motibera

Removing Sensors from Bearingless Motors

Co-Design of Machine and Controls



Nathan Petersen, PhD
CEO and Founder
Motibera, Inc.



POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

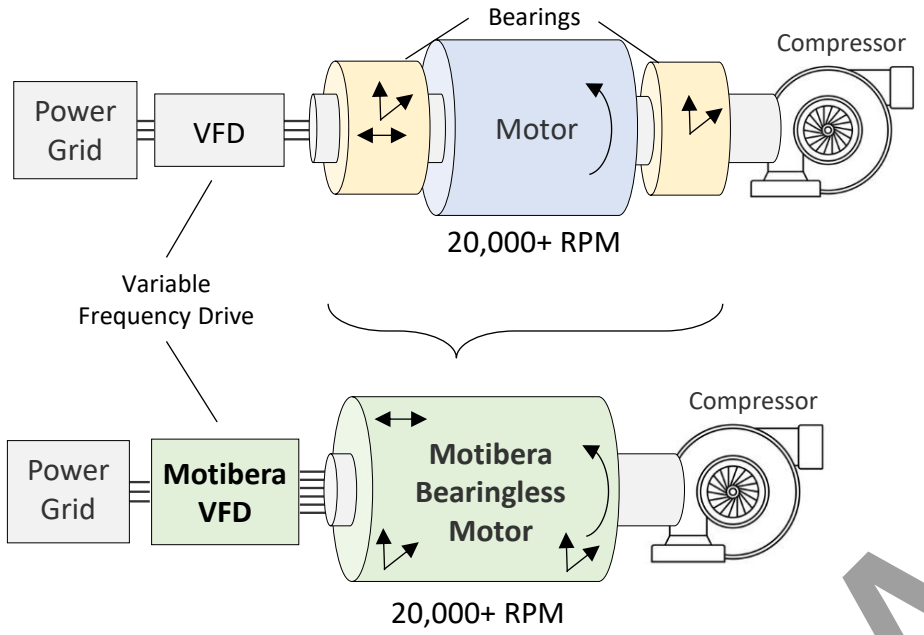
Outline of Presentation

1. The challenge: designing a motor for torque, levitation, and control
2. Why this required high-fidelity electromagnetic modeling
3. How the JMAG workflow was built
4. What the simulations revealed and how they shaped the design
5. How the prototype compared to the model
6. Takeaways for future JMAG-enabled motor development

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

What is a bearingless motor?



Integrated levitation → The motor itself provides stabilizing forces.

Fewer parts → No separate bearing actuators, electronics, or lubrication systems.

More reliable → Same overall motor package, up to 100x more reliable than ball bearings.

Active vibration suppression → Active maglev control allows system to suppress transmitted vibration.

Built-in telemetry → Continuous force monitoring enables predictive maintenance.

Relevant to high-speed compressors, blowers, turbomachinery, e-boosting, fuel-cell air systems, and other rotating equipment where bearing wear, oil management, vibration, or telemetry matter.

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

The same electromagnetic device produces torque and suspension force

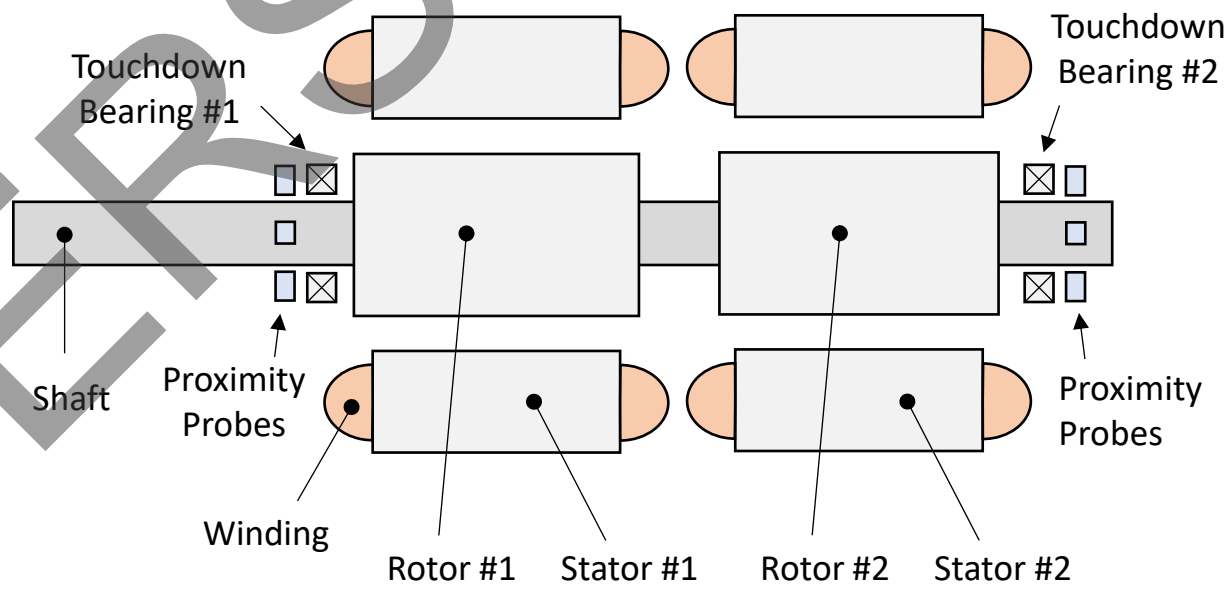
Using a single winding:

- Torque-producing fields spin the rotor
- Suspension fields create radial force

Levitation:

- Active suspension current control stabilizing rotor in center of air gap
- Rotor displacement must be controlled within 10s of µm
- Proximity probes add cost, wiring, volume, and integration complexity

Twin bearingless motor architecture:



POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

Designing a sensorless bearingless motor is a multi-domain problem

A sensorless bearingless motor must simultaneously optimize:

