# Large-Scale FEA for Traction Motor Analysis, Optimization, and Validation

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# Why Large-Scale FEA Matters for Modern Traction Motors

- ***Complex Motor Design Demands***
  - Modern EV motors require high torque, efficiency, low noise, and robust operation under variable conditions.
- ***Need for Large-Scale FEA***
  - FEA captures electromagnetic, thermal, and structural interactions critical for predicting motor behavior accurately.
- ***Early Design Validation***
  - High-fidelity FEA enables earlier design validation and identifying risks sooner.
- ***Design Exploration at Scale***
  - FEA-driven workflows support evaluating thousands of design variants for system optimization and robust manufacturing.



https://www.gm-volt.com/attachments/x11ch_vt156l-jpg.169882/

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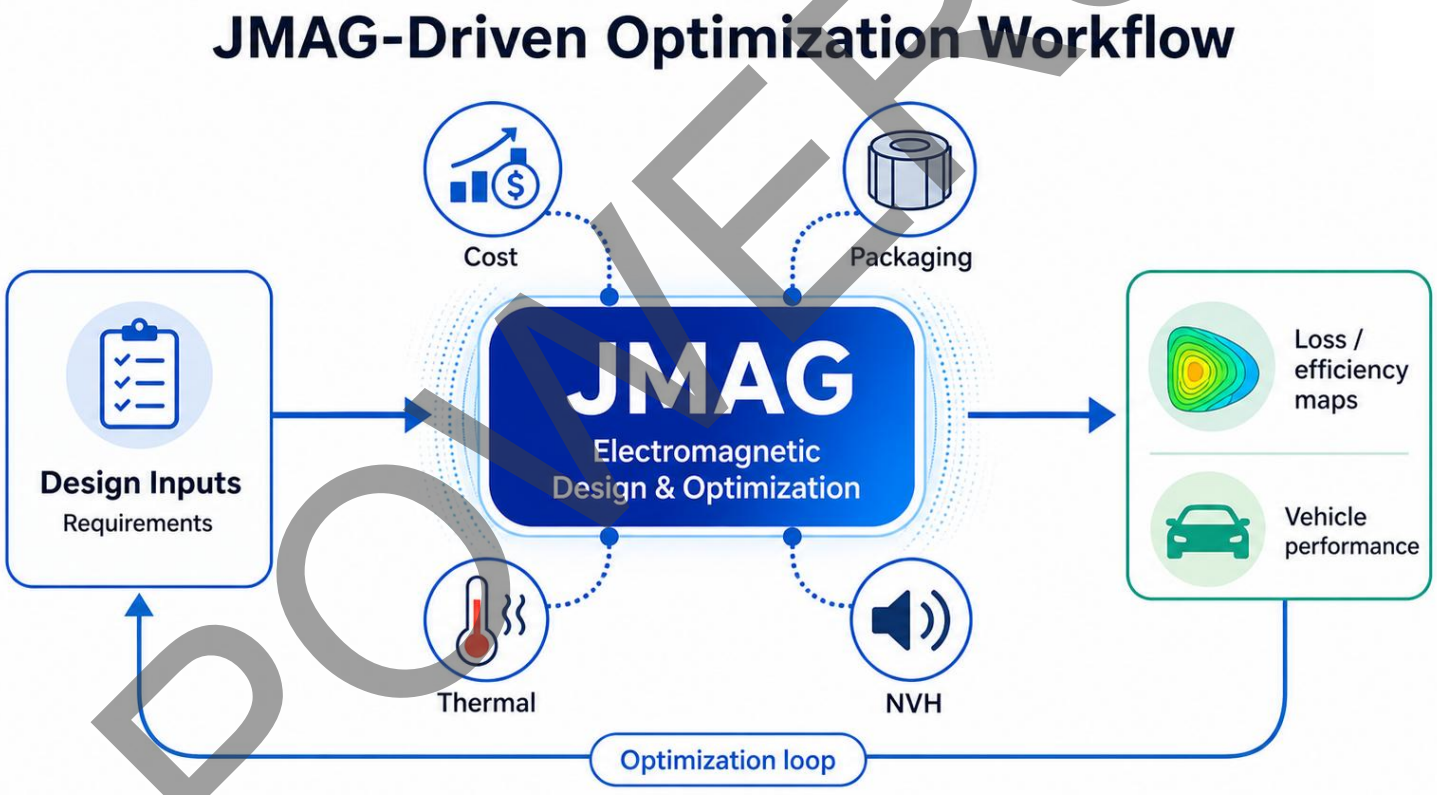
# Motor Design Optimization

## Multi-Objective Design Challenges

- ✓ Traction motor design involves balancing torque, efficiency, thermal limits, mechanical stress, and cost among other factors.

## Simulation-Driven Optimization

- ✓ High-fidelity multidisciplinary simulations enable quantitative trade-off evaluation and robust design convergence.




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# 3D Modeling Capabilities

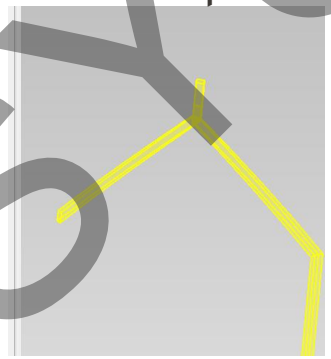
## *Motor Torque & Flux Modeling*

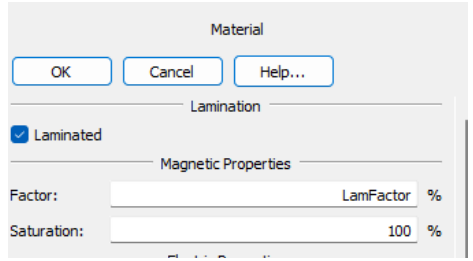
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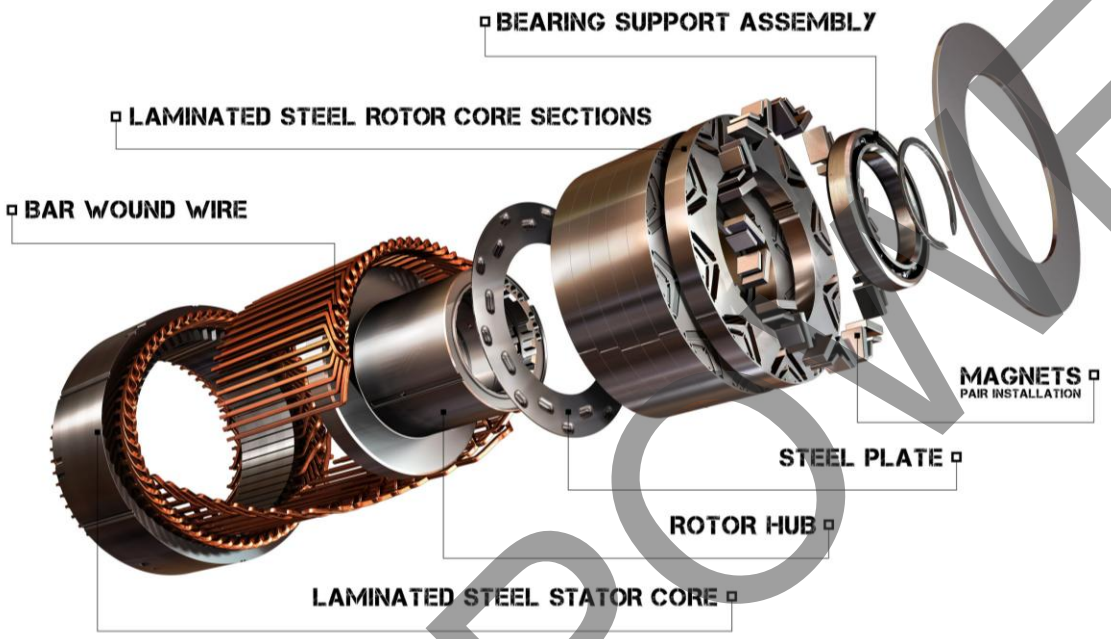
# 3D Modeling Capabilities

- JMAG is a comprehensive finite element tool with excellent 3D modeling capabilities.
  - ✓ Material definition and lamination settings
  - ✓ Robust Coil Template Capability

