Modeling magnetostriction and the effect of mechanical stress on iron loss in electrical machines

Dr. Anouar Belahcen
Adj. Prof. Aalto University
Prof. Tallinn University of Technology
Anouar.belahcen@aalto.fi
Contents

• Introduction
  – Magnetization and stress in iron
  – Iron loss and mechanical stress
  – Magnetostriction and stress
• Causes of stress in electrical machines
• Computation of magnetic forces
• Modeling and measuring magnetostriction
• Hysteresis modeling
• What next
  – Modeling the effect of stress on hysteresis curves
  – Magnetomechanical coupling
  – Validation and verification
Energy conversion and losses

Typical values for induction motors $P < 100$ kW

<table>
<thead>
<tr>
<th>Type of loss</th>
<th>Percentage of total loss (100%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed loss or core</td>
<td>25</td>
</tr>
<tr>
<td>Variable loss: stator $Rl^2$</td>
<td>34</td>
</tr>
<tr>
<td>Variable loss: rotor $Rl^2$</td>
<td>21</td>
</tr>
<tr>
<td>Friction &amp; rewinding loss</td>
<td>15</td>
</tr>
<tr>
<td>Stray load loss</td>
<td>5</td>
</tr>
</tbody>
</table>

Motoring operation mode of electrical machines and related losses

Motoring operation mode

$$P_{in} = \sqrt{3} UI \cos \theta \quad P_{out} = T_{mech} \omega_{mech} \quad \text{Eff} = \frac{P_{out}}{P_{in}}$$
Losses in Electrical Machines

Copper losses
- Stator coils
  - $RI^2$
  - $\propto f^2 B_{Fe}^2$
- Rt. coils and cage
  - $fB_{Fe}^2$
Iron losses
- Eddy-currents
  - $\propto f^2 B_{Fe}^2$
- Hysteresis
  - $\propto fB_{Fe}^2$
PM losses
- Excess
  - $\propto f^{1.5} B_{Fe}^{1.5}$
Friction
- $\propto \omega^3$

Mechanical stress and magnetic properties

Unidirectional stress and flux density

Mechanical stress and magnetic properties

Stress parallel to x-axis and flux density at 45 deg to x-axis
Tensile strain correspond to compressive strain on y-axis
Mechanical stress and iron losses

Measured iron losses under unidirectional stress and flux density

Magnetostriction and stresses

\[ 5 \times 10^{-6} \]

\[ 3.9 \text{ MPa} \]

\[ 0.0 \text{ MPa} \]

\[ -1.7 \text{ MPa} \]

\[ -6.1 \text{ MPa} \]

Causes of stress in electrical machines

- Residual stress due to punching and machining
  - Plastic deformation
  - Uncertain range and strength
  - Partially released with time

- Static stress due to shrink-fitting
  - In average possible to estimate
  - Locally might be of very high strength

- Static stress under own weight

- Dynamic stress due to magnetic forces
  - Modeling its effect on losses is challenging

- Magnetostrictive dynamic stress
  - Modeling and validation still controversial
Computation of magnetic forces

- Maxwell stress tensor
  - Several versions

- Virtual work principle
  - Global version
  - Local version

\[
F^T = -\int_{\hat{S}_e} \left[ \frac{1}{\mu_e} \nabla A \cdot \frac{\partial}{\partial U} \left( \nabla A \right) |J| + \int_{0}^{B} H \cdot dB \frac{\partial}{\partial U} \left( |J| \right) \right] d\hat{S}_e
\]

- Require local magnetic flux density distribution
- Finite Element Method
Measuring magnetostriction

• Unidirectional
  – Epstein frame or equivalent
  – Easy to apply external stress
  – Results are easy to interpret
  – Stress only in the direction of B

• Bi-directional
  – Single sheet tester
  – Complex design and supply
  – Stress in any direction
  – Result may be understood wrong

Aalto University
School of Electrical Engineering
Measuring magnetostriction

Measured magnetostrictive strains with two different methods
Rotational magnetostriction seems to be much higher than alternating
Modeling magnetostriction

- Magnetostrictive forces
  - From measured magnetostriction
  - Does not account stress dependency
  - Large amount of data needed
  - Relatively fast computation

- Coupled magnetomechanical model
  - Needs only 5-8 parameters
  - Relatively challenging identification

\[
\begin{align*}
\tau(B, \varepsilon) &= \lambda I_1 I + \rho \tilde{\psi}_4(I_4) I + 2G \varepsilon + \mu_0^{-1} \left( B \otimes B - \frac{1}{2} (B \cdot B) I \right) \\
&\quad + 2 \rho \psi_4 \left( B \otimes B - (B \cdot B) I \right) \\
&\quad + \frac{\rho}{2} \alpha_5 \left[ B \otimes B \cdot \varepsilon - (B \cdot \varepsilon \cdot B) I \right] \\
&\quad + \frac{\rho}{2} \alpha_6 \left[ B \otimes B + B \otimes B \cdot \varepsilon^2 - (B \cdot \varepsilon^2 \cdot B) I + (B \otimes B \cdot \varepsilon + \varepsilon \cdot B \otimes B) \right]
\end{align*}
\]

\[
\begin{align*}
I_1 &= \text{tr} \varepsilon \\
I_2 &= \frac{1}{2} (\text{tr} \varepsilon)^2 \\
I_3 &= \frac{1}{3} (\text{tr} \varepsilon)^3 \\
I_4 &= B \cdot B \\
I_5 &= B \cdot \varepsilon \cdot B \\
I_6 &= B \cdot \varepsilon^2 \cdot B
\end{align*}
\]

Modeling magnetostriction

\[
\varepsilon_{xy} (\mu \text{m/m}) \quad \sigma_{yy} (\text{MPa})
\]

Modeling magnetostriction

Deformation of the stator of a 2-pole machine (left) a 4-pole machine (right)

Modeling hysteresis losses in steel

\[ B_{\phi_i} = |\mathbf{B}| \cos(\theta_B - \phi_i + \psi) \]

\[ H_{\phi_i} = H_{st}(B_{\phi_i}) + \frac{\sigma d^2}{12} \delta_i \left| \frac{dB_{\phi_i}}{dt} \right|^p + \delta_i \left| \frac{1}{r} \frac{dB_{\phi_i}}{dt} \right|^{1/p} \]

\[ H(t) = \sum_{i=1}^{N} H_{\phi_i} \left[ B_{\phi_i}(t) \right] e_{\phi_i} \]

Preisach Model of hysteresis and improved Mayergoyz vector method

Identification of material parameters

Measurements under rotational field
Measurement results

Anouar Belahcen
14.6.2012
Conclusions

- Mechanical stress has considerable effect on
  - Iron losses
  - Magnetization properties of iron
  - Magnetostriction

- Magnetostriction produces additional stress in iron core

- Adequate modeling combined with advanced techniques for measurement are required for
  - Understanding the coupled phenomena
  - Accurately compute the losses
  - Optimize the machine structure and design