series, so the current in each subsystem has the same magnitude. The rectifier is 18 pulse for $k=3$.

Fig.2. 3 subsystems and 18 pulse rectifier.

$L_c$= commutation inductivity.
The stator current density follows from the sum of the k three phase subsystems:

\[ A_{n,q} = \sum_{j=1}^{k} \sum_{i=1}^{3} I_{n} \cos(\omega t - (i-1) - \frac{2\pi}{3\omega_0} \cos(\theta_q - (i-1) - \frac{\pi}{3p} \cos(\theta_q - (i-1) - \frac{\pi}{3pk}) \right) \]

or

\[ A_{n,q} = \frac{3k}{2} I_n Z_q \sum_{j=1}^{k} \cos(\omega t - q\theta_q - \frac{(n-q)(j-1)\pi}{3k}) \cos(\omega t + q\theta_q - \frac{(n+q)(j-1)\pi}{3k}) \]  

(2.5)

For each subsystem the first term of (2.5) differs from zero for \(|n-q| = 0, 6, 12\), and the second term of (2.5) differs from zero for \(n+q = 6, 12, 18, \ldots\) etc.

For the whole system the result is:

For \(|n-q| = 0, 6k, 12k, \ldots\):

\[ A_{n,q} = \frac{3k}{2} I_n Z_q \cos(n\omega t - q\theta_q) \]

and for \(n+q = 0, 6k, 12k, \ldots\):

\[ A_{n,q} = \frac{3k}{2} I_n Z_q \cos(n\omega t + q\theta_q) \]

In this way many combinations of n and q don’t have a resulting current density. Of course one has to keep in mind that the distribution of the windings of the subsystems might be different from the distribution of the undivided three phase windings.

Transformation to rotor coordinates with (2.4) results in:

for \(n-q = 0\): synchronous components with magnitude \(\frac{3k}{2} I_n Z_q\), frequency zero and pole pair number \(pq\).

for \(|n-q| = 6k, 12k, 18k, \ldots\): asynchronous components with magnitude \(\frac{3k}{2} I_n Z_q\), frequency \((n-q)\omega_0\) and pole pair number \(pq\).

for \(n+q = 6k, 12k, 18k, \ldots\): asynchronous components with magnitude \(\frac{3k}{2} I_n Z_q\), frequency \((n+q)\omega_0\) and pole pair number \(pq\).
2.5. Polyphase systems

For completeness' sake the harmonic components of polyphase systems will be treated. The assumptions for symmetry are for the phase currents a time shift of \( \frac{2\pi}{m\omega_s} \) for successive phases and a shift in space of \( \frac{2\pi}{mp} \) for successive phase windings. For other cases the current and the winding distributions have to be resolved in symmetrical components.

With \( m \) phases and \( m \geq 3 \) the stator current density can be written as:

\[
A_{n,q} = \sum_{i=1}^{m} I_n \cos(n\omega_s(t-(i-1)\frac{2\pi}{m\omega_s}))Z_q \cos(q\varphi(-(i-1)\frac{2\pi}{mp}))
\]

\[
A_{n,q} = \frac{1}{2} \sum_{i=1}^{m} \left( \cos(n\omega_s t-q\varphi-(n-q)(i-1)\frac{2\pi}{m}) + \cos(n\omega_s t+q\varphi-(n+q)(i-1)\frac{2\pi}{m}) \right)
\]

For \( |n-q| = 0, m, 2m, 3m, \ldots \) etc.:

\[
A_{n,q} = \frac{m}{2} Z_q \cos(n\omega_s t-q\varphi)
\]

with: positive rotation and angular velocity \( \frac{n\omega_s}{qp} \)

For \( (n+q) = m, 2m, 3m, \ldots \) etc.:

\[
A_{n,q} = \frac{m}{2} Z_q \cos(n\omega_s t+q\varphi)
\]

with: negative rotation and angular velocity \( \frac{-n\omega_s}{qp} \)
When even harmonics in the phase currents and in the winding distribution are excluded (see 2.2) and the sum of the phase currents has been made zero, for instance with a star connection of the phases, (so \( I_n = 0 \) for \( n = m, 2m, 3m, \ldots \)), then the possible values for \( n \) are \( n = 1, 3, 5, \ldots \) (except \( n = m, 2m, \ldots \)) and for \( q \) \( q = 1, 3, 5, \ldots \).

The next combinations of harmonics with order \( n \) and \( q \) will have a resulting component of the surface current distribution:

- With \( m \) even:
  - Positive rotation: \(|n-q| = 0, m, 2m, 3m, \ldots \).
  - Negative rotation: \((n+q) = m, 2m, 3m, \ldots \).

- With \( m \) odd:
  - Positive rotation: \(|n-q| = 0, 2m, 4m, 6m, \ldots \).
  - Negative rotation: \((n+q) = 2m, 4m, 6m, \ldots \).

Note that odd values for \( m \) result in as many combinations as \( 2m \) and that \( 2m+1 \) phases have less harmonic components as \( 2m \) phases.