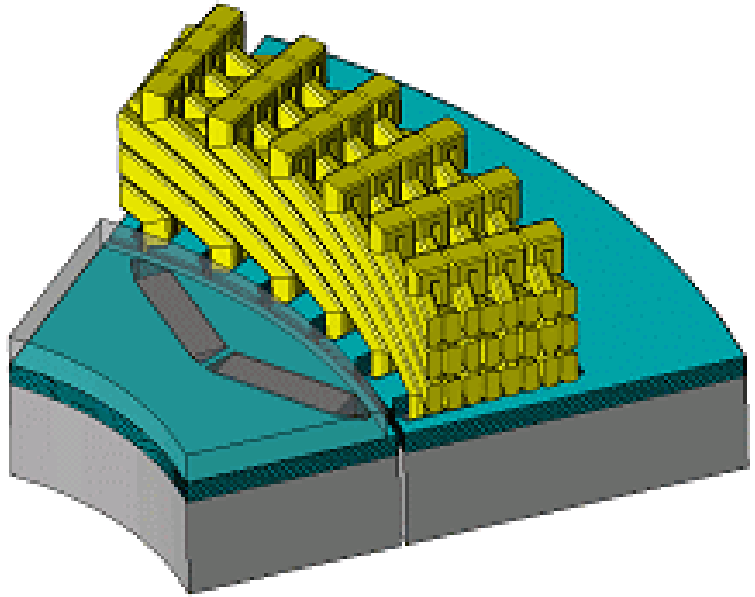
Coil Template






Modeling



general motors

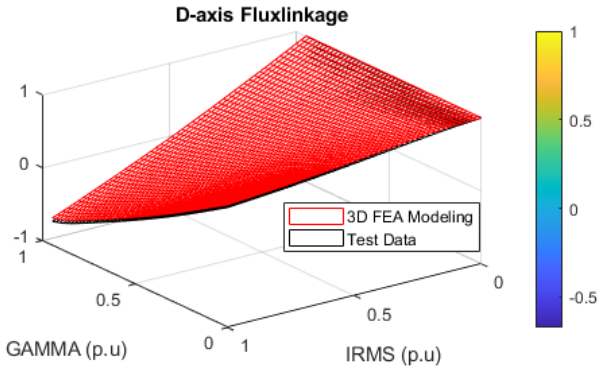
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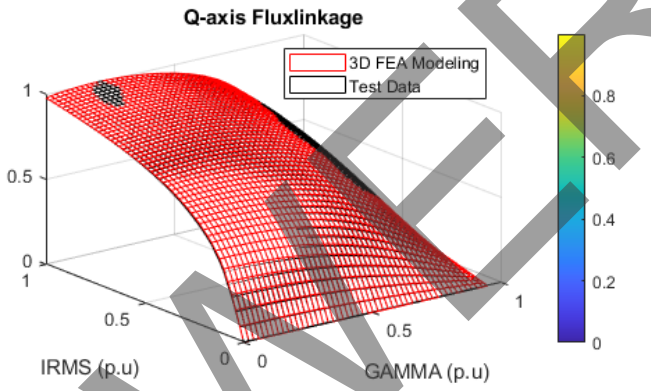
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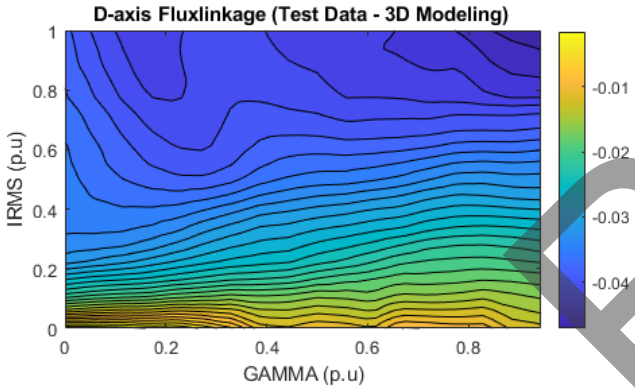
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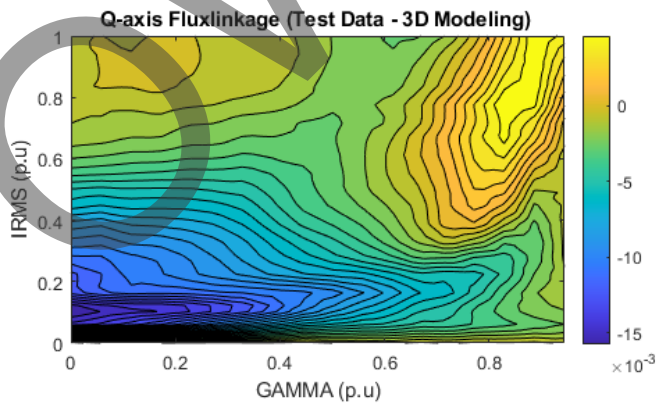
# 3D Modeling Capabilities – (Flux Linkage)

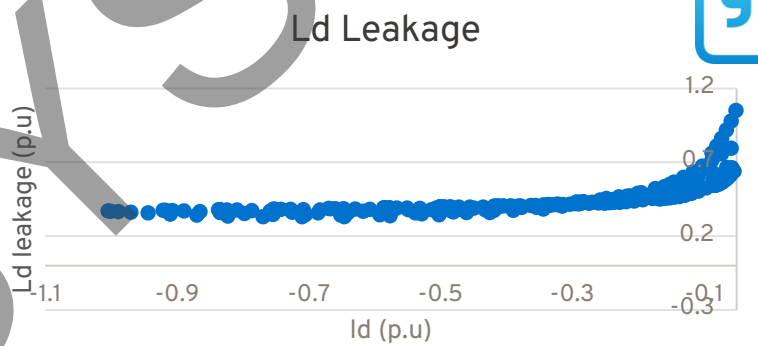
- Excellent flux-linkage and torque predictions achieved using JMAG 3D FEA
  - Characterization as function of current and angle (gamma)
  - Leakage components assessment

