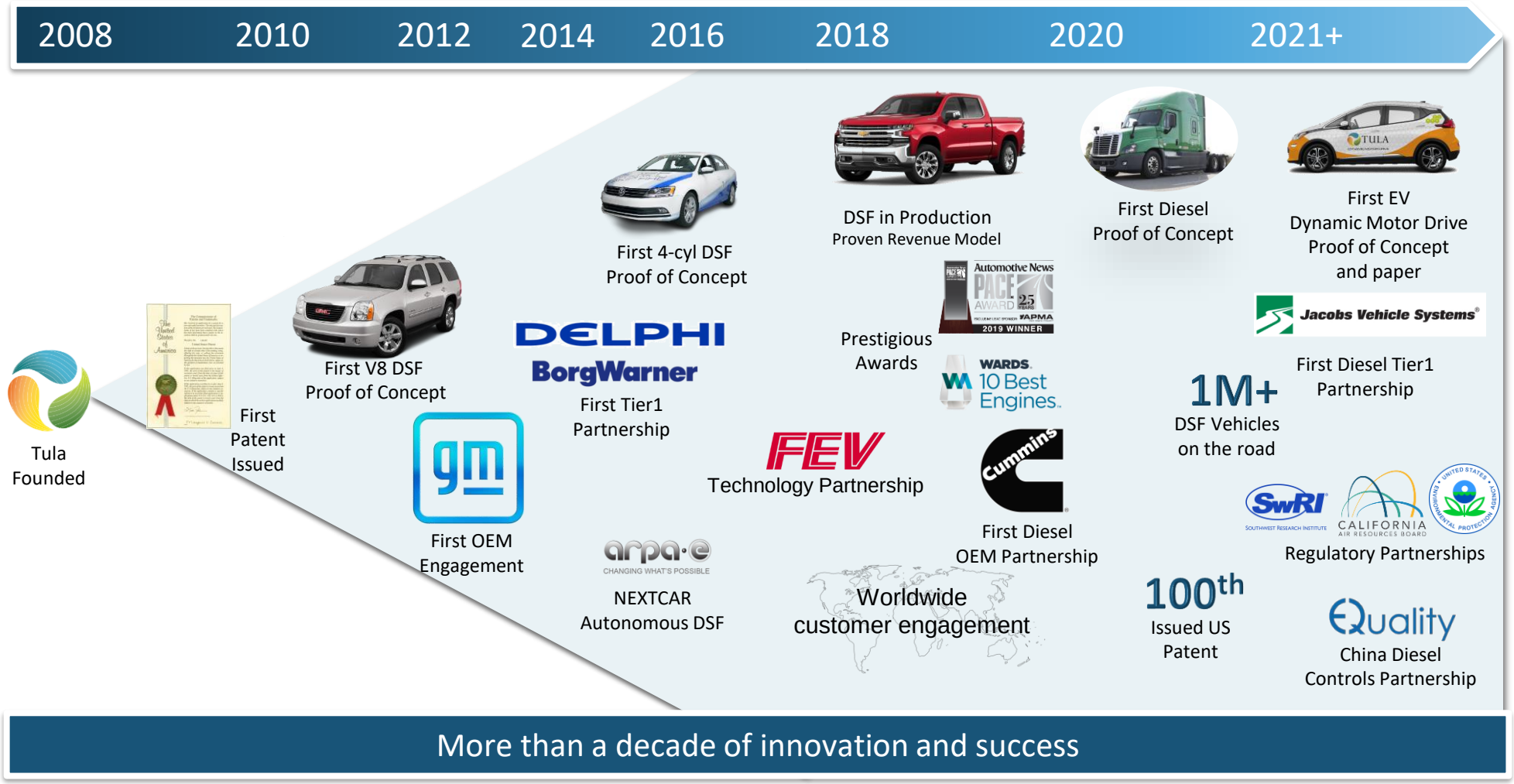
TULA

DYNAMIC MOTOR DRIVE

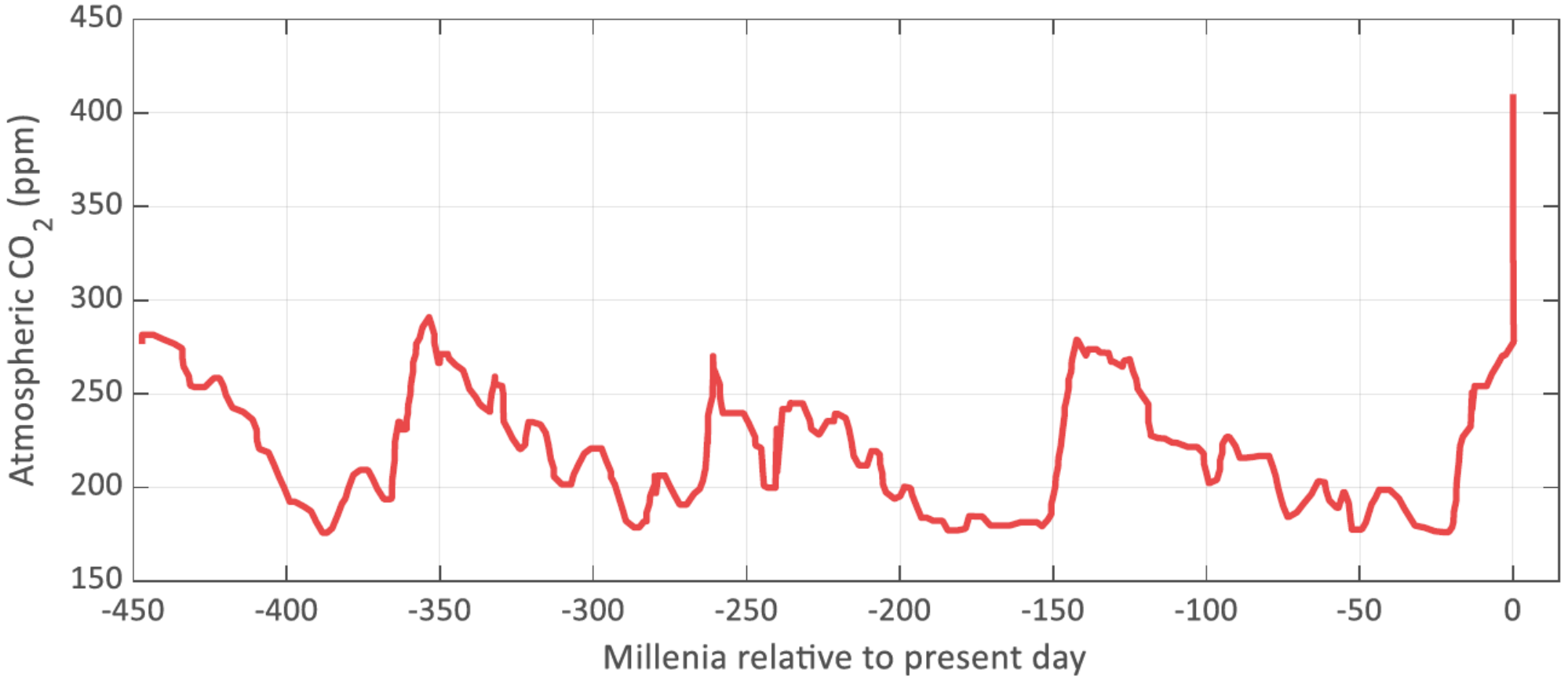
A STRATEGY OPTIMIZING ELECTRIC MOTOR EFFICIENCY

TULA TECHNOLOGY

Tula - Driving Towards the Future

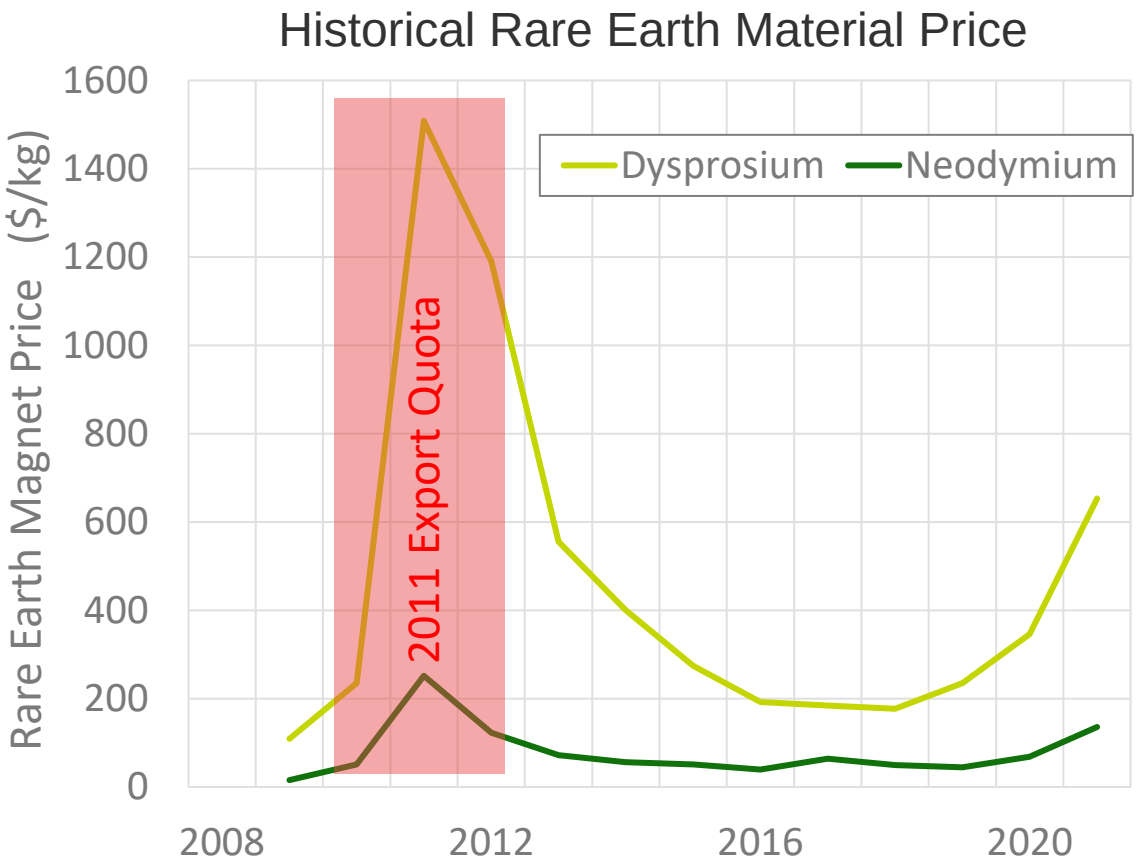


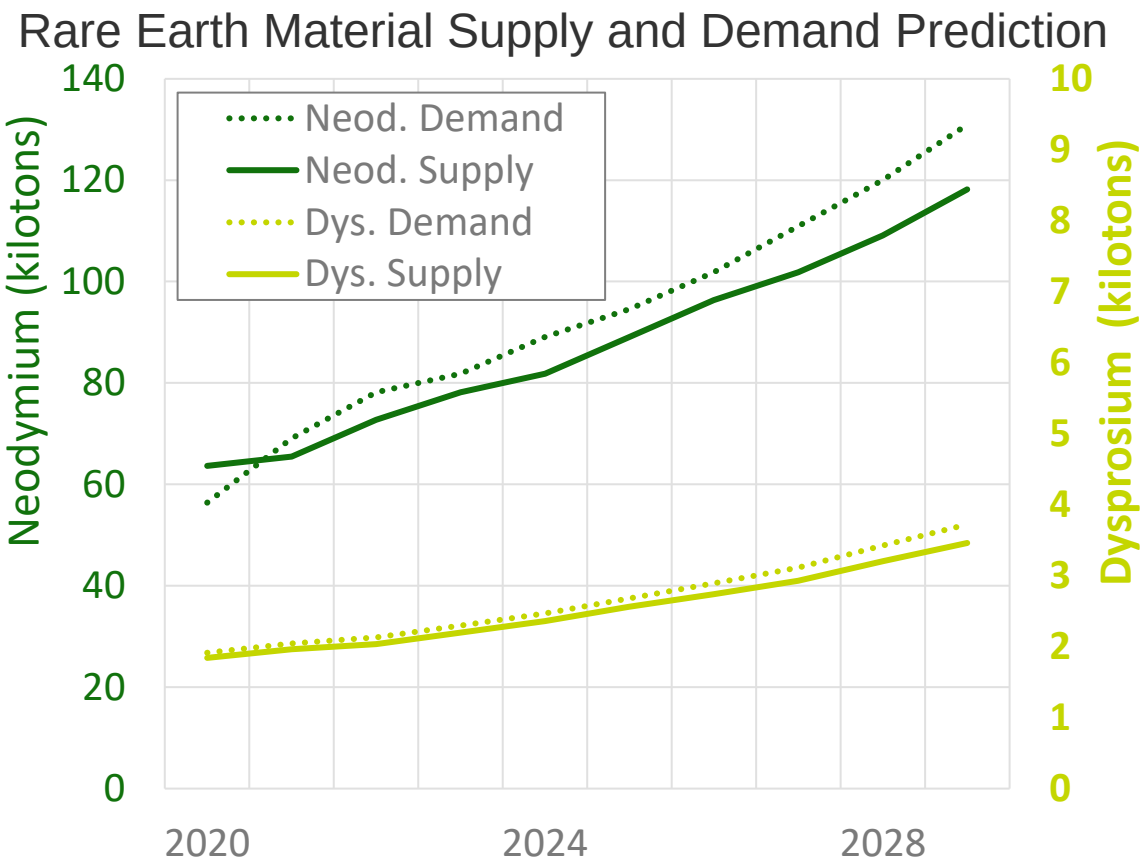
Challenges of Climate Change