The comparison of a 9 phase system with a 3x3 system (a three phase system with \( k=3 \) subsystems) learns that the 3x3 system is a 'modified' 9 phase system.

The main property of a 3x3 system (with three separate star connections) is:

\[ I_n = 0 \] for \( n = 3, 6, 9, \ldots \).

and that of 9 phase systems (with one star connection):

\[ I_n = 0 \] for \( n = 9, 18, 27, \ldots \).

The conditions for \( n+q \) and \( n-q \) are the same for 3x3 and 9 phase systems. In a 9 phase system more values of \( n \) are possible, and by consequence more synchronous (e.g. \( n=q=3 \)) and asynchronous components in the stator current density will remain. With a connection of the subsystems as shown in fig.2 the currents in all subsystems will be the same, with a 9 phase system this is more difficult to ascertain.
3. Rotor losses caused by asynchronous rotating fields

The calculation of the rotor losses can be done in several ways. For instance, treat the conducting parts of the rotor as discrete circuits for each space harmonic, and find the dissipation from a solution of the equivalent circuit equations. One only needs to find the frequency dependent circuit parameters from the field equations but only approximations are possible because of the conducting solid iron core and end effects. So, it seems easier to start with an approximation that at least includes the effects of material properties, dimensions and harmonics.

3.1 Calculation of the rotor losses with an approximate solution of the field equations.

First the rotor losses caused by one component of the stator current density \( \mathbf{A} \), with pole pair number \( pq \) and frequency \( n_{\omega} \), will be calculated.

Around the permanent magnets on the solid rotor iron is a thin conducting shield with thickness \( d \) and conductivity \( \sigma \) (Fig.3.). The magnet poles with height \( h_m \) are not drawn in Fig.3. The assumption for the stator bore is a cylinder (without slots) with a surface current density \( \mathbf{A}_s \) at radius \( r_2 \). The induced current in the rotor has a surface current density \( \mathbf{A}_r \).

The field equations for the airgap are:

\[
\nabla \times \mathbf{H} = 0
\]

and as the volume current density in the airgap equals zero:

\[
\nabla \times \mathbf{H} = 0 \quad (3.1)
\]

with the two dimensional solution in polar coordinates for one component, see for instance [1]:

![Diagram of Rotor with Conducting Shield](image)
Rotor losses

The radius $r_\circ$, which can be freely chosen, will have the value $r_\circ = r_s$.

The integration constants $C_1$ and $C_2$ can be found when the boundary conditions are known. The boundary conditions are:

\begin{align}
\lim_{r \to r_s} H(\theta) &= A_s(\theta) \quad \text{with} \quad A_s = \text{surface current density at the stator bore (A/m).} \\
\lim_{r \to r_s} H(\theta) &= \hat{A}_q \cos pq \theta
\end{align}

(3.4)

(The phase angle $\phi$ is set to zero as losses do not depend on the phase of the current.)

For the rotor two possibilities will be treated:

a) With a conducting shield in the rotor around the permanent magnets at radius $r_2$, the rotor currents will flow in a conducting layer at radius $r_\circ = r_2$. The assumption is perfect screening by the shield (the limit value for high frequency and/or conductivity) and by consequence the boundary condition will be:

\begin{align}
\lim_{r \to r_\circ} B_r &= 0
\end{align}

(3.5)

b) Without a conducting shield on the rotor the assumption is that the eddy currents in the solid iron will flow in a very thin layer at radius $r_\circ = r_1$. The eddy currents in the permanent magnet segments can be made arbitrarily small by making the segments small. These eddy currents will not shield the solid iron core for the lower space harmonics because the small segments are not connected. The space harmonics with high order $q$ will decrease very fast with decreasing $r$ and the contribution to the rotor losses will be low for these high order space harmonics. The boundary condition for the solid iron rotor core will be:

\begin{align}
\lim_{r \to r_1} B_r &= 0
\end{align}

(3.5)
N.B. The assumption of perfect screening implies a high frequency or a high conductivity. The high speed and the division of the stator windings in subsystems with $k > 1$, makes this choice reasonable. (high $\omega_m$, $\omega_s = \omega_m$ and $\omega_r$ is (a multiple of) $6k\omega_m$.) The approximation is reasonable for a conducting shield of copper. For solid iron it seems strange, but because of the skin effect the rotor iron can not carry much flux from one pole to the other (at high frequencies the layer is too thin). As a simplification one can take this part of the flux zero.