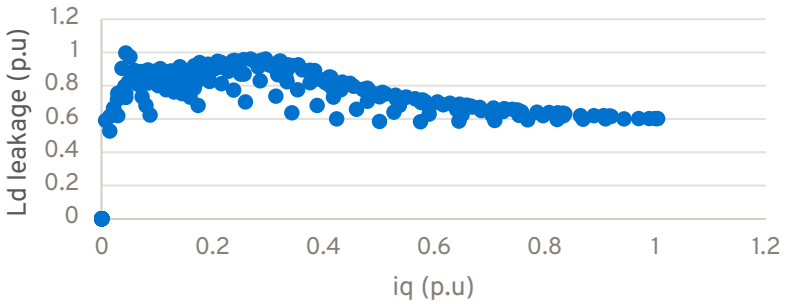


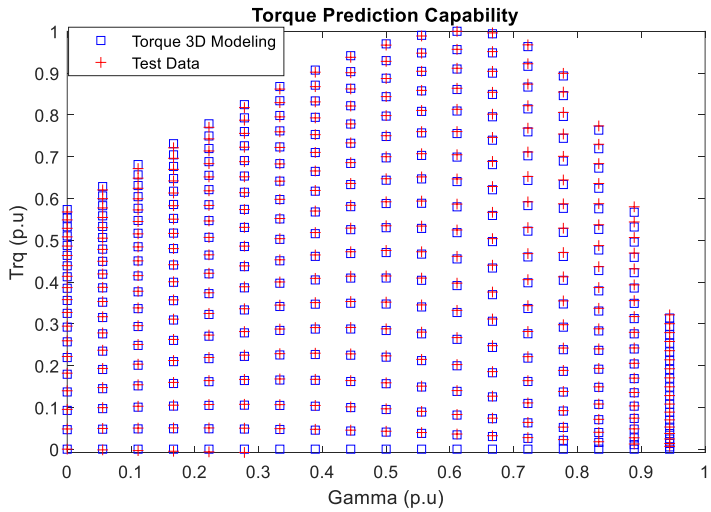



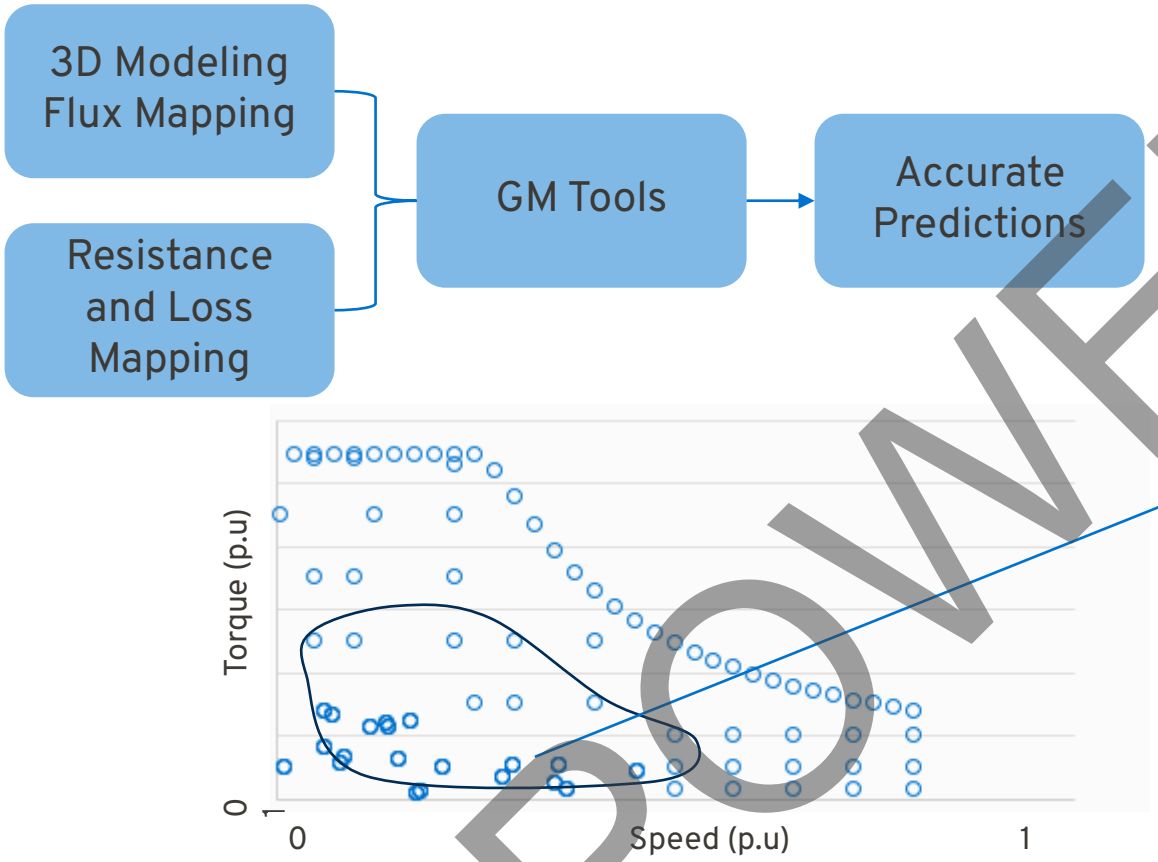



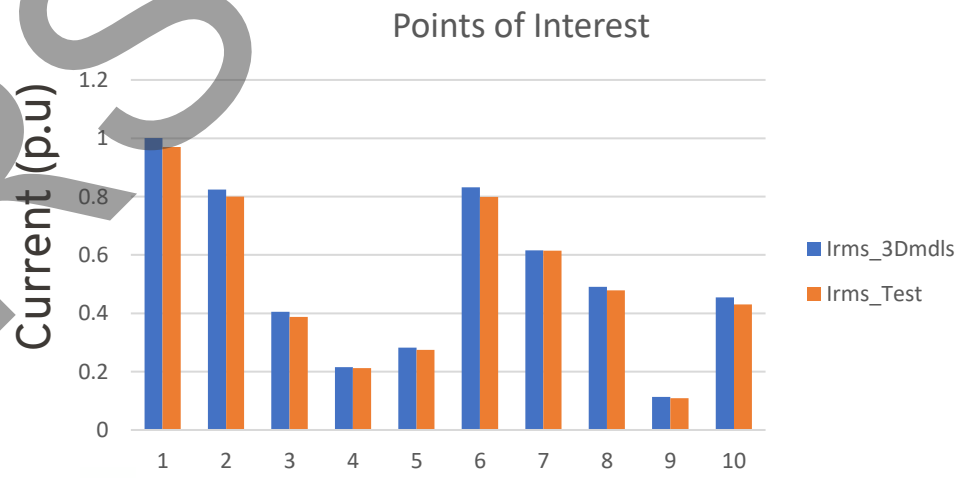



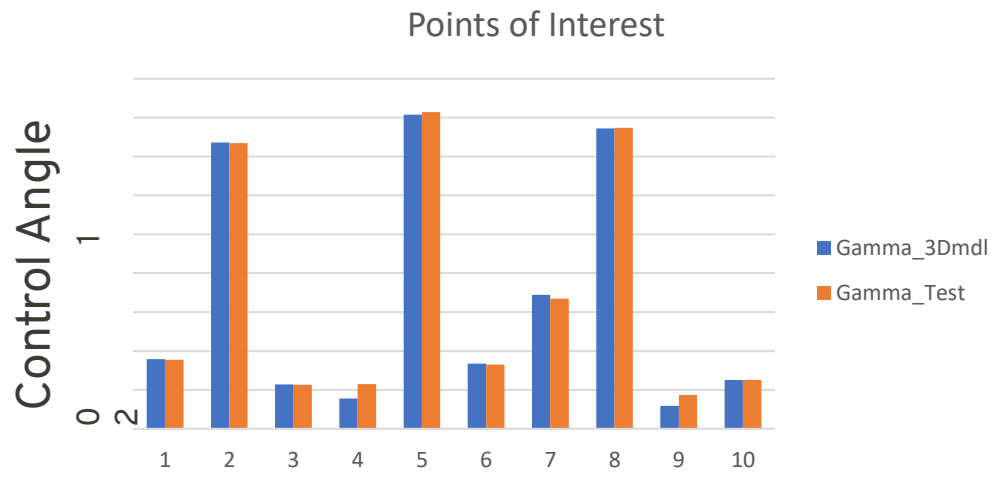

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# 3D Modeling Capabilities - (Current Predictions)

- With accurate flux-linkage and torque profiles high torque-to-current predictions are achieved.
- Points of Interest represent GM's optimization targets for critical operating points