Greenhouse gas emission causes climate change. Automobiles are a major contributor

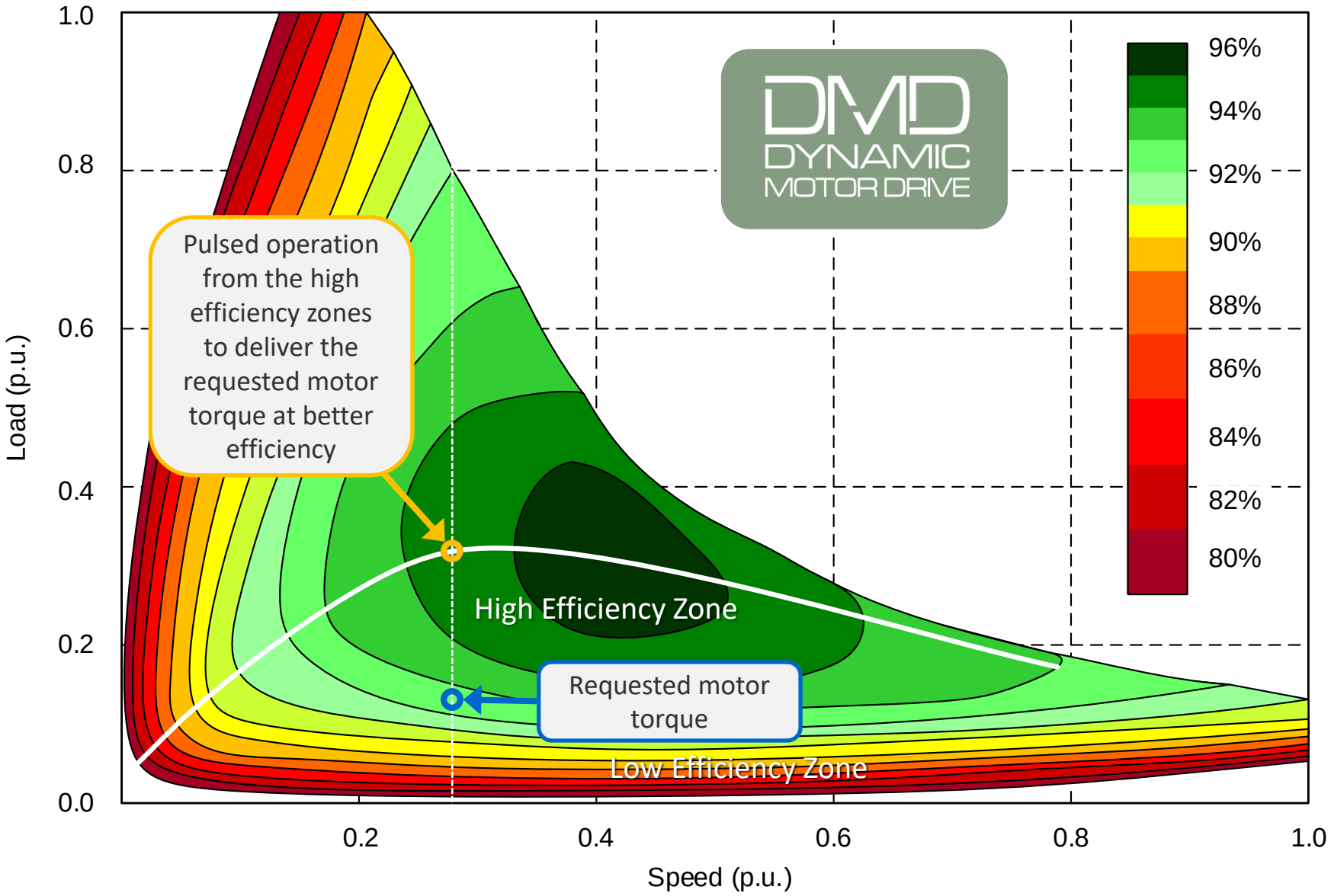
Conventional Solutions Rely on Rare Materials



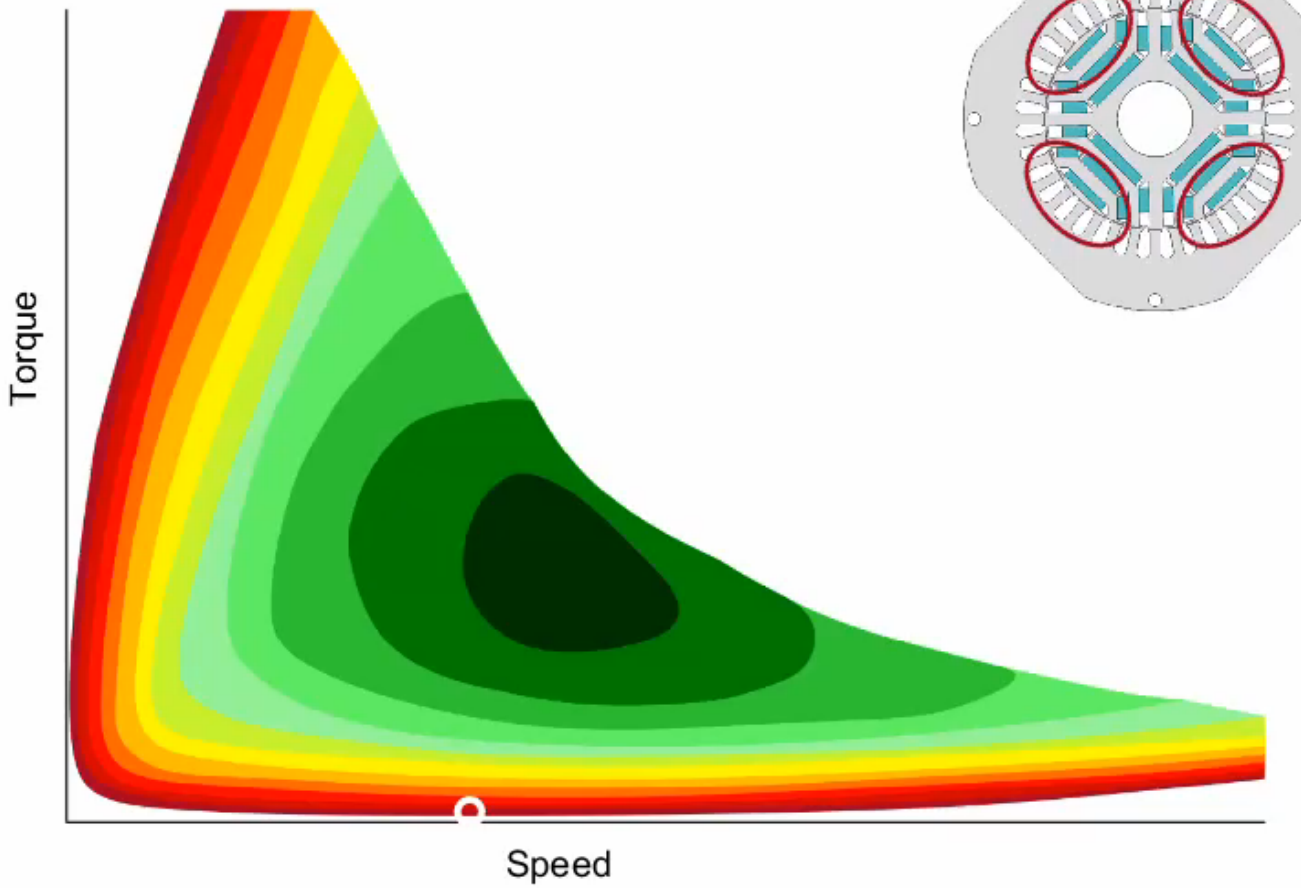


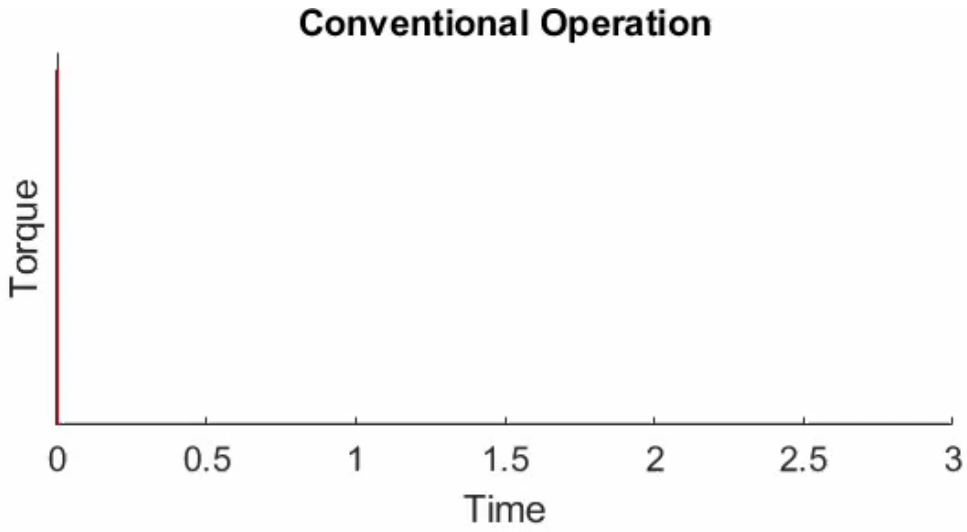
Heavy use of scarce materials can limit the implementation of permanent magnet EVs