The surface current density in the conducting layer at radius $r_s$ can now be found. Combination of (3.5) and (3.3) gives:

$$C_1 \frac{\bar{r}_s^{pq-1}}{r_s} = C_2 \frac{\bar{r}_s^{pq-1}}{r_s}$$

or:

$$C_1 = C_2 \frac{\bar{r}_s^{pq}}{r_s}$$

(3.6)

Substitution in (3.2), (3.4) results in:

$$C_1 + C_2 = \hat{A}_3 \mu_0$$

And with (3.6) the integration constants become:

$$C_1 = \hat{A}_3 \frac{\mu_0}{1 + (\frac{\bar{r}_s}{r_3})^{2pq}} \quad \quad C_2 = \hat{A}_3 \frac{\mu_0}{1 + (\frac{\bar{r}_s}{r_3})}$$

and on radius $r_s$ the solution becomes:

$$B_n = \hat{A}_3 \mu_0 \frac{1}{1 + (\frac{\bar{r}_s}{r_3})^{2pq}} \left( \frac{\bar{r}_s^{pq-1}}{r_3} + \frac{\bar{r}_s^{pq}}{r_3} \right) \cos pq \theta$$

(3.7)

or:

$$\hat{B}_n = \hat{A}_3 \mu_0 \frac{2(\frac{\bar{r}_s}{r_3})^{pq-1}}{1 + (\frac{\bar{r}_s}{r_3})^{2pq}}$$

and the relation between the current density $A_3$ at the stator bore and the current density in the conducting layer $\hat{A}_3$:
Rotor losses

\[ \hat{A}_r = \hat{A}_h = \hat{A}_j \left( \frac{2(r_j)^{n-1}}{r_3} \right) \]

From this surface current density follows the volume current density:

\[ J_v = \frac{A_r}{d_v} \]  \hspace{1cm} (3.9)

for a thin layer with thickness \( d_v \).

For a conducting shield at radius \( r_f = r_2 \) is at low frequencies \( d_s \) the same as the thickness of the conducting shield:

\[ d_s = d \]

At high frequencies the skin effect can be taken into account by using the skin depth \( d_{\text{skin}} \) when this is smaller than the thickness \( d \).

\[ d_s = d_{\text{skin}} \]

For the solid iron the skin depth is the best choice for all relevant frequencies.

The skin depth follows from:

\[ d_{\text{skin}} = \left( \frac{2}{\omega \sigma \mu_0} \right)^{\frac{1}{2}} \]  \hspace{1cm} (3.10)

The conducting losses \( P_v \) in the conducting layer in the rotor, at (average) radius \( r_s \) and thickness \( d_s \) are calculated with an integral over the conducting volume and one period of time:

\[ P_v = \frac{\omega}{2\pi} \int_0^{2\pi} \int_0^{2\pi} \int \int_A \frac{A_j^2}{\sigma} \text{dr} \text{d}\theta \text{dz} \text{dt} \]

As the average of the square of a sine or cosine over one period equals 1/2 the loss from one component of the eddy currents becomes:

\[ P_v = \frac{\pi r_s^4}{6} \hat{A}_j^2 \]  \hspace{1cm} (3.11)

for \( d_s < r_s \).
The total loss caused by the induced currents in the rotor can be obtained by summation of the losses of all relevant components. The square of the total current density should be used in the above integral but as the cross products of different components have an average value equal to zero (The arguments of the cosines differ in pole pair number, frequency or rotation direction). So the sum of the squares is sufficient.
3.2 Quality factor

The main assumption in the calculation of the rotor losses is the 'easy' boundary condition for the conducting shield (3.5) and this depends on the conductivity of the shield. As a test the quality factor of the conducting shield can be used.

The currents in the rotor shield are induced by an electric field originating from the asynchronous components of the stator currents. The electric field strength at radius \( r_2 \) when the shield is absent follows from \( \mathbf{E}_1 = \mathbf{v} \times \mathbf{B}_1 \):

\[
\hat{E}_2 = \frac{\omega_2 r_2}{p} \hat{B}_2
\]  

(3.12)

And the magnetic induction at radius \( r_2 \) follows from the equations (3.2) (3.3) with boundary condition (3.4) at the stator bore and \( B_r = 0 \) at radius \( r_1 \) of the solid iron core:

\[
\hat{B}_2 = \mu_0 \hat{A}_3 \frac{1}{1 - \left( \frac{r_2}{r_3} \right)^{p_2} - \left( \frac{r_1}{r_3} \right)^{p_3} \left( \frac{r_1}{r_2} \right)^{p_4^{+1}}} 
\]

or:

\[
\hat{B}_2 = \mu_0 \hat{A}_3 \left( \frac{r_2}{r_3} \right)^{p_2} - \left( \frac{r_1}{r_3} \right)^{p_3} \left( \frac{r_1}{r_2} \right)^{p_4^{+1}} 
\]

(3.13)

For a conducting shield at \( r_s=r_2 \) a quality factor \( Q_{s,a,q} \) can be defined as:

\[
Q_{s,a,q} = \frac{\hat{E}_2}{\hat{J}_2} 
\]

(3.14)

Or in verbal expression: The quality factor is the quotient of the inducing electric field strength \( \hat{E}_2 \) and the resistive part of it \( \hat{J}_2 \). (Or in equivalent circuit terms the quotient of the induced voltage and the resistive voltage drop.)
The current density \( J_2 \) follows from (3.9) with \( r_s = r_2 \).