1. Torque production

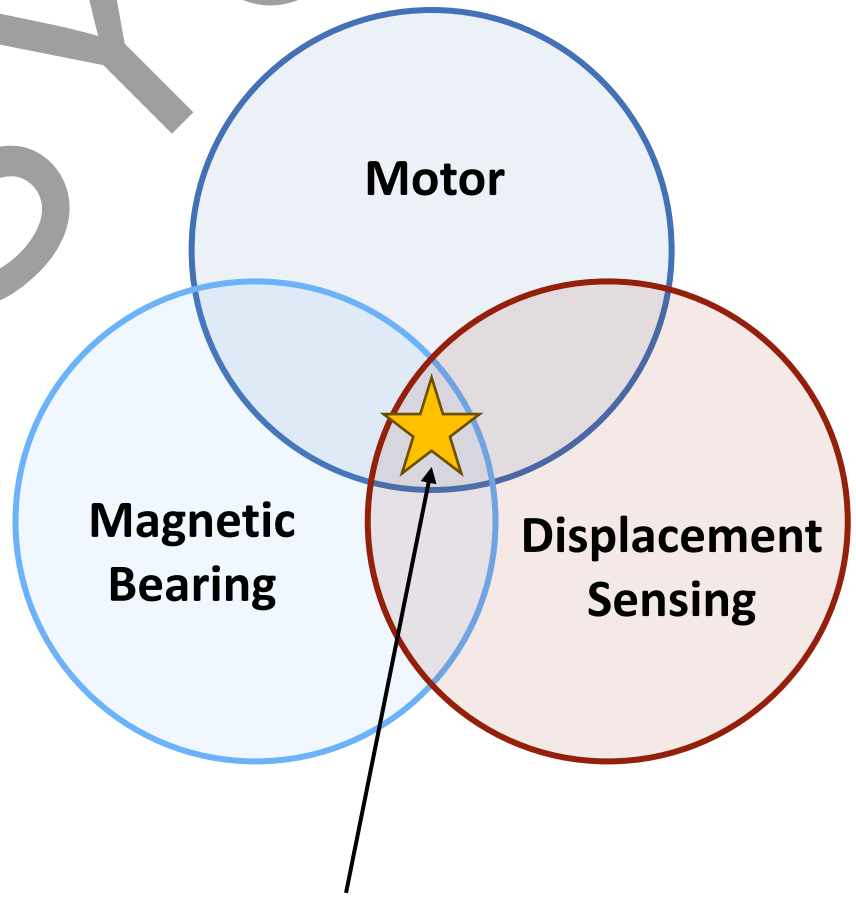
Power density, efficiency, torque ripple

2. Levitation force production

Force capability, force ripple, vector accuracy

3. Sensorless position estimation

Inductance sensitivity, signal quality, estimation accuracy



Is it possible to balance all three performance areas?

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

Rotor eccentricity causes displacement-sensitive mutual inductance [1]

$$\boldsymbol{v}_{\alpha\beta}(t) = \boldsymbol{R}\boldsymbol{i}_{\alpha\beta}(t) + M'\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{Q}(t)\boldsymbol{i}_{\alpha\beta}(t) + \underbrace{\left[\boldsymbol{L} + M'\boldsymbol{Q}(t)\right]}_{\boldsymbol{L}_{\text{effective}}}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\alpha\beta}(t) + \boldsymbol{e}_{\alpha\beta}(t)$$

Vector notation:

$$\boldsymbol{f}_{\alpha\beta}(t) = \begin{bmatrix} f_{\alpha,\mathrm{t}}(t) \\ f_{\beta,\mathrm{t}}(t) \\ f_{\alpha,\mathrm{s}}(t) \\ f_{\beta,\mathrm{s}}(t) \end{bmatrix}$$

$$\boldsymbol{R} = \begin{bmatrix} R & 0 & 0 & 0 \\ 0 & R & 0 & 0 \\ 0 & 0 & R & 0 \\ 0 & 0 & 0 & R \end{bmatrix} \quad \boldsymbol{L} = \begin{bmatrix} L_{\mathrm{t}} & 0 & 0 & 0 \\ 0 & L_{\mathrm{t}} & 0 & 0 \\ 0 & 0 & L_{\mathrm{s}} & 0 \\ 0 & 0 & 0 & L_{\mathrm{s}} \end{bmatrix} \quad \boldsymbol{Q}(t) = \begin{bmatrix} 0 & 0 & x & y \\ 0 & 0 & -y & x \\ x & -y & 0 & 0 \\ y & x & 0 & 0 \end{bmatrix} \quad \boldsymbol{e}_{\alpha\beta}(t) = \begin{bmatrix} -\lambda_{\mathrm{r,t}}\omega_{\mathrm{t}}\sin(\theta_{\mathrm{t}}) \\ +\lambda_{\mathrm{r,t}}\omega_{\mathrm{t}}\cos(\theta_{\mathrm{t}}) \\ -\lambda'_{\mathrm{r,s}}\Delta_{\alpha} \\ +\lambda'_{\mathrm{r,s}}\Delta_{\beta} \end{bmatrix}$$

$$\vec{T}_{\delta\tau} = T_{\delta} + j\tau = k_{\mathrm{t}}e^{-j\theta_{\mathrm{t}}}\left(i_{\alpha_{\mathrm{t}}} + ji_{\beta_{\mathrm{t}}}\right)$$

$$\vec{F}_{xy} = F_x + jF_y = k_f e^{-j\theta_s}\left(i_{\alpha_{\mathrm{s}}} + ji_{\beta_{\mathrm{s}}}\right)$$

$$\Delta_{\alpha} = (y\omega_s - v_x)\cos(\theta_s) + (x\omega_s + v_y)\sin(\theta_s)$$

$$\Delta_{\beta} = (x\omega_s + v_y)\cos(\theta_s) - (y\omega_s - v_x)\sin(\theta_s)$$