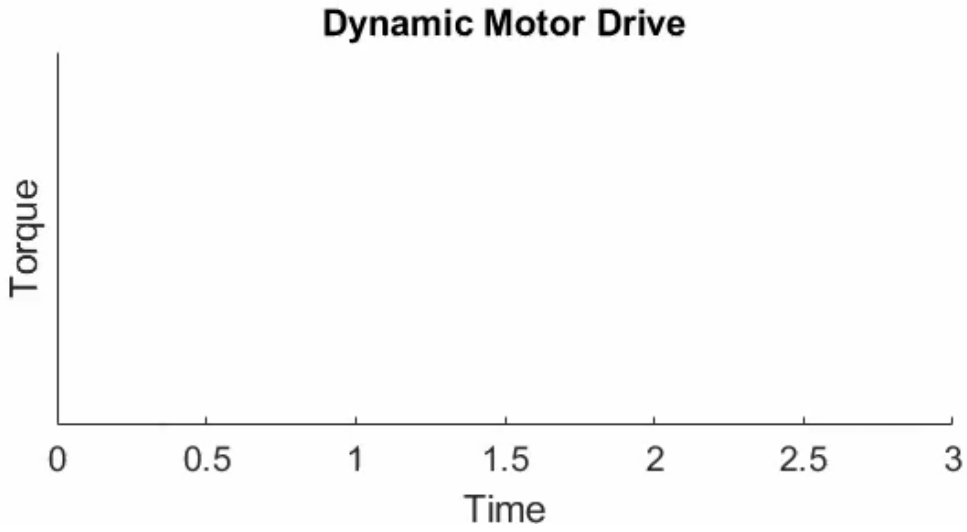
Dynamic Motor Drive (DMD) – The Concept



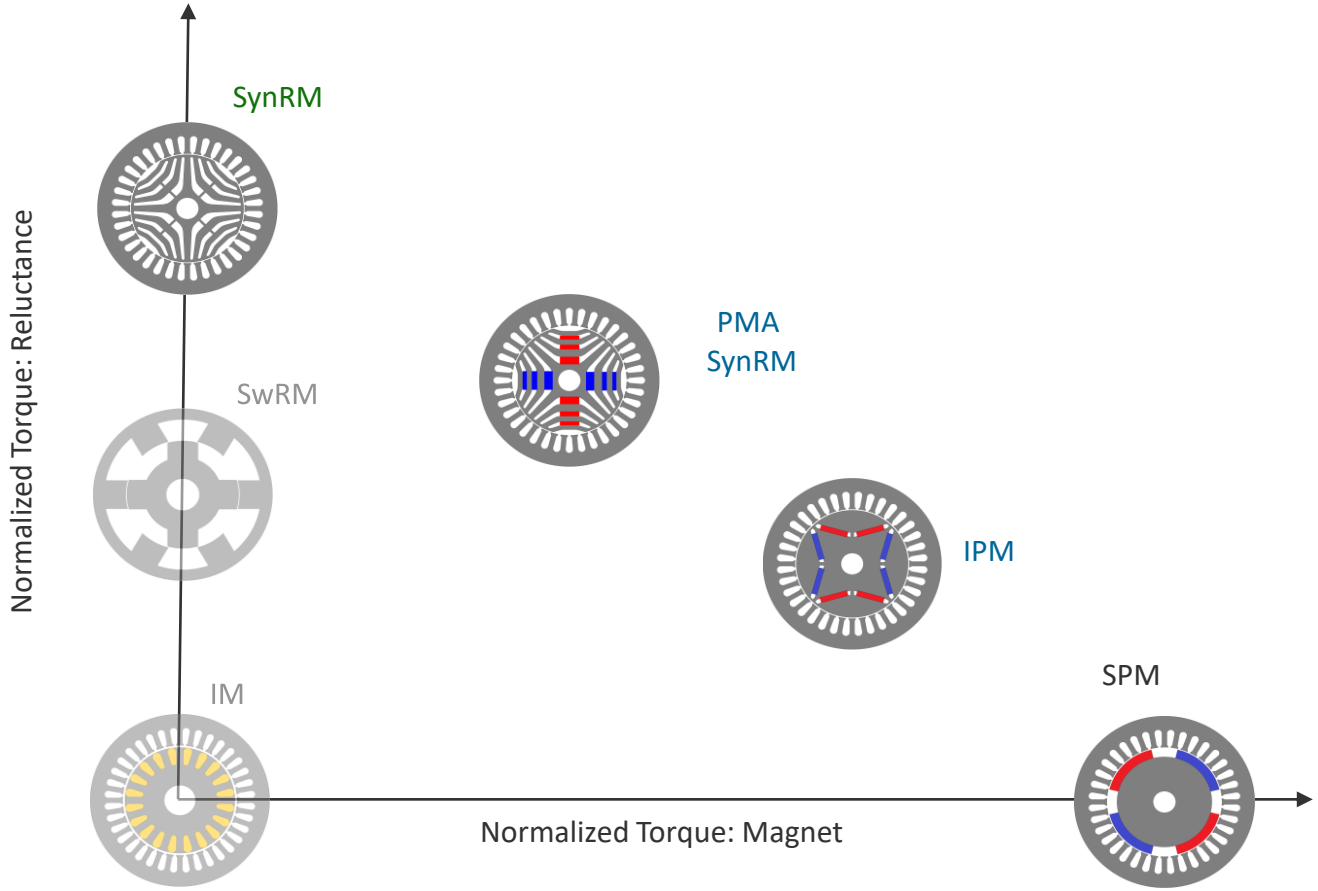
Dynamic Motor Drive (DMD) – The Concept





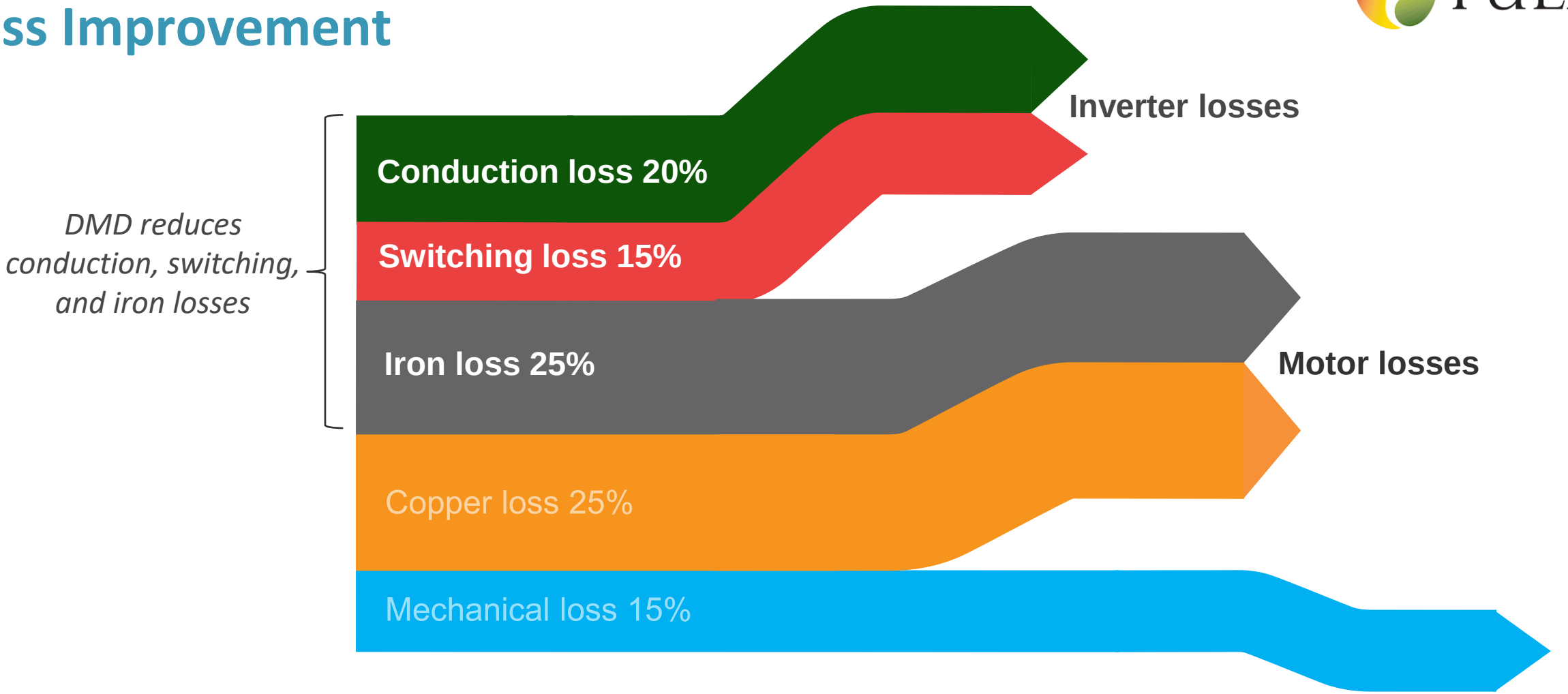


DMD Motor Architecture Selection



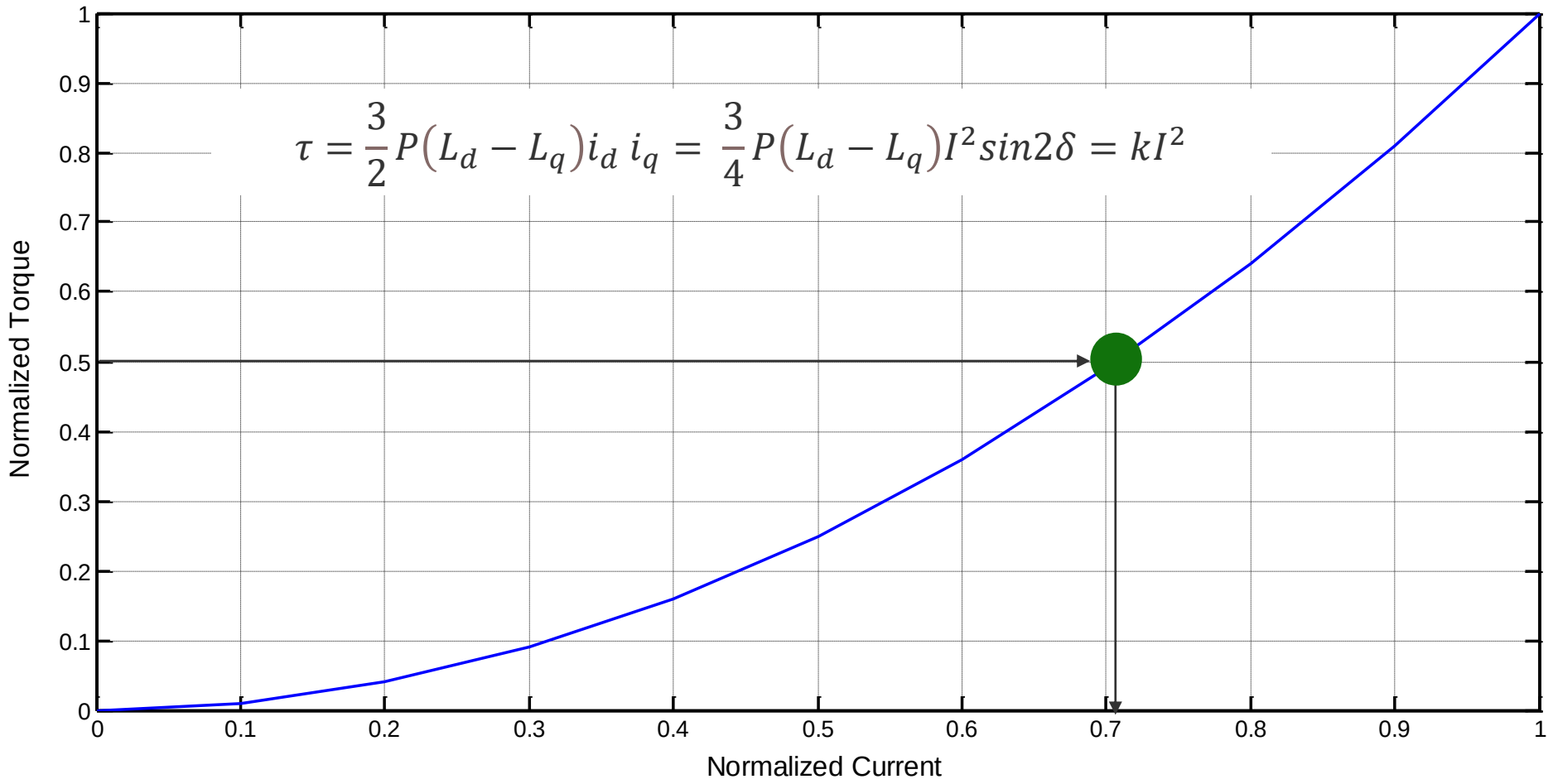
DMD is most effective for Synchronous Reluctance Motors (SynRM)

Loss Improvement



Optimizing these losses improves reluctance motor efficiency significantly

Torque Production of Synchronous Reluctance Motor



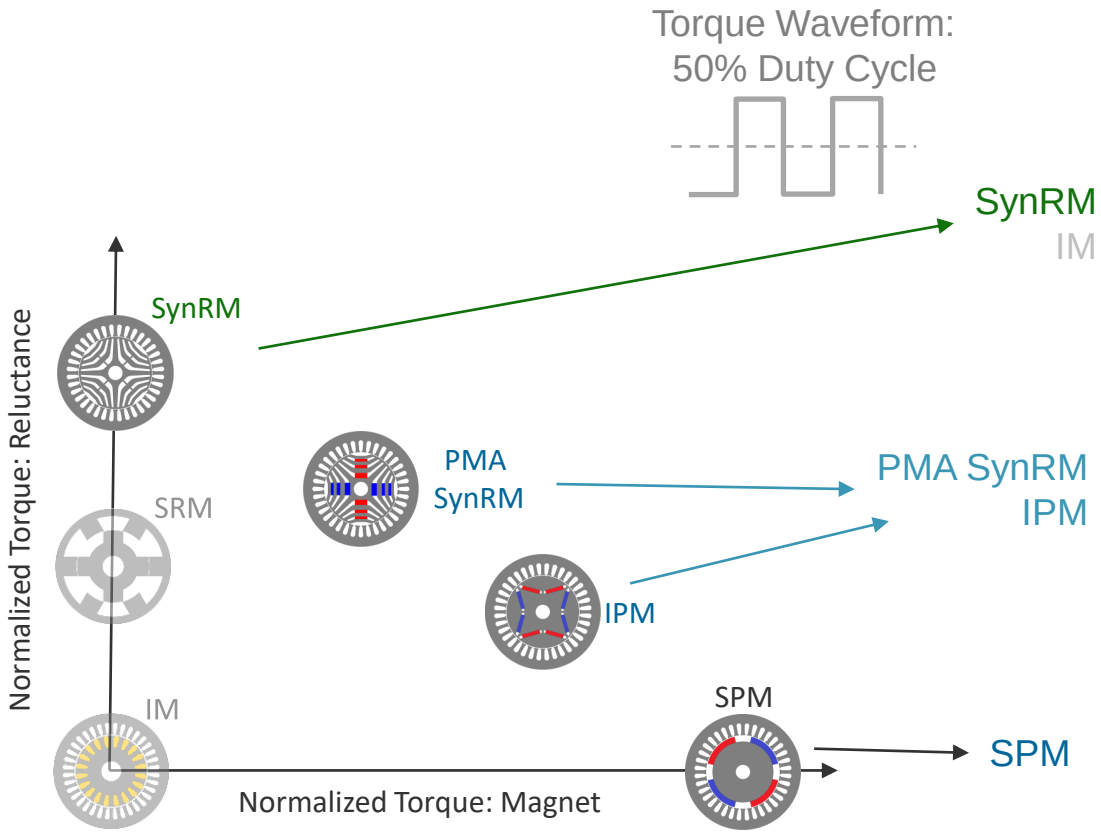
Torque is proportional to current^2 for SynRM's at moderate loads

Optimization of Loss Tradeoffs

	Linear to Current	Quadratic to Current
