Rapid eMotor 3D Virtual Prototype Development to Speed Up Innovation Loop

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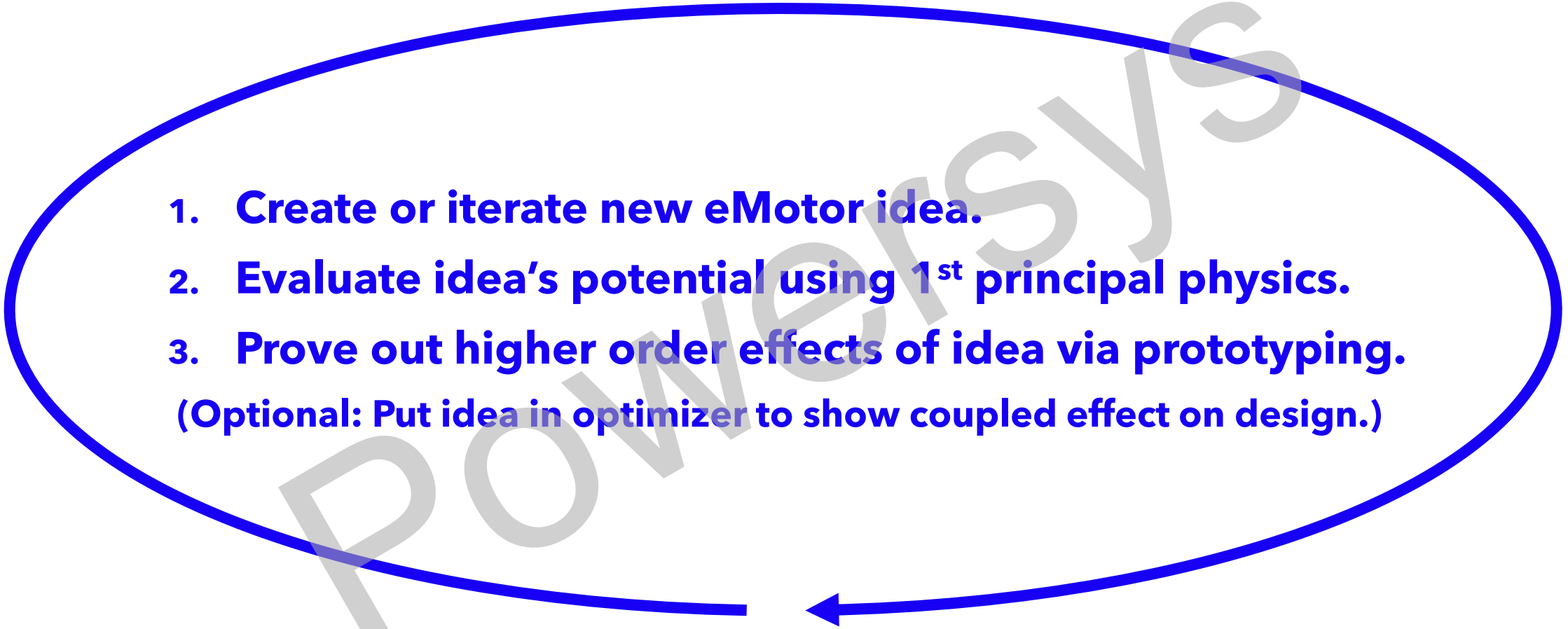
Innovation speed is the difference between winning and losing in emerging technologies.

eMotor Innovation Loop



Speed of this loop is critical to accepting risk and gaining solutions.

Getting Cost out of EVs

Ford's Goal: Make profit on EVs that don't cost $50k to $100k.

Battery cost is significant factor for EV affordability.

eMotor efficiency is directly coupled to battery cost.

eMotor Design Goal: Innovate to maximize and maintain eMotor efficiency.

1. Find ideas that make eMotor more efficient.
2. Find ideas that reduce material and manufacturing cost while maintaining eMotor efficiency.

eMotor efficiency is key innovation area for automotive EVs.