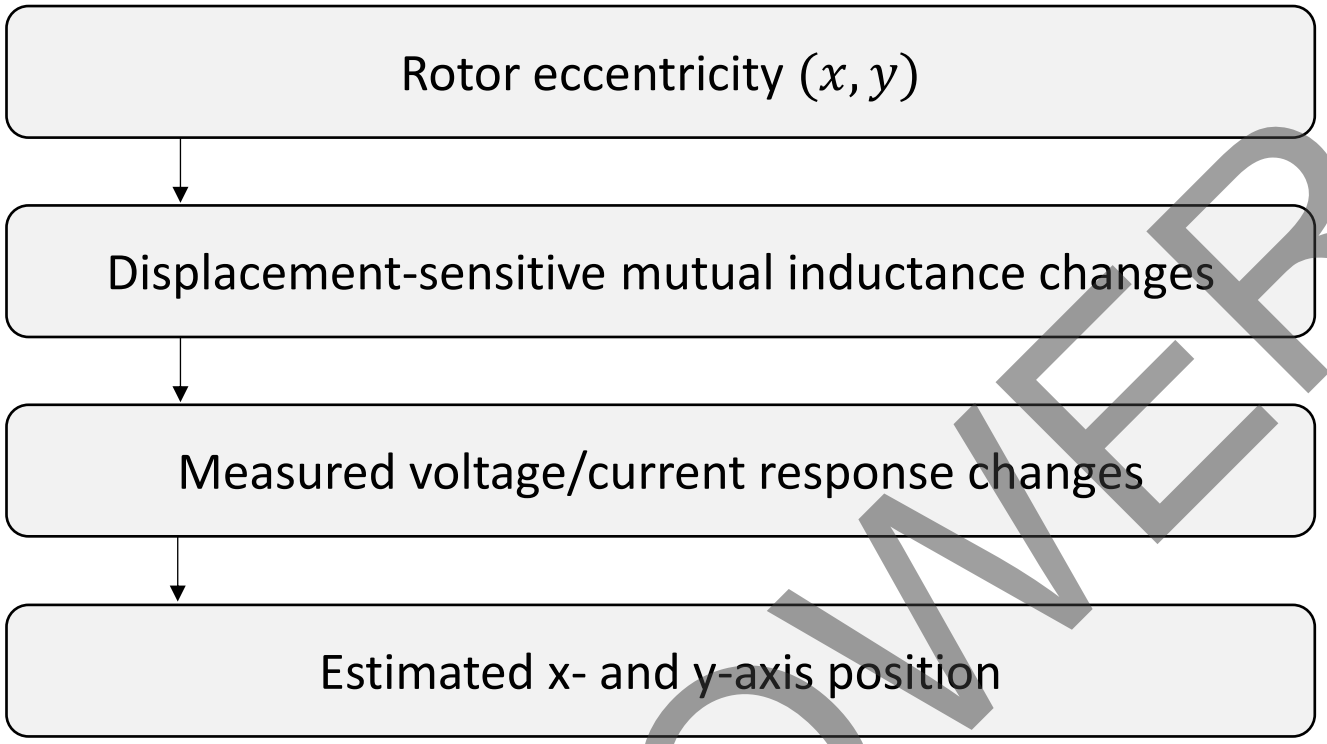
POWERSYS

[1] N. Petersen and E. L. Severson, "Rotor Eccentricity Impact on Electromagnetic Behavior in Combined Winding Bearingless Motors Towards Displacement Self-Sensing," in *IEEE Transactions on Energy Conversion*, 2025.

© 2024-2026 Motibera, Inc. All Rights Reserved.

The machine must be designed to behave like a sensor

Sensorless signal path



Machine design objective

Design for:

- ✓ Large M'
- ✓ Low M_{ripple}
- ✓ Robust under rotation
- ✓ Robust under load / saturation

The controller can only estimate what the machine makes observable.

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

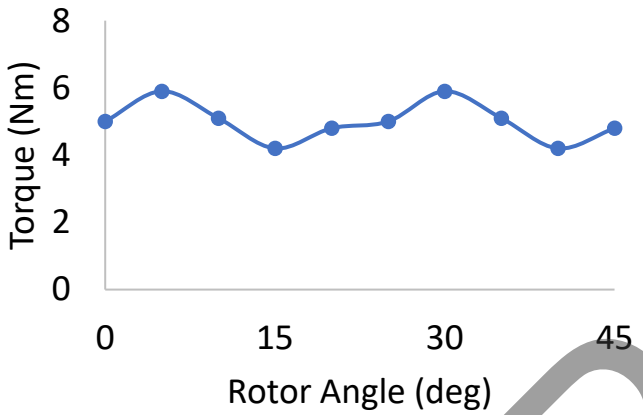
Three coupled objectives: torque, force, and sensing

Power conversion

Rated power: $P_{\text{rated}} = \tau_{\text{rated}}\omega_{\text{mech}}$

Efficiency: $\eta = \frac{P_{\text{out}}}{P_{\text{out}}+P_{\text{loss}}}$

Torque ripple: $\tau_{\text{rip}} = \frac{\max(|\tau(\theta)-\tau|)}{\tau}$

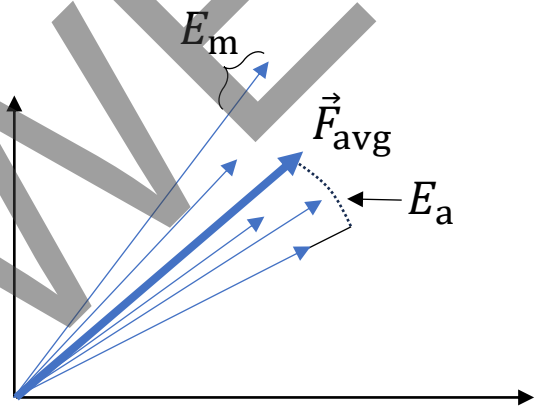


Levitation

Force per amp: $k_{\text{f}} = |\vec{F}_{\text{avg}}|/|\vec{i_s}|$

Force vector accuracy:

- Magnitude: $E_{\text{m}} = \frac{\max(|F(\theta)-F|)}{F}$
- Angle: $E_{\text{a}} = \max(|\phi(\theta) - \phi|)$