Conduction Loss	$V_{ce0}\left(\frac{1}{2\pi}+\frac{m\cos\theta}{8}\right)I$ DMD	$R_{ce}\left(\frac{1}{8}+\frac{m\cos\theta}{3\pi}\right)I^2$ DMD
Switching Loss	$\frac{f_{sw}V_{dc}}{\pi I_{ref}V_{ref}}\left(E_{on}+E_{off}+E_{rr}\right)I$ DMD	-
Copper Loss	-	RI^2 DMD
Hysteresis Loss	$k_h f B^{1.6} V$ DMD	
Eddy Current Loss	-	$k_w \delta^2 f^2 B^2 V$ DMD

Motors using reluctance torque are well suited for DMD

DMD Motor Architecture Selection

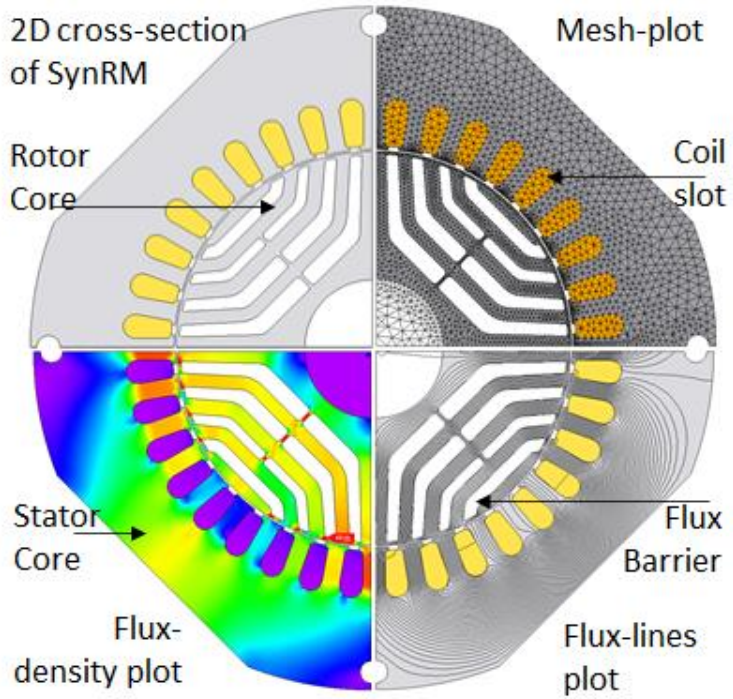


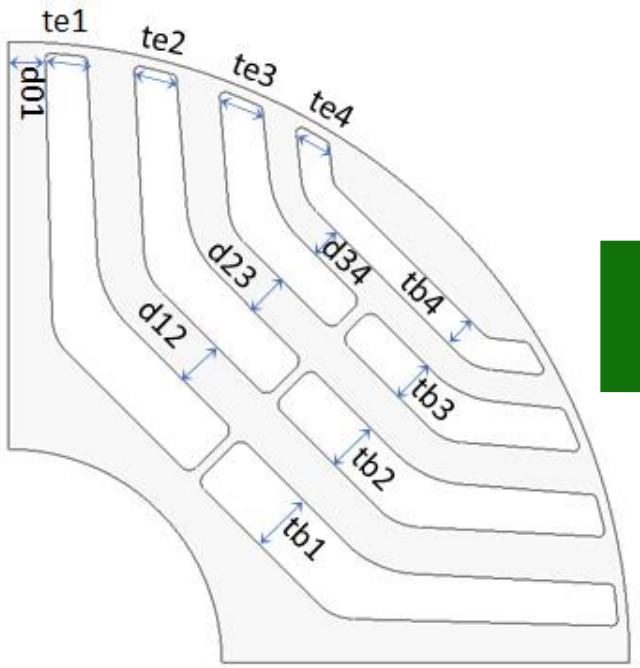
Current for 50% Duty Cycle	Losses I^2	Losses I	Losses Total	Impact of DMD
1.4x	1x	0.7x	=	Reduced Losses
1.4x – 2x	1x-2x	0.7x-1x	=	Implementation Specific
2x	2x	1x	=	Increased Losses

