Calculation of Eddy Current Losses in Permanent Magnets of Synchronous Machines

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Overview

- Introduction
- Considered PM synchronous motors
- Loss calculation methods
- Loss estimation from thermal measurements
- Conclusions
Permanent - Magnet motors with concentrated windings

Increased eddy current losses in the rotor magnets:

- air gap field pulsations due to the slot openings
- flux pulsations in the magnets at load operation

Segmented Magnets

8 PM motors (2 Stators & 4 Rotors):
- Constant power: 45 kW
- Rated speed: 1000 rpm
- Maximum speed: 3000 rpm
Considered PM synchronous motors

**Motor A**
- 7 magnets / pole

**Motor B**
- 1 magnet / pole

**Surface mounted magnets**

**Motor C**
- 7 magnets / pole

**Motor D**
- 1 magnet / pole

**Buried magnets**

24 semi-closed stator slots / 16 poles
Considered PM synchronous motors

Motor E
- 7 magnets / pole
- 1 magnet / pole
Surface mounted magnets

Motor F
- 7 magnets / pole

Motor G
- 7 magnets / pole
Buried magnets

Motor H
- 1 magnet / pole

24 open stator slots / 16 poles
Loss calculation methods

**Flux density for Motor A**

1000 rpm, no-load operation

**B(x) at upper surface**

**FEMAG-DC** (no eddy currents considered!)

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Loss calculation methods

Flux density for **Motor A**

1000 rpm, no-load operation

**Upper surface**

**Middle surface**

**Bottom surface**

FEMAG-DC (no eddy currents considered!)

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Loss calculation methods

Flux density at no-load operation

Motor A

Motor B

Motor C

Motor D

1000 rpm, upper surface

FEMAG-DC (no eddy currents considered!)

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Loss calculation methods

**Flux density at load operation**

Motor A: Sinusoidal current

Motor B

Motor C

Motor D

1000 rpm, upper surface

FEMAG-DC (no eddy currents considered!)

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**Method 1: FEMAG-DC & Analytical Formula**

**Vector potential**

\[ A_z = \sum_{i=0}^{k} B_r (i) \cdot \Delta x, \quad k=0 \ldots n \]

**Current density**

\[ J_z (k, t_{j+1}) = -\kappa_{\text{Meff}} \cdot \frac{A(k, t_{j+1}) - A(k, t_j)}{\Delta t} \]

**Alternating current density**

\[ \int_{b_M} J_z (x) \cdot dx = 0 \quad J_{z-} (k, t_{j+1}) = J_z (k, t_{j+1}) - \overline{J_z (t_{j+1})} \]

**Losses in magnets**

\[ P_{\text{Mu}, m, b} = \int_V \frac{J_{z-}^2}{\kappa_{\text{Meff}}} dV = \sum_{u, m, b} \left( h_M \cdot \Delta x \cdot l_M \cdot \frac{1}{\kappa_{\text{Meff}}} \cdot \sum_{k=1}^{n} J_{z-}^2 (k, t_{j+1}) \right) \]

Considered in each of the three surfaces (upper, middle, bottom)
Method 2: FEMAG DC - Version 05/2007

- No reaction field of eddy currents considered

- Maxwell equations
  \[ \text{rot} \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \vec{J} = \kappa \vec{E} \]

- Fast calculation

- For magnets with rather low conductivity (small eddy currents)

Method 2 is similar to Method 1, but
\[ \int_{A_M} J_z(x, y) \cdot dx \cdot dy = 0 \]
is considered over the magnet cross section and not only in the three surfaces
Loss calculation methods

Influence of eddy current reaction field

Penetration depth:  \[ d_E = \frac{1}{\sqrt{\kappa_{Mg} \cdot \pi \cdot f_{B,Mg} \cdot \mu_{Mg}}} \]