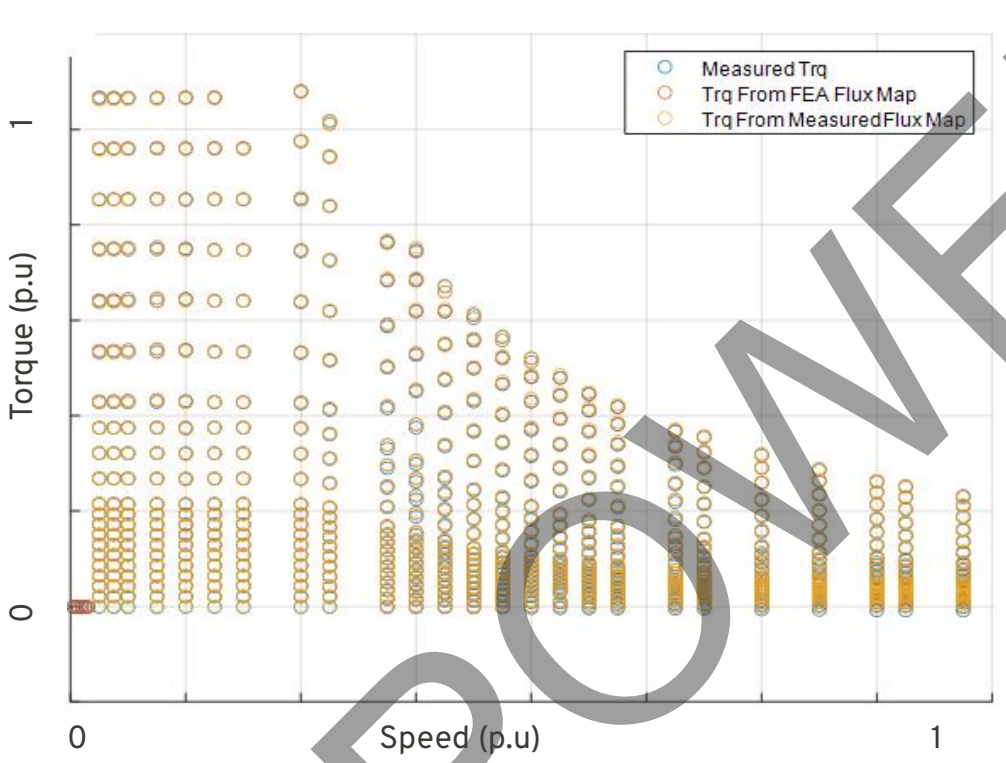



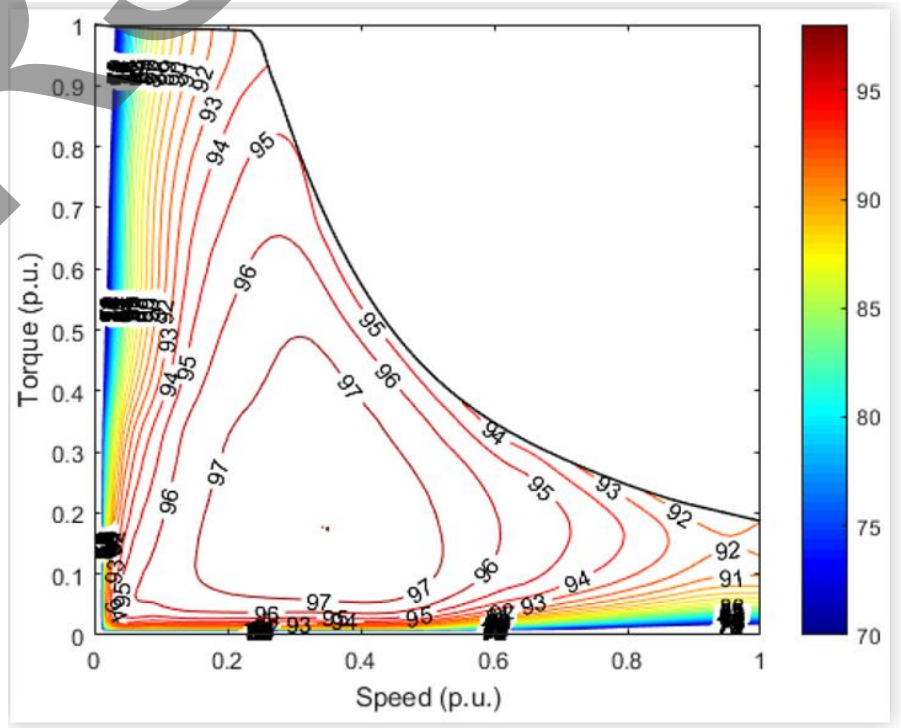




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# 3D Modeling Capabilities – (Accuracy and Motor Maps)

- Accurate predictions allow for a targeted optimization process
  - Great torque match across the entire operation region
  - Excellent efficiency profile



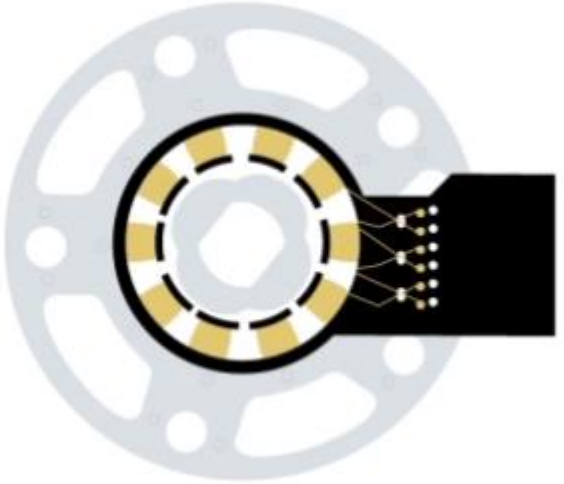

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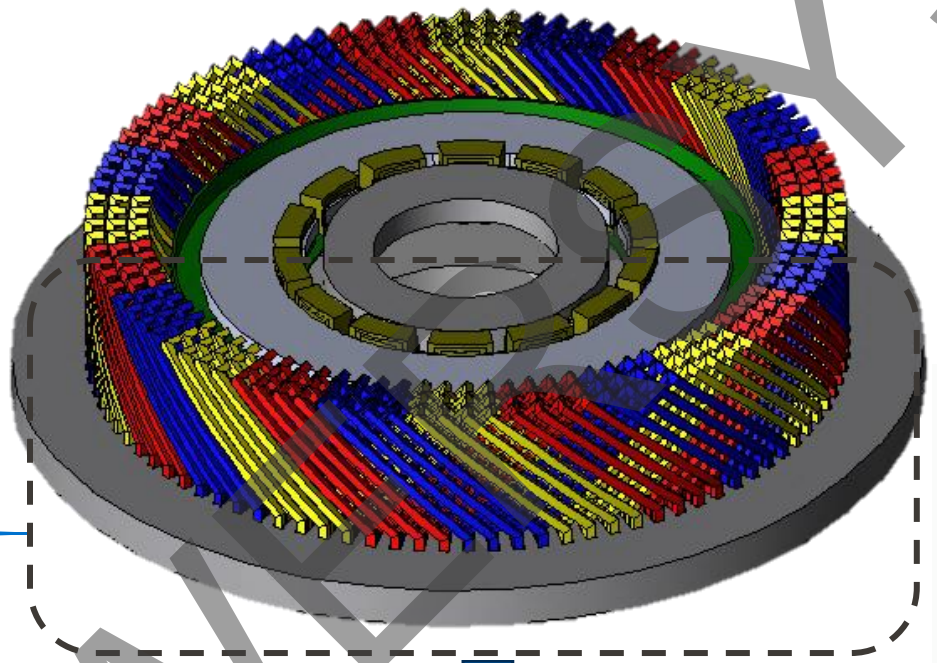
# 3D Modeling Capabilities

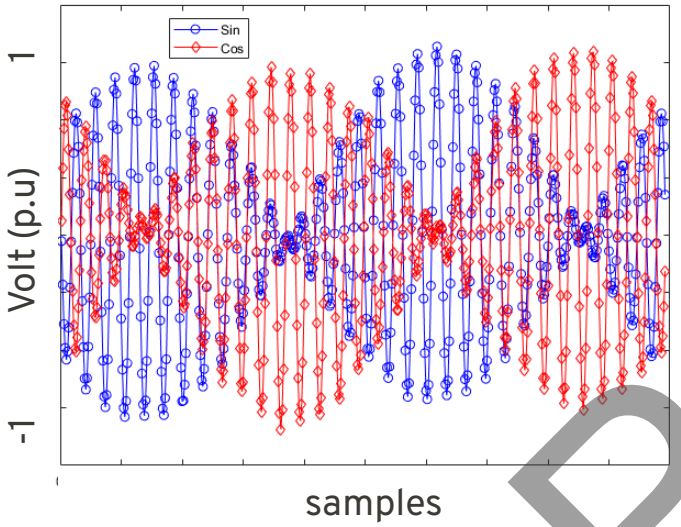
## *Resolver Modeling*

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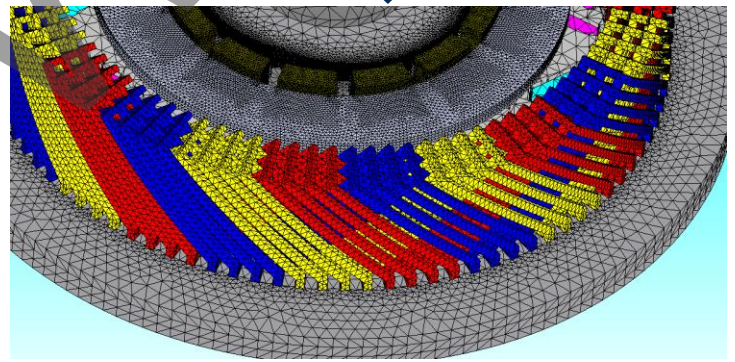
# 3D Modeling Capabilities – (Resolver Modeling)



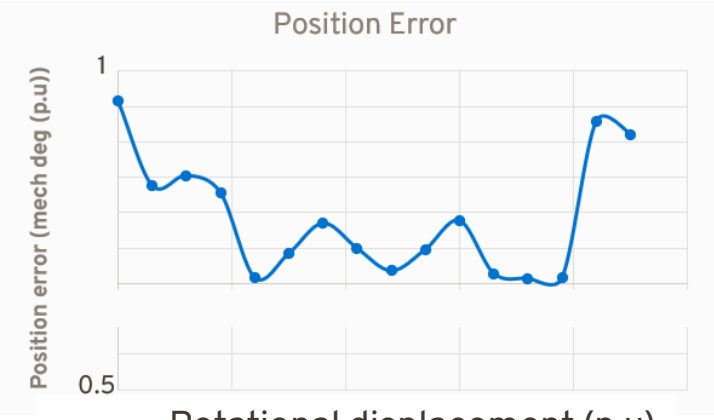





Meshing Capabilities



Results




general motors

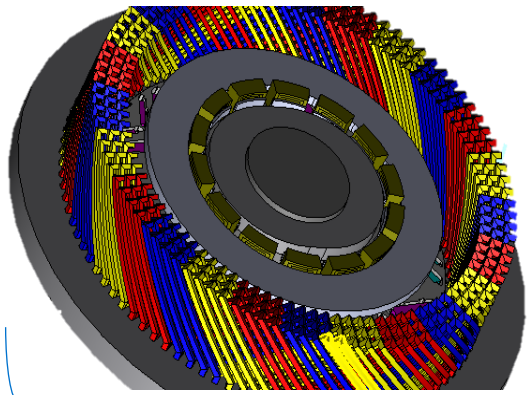
https://www.minebeamitsumi.com/english/strengths/column/resolver/ (animation)