Different eMotor Model Solutions for Different Goals

Power Unit Sizing

Goal = Find best eMotor spec.

Done inside a stochastic optimizer.

Outputs spec and base design.

Simulation Scale	Vehicle
EM Solver Level	1D Closed Form
Thermal Solver Level	1D Fit
Electric Solver Level	1D Fit
Mechanical Solver Level	1D Fit
Acoustic Solver Level	1D Constraint

Stochastic eMotor Optimization

Goal = Find best eMotor design.

Done inside a stochastic optimizer.

Outputs optimized detailed design.

Simulation Scale	eMotor
EM Solver Level	2D FEA
Thermal Solver Level	1D Closed Form
Electric Solver Level	1D Closed Form
Mechanical Solver Level	2D FEA
Acoustic Solver Level	1D Constraint

Virtual Prototyping

Goal = Deliver CAE design results.

Done for a single design.

Outputs detailed design results.

Simulation Scale	eMotor + Power Unit
EM Solver Level	2D/3D FEA (Sine + Harm)
Thermal Solver Level	3D CFD
Electric Solver Level	Detailed Circuit Simulator
Mechanical Solver Level	2D/3D FEA
Acoustic Solver Level	3D FEA

Rapid virtual prototyping is a key enabler for speeding up innovation loop.

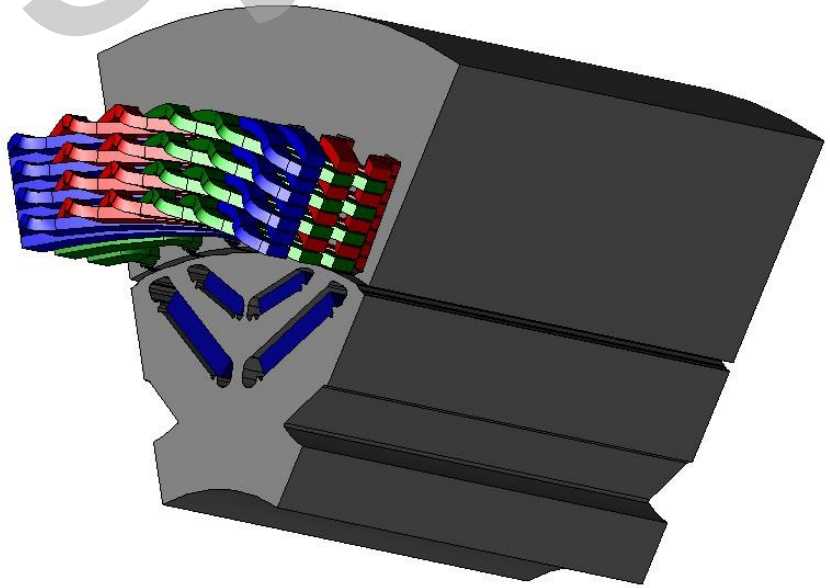
Goal of eMotor Loss Virtual Prototype

The goal of a virtual prototype is to provide a <u>24 hour</u> loop end to end from a human idea to the numerical value of a top-level metric performed on a 20-core workstation with all critical physics being fully captured in the model equations and geometry.

Tool must have an efficient HIL interface as well as an efficient solver.