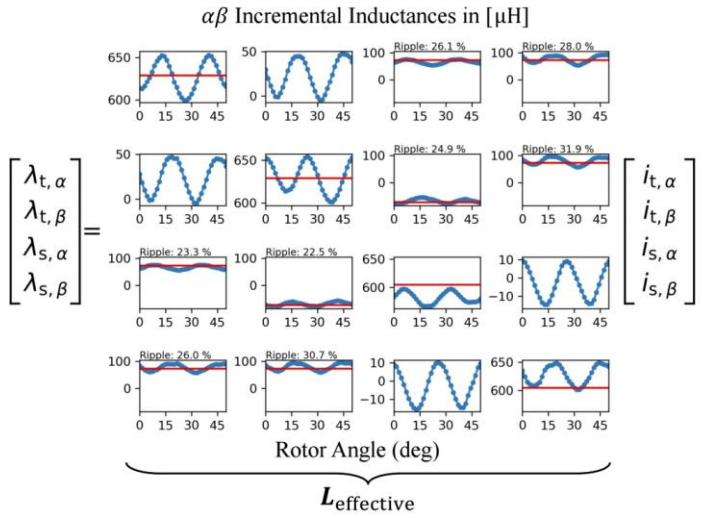


Self-sensing

Inductance sensitivity to displacement

Mutual inductance ripple

Robustness to full-load operation



POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

Using JMAG to compute eccentric inductance metrics

Custom JMAG/Python metric extraction: not standard motor KPI

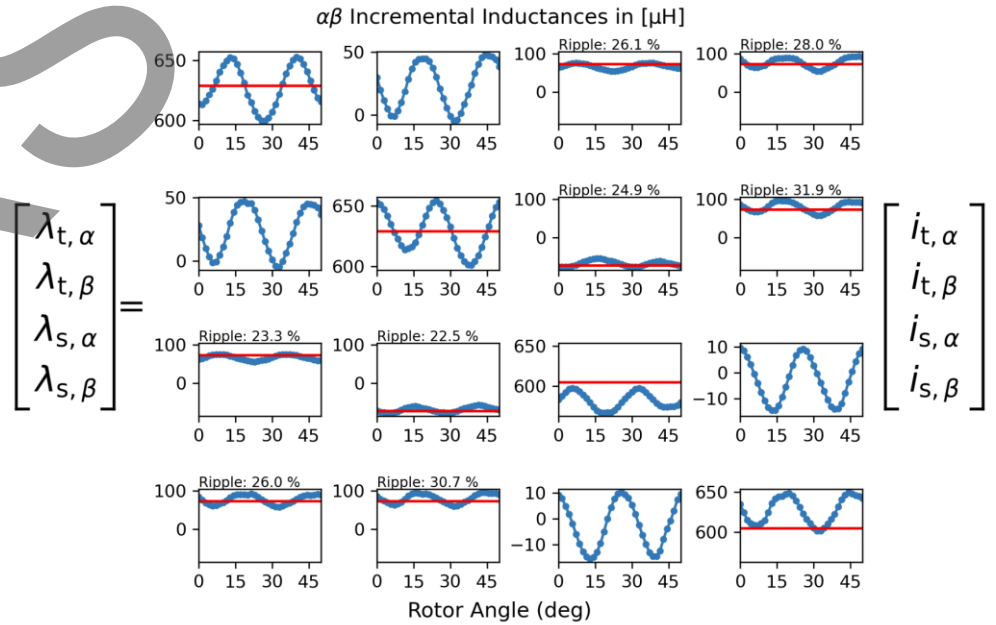
- Inductance matrix $\boldsymbol{L}_{\mathrm{eff}}$ vs. rotor angle
  - 50% static eccentricity at $45°$
    i.e., $\vec{\delta} = x + jy = \frac{1}{2} g_0 e^{j\pi/4}$
  - Requires 9 transient JMAG solves to get both apparent and incremental $\boldsymbol{L}_{\mathrm{eff}}$
- Calculation of L_{t}, L_{s}, and M'
  - Self-inductances (L_{t} and L_{s}) computed as mean of α and β inductances
  - Mutual inductance M computed as mean $M(\theta)$ for all 8 cross-axis terms
  - $M_{\mathrm{ripple}} = \frac{\max(|M(\theta) - M|)}{M}$
  - M' computed as $M/|\vec{\delta}|$

M': useful displacement sensitivity

M_{ripple}: sensing error source

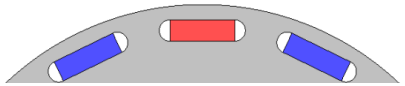
Example evaluation results:

$$\boldsymbol{L}_{\mathrm{eff}} = \begin{bmatrix} L_{\mathrm{t}} & 0 & 0 & 0 \\ 0 & L_{\mathrm{t}} & 0 & 0 \\ 0 & 0 & L_{\mathrm{s}} & 0 \\ 0 & 0 & 0 & L_{\mathrm{s}} \end{bmatrix} + M' \begin{bmatrix} 0 & 0 & x & y \\ 0 & 0 & -y & x \\ x & -y & 0 & 0 \\ y & x & 0 & 0 \end{bmatrix}$$



$$\begin{bmatrix} \lambda_{\mathrm{t},\alpha} \\ \lambda_{\mathrm{t},\beta} \\ \lambda_{\mathrm{s},\alpha} \\ \lambda_{\mathrm{s},\beta} \end{bmatrix} = \begin{bmatrix} i_{\mathrm{t},\alpha} \\ i_{\mathrm{t},\beta} \\ i_{\mathrm{s},\alpha} \\ i_{\mathrm{s},\beta} \end{bmatrix}$$

$L_{\mathrm{t}} = 630\ \mu\mathrm{H}$, $L_{\mathrm{s}} = 605\ \mu\mathrm{H}$, $M = 73\ \mu\mathrm{H}$
$M' = 181\ \mu\mathrm{H/mm}$, $M_{\mathrm{ripple}} = 31.9\%$



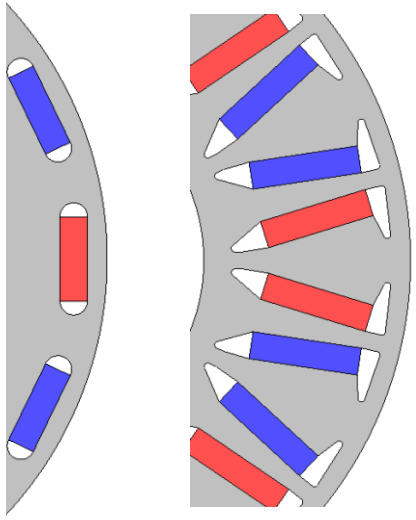
Custom inductance metrics were extracted from automated JMAG solves.