Ratio \( b_{Mg} / d_E \leq 1 \rightarrow \) no eddy current reaction field

**Ex.:** \( n = 3000 \text{ rpm}; f_s = 400 \text{ Hz}; f_{B,Mg} = 1200 \text{ Hz} (q = \frac{1}{2}) \)

<table>
<thead>
<tr>
<th>Motor A</th>
<th>Motor B</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b_{Mg,A} = 3.6 \text{ mm} )</td>
<td>( b_{Mg,B} = 27.3 \text{ mm} )</td>
</tr>
<tr>
<td>( \kappa_{Mg,A} = 0.62 \cdot 10^6 \text{ S/m} )</td>
<td>( \kappa_{Mg,B} = 0.43 \cdot 10^6 \text{ S/m} )</td>
</tr>
<tr>
<td>( d_{E,A} = 17.8 \text{ mm} )</td>
<td>( d_{E,B} = 21.6 \text{ mm} )</td>
</tr>
<tr>
<td>( b_{Mg,A} / d_{E,A} = 0.2 )</td>
<td>( b_{Mg,B} / d_{E,B} = 1.26 )</td>
</tr>
</tbody>
</table>
**Method 3: 2D Time-step calculation**

- Reaction field of eddy currents considered
- Full set of Maxwell equations
  \[ \text{rot}\vec{E} = -\partial\vec{B} / \partial t \]
  \[ \vec{J} = \kappa\vec{E} \]
  \[ \text{rot}\vec{H} = \vec{J} \quad \vec{B} = \mu\vec{H} \]
- For general purpose up to medium frequencies valid
- Very time consuming
Loss calculation methods

Comparison

No-load 1000 rpm

Motor A
Motor B
Motor C
Motor D
Motor G
Motor H

q = ½

q = ¼
Loss calculation methods

Comparison
Sinusoidal current

Load 1000 rpm

Load 3000 rpm

Method1: FEMAG + Analytical
Method2: FEMAG
Method3: Time stepping

$q = 1/2$
$q = 1/4$

Motor A
Motor B
Motor C
Motor D
Motor G
Motor H

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Loss estimation from thermal measurements

**Losses at adiabatic heating**

Losses: \[ P = m \cdot c \cdot \frac{d \vartheta}{dt} \]

Useful only as the ratio of the \( \frac{d \vartheta}{dt} \) values by the different motor configuration!!

Magnet temperature

Motor A: 1000 rpm load operation

Motor G

Temperature sensor

Motor A

7 magnets
Loss estimation from thermal measurements

**Comparison**
(all values related to Motor A, 1000 rpm, no-load operation $P_{Mg0,A}$)

### No-load 1000 rpm

![Graph](graph1)

- Calculated
- Measured

**Losses in rotor iron bridge and magnets**

### No-load 3000 rpm

![Graph](graph2)

**Losses in rotor iron bridge and magnets**

Motor A: 7 magnets
Motor B: 1 magnet
Motor C: $q = \frac{1}{2}$
Motor E: $q = \frac{1}{4}$
Loss estimation from thermal measurements

Comparison
(all values related to Motor A, 1000 rpm, no-load operation $P_{Mg0,A}$)

Load 1000 rpm

Load 3000 rpm

Losses in rotor iron bridge and magnets

Motor A  7 magnets  $q = \frac{1}{2}$
Motor B  1 magnet
Motor C

Motor E
Motor F  $q = \frac{1}{4}$
Motor G
Conclusions

- 3 loss calculation methods: FEMAG-DC & analytical formula
  
  FEMAG-DC
  Time stepping

- 8 motors: 2 Stators \((q = \frac{1}{2}; q = \frac{1}{4})\)
  
  4 Rotors (segmented/non-segmented; surface/buried)

- eddy-current losses in magnets are possible to be calculated with DC method (no eddy current reaction field) due to the rather low conductivity of rare-earth magnets

- loss estimation from adiabatic thermal heating is possible mainly for surface-mounted permanent magnets

- for buried magnets: influence of bridge losses to be investigated further
Calculation of Eddy Current Losses in Permanent Magnets

Thank you for your attention!

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