(The approximation \( B_1 = 0 \) at the solid iron surface on radius \( r = r_1 \) results in too low values of \( B_2, E_2 \) and \( Q_{s,\alpha q} \) at low rotor frequencies.)

The analogy with an equivalent short-circuited rotor winding helps with the interpretation. For low values of \( Q_{s,\alpha q} < 1 \), there is no shielding of the asynchronous field components but mainly a phase shift. \( Q_{s,\alpha q} = 1 \) marks the 3 dB point for dissipation in the shield and the field within the shield. For high values of \( Q_{s,\alpha q} \) the shield behaves as an inductive circuit with excellent shielding of the asynchronous components. At high frequencies, when the skin effect in the shield becomes important (\( d_{\text{skin}} \) smaller than thickness \( d \)), the approximation with one equivalent short-circuited rotor circuit becomes bad.

When there is no conducting shield around the permanent magnets the rotor losses in the solid iron core can only be estimated with (3.11), but a simple check with a quality factor is not possible.
4. Comparison of rotor losses

The rotor losses have been calculated for two different configurations of the high speed generator: the first with a usual three phase winding, the second with a 3x3 phase winding. For both winding configurations the calculations are carried out with and without a copper shield around the permanent magnets on the rotor to demonstrate the effect of shielding.

4.1. Summary of the results from chapter 2 and 3

The order of the harmonics in the stator current has the symbol n, and the (relative) order of the space harmonics q.

The number of subsystems is k.

So the usual three phase stator winding has k=1, and one phase is distributed over 3 adjacent slots per pole. The winding has a star connection.

The 3x3 phase stator winding has k=3, and one phase per slot per pole. Each subsystem has its own star connection.

The description of the asynchronous components in rotor coordinates can be found in chapter 2, and they are for the two stator configurations:

a) The order n of the harmonics in the stator current can only be odd, because of a balanced load by a full bridge rectifier.

b) The components of the stator current are zero if n equals (a multiple of) 3.

c) Asynchronous components can exist if \( |n\pm q| = 6k, 12k, 18k, \text{ etc.} \)

and the resulting rotor currents have a rotor frequency \( \omega_2 = |n\pm q| \omega_s \) with \( \omega_s \) as the fundamental frequency of the stator currents.

The velocity of the asynchronous components in rotor coordinates equals

\[
\frac{|n\pm q| \omega_s}{pq}
\]

d) If \( n = q \) then the resulting components are synchronous; they can contribute to the torque.
For the surface current density at the stator bore $A_s$:

$$\dot{A}_s = \frac{3k}{2} \dot{Z}_q I_n$$  \hfill (4.1)$$

With $I_n$ for the $n^{th}$ harmonic of the stator current and $Z_q$ the winding density for the $q^{th}$ space harmonic of a stator phase winding.
4.2 Winding density of space harmonics

A good approximation of the current distribution at the stator bore of a full pitch winding, see fig. 4, is a Dirac function. A continuous distribution will result in too low values of the higher space harmonics, e.g. the slot harmonics. The integral of the current density $j_n$ over the interval $\delta$ equals $l_n$. For the field in the air-gap it doesn’t make much difference whether the conductor is in a slot or a very thin surface winding at the stator bore as long as $\mu_r \gg 1$ in the stator core.

($\oint Hdl = I$ and $H=0$ in ideal iron).

![Fig.4 Current density for a full pitch winding.](image)

The Fourier coefficients of the surface current density follow from (order only odd):

$$l_n \hat{\beta}_q = \frac{2p}{\pi r_s} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} j_n \cos(pq \theta_s) \, d(p \theta_s)$$
or with using a Dirac function for the current density:

\[ I_u Z_u = \frac{2p}{\pi r_s} I_u \]

for all space harmonics with

\[ \frac{pq \delta}{\pi} < 1 \]

For the 3x3 phase system with one phase winding per pole per slot:

\[ Z_q = \frac{2p}{\pi r_s} \] (4.2)

For the 3 phase system with three windings per pole in three adjacent slots, and the coordinate axis in the middle one, follows in a similar way for the surface current density:

\[ I_u Z_u = \frac{2p}{\pi r_s} (\cos(pq\theta_s) + \cos(pq(\theta_s - \frac{\pi}{9p})) + \cos(pq(\theta_s + \frac{\pi}{9p}))) I_u \]

And the distribution density:

\[ Z_q = \frac{2p}{\pi r_s} (1 + 2\cos(q\frac{\pi}{9})) \] (4.3)
4.3 Harmonics of the stator currents

When the stator current waveform is not yet known from calculation or measurement the following approximations can be made for a first estimation of the rotor losses.