DMD is more effective for motors actively making use of reluctance torque

Tula Designed SynRM

No permanent magnets

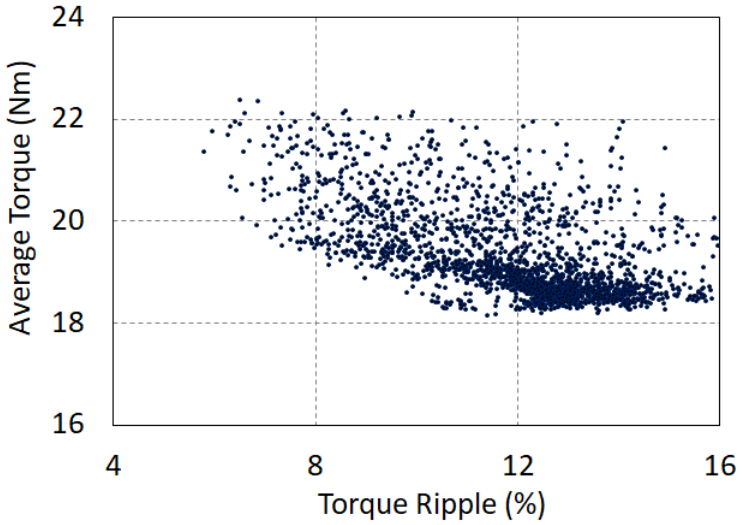


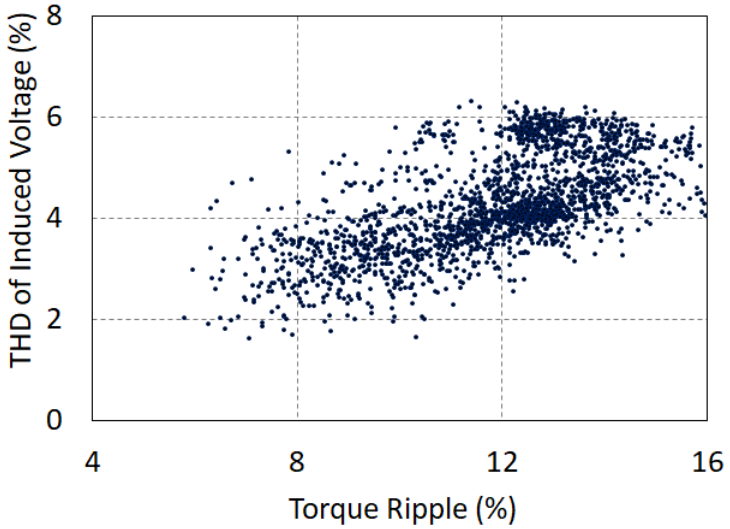


Flux barriers increase torque production

A proof-of-concept motor was designed and built by Tula to prove out DMD Strategy

Synchronous Reluctance Motor (SynRM) Design

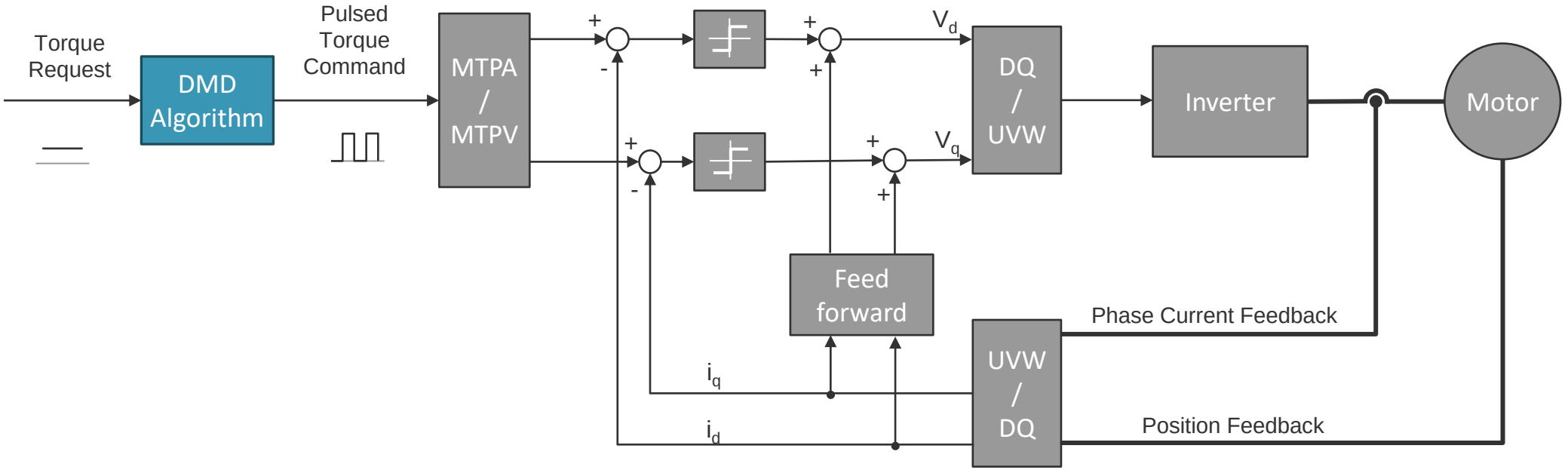




As a proof of concept, Tula has designed a 15kW SynRM using a multi-objective genetic algorithm (GA), optimizing torque, torque ripple, and harmonic distortions

Control Optimation for DMD

Conventional control methods and hardware

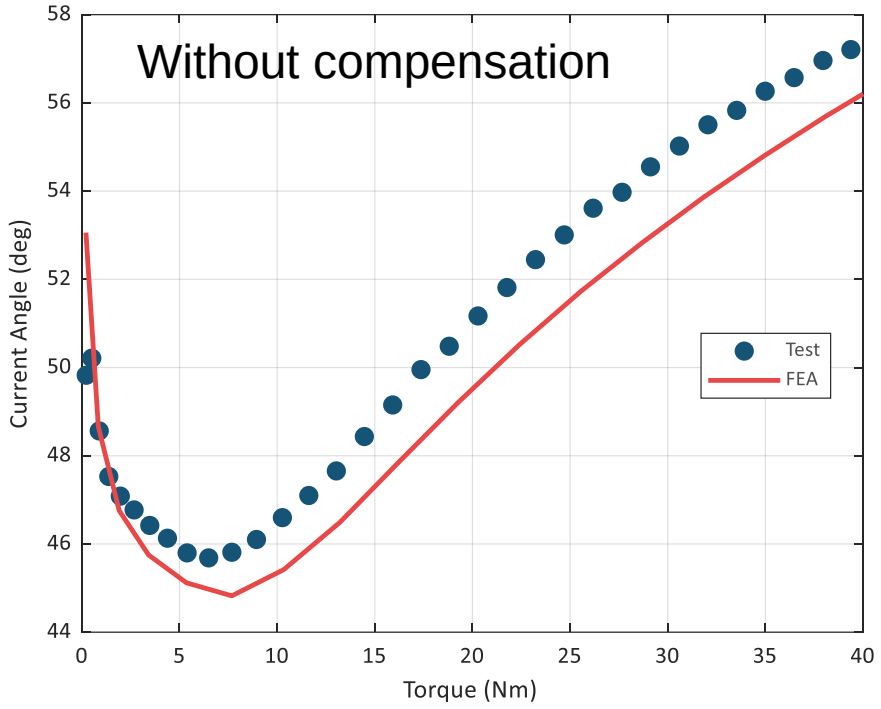


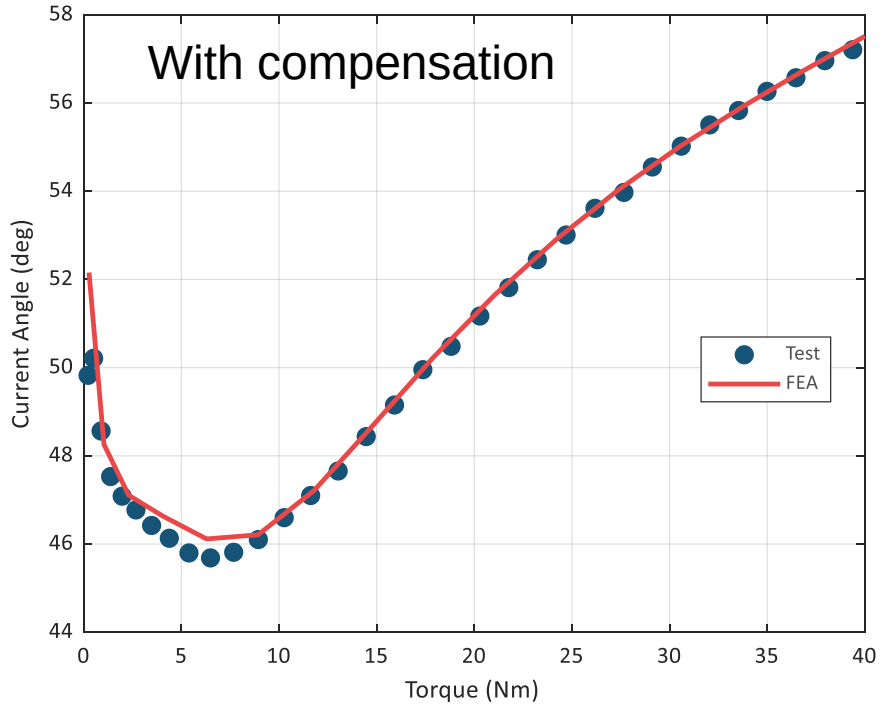
Tula's DMD algorithms were developed to allow implementation with conventional control algorithms

Time-optimized control methods optimize efficiency during transitions between high and low torque