<u>Key losses that need to be modeled</u>

- **Unwanted eddy currents**
- **Local degradation of electrical steel**



1st order = worse… obviously

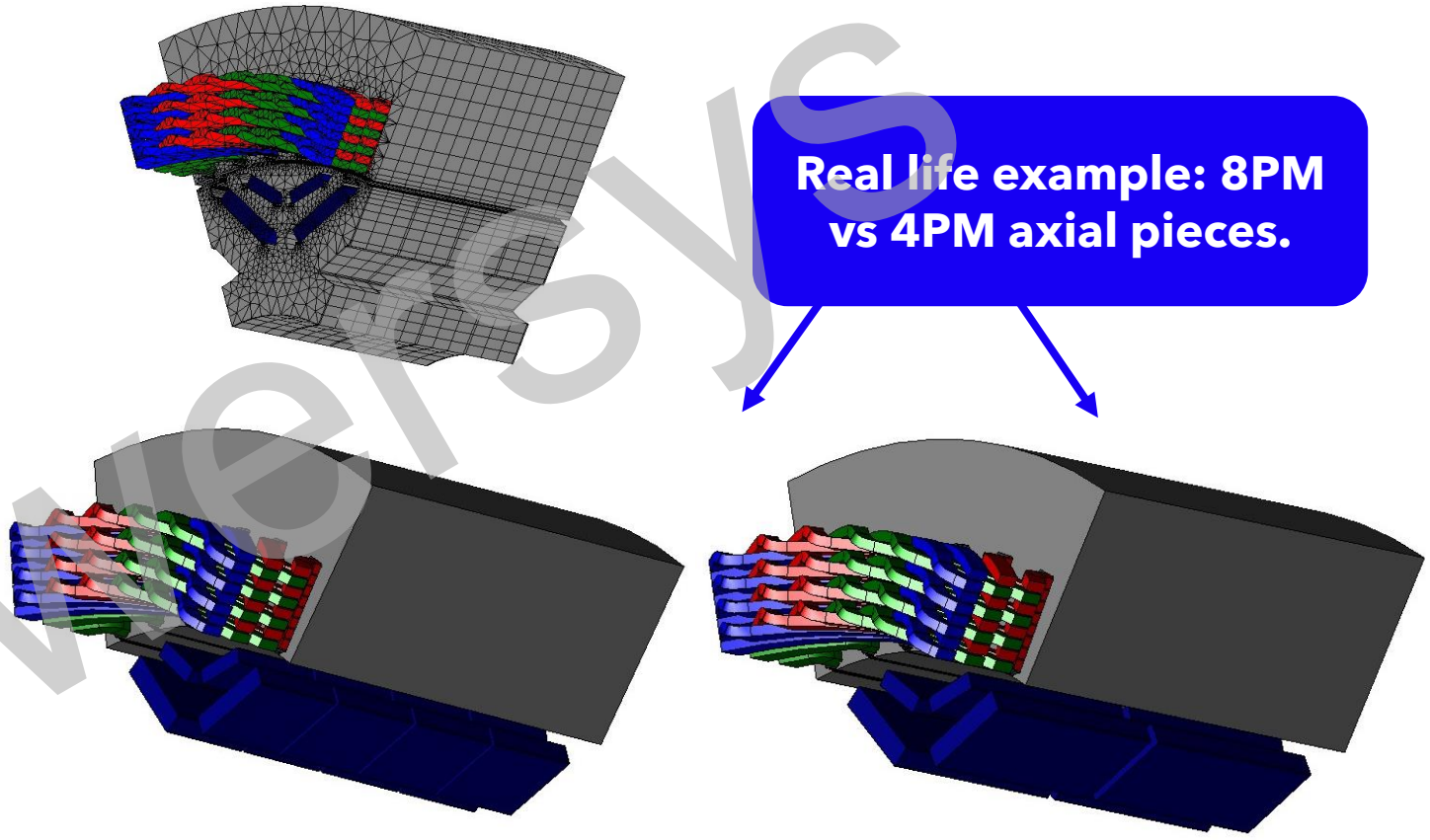
Key is to compute actual $ impact on top level metric

Innovate how to minimize till they are not impactful

Accurately compute top-level loss impact in 24 hours end to end.

