Robust Design of Induction Motor
Design of Three Phase Induction Motor

- Stator
- Rotor Ring
- Rotor Radius
- Ring Thickness
- Phase Angle
- Air Gap

Coil Winding
Phase Group A, B, C
Field Simulation in Infolytica-MagNet
Dynamical Simulation in Infolytica-MagNet

- Magnetic Force/Torque
- Ohmic Loss
- Speed
- Current
Design Specifications

- Max. Torque $\leq 3.6 \text{ N}\cdot\text{m}$
- Max. Current $\leq 4020 \text{ A}$
- Max. Flux Density $\leq 0.115 \text{ T}$
- Max Energy Loss $\leq 345,000 \text{ W}\cdot\text{s}$
- Corridor for Rotor Speed
  - Rising = 65 deg/s$^2$
  - Bandwidth = 3000 deg/s

Initial Design Parameters with its Uncertainty

<table>
<thead>
<tr>
<th>Name</th>
<th>Nominal</th>
<th>Tolerance</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Radius</td>
<td>2</td>
<td>0.04</td>
<td>cm</td>
</tr>
<tr>
<td>Ring Thickness</td>
<td>1</td>
<td>0.04</td>
<td>cm</td>
</tr>
<tr>
<td>Air Gap</td>
<td>0.05</td>
<td>0.01</td>
<td>cm</td>
</tr>
<tr>
<td>Phase Angle</td>
<td>45</td>
<td>2</td>
<td>deg</td>
</tr>
<tr>
<td>Coercivity Scale</td>
<td>1</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Conductivity Scale</td>
<td>1</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Friction Coefficient</td>
<td>0.001</td>
<td>0.001</td>
<td>Nms/rad</td>
</tr>
</tbody>
</table>
Stochastic Distributions of Design Parameters

- **Rotor Radius**
  - Mean: 2.00003
  - Skewness: 0.00236228
  - Kurtosis: 2.84128
  - Variance: 4.34185e-005

- **Ring Thickness**
  - Mean: 0.999998
  - Skewness: -0.0008806
  - Kurtosis: 2.84786
  - Variance: 4.3407e-005

- **Air Gap**
  - Mean: 0.0499392
  - Skewness: 0.00066052
  - Kurtosis: 2.83742
  - Variance: 2.70879e-006

- **Phase Angle**
  - Mean: 41.0006
  - Skewness: 0.0074419
  - Kurtosis: 2.8523
  - Variance: 0.107739

- **Conductivity Scale**
  - Mean: 0.999978
  - Skewness: 0.0031478
  - Kurtosis: 2.83161
  - Variance: 4.34207e-005

- **Friction Coefficient**
  - Mean: 0.00100003
  - Skewness: -0.00051452
  - Kurtosis: 2.66358
  - Variance: 2.71323e-004
OptiY Process Work Flow
Design of Experiment

75 Calculations of Original Model in MagNet
Probabilistic Simulation for Initial Design

Total Failure Probability = 52.597%
Probabilistic Simulation for Initial Design

- **Max Current**
  - Mean: 3387.54
  - Standard Deviation (Sigma): 1213.32
  - Variance: 147.215
  - Skewness: -0.692457
  - Kurtosis: 1.0421
  - Failure Probability: 0.00013/0.52597

- **Max Flux Density**
  - Mean: 0.11417
  - Sigma: 0.000392056
  - Variance: 1.18708e-007
  - Skewness: -0.241314
  - Kurtosis: 2.04113
  - Failure Probability: 0.00011/0.52597

- **Loss**
  - Mean: 332881
  - Sigma: 3036.46
  - Variance: 9.2200e+006
  - Skewness: -0.199063
  - Kurtosis: 1.11736
  - Failure Probability: 0/0.52597

- **Max Torque**
  - Mean: 3.37119
  - Sigma: 0.0224931
  - Variance: 0.000505958
  - Skewness: 0.593112
  - Kurtosis: 2.61698
  - Failure Probability: 0/0.52597
Sensitivity Study for Initial Design

- Rotor radius and ring thickness have most influence on rotor acceleration
- Friction coefficient is the most important factor on constant rotor speed
Sensitivity Study for Initial Design

- **Max Current**
  - Ring Thickness: 31.43%, 34.77%
  - Rotor Radius: 27.20%, 26.71%
  - Air Gap: 14.45%, 14.08%
  - Coercivity Scale: 61.11%, 5.85%
  - Conductivity Scale: 60.50%, 5.79%
  - Phase Angle: 6.04%, 5.79%
  - Friction Coefficient: 5.93%, 5.68%

