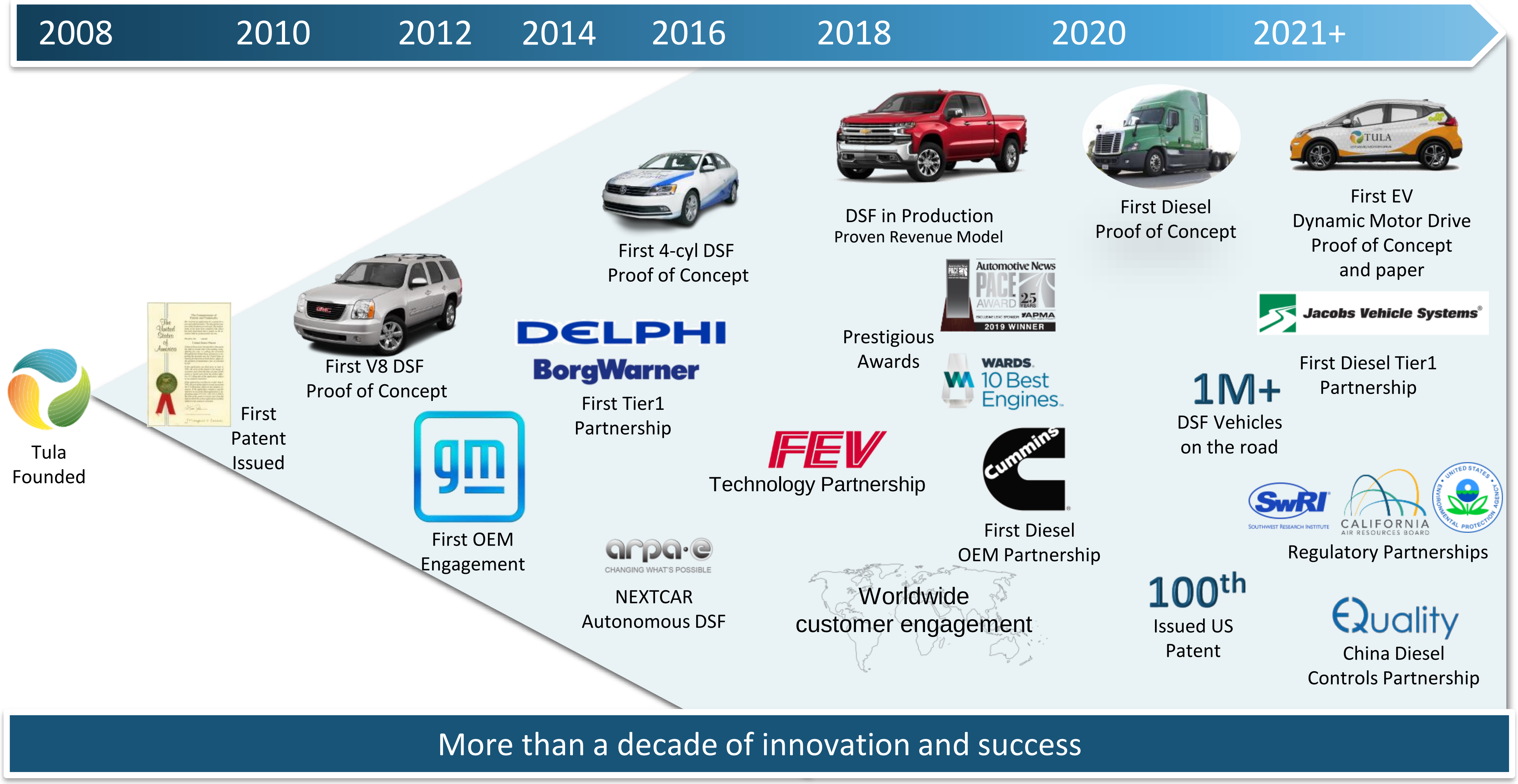

TULA

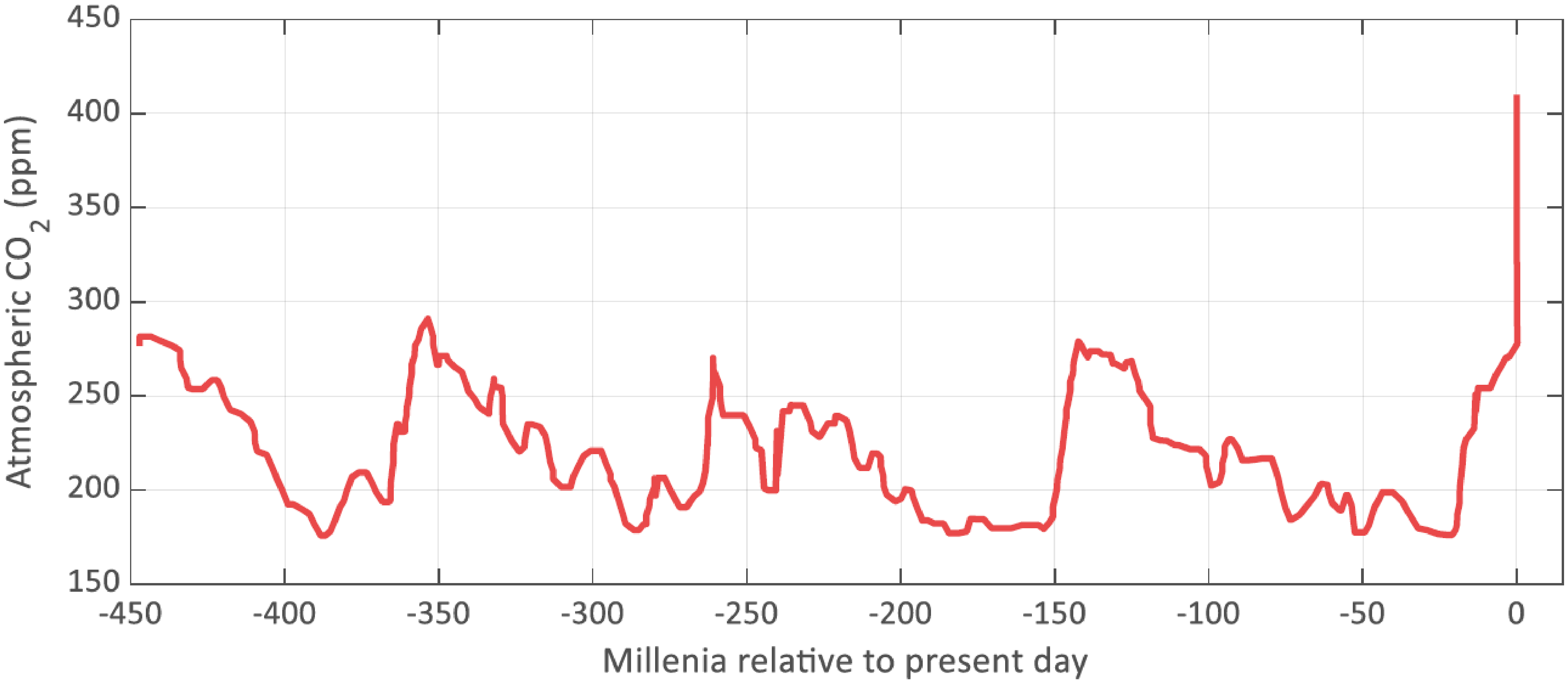
# OPTIMIZING ELECTRIC MOTOR CONTROLS WITH DYNAMIC MOTOR DRIVE

TULA TECHNOLOGY

# Tula - Driving Towards the Future

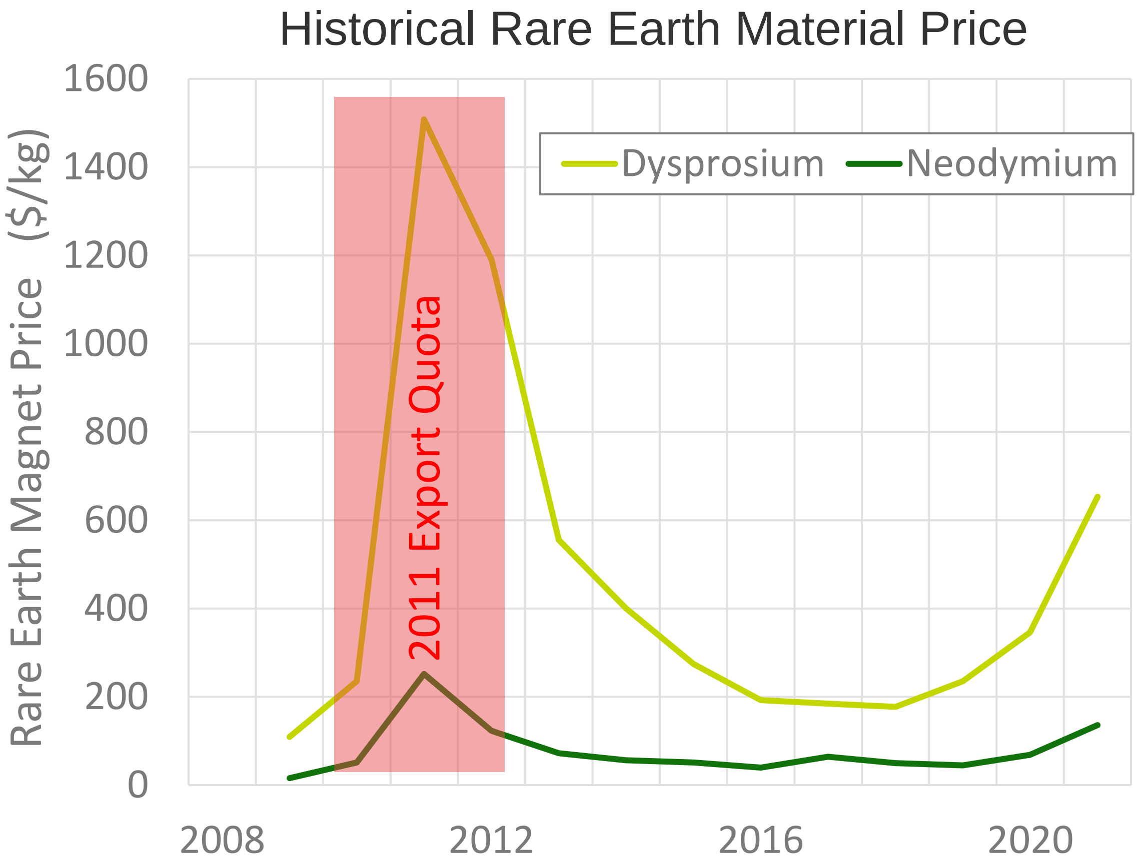