If the commutation time of the stator current is neglectable a harmonic with order \( n \) will have an amplitude:

\[
\hat{i}_n = \frac{2\sqrt{3}}{n\pi} I_{dc}
\]

(4.4)

In case the commutation time can not be neglected an approximation with linear commutation during an interval \( \mu \) can be used:

\[
\hat{i}_n = \frac{2\sqrt{3}}{n\pi} I_{dc} \frac{\sin(n \mu/2)}{n \mu/2}
\]

(4.5)

The amplitude of all components in the eddy currents in the rotor shield, or at the surface of the solid rotor iron when there is no shield and no shielding by the segmented permanent magnets, follows from the in chapter 3 deduced relation (3.8):

\[
\hat{\alpha}_s = \hat{\alpha}_3 \frac{2\frac{r_s}{r_3}^{\mu-1}}{1 + \left(\frac{r_s}{r_3}\right)^{\mu_4}}
\]

(4.6)

with \( r_s = r_2 \) for a conducting shield

or \( r_s = r_1 \) for the solid iron, in absence of a shield.
5. Numerical calculation

The calculations have been carried out for a design of a 1400 kW generator with dimensions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator bore (diameter)</td>
<td>272 mm</td>
</tr>
<tr>
<td>Diameter of the solid iron rotor core</td>
<td>220 mm</td>
</tr>
<tr>
<td>Outside diameter of the permanent magnets</td>
<td>250 mm</td>
</tr>
<tr>
<td>Thickness of the conducting shield</td>
<td>1 mm</td>
</tr>
<tr>
<td>Outside diameter of the conducting shield</td>
<td>252 mm</td>
</tr>
<tr>
<td>Active rotor length</td>
<td>620 mm</td>
</tr>
<tr>
<td>Other properties:</td>
<td></td>
</tr>
<tr>
<td>specific conductivity of copper (in conducting shield)</td>
<td>(50 \times 10^6 , (\Omega m)^{-1})</td>
</tr>
<tr>
<td>specific conductivity of the solid rotor iron</td>
<td>(5 \times 10^6 , (\Omega m)^{-1})</td>
</tr>
<tr>
<td>relative permeability of the solid rotor iron</td>
<td>1000</td>
</tr>
</tbody>
</table>

and design parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pole pair number p:</td>
<td>2</td>
</tr>
<tr>
<td>speed</td>
<td>18000 rpm</td>
</tr>
<tr>
<td>stator frequency</td>
<td>600 Hz</td>
</tr>
</tbody>
</table>

With a 3x3 phase system the rotor frequency is (a multiple of) \(10800 \, \text{Hz}\).

The skin depth in copper, as follows from (3.10),

<table>
<thead>
<tr>
<th>Material</th>
<th>Skin Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>copper</td>
<td>0.684 mm</td>
</tr>
<tr>
<td>solid rotor iron</td>
<td>0.068 mm</td>
</tr>
</tbody>
</table>

The calculations have been done for the stator current at full load, for several configurations:

- With conducting shield and perfect shielding. Only the shield will have eddy current losses by asynchronous components of the stator current field.

  For these cases the quality factor \(Q_s\) according to eq. (3.14) is given.

- Without conducting shield and no influence of the conducting permanent magnet segments. The rotor loss will be concentrated in the solid iron.
- A three phase winding with one phase in 3 adjacent slots (of the 9) per pole.
- A 3x3 phase winding with one phase per slot (of the 9) per pole.
- A 4x3 phase winding with one phase per slot (of the 12) per pole.

In most cases the skin depth is less than the thickness of the conducting shield, and this value is used for the loss calculation.

For these preliminary calculations the commutation time of the stator currents has been taken zero, and the harmonics of the current are according eq. (4.4).

A two dimensional finite element calculation has been done for an air-gap winding at the stator bore with \( n=17, \ q=1 \), frequency \( 18 \times 600 \) Hz and \( \text{Idc}=969\text{A} \). The shielding effect can be seen in fig.5. The loss according to the finite element calculation is \( P_r=57\text{W} \). The approximation according to (3.11) has also the result \( P_r=57\text{W} \).

![Fig.5. Flux lines for \( n=17 \) and \( q=1 \).]
Table 1 lists the configurations.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Number of slots Q</th>
<th>Number of subsystems k</th>
<th>thickness rotor shield d (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 phases 3 slots/pole/phase</td>
<td>36</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1a</td>
<td>3 phases 3 slots/pole/phase</td>
<td>36</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>3*3 phases 1 slot/pole/phase</td>
<td>36</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>2a</td>
<td>3*3 phases 1 slot/pole/phase</td>
<td>36</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4*3 phases 1 slot/pole/phase</td>
<td>48</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Types 1 and 1a in Table 1 have a usual three phase winding. To show the effect of a conducting shield in the rotor the losses with and without a shield will be compared.

Types 2 and 2a in Table 1 have a 3*3-phase stator winding. The losses with and without a shield will be compared. These configurations have a 18 pulse rectifier.

Type 3 has a 4*3-phase stator winding with 48 slots. This configuration has a 24 pulse rectifier. The effect of increasing values of k will be seen.
5.1. Results of the calculations

The calculations have been limited to harmonics of order 1 to 25 for both \( n \) (harmonics in the phase current) and \( q \) (space harmonics). In this way two kinds of important combinations are included:

- the slot harmonics and the fundamental of the stator current.
- the harmonics in the stator current and the fundamental in space.