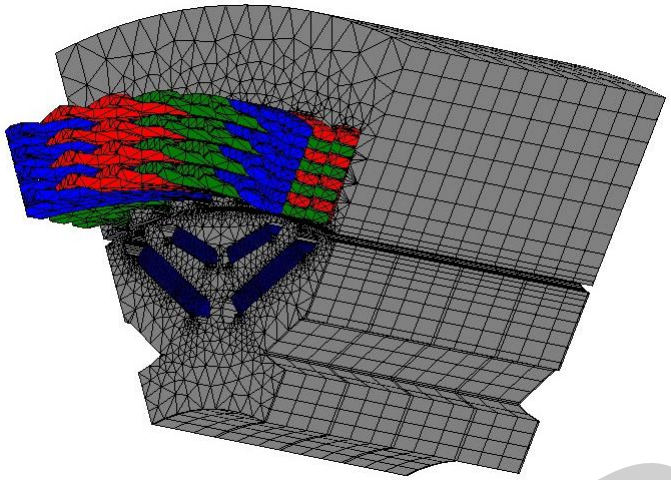
3D FEA Model Details (8PM & 4PM)

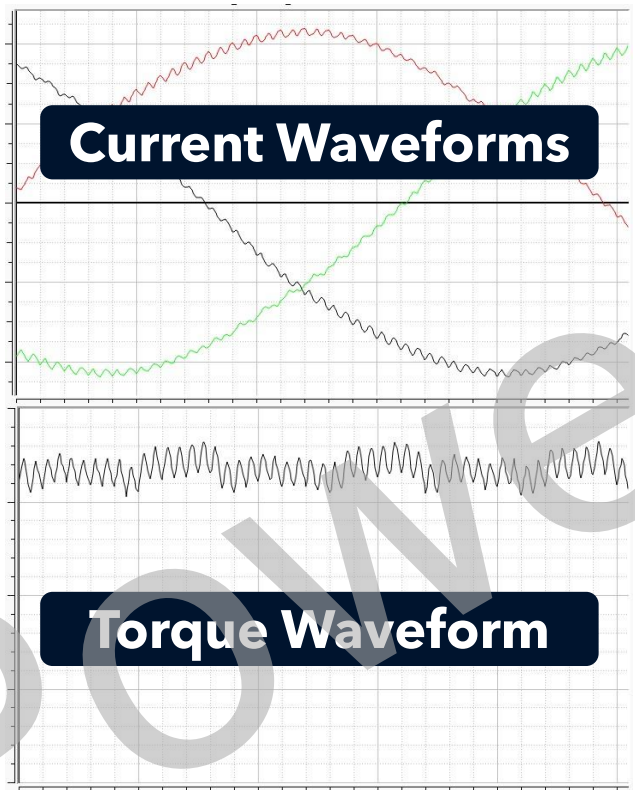
Model Portion	½ of 1 Pole
Axial Meshing	3mm 6mm 12mm
Critical Feature Mesh	0.5mm 1mm 2mm
PWM Strategy	Externally computed current source
PWM Time Step	10 per Tsw 20 per Tsw 40 per Tsw
Non-Linear Strategy	Start from previous Ts
End Winding Geometry	Actual hairpin geometry
# Mesh Elements	153570 (1mm feature, 6mm axial)
Cycle simulated	1/2, 1/4, 1/6