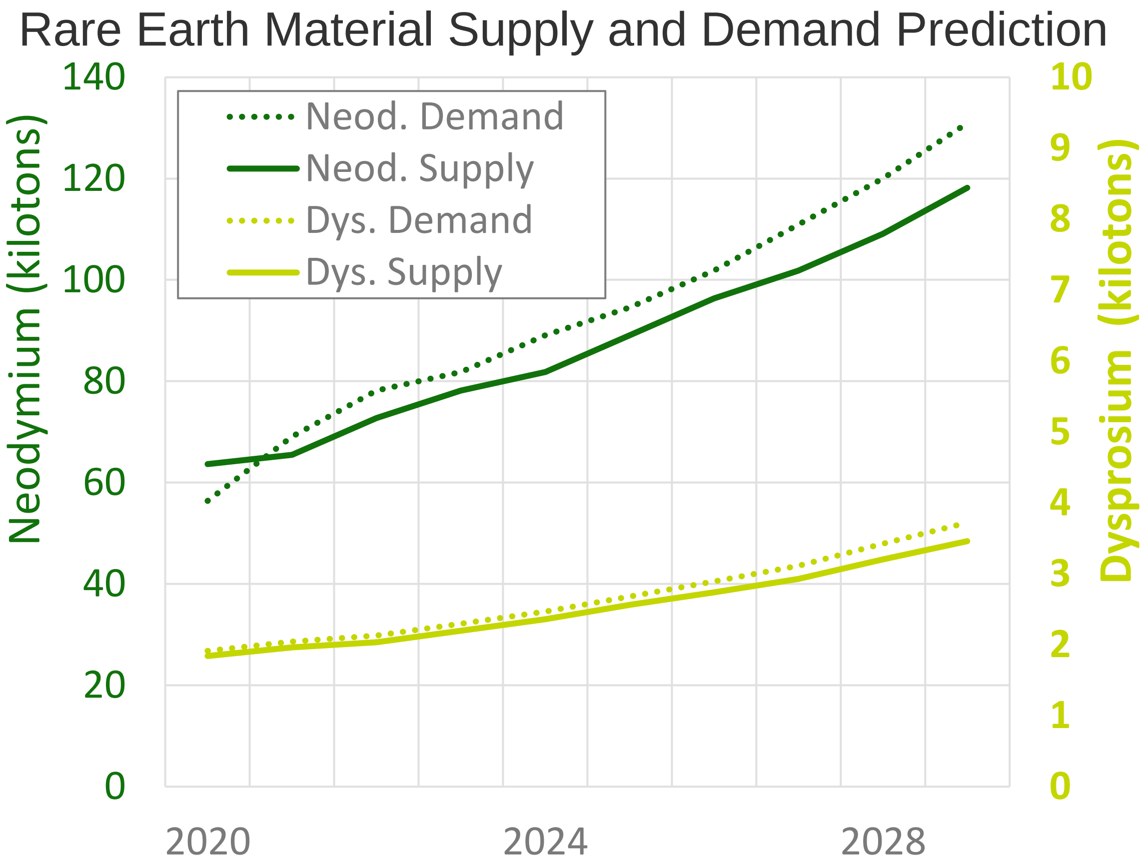
# Challenges of Climate Change




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

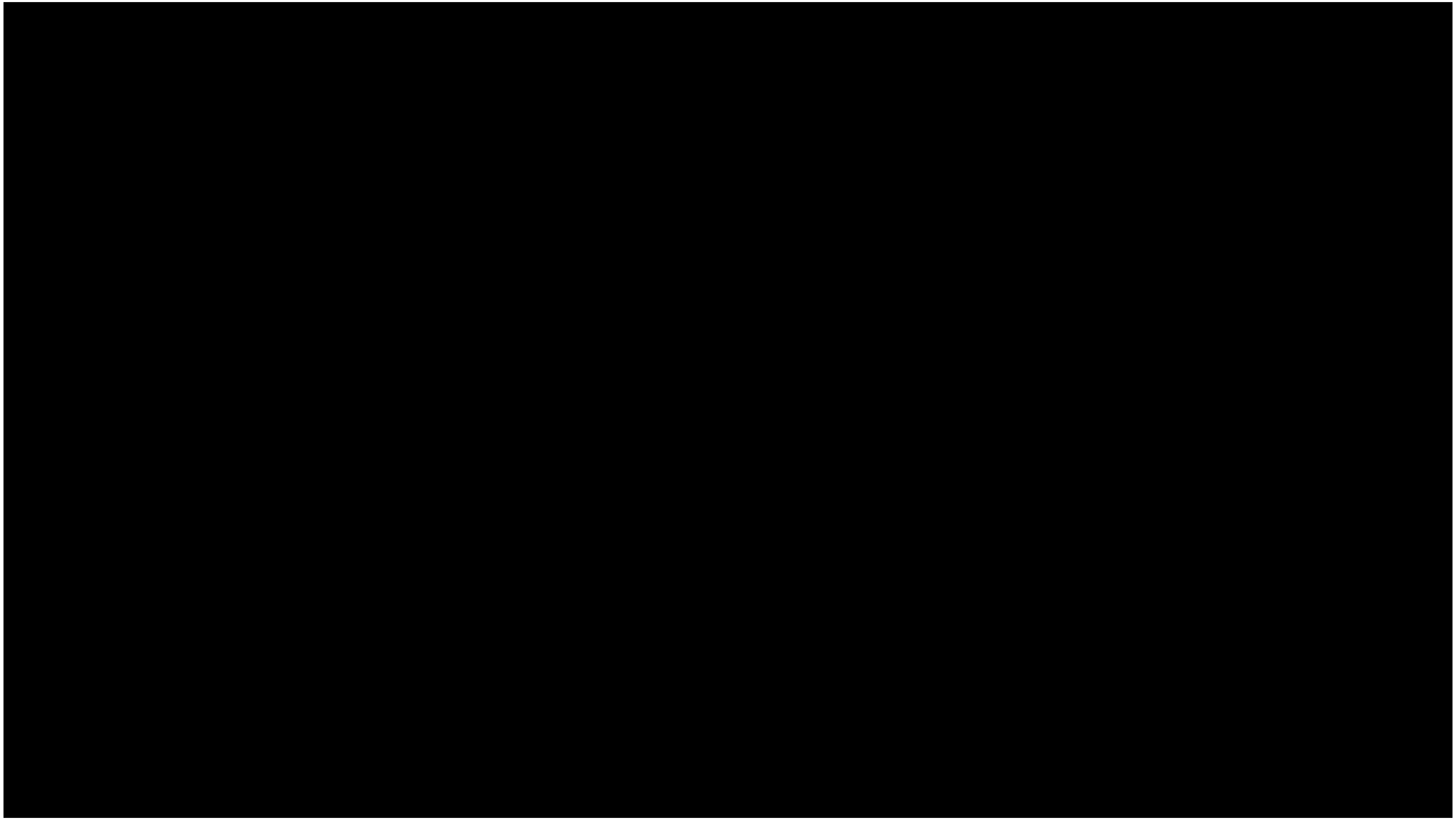
# Conventional Solutions Rely on Rare Materials