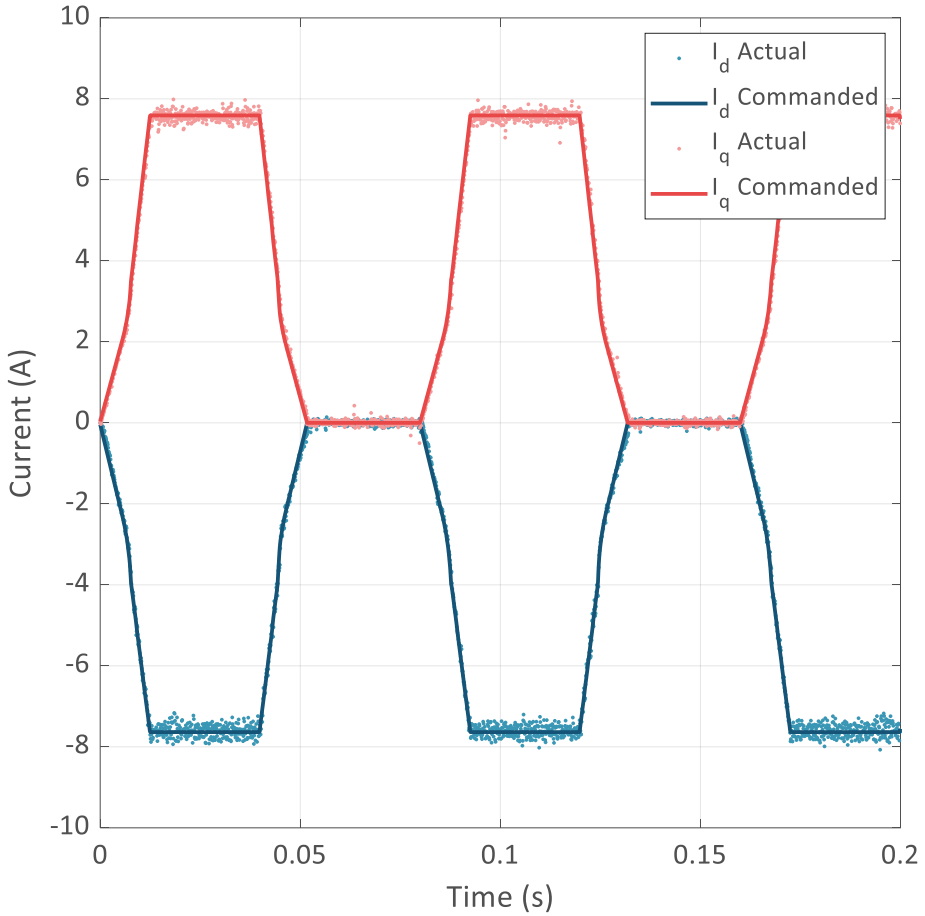
Torque Control Law

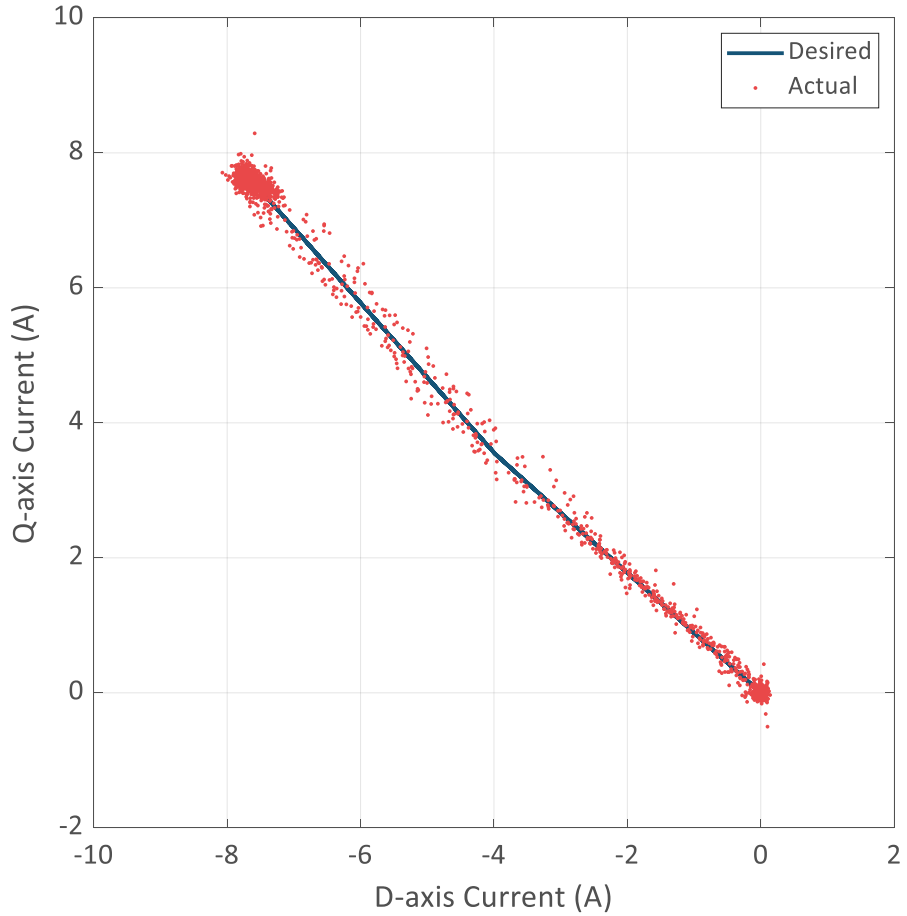
- Max torque per Ampere (MTPA) curve generated from Finite Element Analysis has around 1^{o} error from test results
- This inaccuracy is corrected by compensating the iron loss model





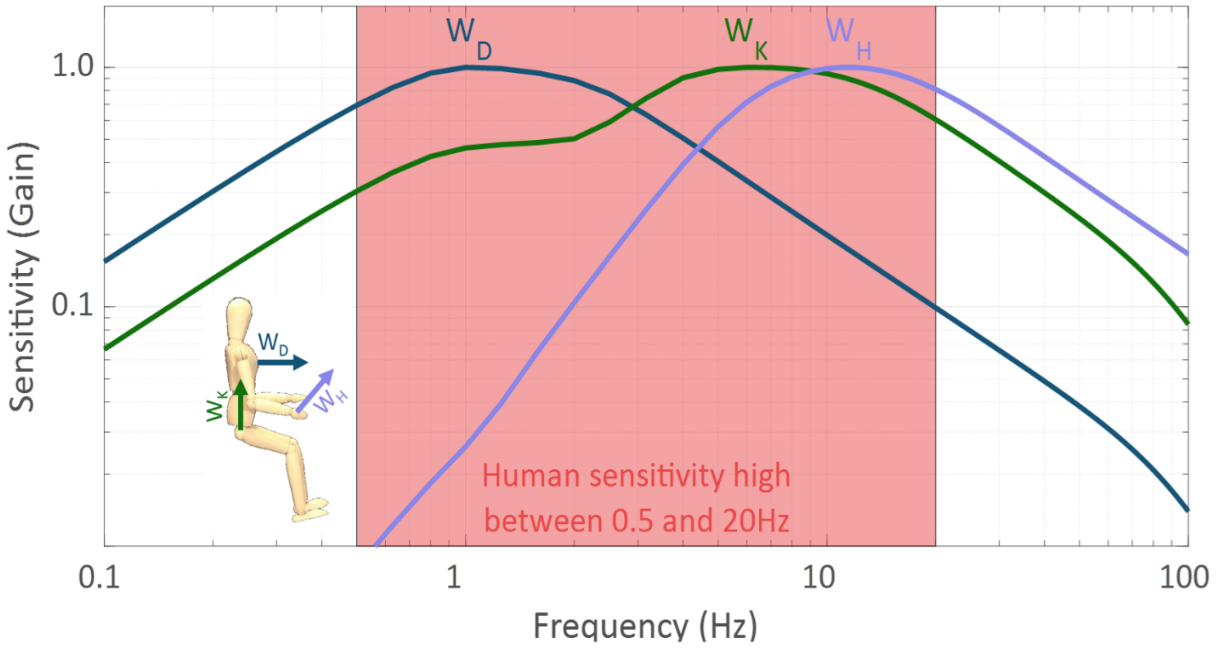
Current Control Achieving Desired Response Speed

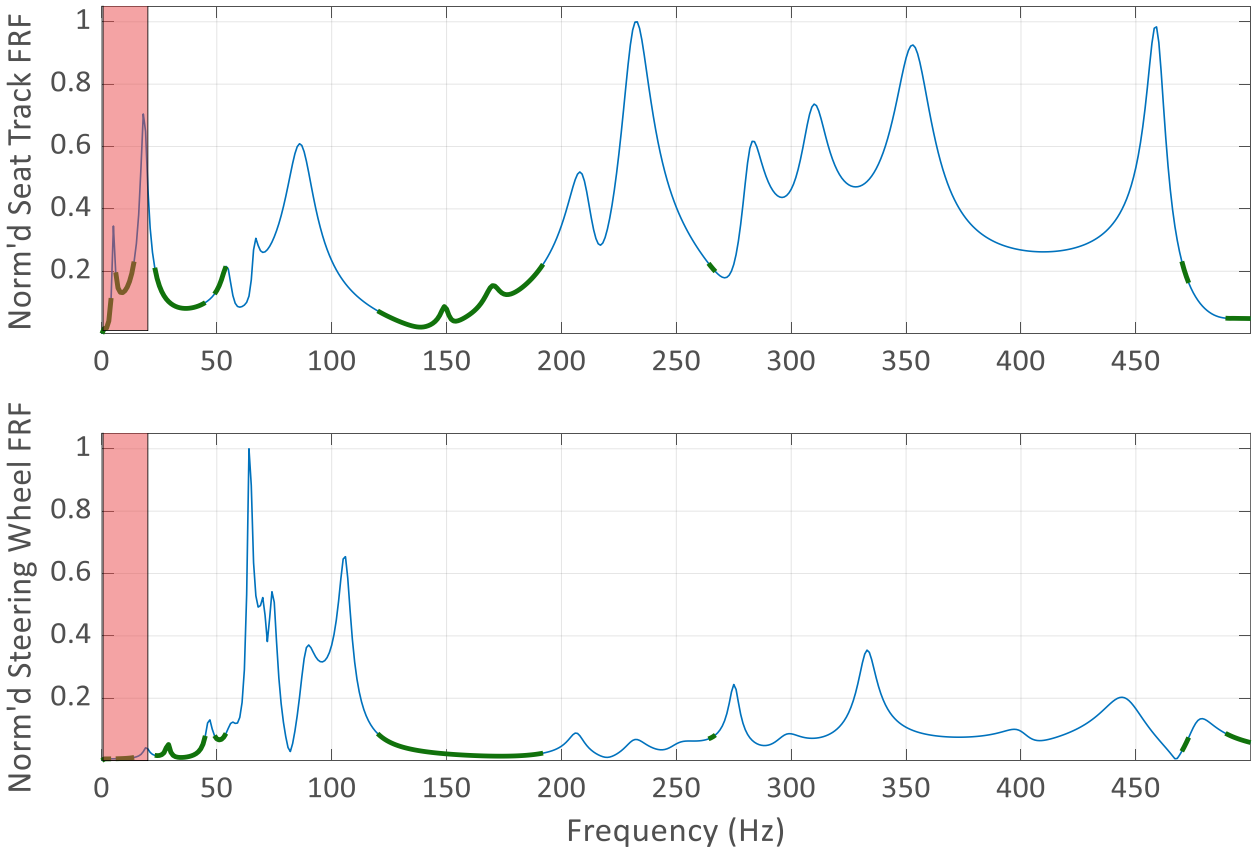




Excellent current tracking realized by deadbeat control

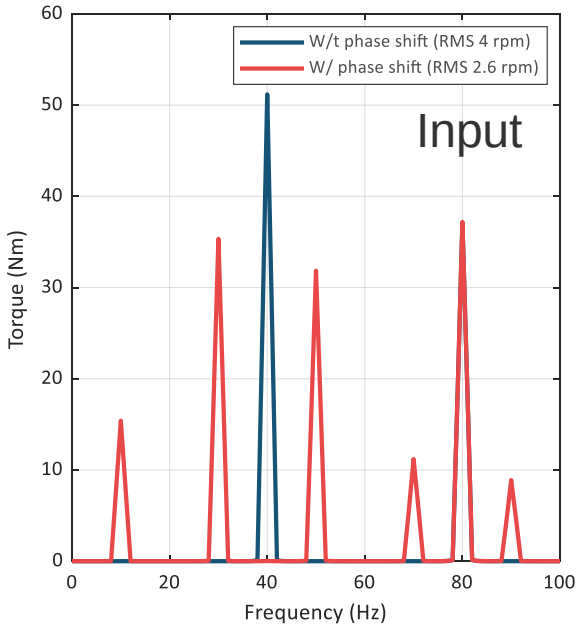
Vehicle Sensitivity and Human Perception