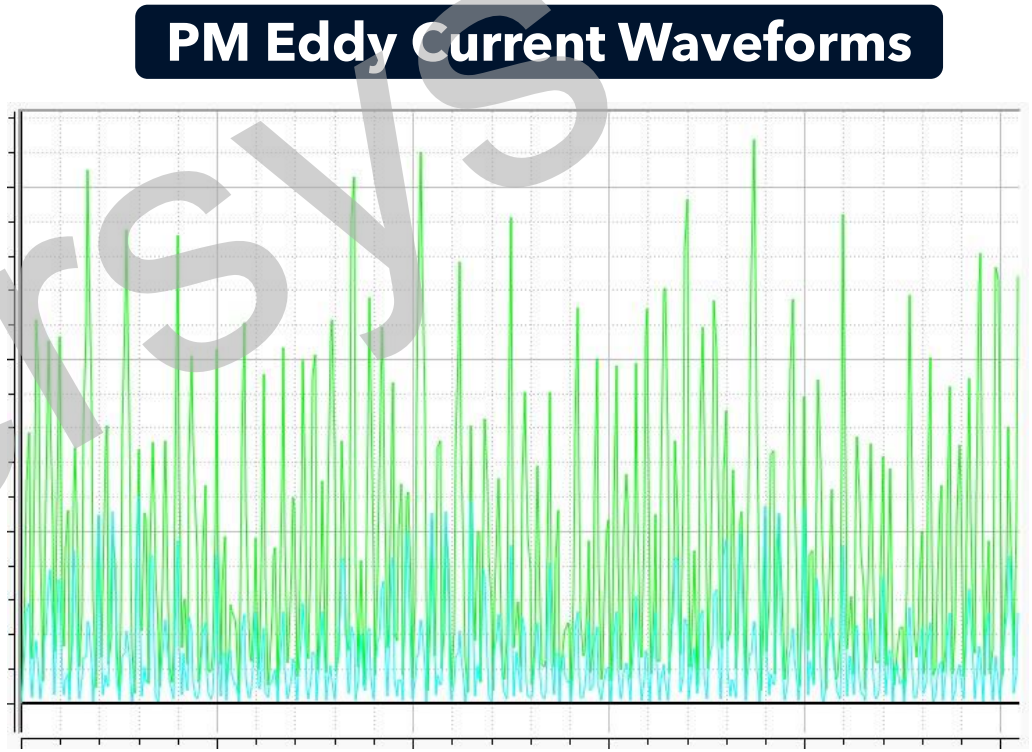


Simulation strategy set forth including all critical physics while being numerically tuned for speed.