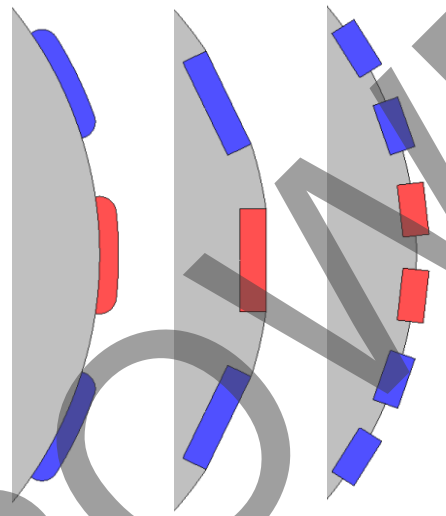
POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

JMAG enabled a custom multi-objective design workflow

	Obj.	Eq.	Unit	Description	Target
Power Conversion	O_1	$-\eta_{\text{rated}}$	%	Maximize rated efficiency	$-O_1 \geq 85\%$
	O_2	$-P_{\text{rated}}$	kW	Maximize rated power output	$-O_2 \geq 1\ \text{kW}$
Sensing	O_3	$-G_{xy,\text{pu}}$	%/mm	Maximize self-sensing sensitivity	$-O_3 \geq 0.5\%$
	O_4	M_{ripple}	%	Minimize mutual inductance ripple	$O_4 \leq 10\%$

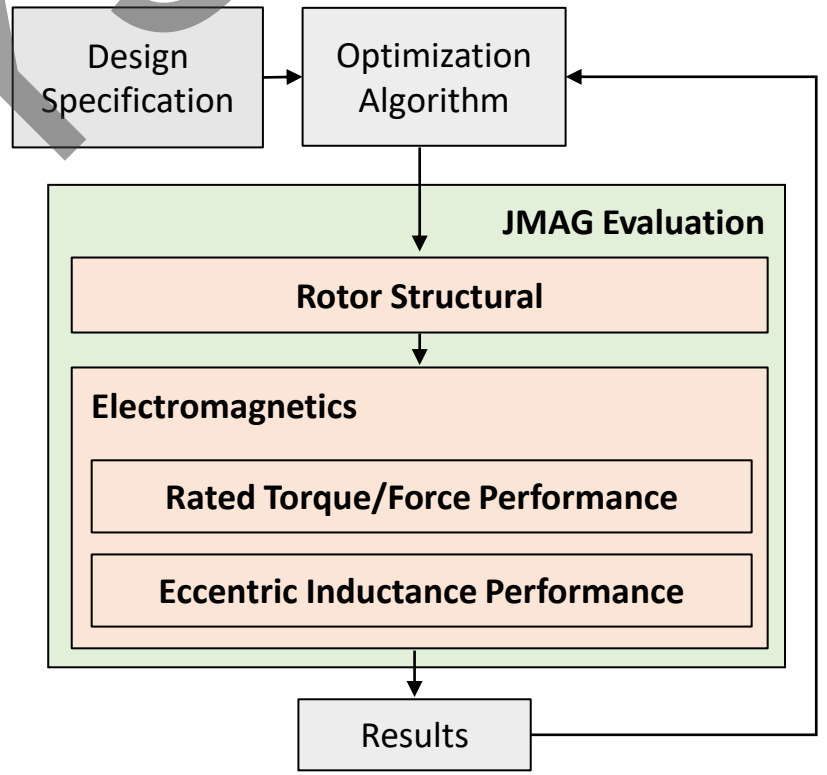




100% automated with

JMAG® Simulation Technology for Electromechanical Design

python™



The workflow scaled to 100k solves across topology families.

Project Compute Scale:

- Over 6,000 design variants across rotor families
- 16 JMAG 2D solves per design variant
- ~100,000 total JMAG solves
- Multi-week runtime on workstation hardware

➔ **Strong candidate for PSL / expanded parallel simulation**

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

JMAG revealed which rotor topologies could support accurate self-sensing

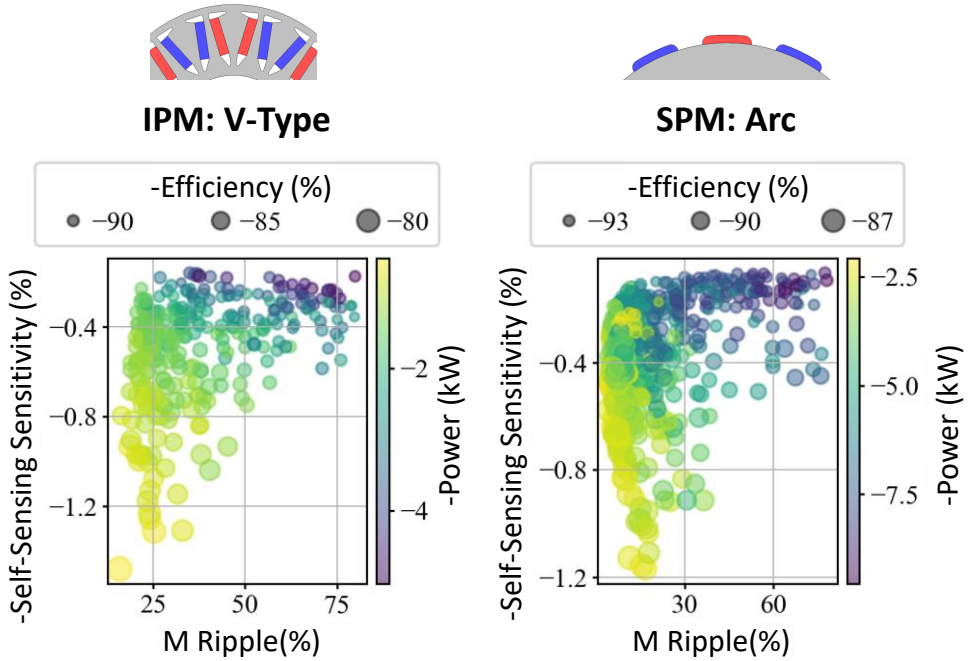
JMAG revealed that topology choices affected sensing behavior as strongly as power performance:

- Smooth, lightly saturated rotor surfaces are critical for accurate self-sensing
- IPM-style rotors degraded sensing performance due to rotor edge saturation
- Air gap and magnet geometry created strong tradeoffs
- Generally, self-sensing performance conflicted with power conversion metrics

Metrics across design types for best M_{ripple} capabilities:

Metric	IPM Tangential	IPM V-Type	SPM Arc	SPM Inset
Lowest M_{ripple}	25%	20%	10%	18%
Sensitivity	0.8%	0.9%	0.8%	0.5%
Power	0.8 kW	0.8 kW	3 kW	5 kW

JMAG revealed which rotor topologies were incompatible with accurate self-sensing.