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

# Dynamic Motor Drive (DMD) – The Concept



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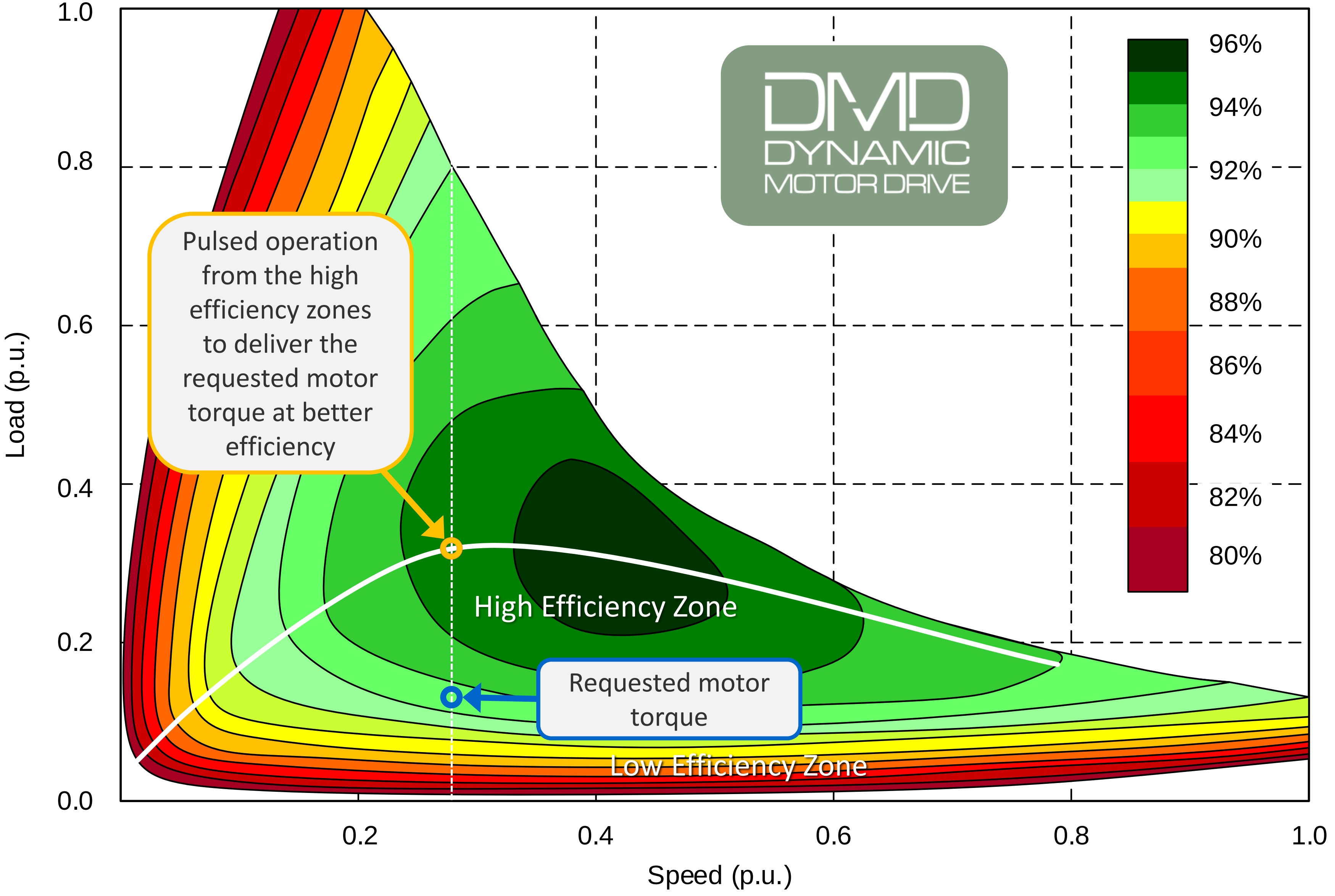
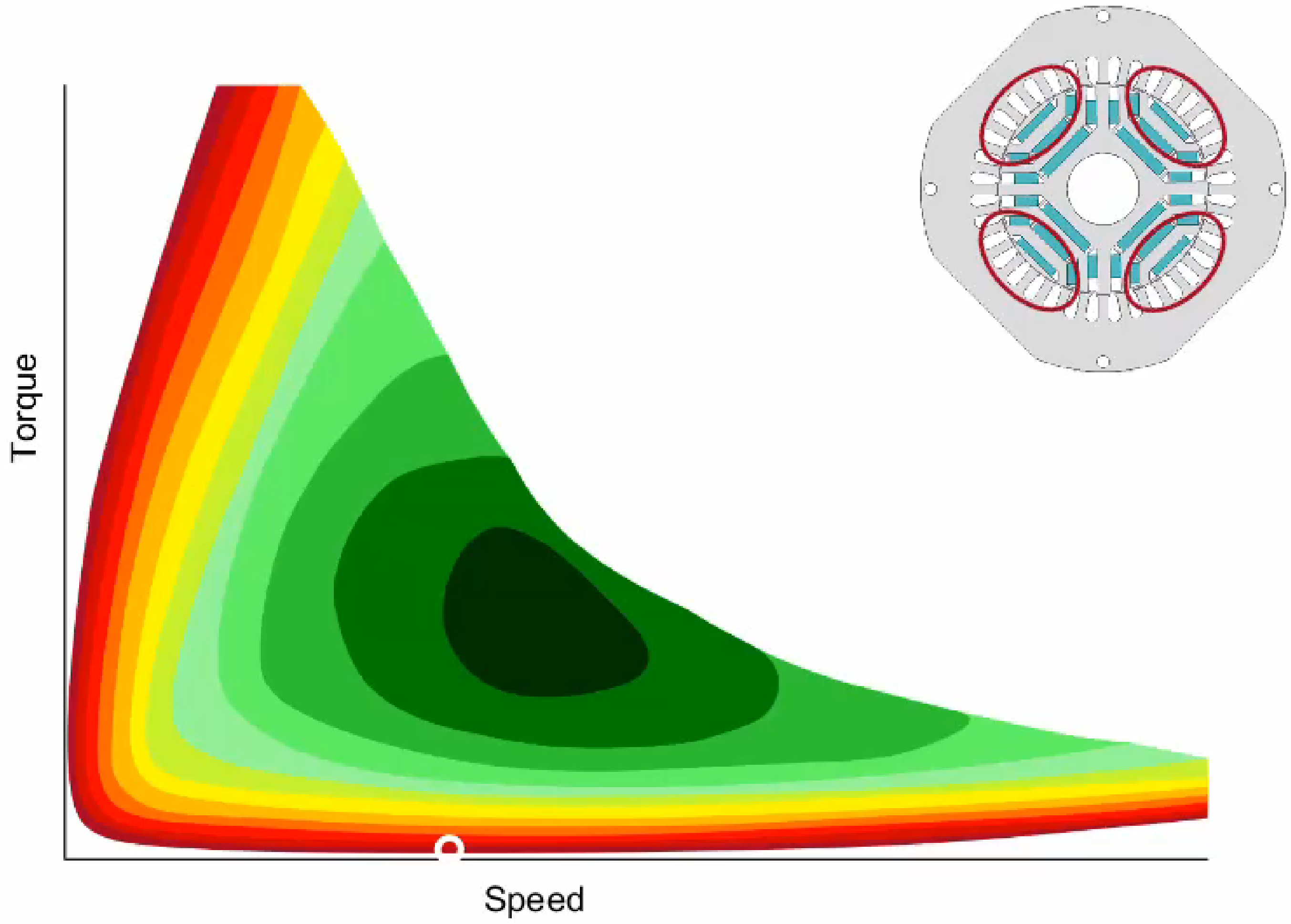
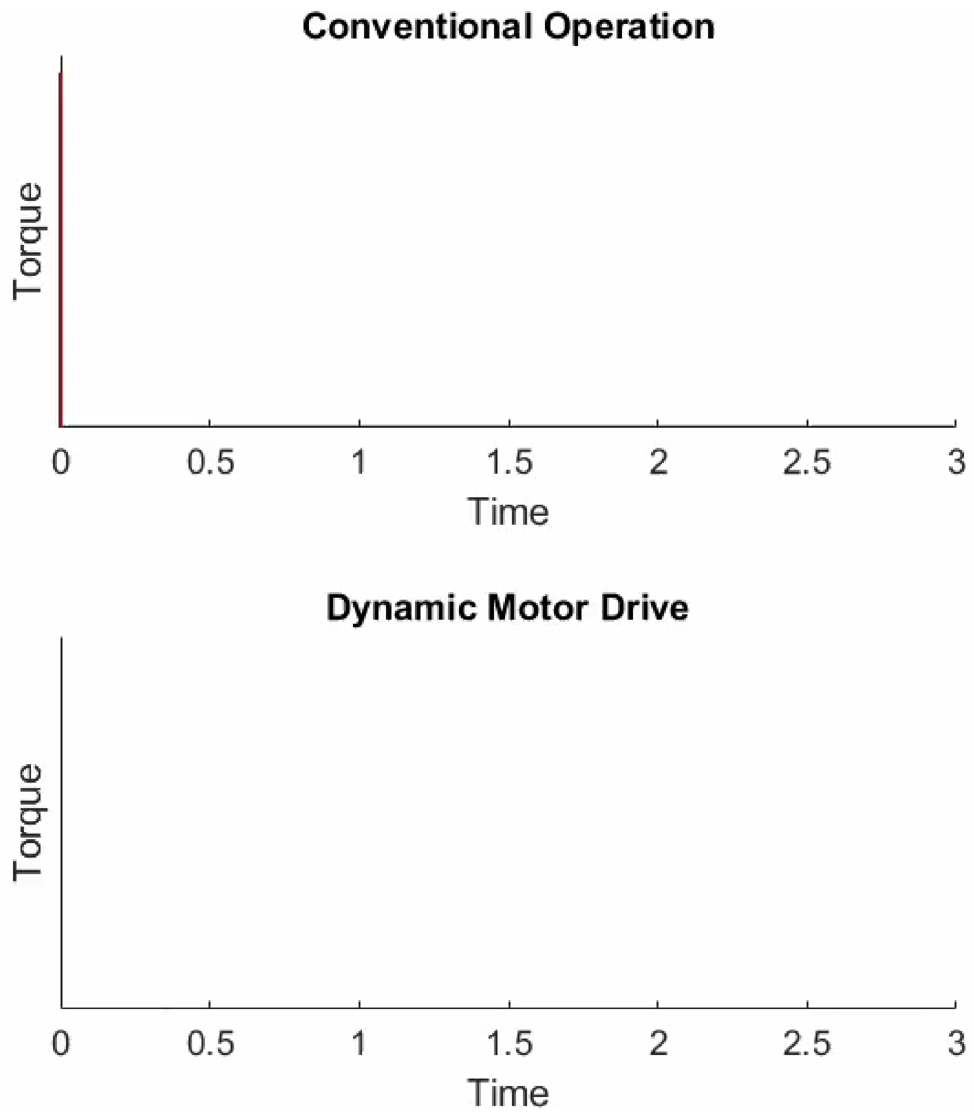
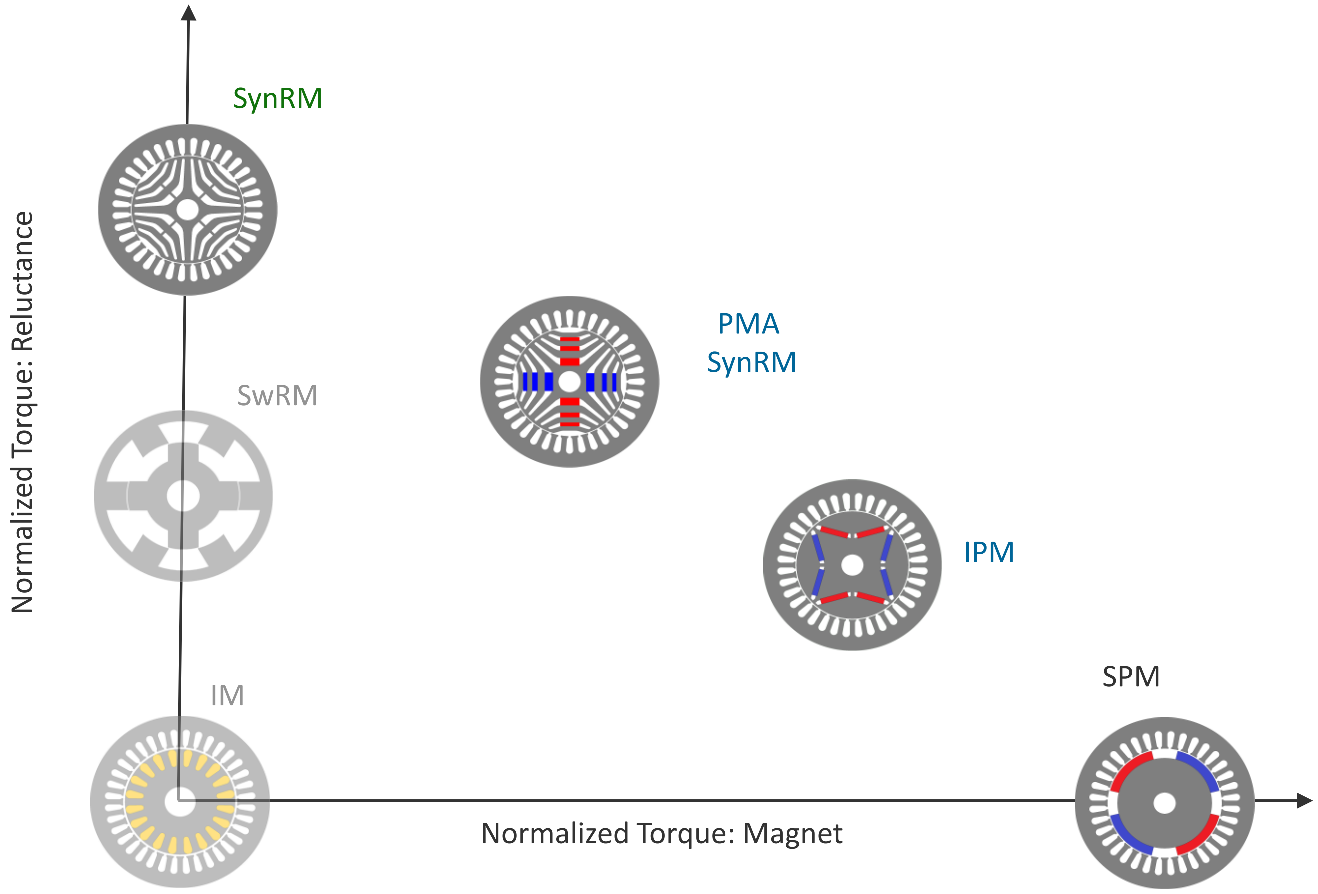