For type 1 and 1a (the usual 3 phase winding) the next combinations of \( n \) and \( q \) can have a resulting asynchronous component:

\[
\begin{align*}
n: & \quad 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 1 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 5 \ 7 \ 7 \ 7 \ 7 \ 7 \ 7 \ 7 \ 7 \\
q: & \quad 5 \ 7 \ 11 \ 17 \ 19 \ 23 \ 25 \ 1 \ 7 \ 11 \ 13 \ 17 \ 19 \ 23 \ 25 \ 1 \ 5 \ 11 \ 13 \ 17 \ 19 \ 23 \ 25 \\
\end{align*}
\]

\[
\begin{align*}
n: & \quad 11 \ 11 \ 11 \ 11 \ 11 \ 11 \ 11 \ 13 \ 13 \ 13 \ 13 \ 13 \ 13 \ 13 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \\
q: & \quad 1 \ 5 \ 7 \ 13 \ 17 \ 19 \ 23 \ 25 \ 1 \ 5 \ 7 \ 11 \ 17 \ 19 \ 23 \ 25 \ 1 \ 5 \ 7 \ 11 \ 13 \ 17 \ 19 \ 23 \ 25 \\
\end{align*}
\]

\[
\begin{align*}
n: & \quad 19 \ 19 \ 19 \ 19 \ 19 \ 19 \ 19 \ 19 \ 23 \ 23 \ 23 \ 23 \ 23 \ 23 \ 23 \ 23 \ 25 \ 25 \ 25 \ 25 \ 25 \ 25 \ 25 \ 25 \\
q: & \quad 1 \ 5 \ 7 \ 11 \ 13 \ 17 \ 23 \ 25 \ 1 \ 5 \ 7 \ 11 \ 13 \ 17 \ 19 \ 25 \ 1 \ 5 \ 7 \ 11 \ 13 \ 17 \ 19 \ 23 \\
\end{align*}
\]

For type 2 and 2a (the 3\(*3\) phase winding) the combinations of \( n \) and \( q \) are:

\[
\begin{align*}
n: & \quad 1 \ 1 \ 5 \ 7 \ 11 \ 11 \ 13 \ 13 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \ 17 \\
q: & \quad 13 \ 17 \ 19 \ 25 \ 7 \ 25 \ 5 \ 23 \ 1 \ 19 \ 1 \ 17 \ 5 \ 13 \ 7 \ 11 \\
\end{align*}
\]

For type 3 (the 4\(*3\) phase winding) the combinations of \( n \) and \( q \) are:

\[
\begin{align*}
n: & \quad 1 \ 1 \ 5 \ 7 \ 11 \ 13 \ 17 \ 19 \ 23 \ 23 \ 25 \ 25 \\
q: & \quad 23 \ 25 \ 19 \ 17 \ 13 \ 11 \ 7 \ 5 \ 1 \ 25 \ 1 \ 23 \\
\end{align*}
\]

Please note that the combinations of \( n=5, 7, 11, 13 \) with \( q=1 \) vanish when a 3\(*3\) phase winding is applied.
The results of the loss calculations are listed in Table 2.

Table 2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>DC current $I_{dc}$ (A)</th>
<th>Rotor loss $P_v$ (kW)</th>
<th>Quality factor (minimal-) $Q_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 phases, 3 slots/pole/phase, no shield</td>
<td>969</td>
<td>88</td>
<td>not relevant</td>
</tr>
<tr>
<td>1a</td>
<td>3 phases, 3 slots/pole/phase, with shield</td>
<td>969</td>
<td>2,1</td>
<td>7 ($n=1$ $q=7$) 23 ($n=7$ $q=1$)</td>
</tr>
<tr>
<td>2</td>
<td>3*3 phases, 1 slot/pole/phase, no shield</td>
<td>969</td>
<td>11</td>
<td>not relevant</td>
</tr>
<tr>
<td>2a</td>
<td>3*3 phases, 1 slot/pole/phase, with shield</td>
<td>969</td>
<td>0,9</td>
<td>5 ($n=1$ $q=19$) 47 ($n=19$ $q=1$)</td>
</tr>
<tr>
<td>3</td>
<td>4*3 phases, 1 slot/pole/phase, with shield</td>
<td>726</td>
<td>0,3</td>
<td>4 ($n=1$ $q=25$) 54 ($n=25,q=1$)</td>
</tr>
</tbody>
</table>

More detailed information can be found in the annex.
6. Summary of the results

1. The value of the rotor losses for a usual three phase winding without a conducting shield in the rotor is unacceptable high, \( P_r = 88 \text{ kW} \). The cooling capacity of a liquid cooling system is about 2 kW.