- **Max Flux Density**
  - Ring Thickness: 78.57%, 77.13%
  - Rotor Radius: 5.92%, 5.0%
  - Conductivity Scale: 5.54%, 5.09%
  - Coercivity Scale: 4.07%, 3.77%
  - Friction Coefficient: 2.62%, 2.33%
  - Air Gap: 2.47%, 2.2%
  - Phase Angle: 2.44%, 2.18%

- **Loss**
  - Rotor Radius: 45.18%, 44.31%
  - Ring Thickness: 30.68%, 30.01%
  - Phase Angle: 14.6%, 14.14%
  - Friction Coefficient: 9.32%, 8.74%
  - Conductivity Scale: 1.45%, 1.16%
  - Coercivity Scale: 0.27%, 0%
  - Air Gap: 0.27%, 0%

- **Max Torque**
  - Rotor Radius: 94.35%, 92.83%
  - Conductivity Scale: 1.64%, 1.36%
  - Air Gap: 1.63%, 1.35%
  - Coercivity Scale: 1.62%, 1.38%
  - Friction Coefficient: 0.89%, 0.61%
  - Air Gap: 0.75%, 0.48%
  - Phase Angle: 0.68%, 0.41%
Robust Design Optimization

Optimization Results:

Robust Design Parameters with its Uncertainty

Robust Design Goal to Minimize the Failure Probability
Probabilistic Simulation for Robust Design

Total Failure Probability = 0.013%
Probabilistic Simulation for Robust Design

- Max Current
  - Mean: 2920.59
  - Sigma: 7839.95
  - Variance: 613035
  - Skewness: 0.045279
  - Kurtosis: 3.5852
  - Failure Probability: 0/3000013

- Max Flux Density
  - Mean: 0.112937
  - Sigma: 0.000121343
  - Variance: 0.04115e-008
  - Skewness: -0.0073075
  - Kurtosis: 2.83475
  - Failure Probability: 0/000013

- Loss
  - Mean: 0.00189
  - Sigma: 0.00124
  - Variance: 0.00035

- Max Torque
  - Mean: 3.14565
  - Sigma: 0.01205
  - Variance: 0.01205
  - Skewness: 0.319128
  - Kurtosis: 2.94721
  - Failure Probability: 0/000013
Sensitivity Study for Robust Design

- Ring thickness has most influence on rotor acceleration
- Friction coefficient is the most important factor on constant rotor speed
Sensitivity Study for Robust Design

- **Max Current**
  - Ring Thickness: 67.45%, 66.27%
  - Rotor Radius: 25.44%, 24.83%
  - Air Gap: 6.49%, 6.13%
  - Coercivity Scale: 0.67%, 0.4%
  - Phase Angle: 0.59%, 0.31%
  - Conductivity Scale: 0.54%, 0.27%
  - Friction Coefficient: 0.41%, 0.13%

- **Max Flux Density**
  - Ring Thickness: 74.6%, 72.56%
  - Coercivity Scale: 11.01%, 10.59%
  - Conductivity Scale: 9.51%, 8.37%
  - Rotor Radius: 2.63%, 2.34%
  - Friction Coefficient: 2.38%, 2.09%
  - Phase Angle: 1.14%, 0.86%
  - Air Gap: 1.07%, 0.8%

- **Loss**
  - Rotor Radius: 18.86%, 18.12%
  - Ring Thickness: 17.16%, 16.84%
  - Phase Angle: 10.77%, 10.46%
  - Friction Coefficient: 14.06%, 13.78%
  - Conductivity Scale: 11.72%, 11.48%
  - Coercivity Scale: 11.19%, 10.35%
  - Air Gap: 11.19%, 10.35%

- **Max Torque**
  - Rotor Radius: 31.57%, 31.08%
  - Ring Thickness: 12.11%, 11.85%
  - Conductivity Scale: 11.05%, 11.43%
  - Coercivity Scale: 11.63%, 11.38%
  - Phase Angle: 11.35%, 11.11%
  - Air Gap: 11.35%, 11.11%
  - Friction Coefficient: 11.28%, 11.04%
Conclusion

Nominal design using classical nominal simulation cannot warranty the reliability and quality of the products, because the nominal parameters are only one fix value.

Robust design is a power-full tool for design of reliable and quality product in the early design stage without any cost. It considers the uncertainty parameters as stochastic distributions.

In the case of the induction motor, the failure probability has been reduced from **52,597% to 0,013%** for the mass manufacturing.

**OptiY®** is the leading software platform for robust design of all engineering fields using different commercial CAD/CAE-software or in-house codes.