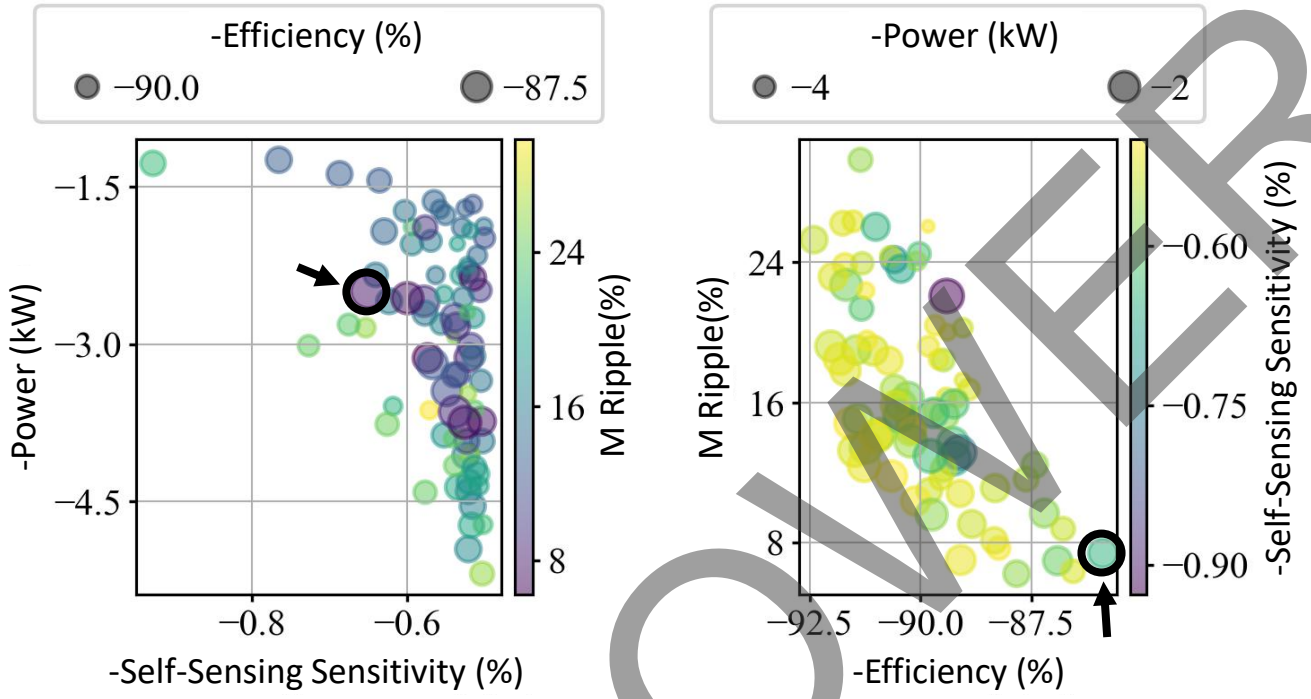


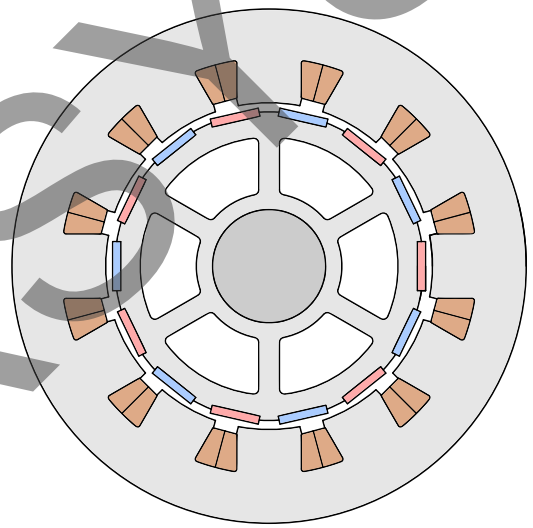
POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