2. The use of a conducting shield will decrease the rotor losses considerable to about 2 kW.

3. The subdivision of the stator 3 phase winding in 3x3 phases results also in a lower rotor loss, 11 kW for \( k = 3 \) in stead of 88 kW when there is no shield.

4. The best results can be obtained with a combination of subsystems in the stator windings and a conducting shield in the rotor, which results in a loss of .9 kW.

5. The calculations do not take the effect of a rise time of the current (ca. 30 degrees at rated load) in account. Inclusion of this effect would result in lower values of \( P_r \). The unavoidable asymmetries in the geometry and the phase currents and a ripple in the DC current will increase the rotor losses.

6. End effects in the rotor might cause an increase of the rotor losses, especially for components with low \( q \). The current path in the rotor will close at the axial ends of the rotor and for low \( q \) and high \( n \) this might be relative long and narrow. Three dimensional finite element calculations and/or measurements are necessary for an evaluation of the end effects.
7. Conclusions

1. The combination of a conducting shield in the rotor, around the permanent magnets and the solid iron core, and the subdivision of a three phase stator winding in several three phase subsystems makes it possible to reduce the rotor loss to an acceptable level, e.g. .1 to .2% of rated power. Consequently, the cooling of the rotor to an acceptable temperature level is feasible.

2. The influence of end effects on the rotor losses are not yet known.

2. Two dimensional finite element simulation agrees with the obtained two dimensional derivation of the rotor losses. An evaluation of the end effects with three dimensional finite element simulation and/or laboratory measurements is still needed.
8. Literature


[2] Kerkenaar, R., Een elektromechanisch voorontwerp van een 500 kW-generator met een
toerental van 25000 omw/min.
NOVEM projectnummer: 42.310-008.2.
TUE rapport nr. EMV 93-10, 1993.


Gasturbine.
NOVEM projectnummer: 248.101-008.3.
TUE rapport EMV.
ANNEX
Annex

program harm5;
{
Berekening voor k=Q/2pm deelsystemen
}
var
p, k, n, q, n_max, q_max: integer;
max1, test: integer;

Idc, r, r1, r2, r3, sigma, sigma_cu, sigma_fe, mu, mu_0, mu_r_fe,
d, ds, l, A3, A2, Pinyin, Pv, Pv_tot, B2, E2, Qs: real;
c, c1, c2, c3, l1, l2, l3, Zq: real;
omega_s, omega_r, f: real;

File_Name, File_Name_In, File_Name_Out, parameter: string;
Out_File, In_File: text;

geg_str: array[0..24] of string[25];

function n..gelijk_q:boolean;
begin
  if (n-q=0) then n..gelijk_q:=true
  else n..gelijk_q:=false
end;

function n_even:boolean;
begin
  n_even:=not(odd(n));
end;

function n_veelv_3:boolean;
begin
  if (n MOD 3 = 0) then n_veelv_3:=true
  else n_veelv_3:=false;
end;

function test_1:boolean;
begin
  if (abs(n-q) MOD (6*k) = 0) then test_1:=true
  else test_1:=false;
end;
function test_2:boolean;
begin
  if ((n+q) MOD (6*k) = 0) then test_2:=true
  else test_2:=false;
end;

Procedure invoer;
var i, j, len: integer;
begin
  j:=0;
  assign(In_File,File_Name_In);
  reset(In_File);
  While not Eof(In_File) do
  begin
    readln(In_File,parameter);
    i:=Pos('=',parameter);
    len:=Length(parameter);
    parameter:=Copy(parameter,i+1,len-i);
    geg_str[j]:=parameter;
    j:=j+1;
  end;
  Val(geg_str[1],max1,test);
  Val(geg_str[2],k,test);
  Val(geg_str[3],p,test);
  Val(geg_str[4],f,test);
  Val(geg_str[5],ldc,test);
  Val(geg_str[6],r1,test);
  Val(geg_str[7],r2,test);
  Val(geg_str[8],r3,test);
  Val(geg_str[9],d,test);
  Val(geg_str[10],l,test);
  close(In_File);
end;

begin
  File_Name:=paramstr(1);

File_Name_Out:=File_Name+'.out';
File_Name_In:=File_Name+'.in';

invoer;

omega_s:=f*2*pi;
sigma_cu:=50e6; mu_0:=4*pi*1e-7; mu_r_fe:=1000 ;sigma_fe:=5e6;
P_v_tot:=0;
if (d>=0) then
begin
  r:=r2;
  sigma:=sigma_cu;
  mu:=mu_0;
end;
if (d=0) then
begin
  r:=r1;
  sigma:=sigma_fe;
  mu:=mu_0*mu_r_fe;
end;
n_max:=max1; q_max:=max1;

assign(Out_File,File_Name_Out);
rewrite(Out_File);
writeln(Out_File,'data: ');
writeln(Out_File,'k='+geg_str[1]);
writeln(Out_File,'p='+geg_str[2]);
writeln(Out_File,'f='+geg_str[3]);
writeln(Out_File,'Idc='+geg_str[5]);
writeln(Out_File,'rl='+geg_str[6]);
writeln(Out_File,'r2='+geg_str[7]);
writeln(Out_File,'d='+geg_str[9]);
writeln(Out_File,'l='+geg_str[10]);
writeln(Out_File,'');
close(Out_File);