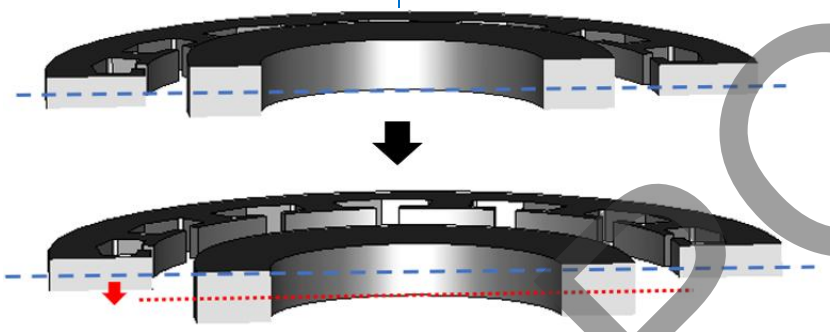
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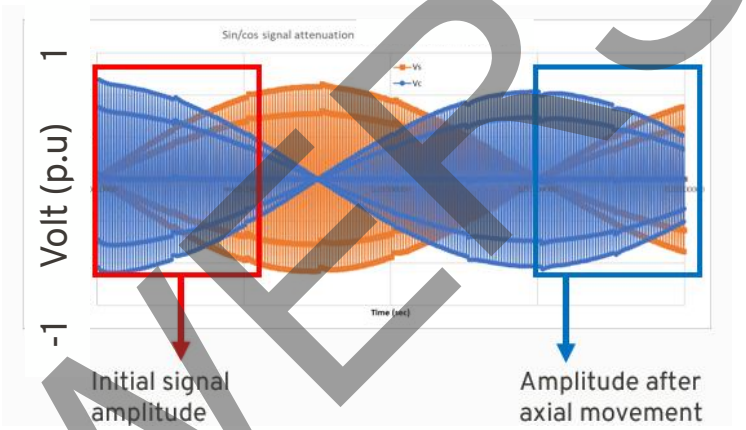
# 3D Modeling Capabilities – (Resolver Modeling)

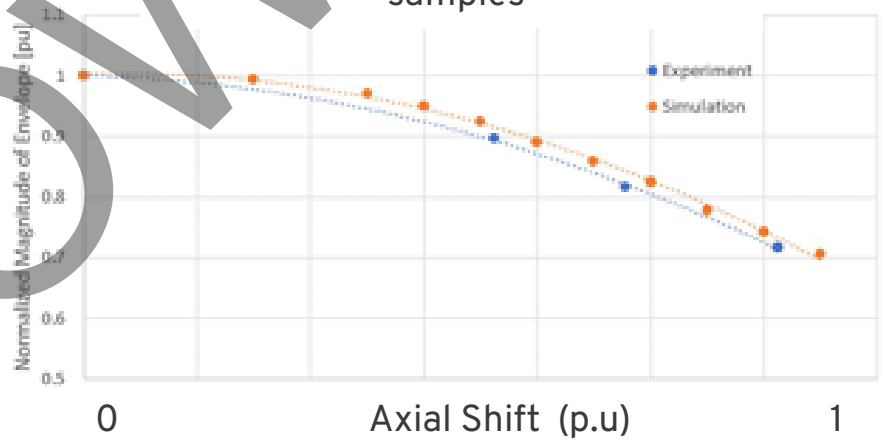
- **Evaluate impact of resolver axial movement causing misalignment between resolver stator and rotor**
  - Loss of position tracking diagnostics

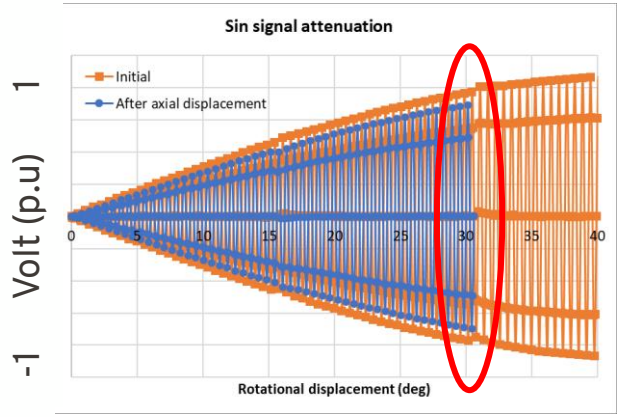
## Resolver misalignment

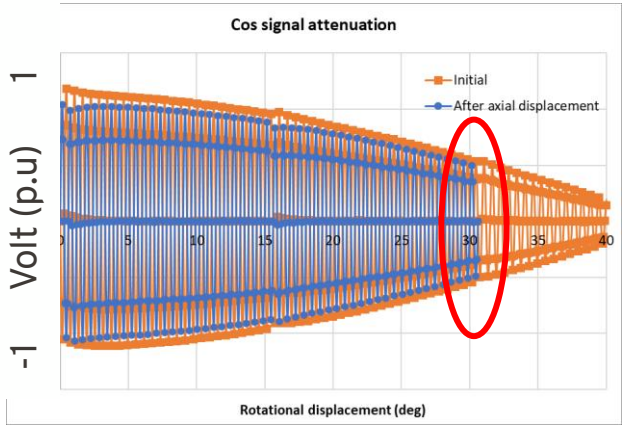







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# 2D FEA JMAG Modeling

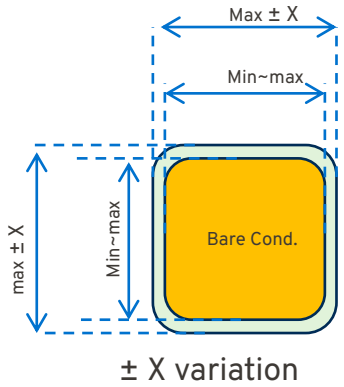
- ✓ Manufacturing Parameter Variation Effects
- ✓ Monte Carlo + JMAG 2D FEA
- ✓ Sensitivity analysis study

- ✓ Capture high-fidelity details across domains
- ✓ Fasts solver performance unlocks deeper exploration, incorporating real-world non-ideal effects into design decisions

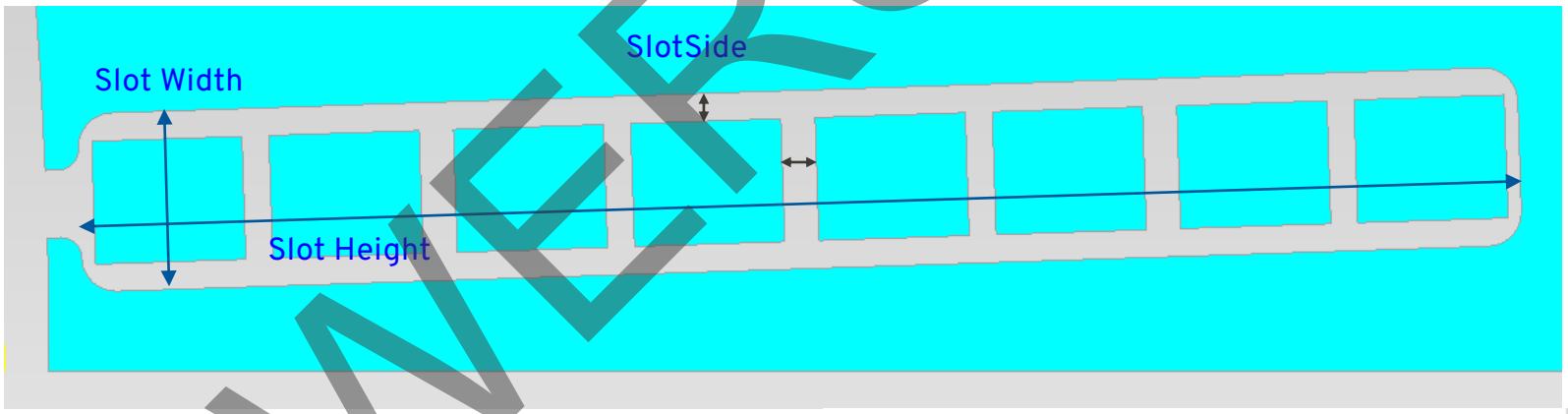
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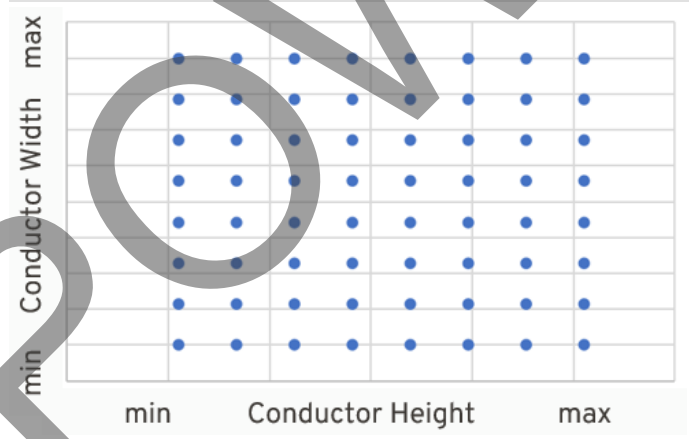
# Manufacturing Parameter Variation Effects