The selected design for prototyping balanced our objectives

Efficiency	Power	Sensitivity	M Ripple
85.9%	2.5 kW	0.65%	7.4%

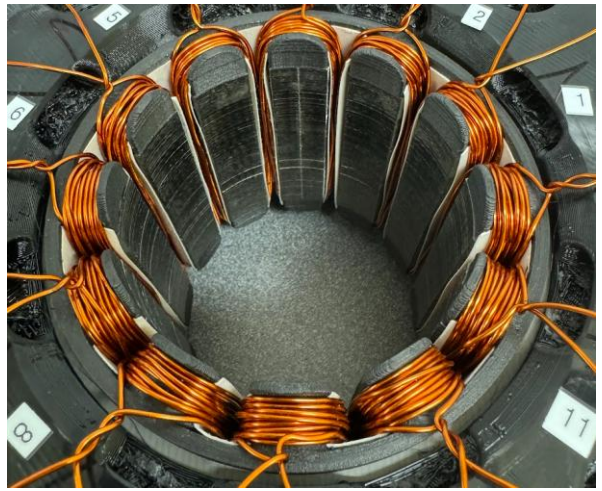




12 slot, 14 pole, 6 phase
Type: $p_s = p + 1$

- Stator OD: 100 mm
- Rotor OD: 62 mm
- Axial length: 64 mm



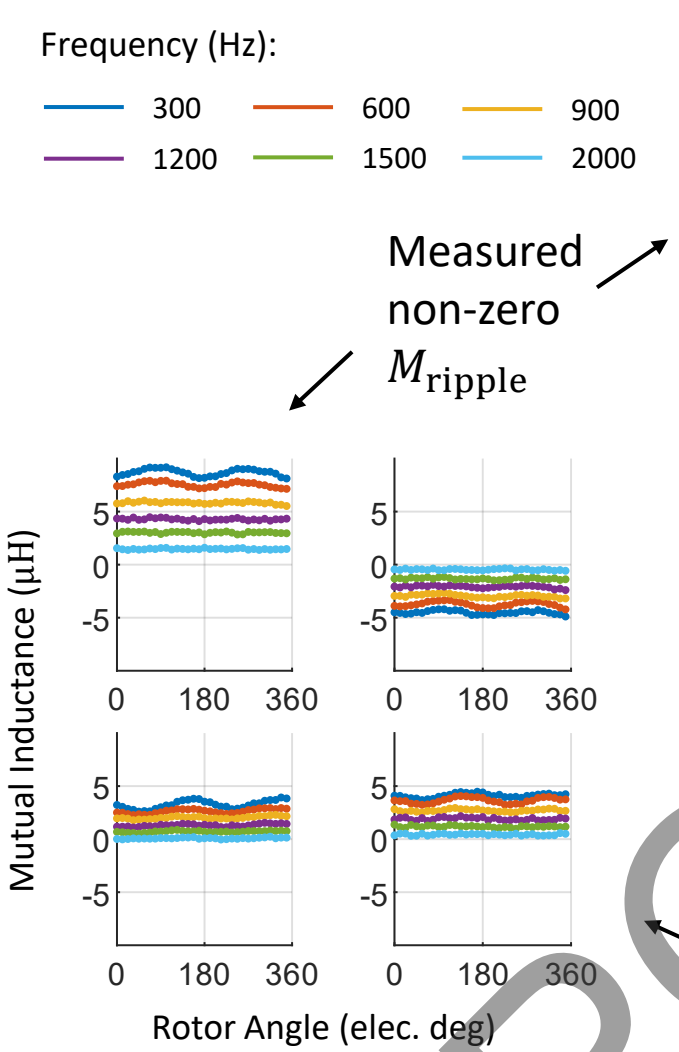


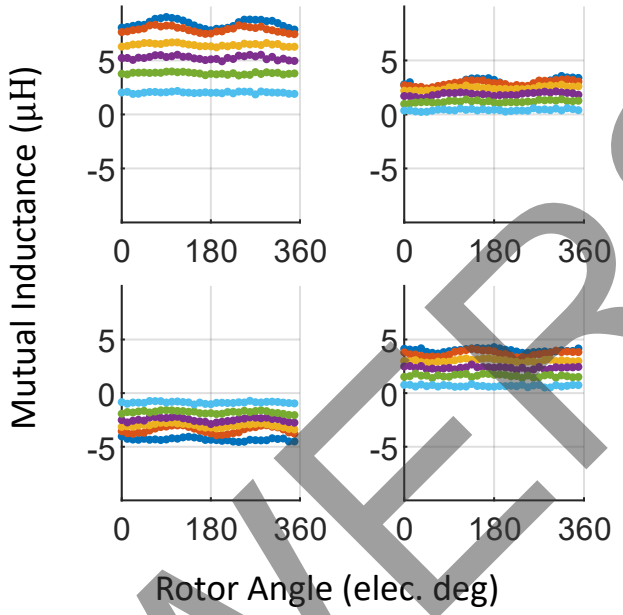
The selected design balanced power, levitation, and sensing.

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

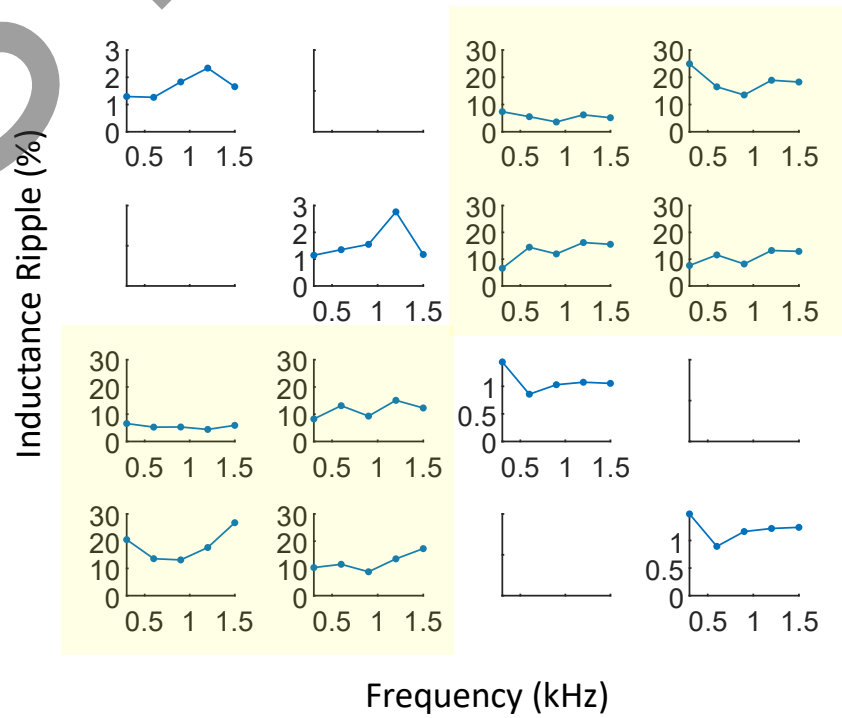
The measured mutual inductance ripple matched the JMAG prediction





$$\begin{bmatrix} L_t & 0 & xM' & yM' \\ 0 & L_t & -yM' & xM' \\ xM' & -yM' & L_s & 0 \\ yM' & xM' & 0 & L_s \end{bmatrix}$$

Ripple computed as: $\dfrac{\max(|L(\theta)-\langle L(\theta)\rangle|)}{\langle L(\theta)\rangle}$



- JMAG prediction: ~9% M_{ripple}
- Measured hardware: same range across test frequencies

The measured mutual inductance ripple matched the FEA prediction.

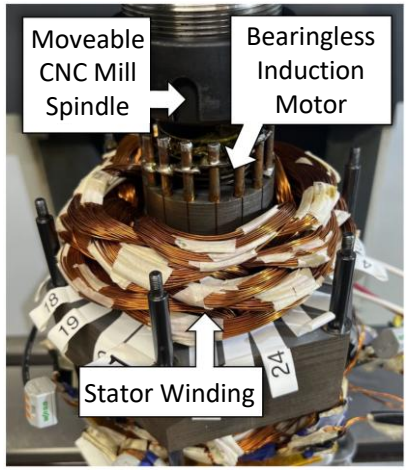
POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

JMAG optimization increased displacement sensitivity by 219×

Existing Motor Prototype

Bearingless induction motor



$$L_t = 3100\ \mu\text{H}$$
$$L_s = 2300\ \mu\text{H}$$
$$M' = 22\ \mu\text{H/mm}$$

$$\frac{M'}{L_t L_s} = 3.1\ \frac{1}{\text{H·mm}}$$

219x larger!!

Sensorless Bearingless Motor

Bearingless surface PM motor



$$L_t = 185\ \mu\text{H}$$
$$L_s = 180\ \mu\text{H}$$
$$M' = 22.5\ \mu\text{H/mm}$$

$$\frac{M'}{L_t L_s} = 676\ \frac{1}{\text{H·mm}}$$

JMAG-optimized sensorless bearingless motor is 219x more sensitive than this baseline motor.