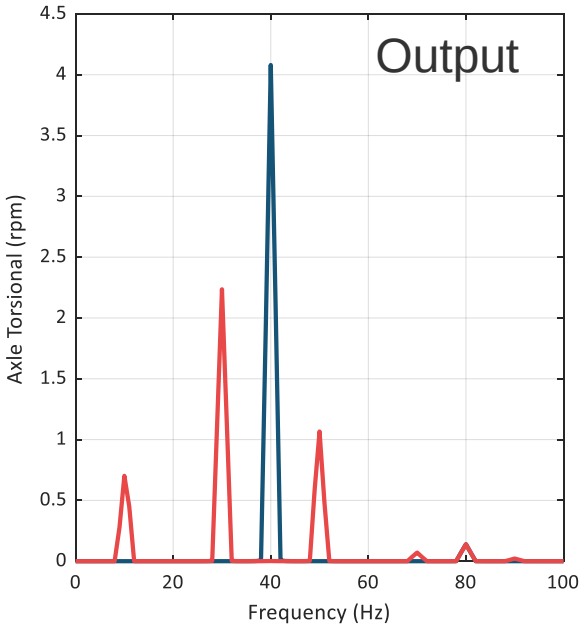




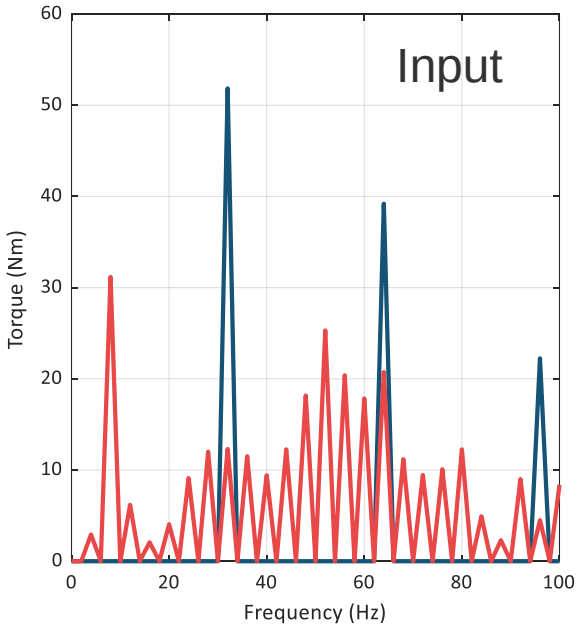
Torque modulation frequency selected has less human sensitivity

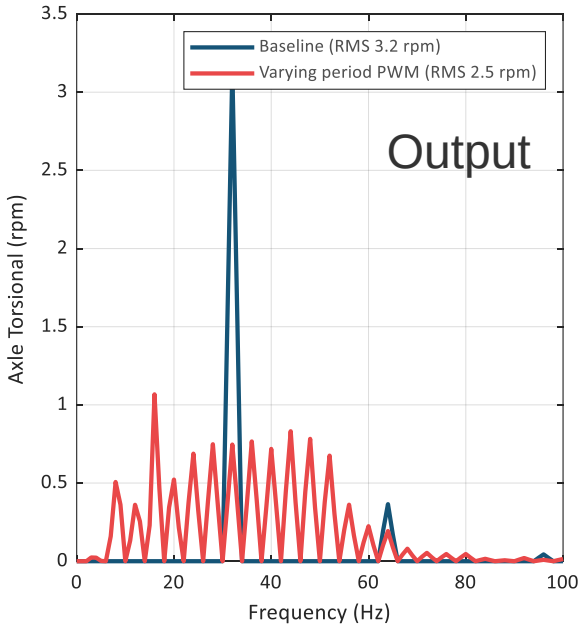
Vibration Mitigation Strategies





Switching modulation waveform phase between 0 and 180 degrees every 3 cycles

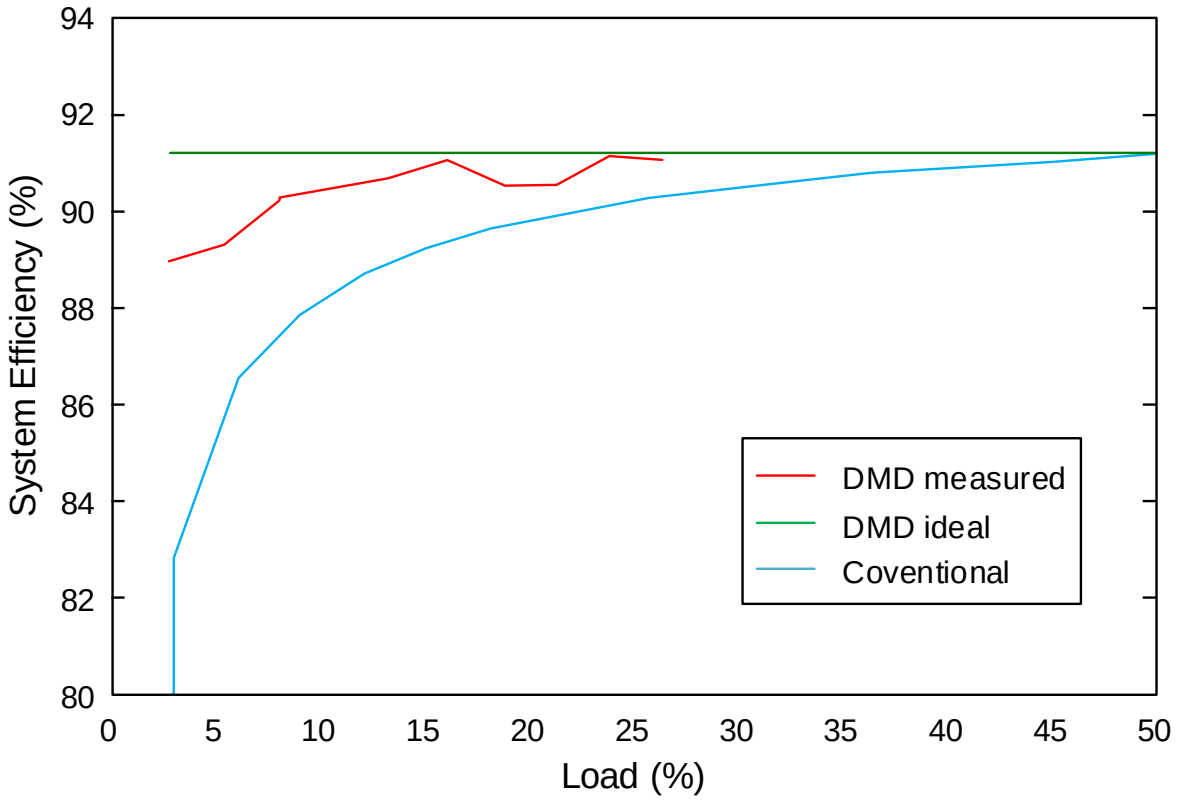


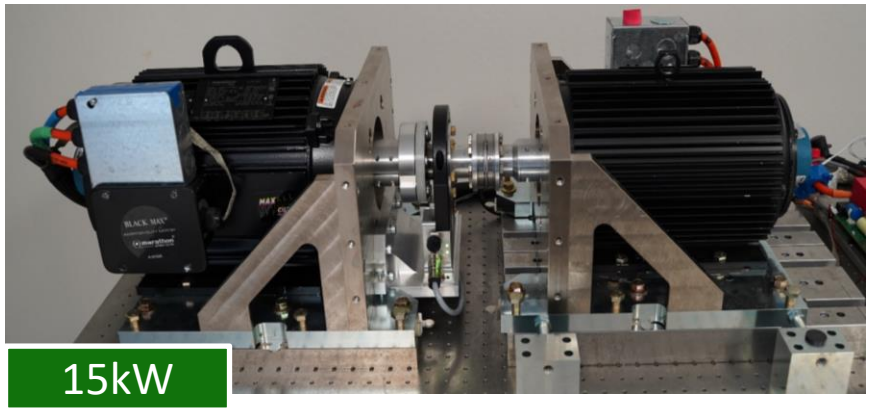


Changing torque modulation frequency randomly between 4 Hz and 40 Hz

Phase shifting and frequency changing are effective to lower and spread the vibration frequency