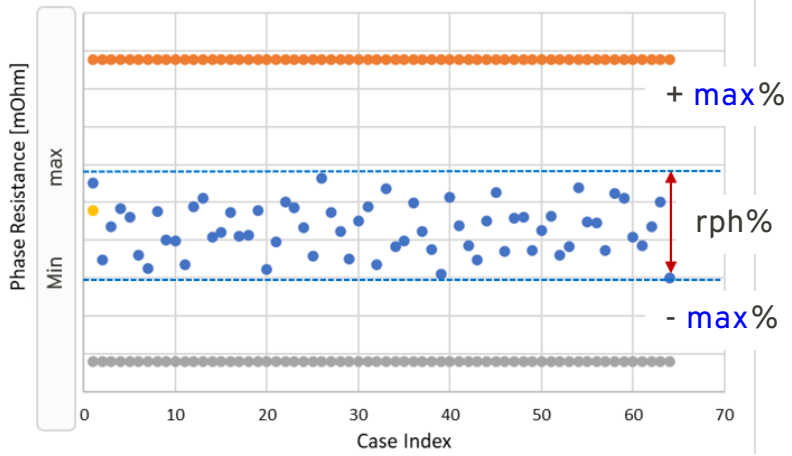
- Similar parametric changes evaluations have been performed for resistance variation
  - The resistance is defined in the drawing as follows: measured phase resistance shall be X mΩ ± max% corrected to T°C. The resistance balance shall be less than diff% difference between phases
  - The drawing allows ± X mm variation for conductor size




± X variation



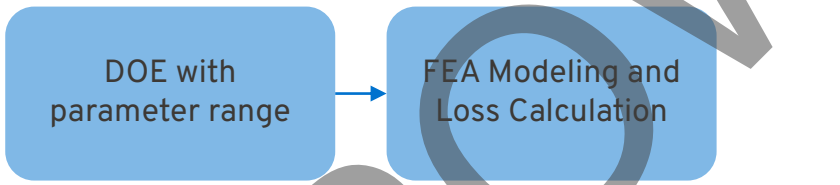

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# Manufacturing Parameter Variation Effects

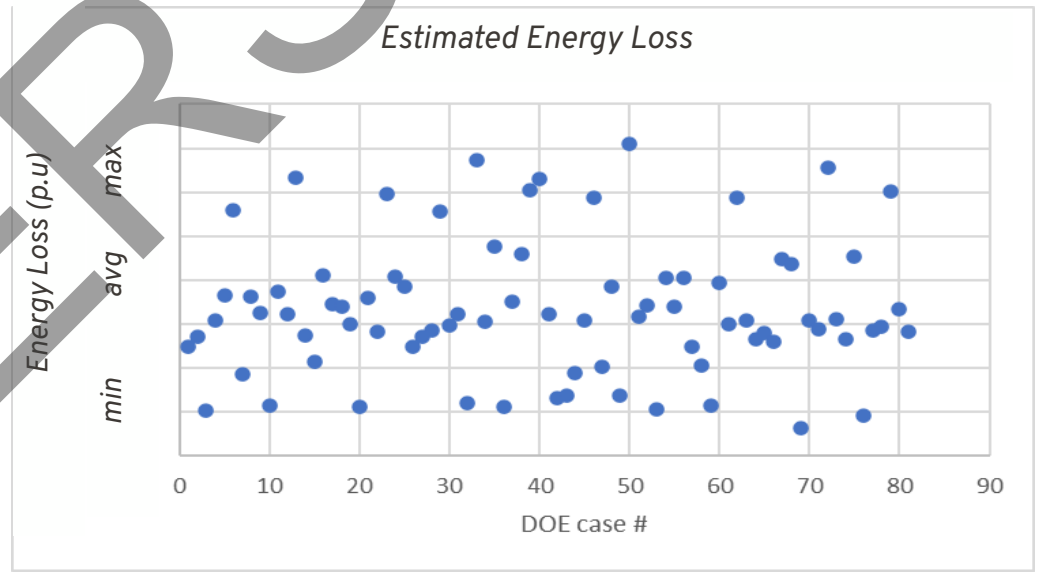
- Goal is to understand the potential variation from manufacturing tolerances
- Considering the 6 most significant tolerances that were identified from previous studies

  - ✓ Magnet Slot Clearance
  - ✓ Airgap
  - ✓ Slot Width
  - ✓ Conductor Width
  - ✓ Conductor Height
  - ✓ Magnet Br

- DOE considers extreme variation “Peak-Peak”




Losses for all representative points



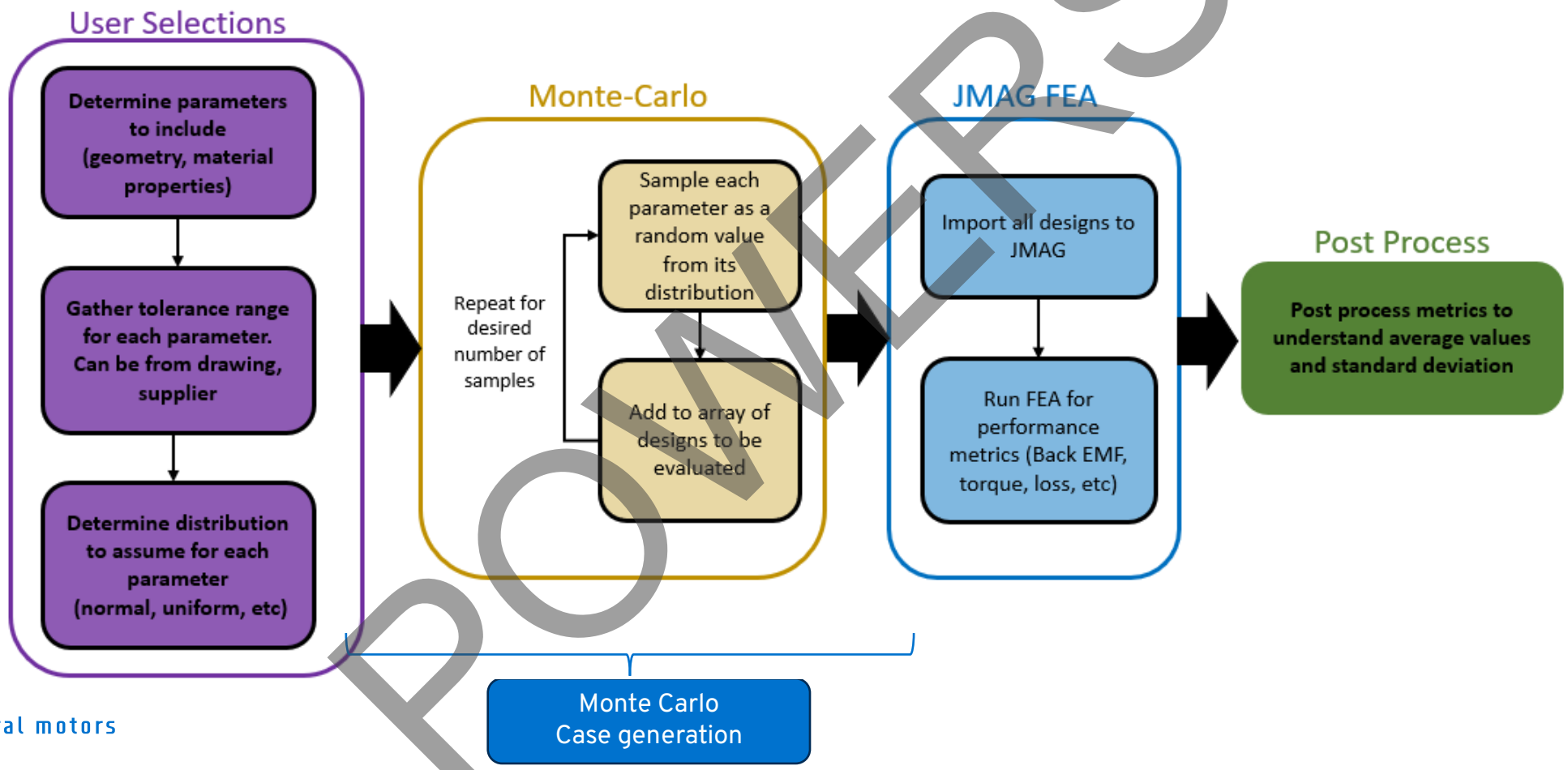

❑ Peak to Peak variation is not be the best for variation assessment.