POWERSYS

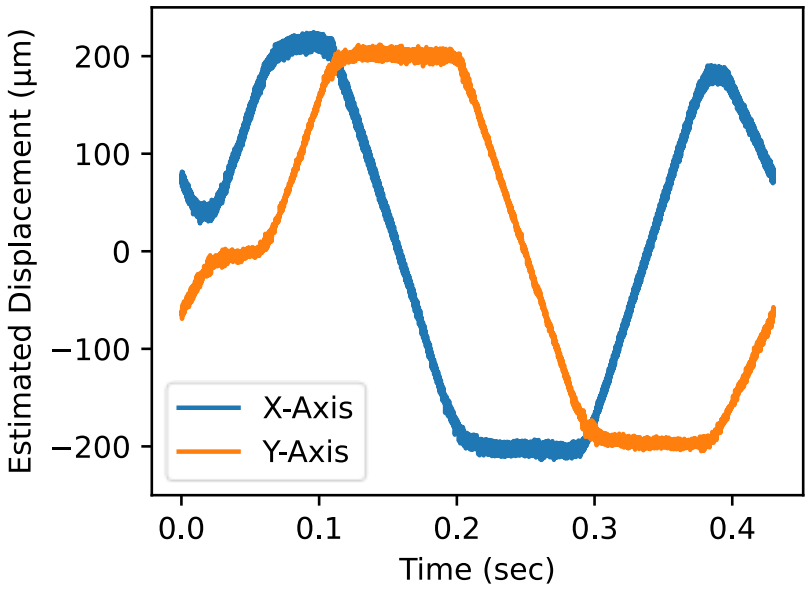
© 2024-2026 Motibera, Inc. All Rights Reserved.

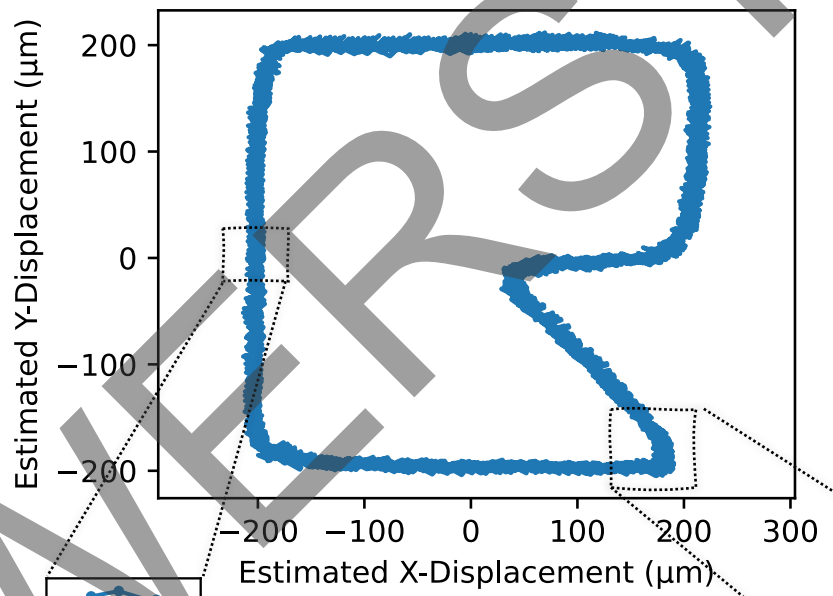
Preliminary online self-sensing confirms the machine/control co-design

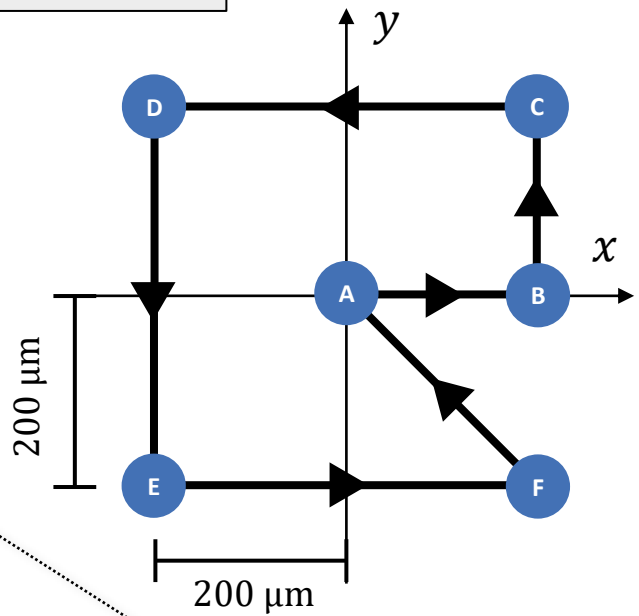
Estimated rotor displacement:

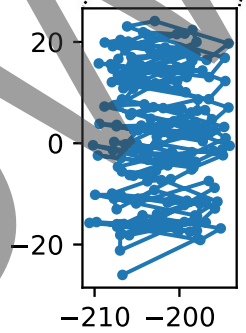
(*logged directly from real-time controller*)

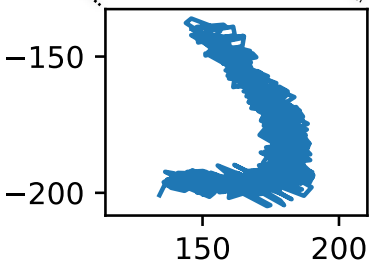
This result depended on machine geometry optimized for self-sensing — not only the control algorithm.











Self-sensing algorithm settings:

- Injection voltage magnitude: 2 V
- Injection carrier frequency: 1 kHz
- Notch filter width: 1.6 kHz
- Control/sampling rate: 20 kHz

Self-sensing exhibits high resolution of 15 μm for transient motion at 800 Hz bandwidth.

The optimized machine enabled real-time sensorless displacement estimation.

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.

JMAG enables advanced non-standard motor design workflow

Key takeaways:

- JMAG flexibility supports custom electromagnetic design problems
- Python scripting enables specialized post-processing
- Large simulation studies made topology-level decisions possible
- Hardware validation confirmed the model was accurate
- More parallel simulation capacity would dramatically accelerate iteration

JMAG was not just used to analyze the motor — it enabled the design.



Nathan Petersen, PhD
CEO and Founder
nathan@motibera.com

motibera

Advanced bearingless motors and drives.

POWERSYS

© 2024-2026 Motibera, Inc. All Rights Reserved.