# Dynamic Motor Drive (DMD) – The Concept



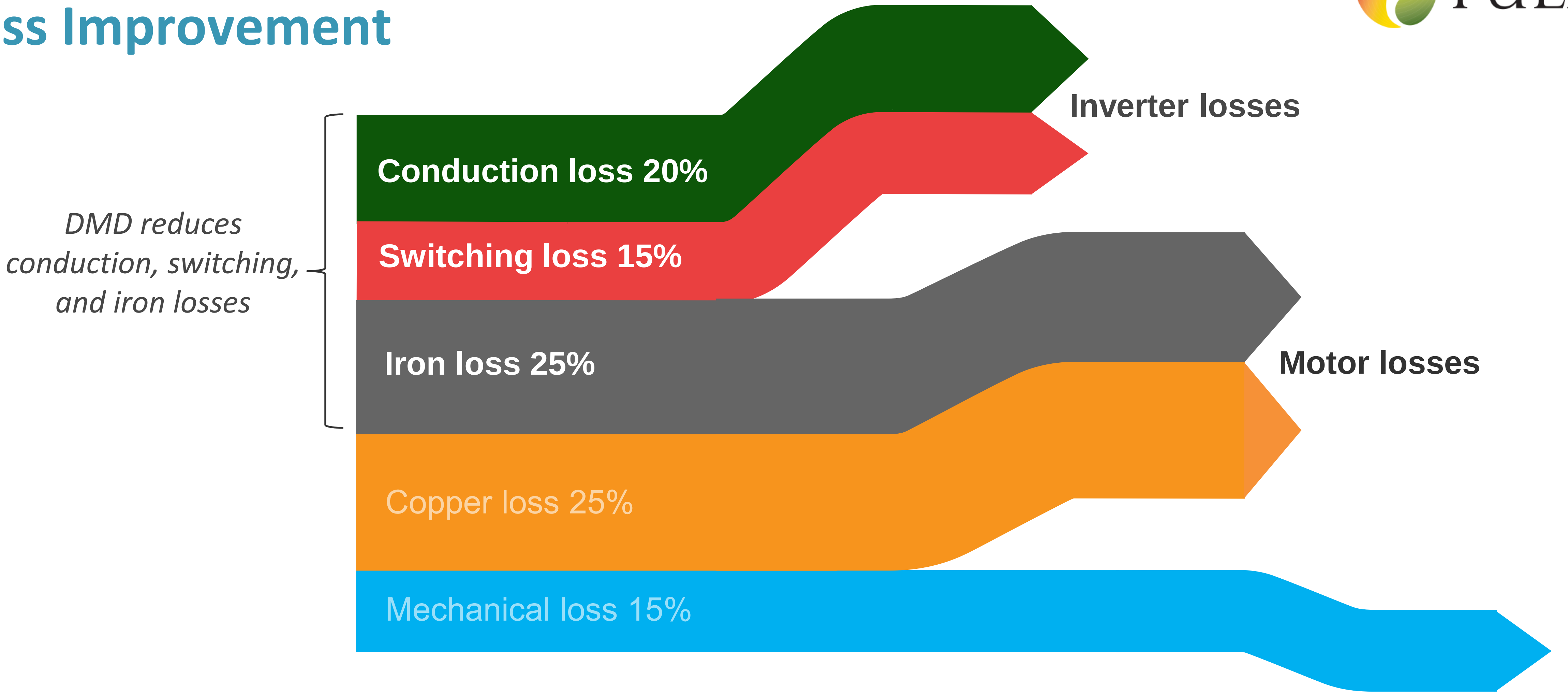



# DMD Motor Architecture Selection



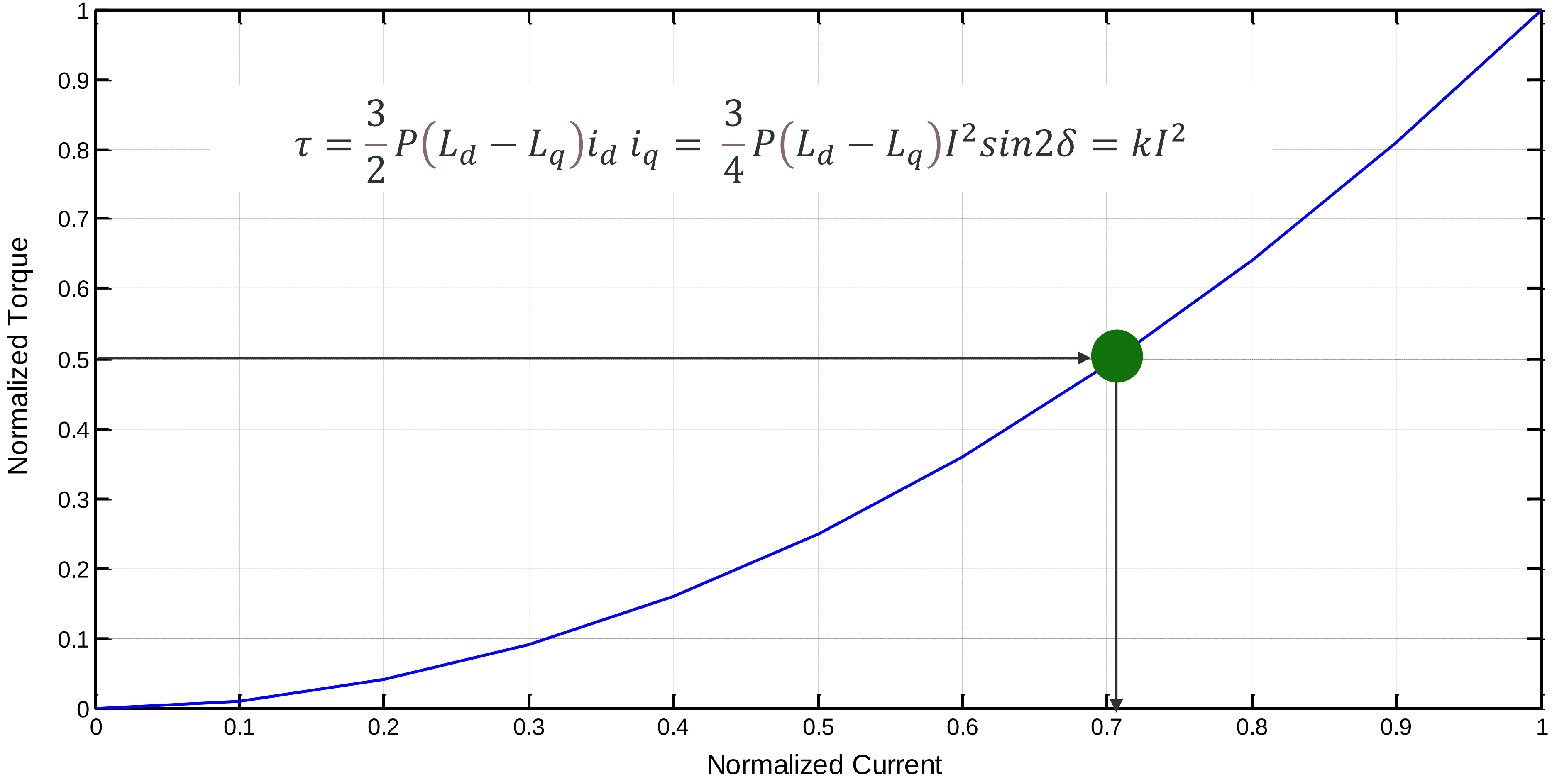

DMD is most effective for Synchronous Reluctance Motors (SynRM)

# Loss Improvement




Optimizing these losses improves reluctance motor efficiency significantly

# Torque Production of Synchronous Reluctance Motor




$$\tau = \frac{3}{2}P\left(L_d - L_q\right)i_d\, i_q = \frac{3}{4}P\left(L_d - L_q\right)I^2 sin2\delta = kI^2$$

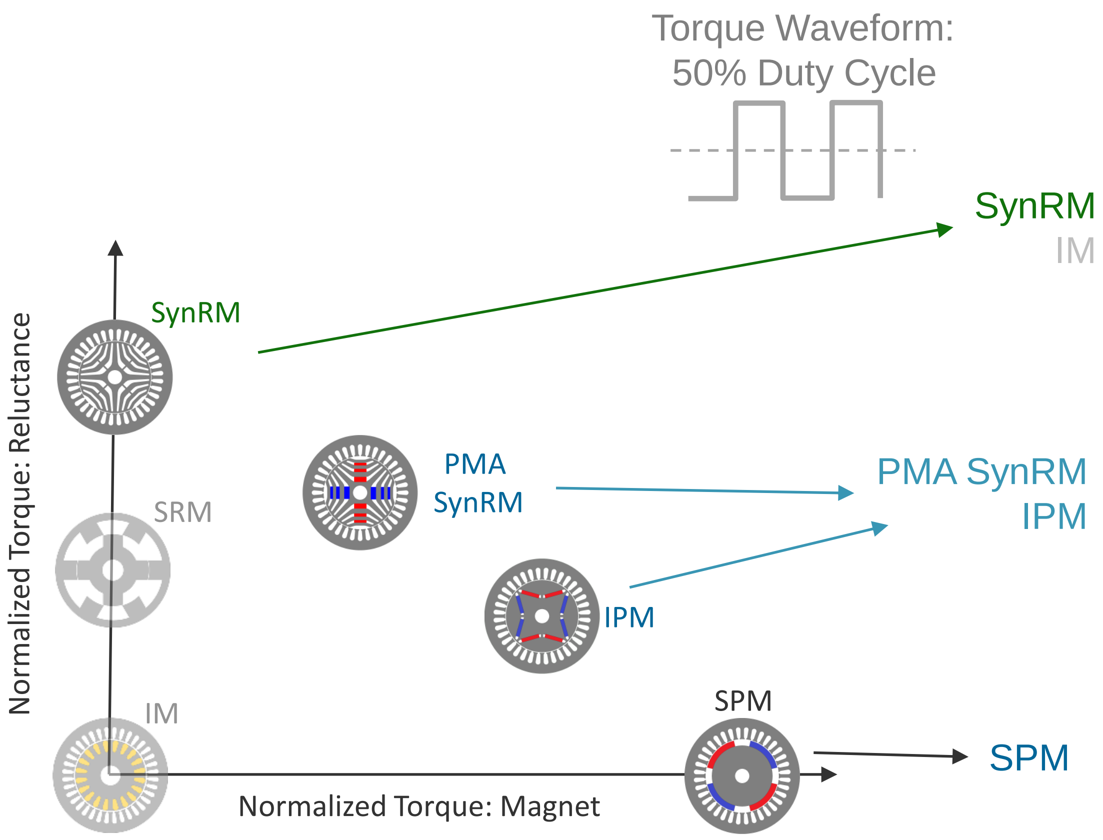
Torque is proportional to current$^2$ for SynRM's at moderate loads

# 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

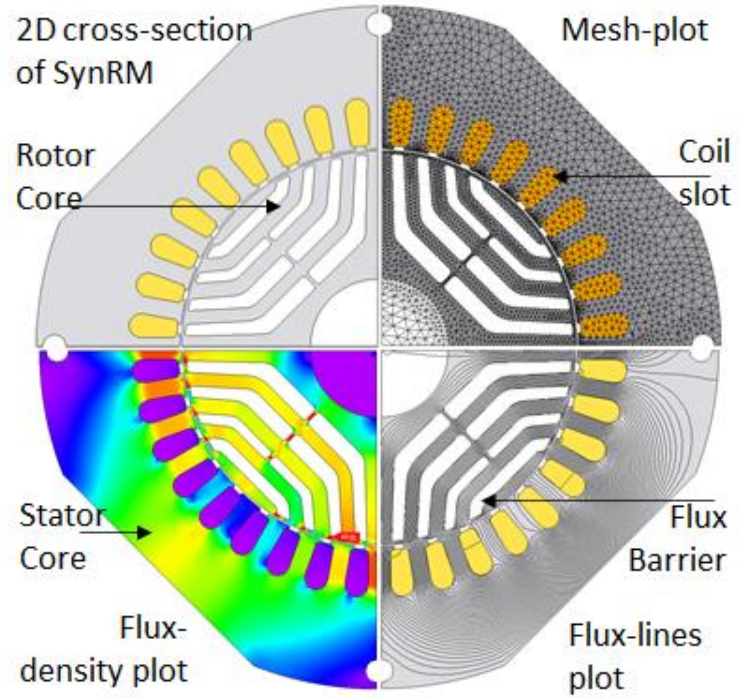


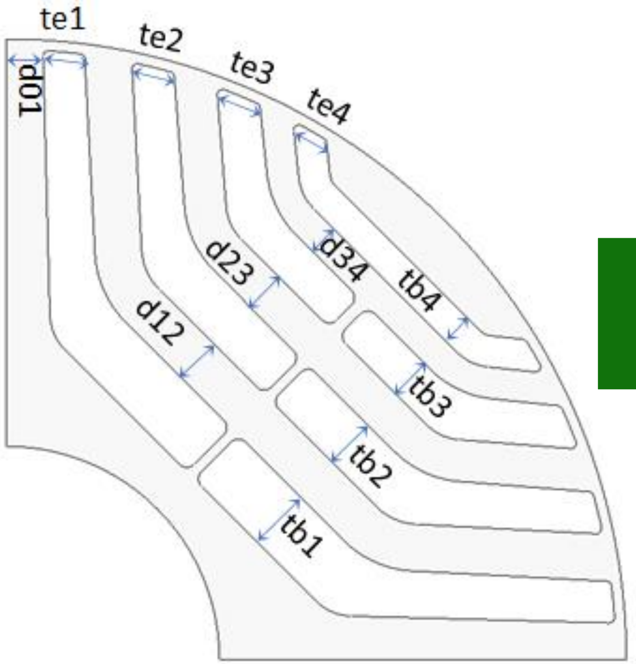

| Current for 50% Duty Cycle | Losses: $I^2$ | Losses: I | Losses: Total | Impact of DMD |
|---|---|---|---|---|
| 1.4x | 1x + | 0.7x = | | Reduced Losses |
| 1.4x – 2x | 1x-2x + | 0.7x-1x = | | Implementation Specific |
| 2x | 2x + | 1x = | | Increased Losses |