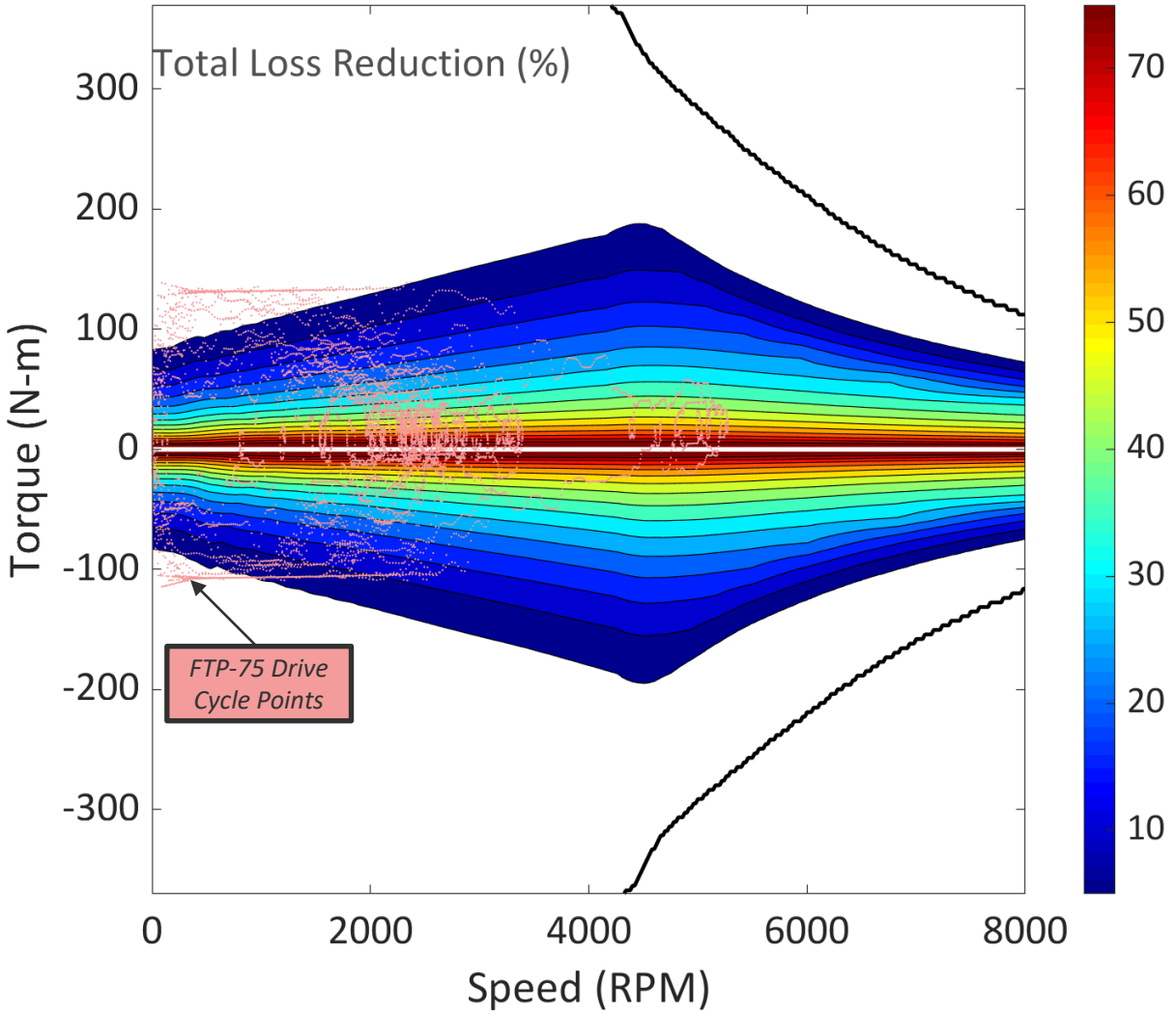
Test Results of Efficiency Improvement of 15kW SynRM

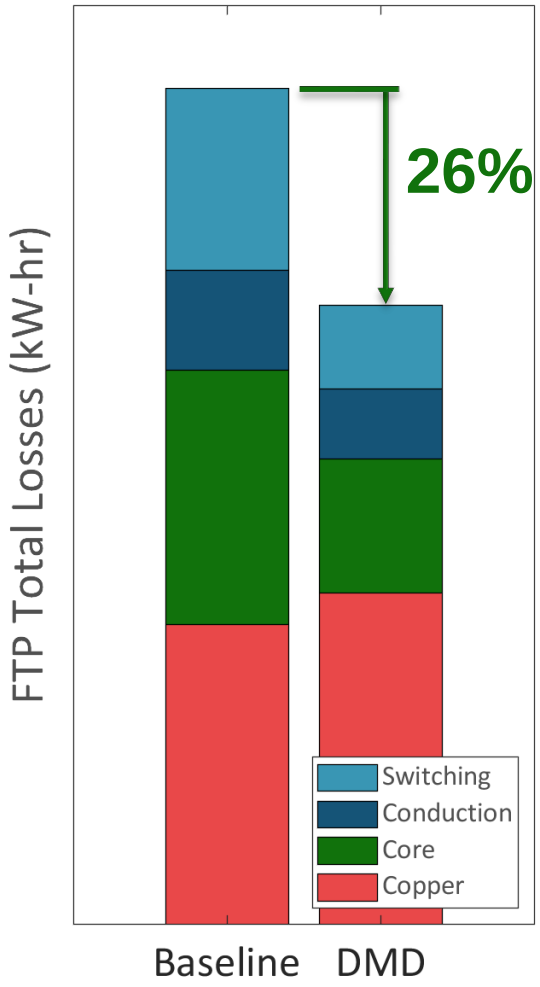




- Up to 7% efficiency improvement is verified at low loads with initial controller
- Advanced controller is under developing to narrow the gap to ideal values

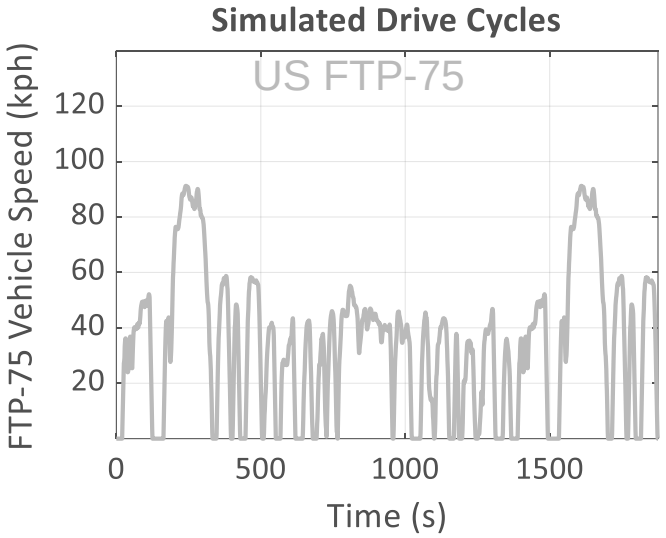
Simulation Results on Efficiency Improvement

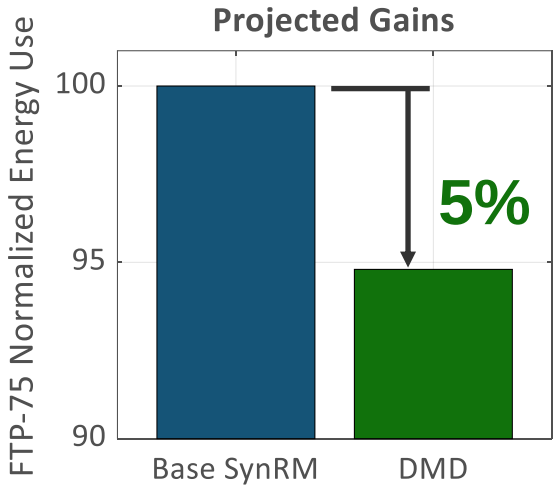


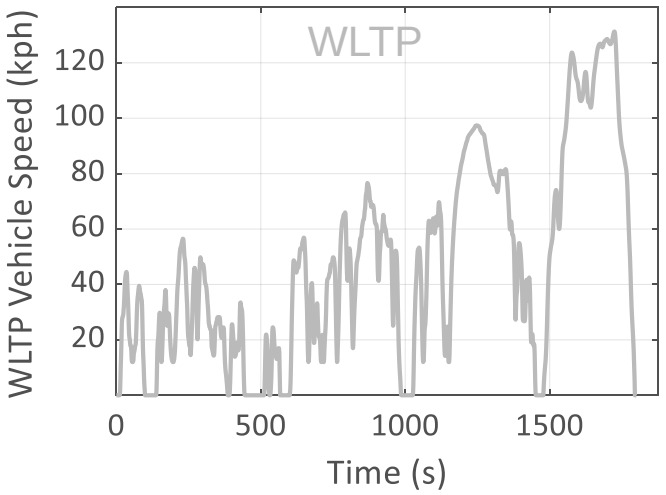


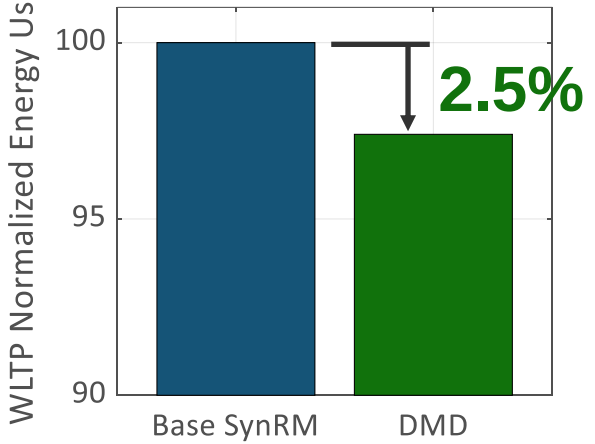
Drive cycle losses are reduced by 26%

Simulation Results on Efficiency Improvement



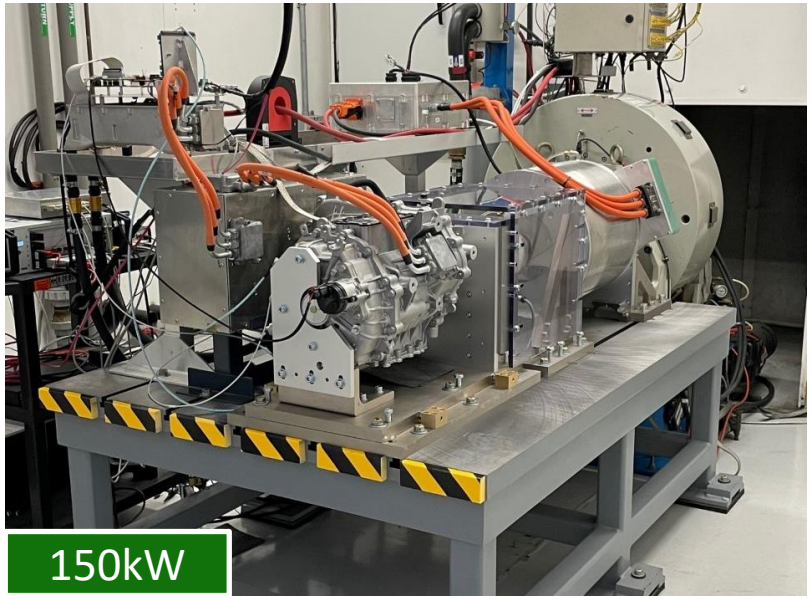






Substantial energy usage reduction of 2.5-5% for a 150kW application

Future Plan on Full-Sized Traction Motor Test



150kW

Our 150kW vehicle traction-motor development dyno is now operable and collecting initial data

We have implemented control on two demonstration Bolts

DMD Enables Better Efficiency

- Dynamic Motor Drive is a control strategy optimizing motor and inverter system efficiency
- It requires no additional hardware and is easy to implement in software with IP licensed from Tula
- Significant efficiency improvements on relevant drive cycles are achieved, helping to reduce or eliminate rare earth material dependence and downsize the battery capacity required
- The strategy makes use of a very fast response speed of the proposed current controller to realize optimal efficiency at both steady and transient states
- Vibration issues can be mitigated by using industry-proven techniques developed with Tula's Dynamic Skip Fire technology