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# Manufacturing Parameter Variation Effects

- Monte Carlo generates many random designs using a certain distribution to sample each parameter

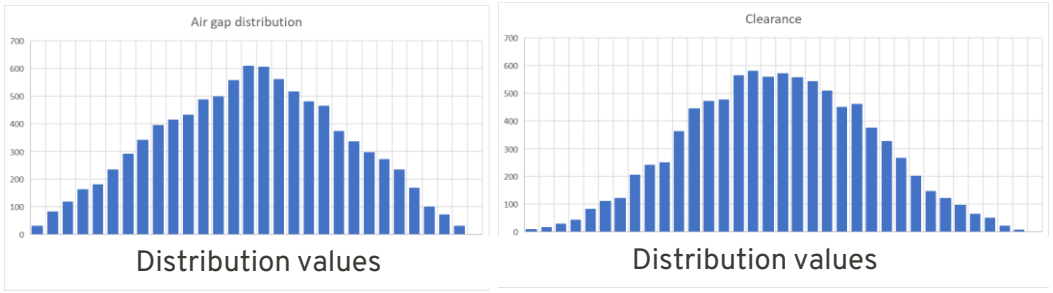
✓ Monte Carlo (MC) analysis presents more realistic distribution of parameters

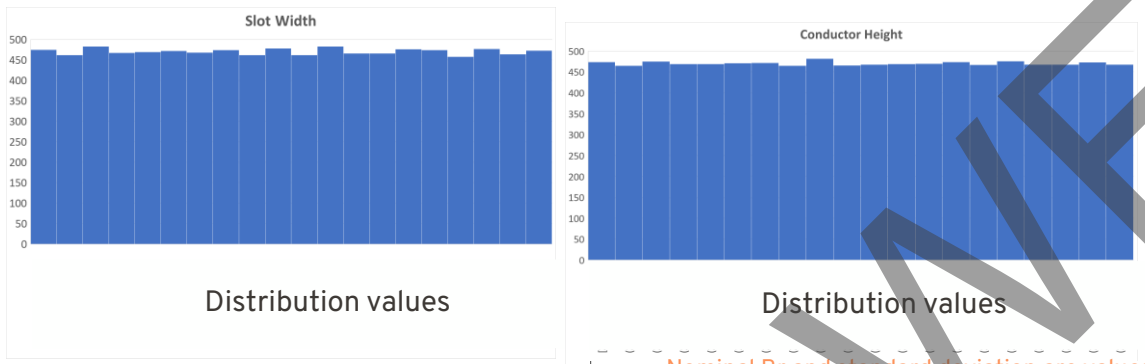


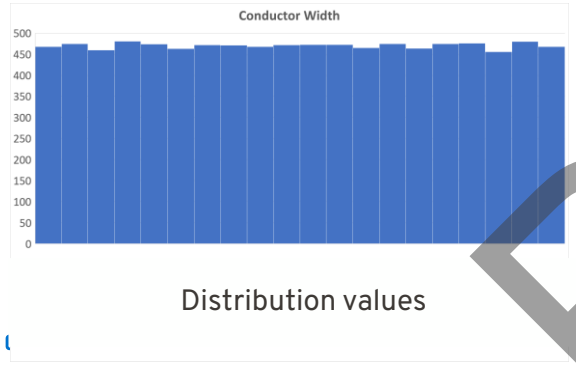

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# Manufacturing Parameter Variation Effects

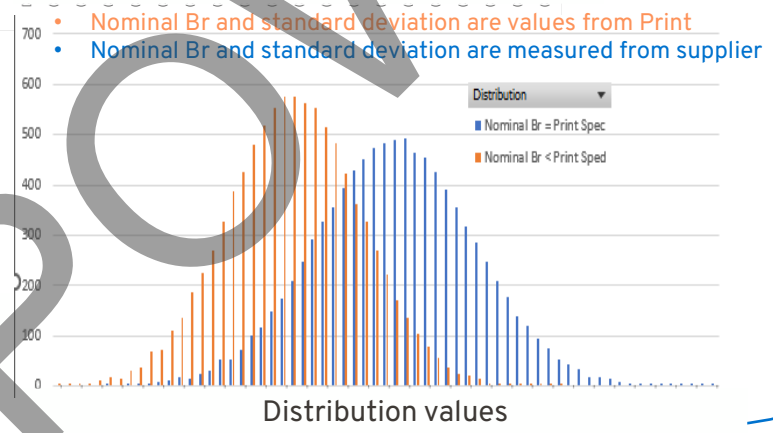
## *Distributions*



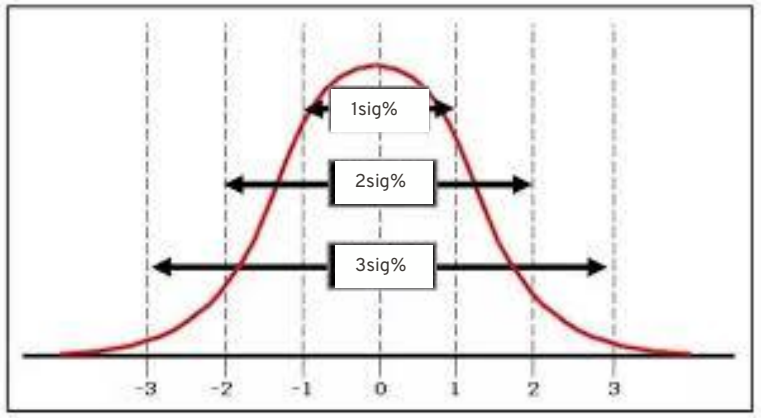




- Nominal Br and standard deviation are values from Print
- Nominal Br and standard deviation are measured from supplier




| | GM Requirement | Supplier Data |
|---|---|---|
| Average | gm-avg | supl_avg |
| Standard Deviation | Dev_gm | Dev_supl |
| +2 Sigma | Sig_gm | Sig_supl |
| -2 Sigma | -sig_gm | -sig_supl |
| % deviation (+2 to average) | %dev_gm | %dev_supl |
| % deviation (+3 to average) | %dev_gm+3 | %dev_supl+3 |

Monte Carlo Case generation




- -2 sigma to +2 sigma variation covers 95% of possible outputs.
- 2 sigma is %dev_gm or %dev_supl variation from average System loss
  - Motor can see %dev_gm*2 to %dev_supl*2 variation in loss

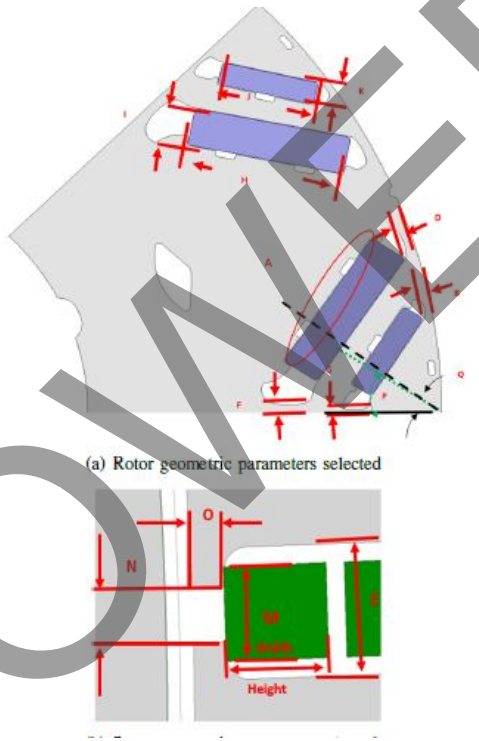
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# Manufacturing Parameter Variation Effects on Performance and Energy Loss

- EV traction motors are highly optimized, but small deviations in geometry or materials can degrade efficiency and torque.
- A sensitivity analysis study that pinpoints which manufacturing variations have the biggest impact on Ultium traction motor performance and energy loss.