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

# Tula Designed SynRM

No permanent magnets

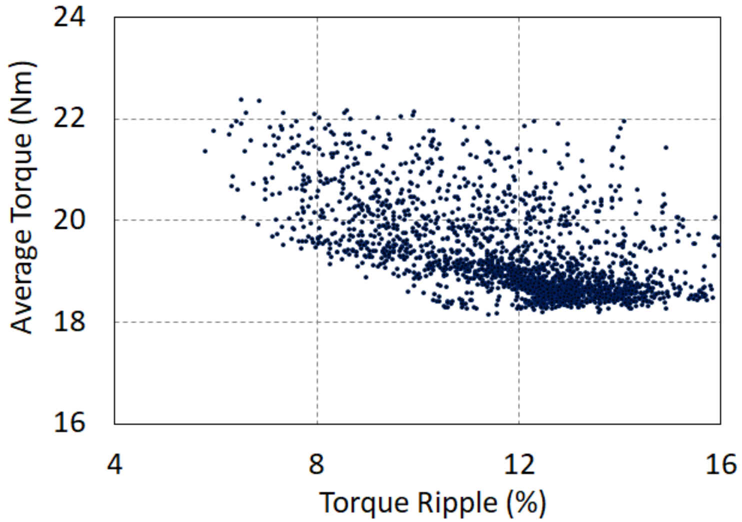


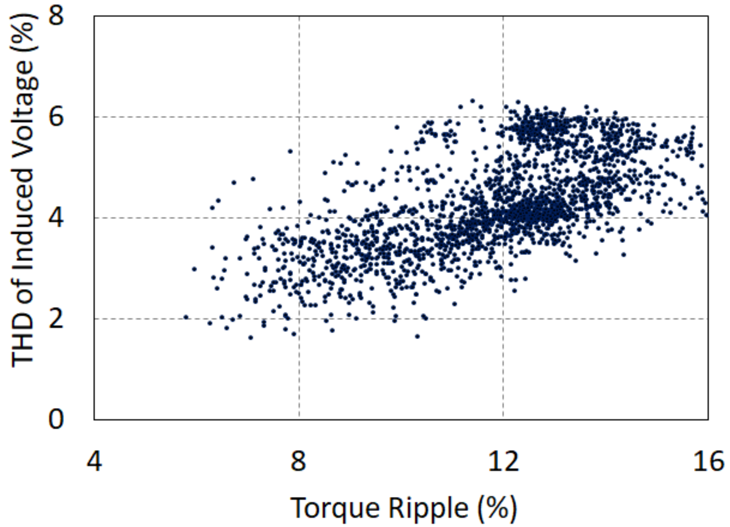




Flux barriers increase torque production

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

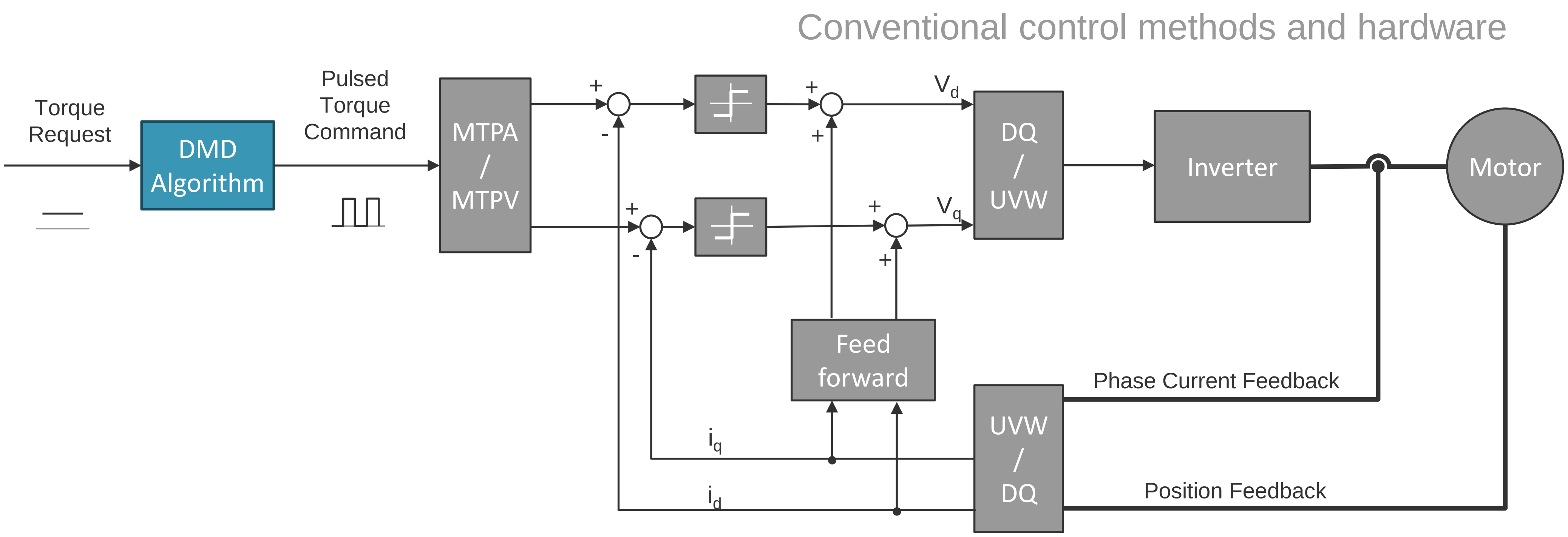
# Synchronous Reluctance Motor (SynRM) Design