n:=1;
while (n<=n_max) do
begin{n
q:=1;
while (q<=q_max) do
begin{q
if (not n_even
and not n_gelijk_q
and (test_1 or test_2)
and not n_veelv_3)
then
begin {berekening}

if (test_1) then
begin
omega_r:=abs(n-q)*omega_s;
ds:=sqrt(2/(omega_r*sigma*mu))
end;

if (test_2) then
begin
omega_r:=(n+q)*omega_s;
ds:=sqrt(2/(omega_r*sigma*mu))
end;

if (d<>0) then
begin
  if (ds>d) then ds:=d;
end;

Zq:=(2*p)/(pi*r3);

A3:=((3*k)/2)*(Zq)*((2*sqrt(3))/(pi*n))*ldc;
c:=ln(r/r3);
c1:=exp((p*q-1)*c); c2:=exp(2*p*q*c);
A2:=A3*c1/(1+c2);
Pv:=pi*r1*r2*sqrt(A2)/(sigma*ds);
Pv_tot:=Pv_tot+Pv;

if (d<>0) then
begin
  l1:=ln(r2/r3); l2:=ln(r1/r2); l3:=ln(r1/r3);
c1 := \exp((p^*q-1)^11); c2 := \exp(2*p^*q^12); c3 := \exp(2*p^*q^13);
B2 := \mu_0*A3*c1*(1-c2)/(1+c3);
E2 := \omega_r*B2*r2/(p^*q);
Qs := E2/(A2/(\sigma*ds));
end;

append(Out_File);
if (d<>0) then
begin
writeln(Out_File,'asyn ,n,' ,',q',' ,Pv:3:1,' ,Pv_tot:3:1,' ,ds*1000:3:3,' ,Qs:3:1);
end
else
begin
writeln(Out_File,'asyn ,n,' ,',q',' ,Pv:3:1,' ,Pv_tot:3:1,' ,ds*1000:3:3);
end;
close(Out_File);
end

if (n_gelijk_q and not n_even and not n_veelv_3) then
begin
append(Out_File);
writeln(Out_File,'syn ',n,' ',',q','
q:=q+1;
end(q);
n:=n+1;
end(n);
append(Out_File);
writeln(Out_File,'Pv= ',Pv_tot:3:1);
close(Out_File);
end.
data:
mega362.in (type 2)
max1=25
k=3
p=2
f=600
Idc=969
r1=0.110
r2=0.126
r3=0.136
d=0
l=0.620

syn 1 1
asyn 1 17 4.2 4.2 0.068
asyn 1 19 0.8 5.0 0.068
syn 5 5
asyn 5 13 5.0 10.0 0.068
asyn 5 23 0.0 10.0 0.068
syn 7 7
asyn 7 11 14.0 23.9 0.068
asyn 7 25 0.0 23.9 0.068
asyn 11 7 167.6 191.5 0.068
syn 11 11
asyn 11 25 0.0 191.5 0.048
asyn 13 5 640.0 831.5 0.068
syn 13 13
asyn 13 23 0.0 831.5 0.048
asyn 17 1 5629.5 6461.0 0.068
syn 17 17
asyn 17 19 0.0 6461.0 0.048
asyn 19 1 4506.7 10967.7 0.068
asyn 19 17 0.0 10967.7 0.048
syn 19 19
asyn 23 5 204.5 11172.2 0.068
asyn 23 13 0.3 11172.5 0.048
syn 23 23
asyn 25 7 32.4 11205.0 0.068
asyn 25 11 1.5 11206.5 0.048
syn 25 25
Pv= 11206.5
data:
mega362a.in (type 2a)
max I=25
k=3
p=2
f=600
Idc=969
r1=0.110
r2=0.126
r3=0.136
d=0.001
l=0.620

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max1=25
k=4
p=2
f=600
Idc=726
r1=0.110
r2=0.126
r3=0.136
d=0.001
l=0.620

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asyn 1 25 37.6 106.7 0.593 4.3
syn 5 5
asyn 5 19 9.3 116.0 0.593 5.6
syn 7 7
asyn 7 17 8.7 124.8 0.593 6.3
syn 11 11
asyn 11 13 11.7 136.5 0.593 8.3
asyn 13 11 15.0 151.5 0.593 10
syn 13 13
asyn 17 7 25.4 176.9 0.593 16.5
syn 17 17
asyn 19 5 31.7 208.6 0.593 23.8
syn 19 19
asyn 23 1 36.0 244.6 0.593 54.1
syn 23 23
asyn 23 25 0.1 244.7 0.419 6.0
asyn 25 1 30.5 275.1 0.593 54.1
asyn 25 23 0.2 275.3 0.419 6.5
syn 25 25
Pv= 275.3
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