3D FEA Model Results



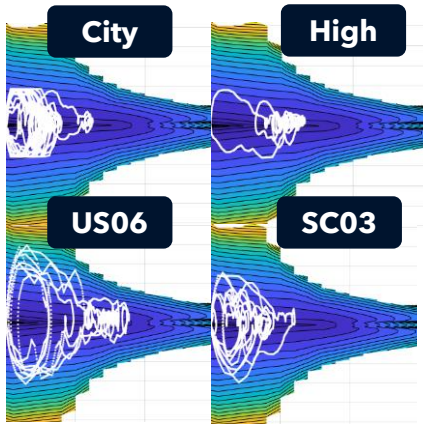


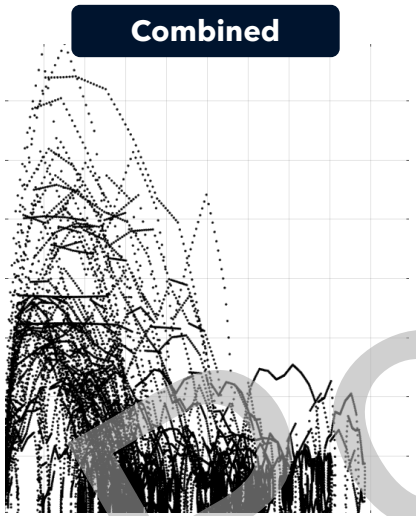


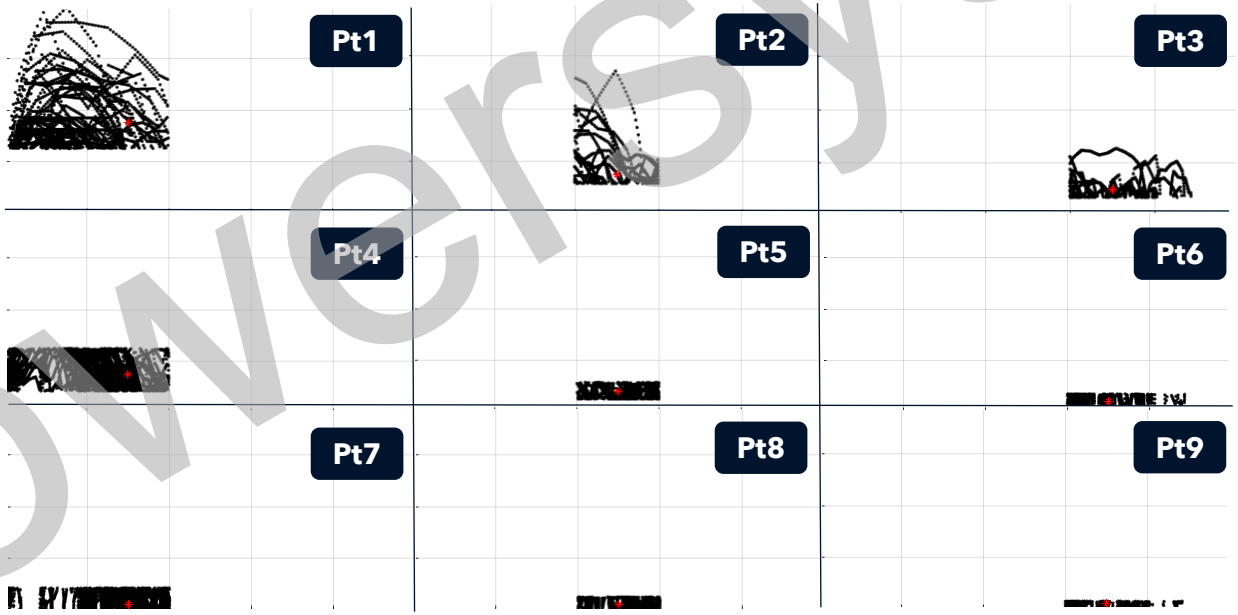
Full simulation runs smoothly and produces good results.

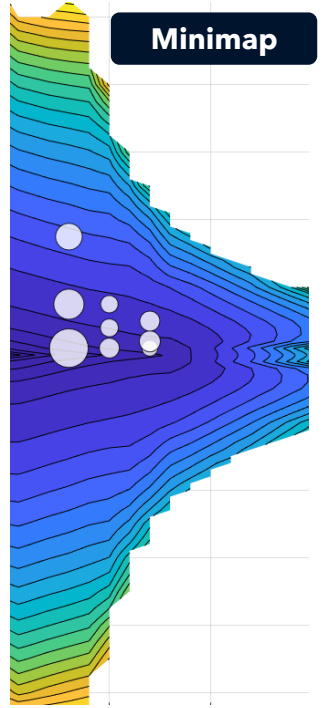
Rapid Loss Calculation Strategy (OP Selection)

Key is to choose strategic points to get reasonably accurate A/B top level number without running 3D FEA for all points on cycle or even full map.



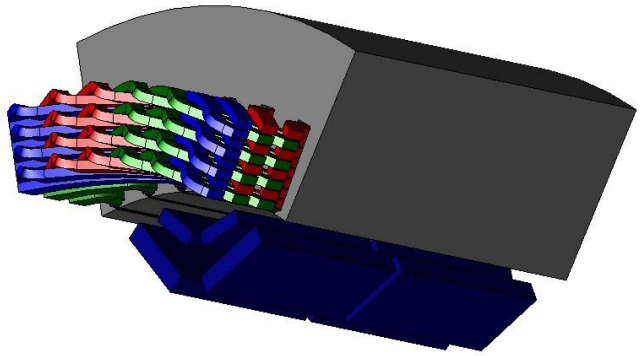


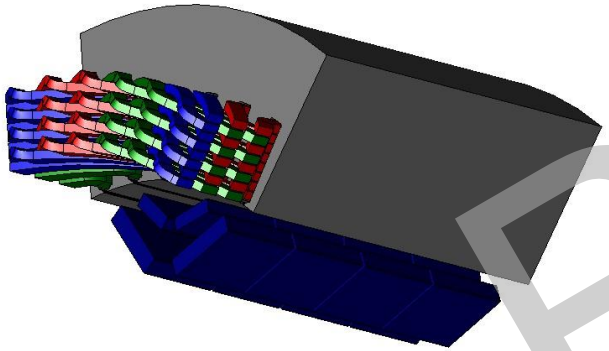




Use nine strategically placed operating points to compute 5 cycle loss energy.