PARAMETER AND THEIR TOLERANCES RANGE IN PER UNIT

| Variable Name | Parameter Label | Min Variance (per unit) | Max Variance (per unit) |
|---|---|---|---|
| Clearance | A | 0.6 | 2.0 |
| Small Magnet Bridge | B | 0.933 | 1.067 |
| Airgap | C | 0.807 | 1.148 |
| Large Magnet Bridge | D | 0.963 | 1.037 |
| Slot Width | E | 0.962 | 1.038 |
| Large Magnet Web | F | 0.923 | 1.1 |
| Small Magnet Web | G | 0.878 | 1.159 |
| Large Magnet Length | H | 0.995 | 1.005 |
| Large Magnet Width | I | 0.99 | 1.01 |
| Small Magnet Length | J | 0.992 | 1.008 |
| Small Magnet Width | K | 0.982 | 1.018 |
| Conductor Area | M | 0.98 | 1.02 |
| Slot Opening Width | N | 0.9 | 1.1 |
| Slot Opening Height | O | 0.9 | 1.1 |
| Small Magnet Angle | P | 0.999 | 1.001 |
| Large Magnet Angle | Q | 0.999 | 1.001 |
| Magnet Br | R | 0.979 | 1.027 |



(a) Rotor geometric parameters selected

Design of Experiments → Taguchi L128 Orthogonal Array (OA)

- ✓ Full factorial for 17 variables is $10^{14}$ combinations
- ✓ L128 OA reduces this to just 128 FEA simulations while capturing all main effects
- ✓ Variables in the OA are uncorrelated by design clean, unbiased results

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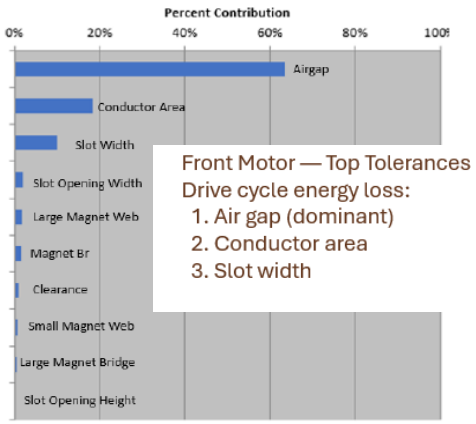


N. F. Ershad, W. Jensen, J. Kim, M. Muir, E. Kaiser and A. Ramm, "Manufacturing Parameter Variation Effects on Performance and Energy Loss on Ultium Traction Motors," *2022 IEEE Energy Conversion Congress and Exposition (ECCE)*, Detroit, MI, USA, 2022, pp. 01-06, doi: 10.1109/ECCE50734.2022.9947603.

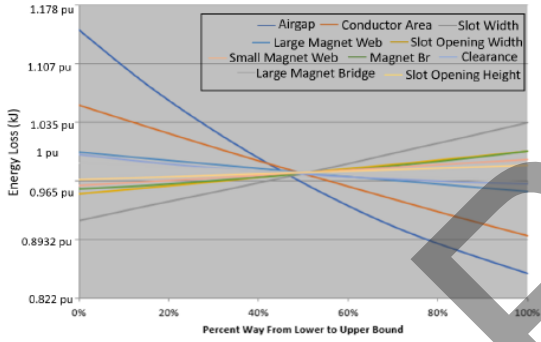
# Manufacturing Parameter Variation Effects on Performance and Energy Loss

## Analysis of Variance (ANOVA)

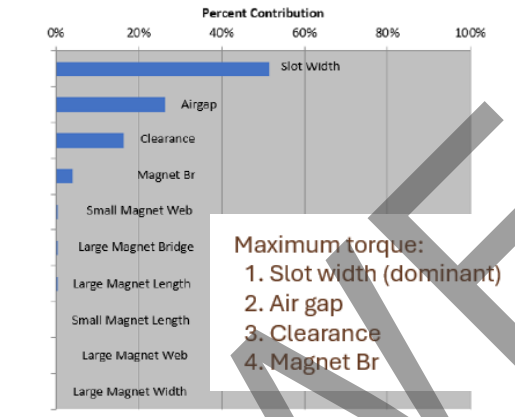
- Decomposes total variance in results into contribution from each tolerance parameter
- Produces percent-contribution charts and main-effects plots
- Identifies the "vital few" tolerances that drive most of the performance variation



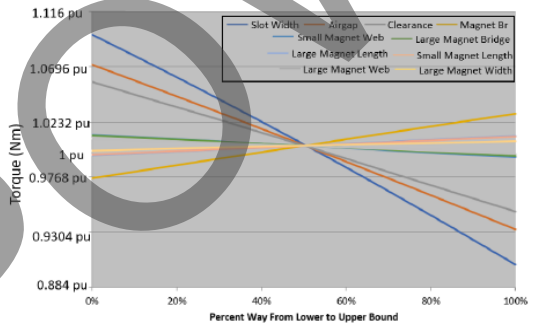

(a) Percent contribution from ANOVA result for total energy loss



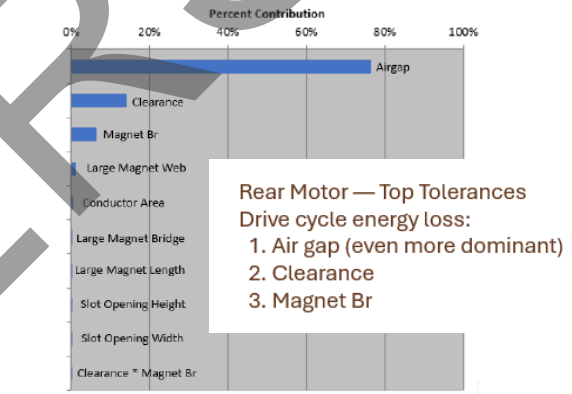

(b) Main effects from ANOVA result for total energy loss in front motor



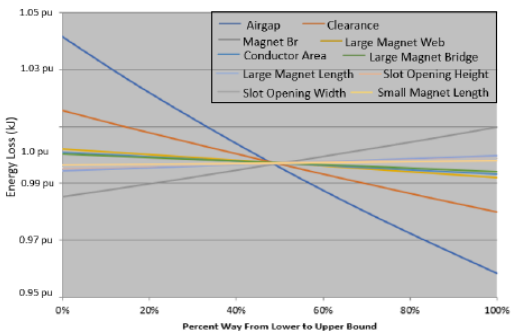

(a) Percent contribution from ANOVA result for maximum torque



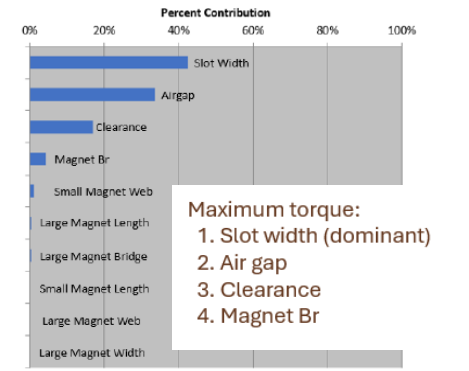

(b) Main effects from ANOVA result for maximum torque in front motor



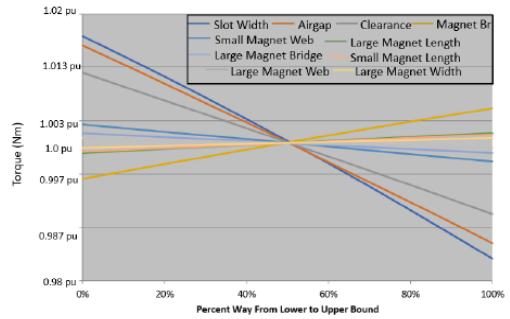

(a) Percent contribution from ANOVA result for total energy loss




(b) Main effects from ANOVA result for total energy loss in rear motor




(a) Percent contribution from ANOVA result for maximum torque




(b) Main effects from ANOVA result for maximum torque in rear motor

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# Conclusion

- ❑ JMAG enables high-fidelity Multiphysics FEA for traction motor design, capturing electromagnetic performance, losses, and system-level interactions within a unified environment
- ❑ Seamless 2D and 3D modeling allows efficient workflows, leveraging fast 2D analysis with targeted 3D FEA for critical physics (flux linkage, leakage, sensor behavior, and misalignment)
- ❑ Accurate prediction of torque and current maps enables reliable FEA-in-the-loop optimization to enable better designs early in the development process.
- ❑ Large-scale design studies (DOE, Monte Carlo, sensitivity analysis) supports evaluation of manufacturing variation and design robustness
- ❑ Strong simulation-to-test correlation validates JMAG as a key tool for motor development

- ❑ Overall, JMAG provides a scalable, efficient, and validated platform that is critical for advancing simulation-driven electric motor design and optimization
  - ✓ Enabling high-confidence, simulation-driven electric drive design

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