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

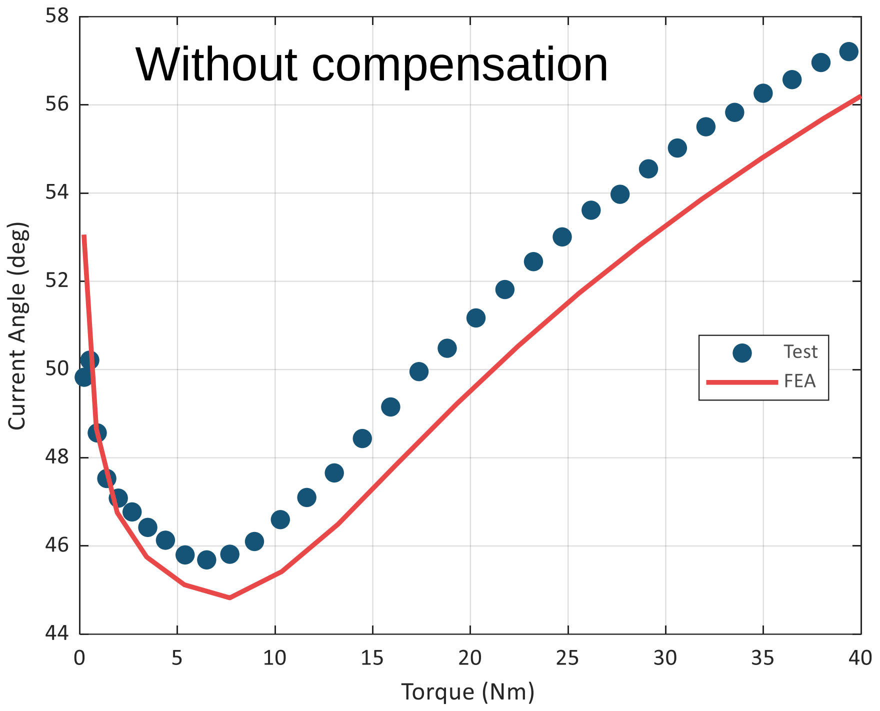


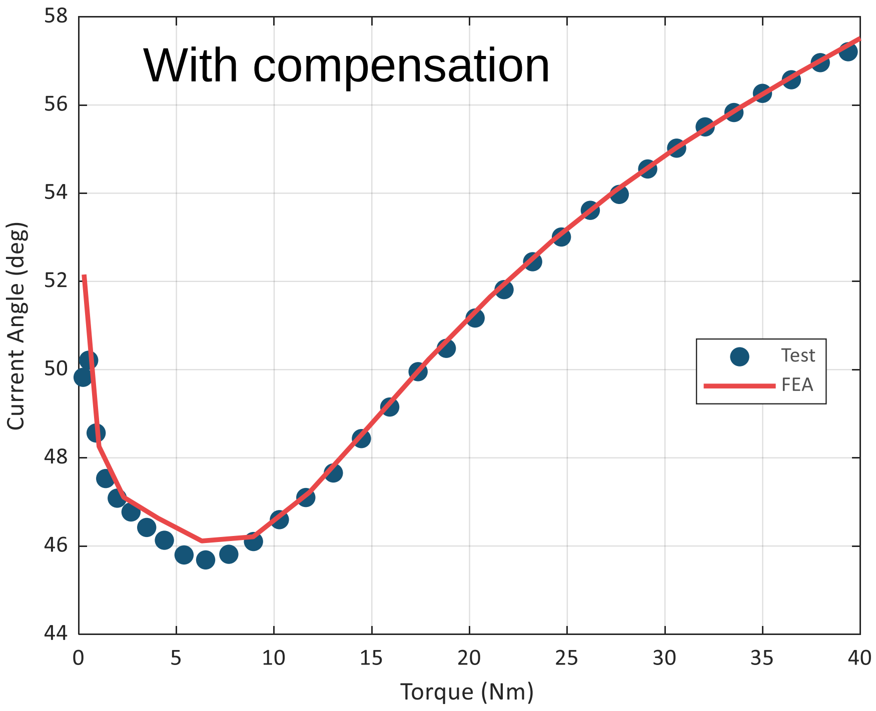

Tula's DMD algorithms were developed to allow implementation with conventional control algorithms

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

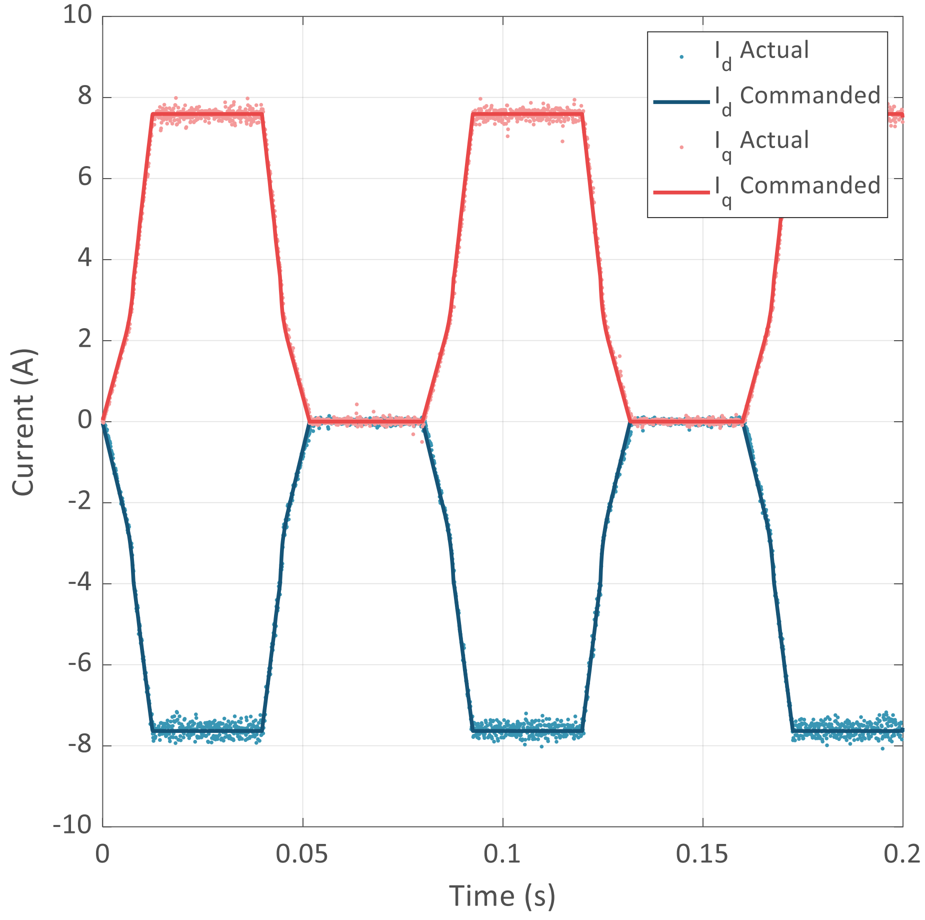
# Torque Control Law

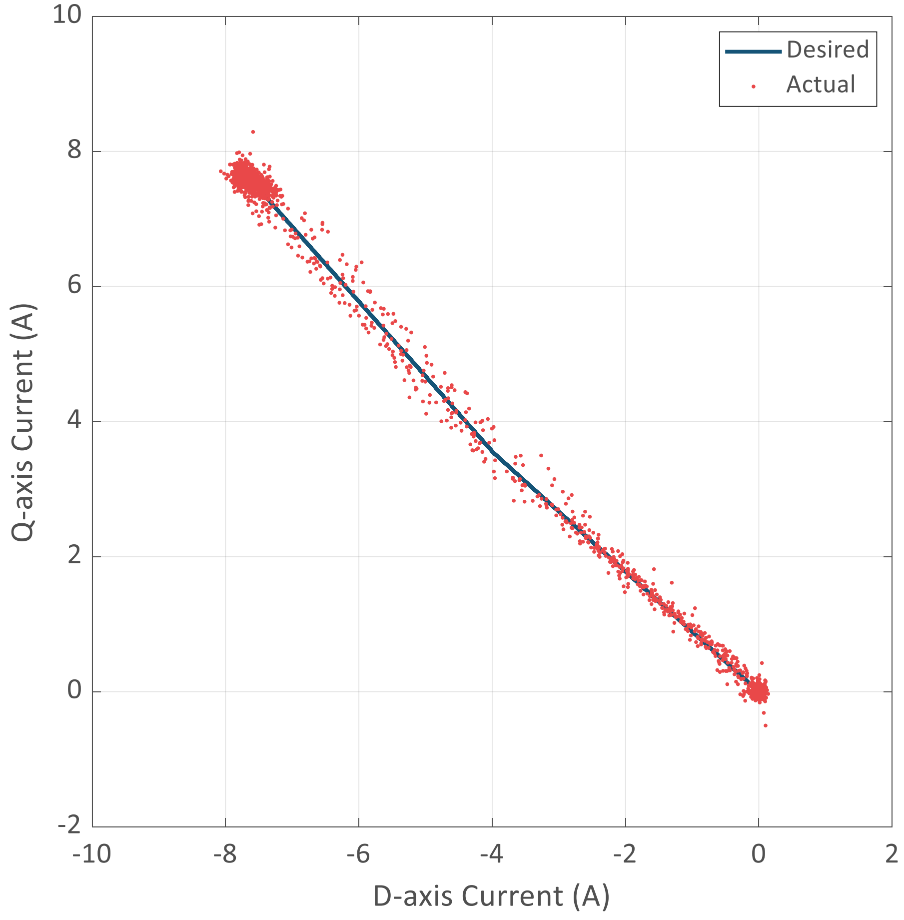
- Max torque per Ampere (MTPA) curve generated from Finite Element Analysis has around 1º error from test results
- This inaccuracy is corrected by compensating the iron loss model



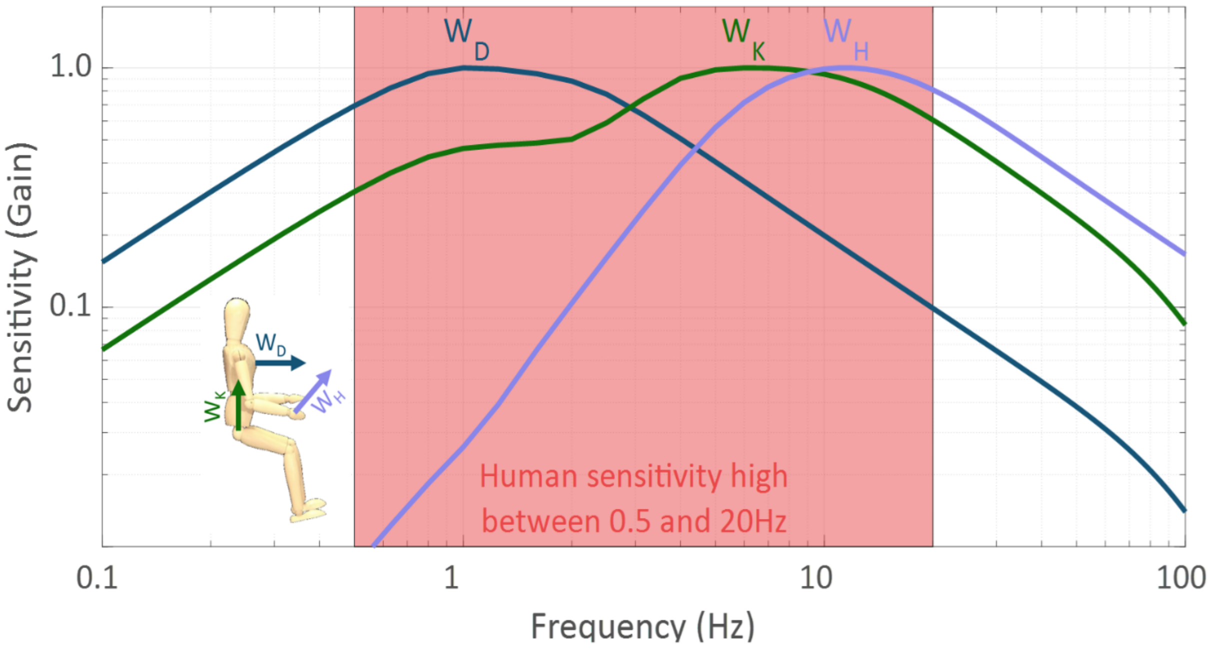
# Current Control Achieving Desired Response Speed