8PM vs 4PM Top Level Cost Comparison





Time to run total simulation = 6.00hr

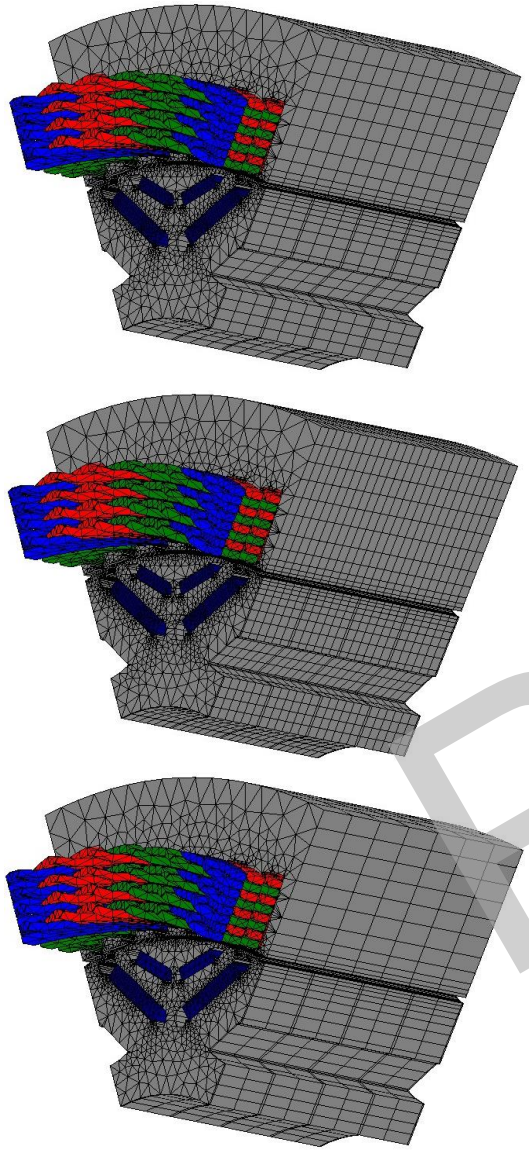
5 cycle loss difference = 0.1048 Wh/mi

1Wh/mi cost of 300mi vehicle ~$30 of battery

4PM version has ~$3.15 more loss than 8PM version

Virtual prototype successfully computed top level requirement in <24 hours.

Comparison of Different Numerical Fidelities



Magnet Mesh	Axial Mesh	Steps per Tsw	Time	$ Cost Delta
1mm	6mm	20	6.00hr	$3.15
1mm	6mm	40	12.77hr	$3.02
1mm	6mm	10	3.57hr	$3.21
1mm	3mm	20	9.73hr	$3.14
1mm	12mm	20	5.17hr	$1.72
1mm	12mm	40	10.15hr	$1.38
1mm	12mm	10	2.37hr	$2.16
2mm	12mm	20	4.15hr	$1.75

Some sensitivity with time steps and mesh.

Opportunity to study further with physical test verification.

Virtual Prototype Mission Ongoing

Keys to Success

- **Stable and computationally efficient software.**
- **Rapid and predictable HIL usage.**
- **Expertise to customize for specific needs.**

Large scale 3D Jmag model runs stably and efficiently.

PWM current import process custom created by Powersys works well.

The loss virtual prototype model computes drive cycle loss ***within 24hr time goal***.

The loss virtual prototype model computes top level metrics with physics not in with ***standard*** 2D model.

Loss virtual prototype model up and running

Next Step: study further with physical test verification