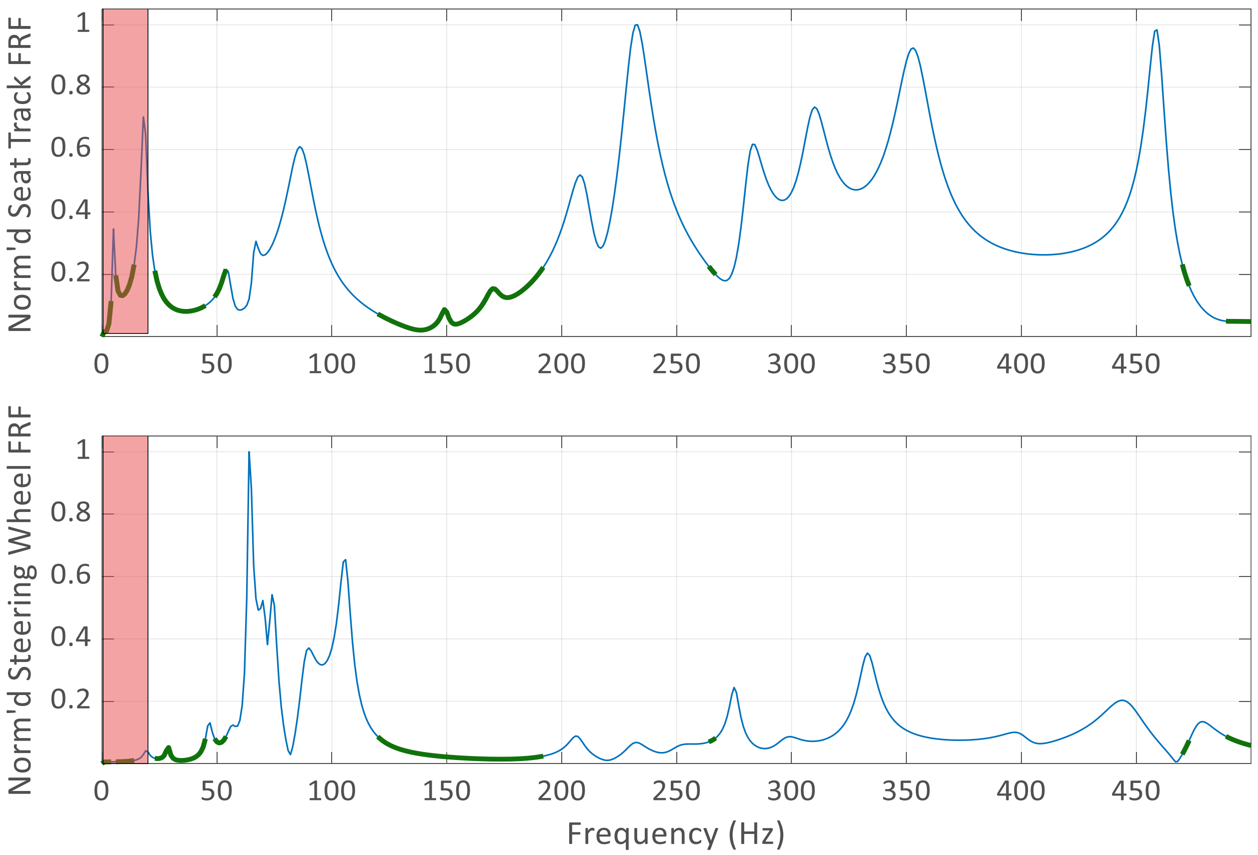



**Excellent current tracking realized by deadbeat control**

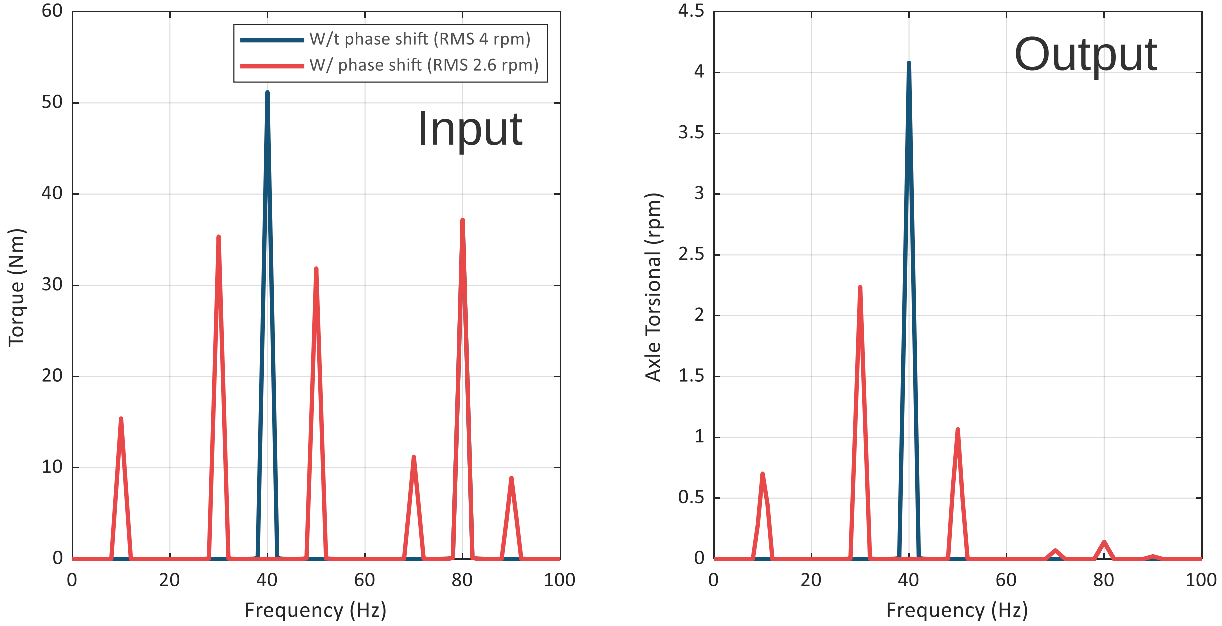
# Vehicle Sensitivity and Human Perception



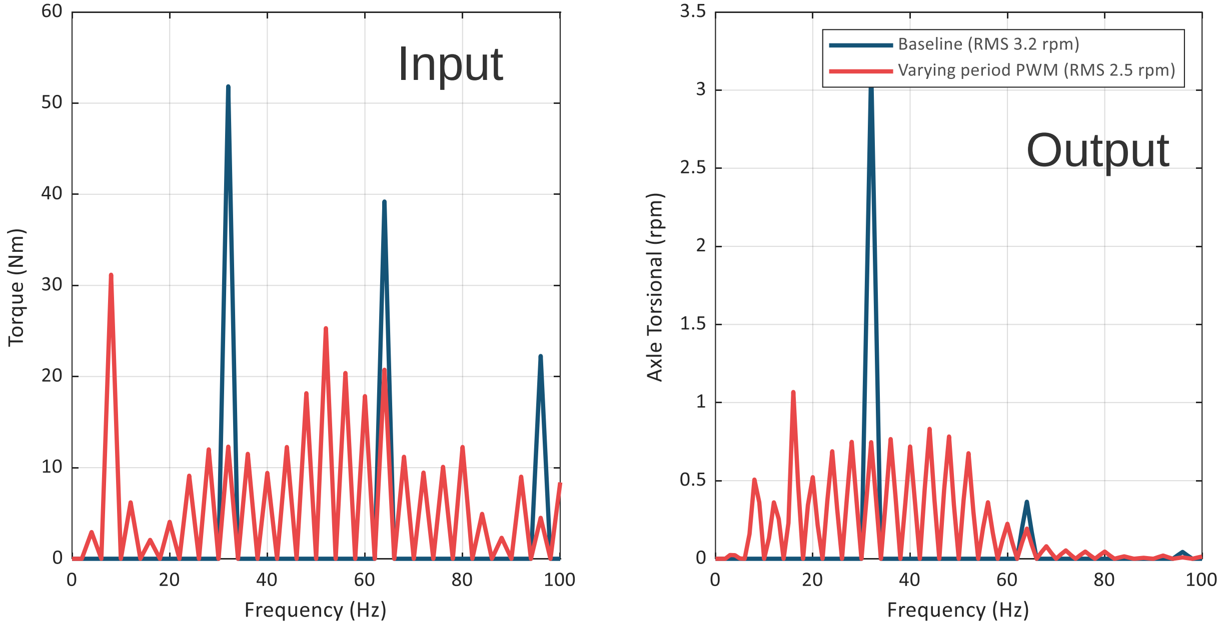




Torque modulation frequency selected has less human sensitivity

# Vibration Mitigation Strategies



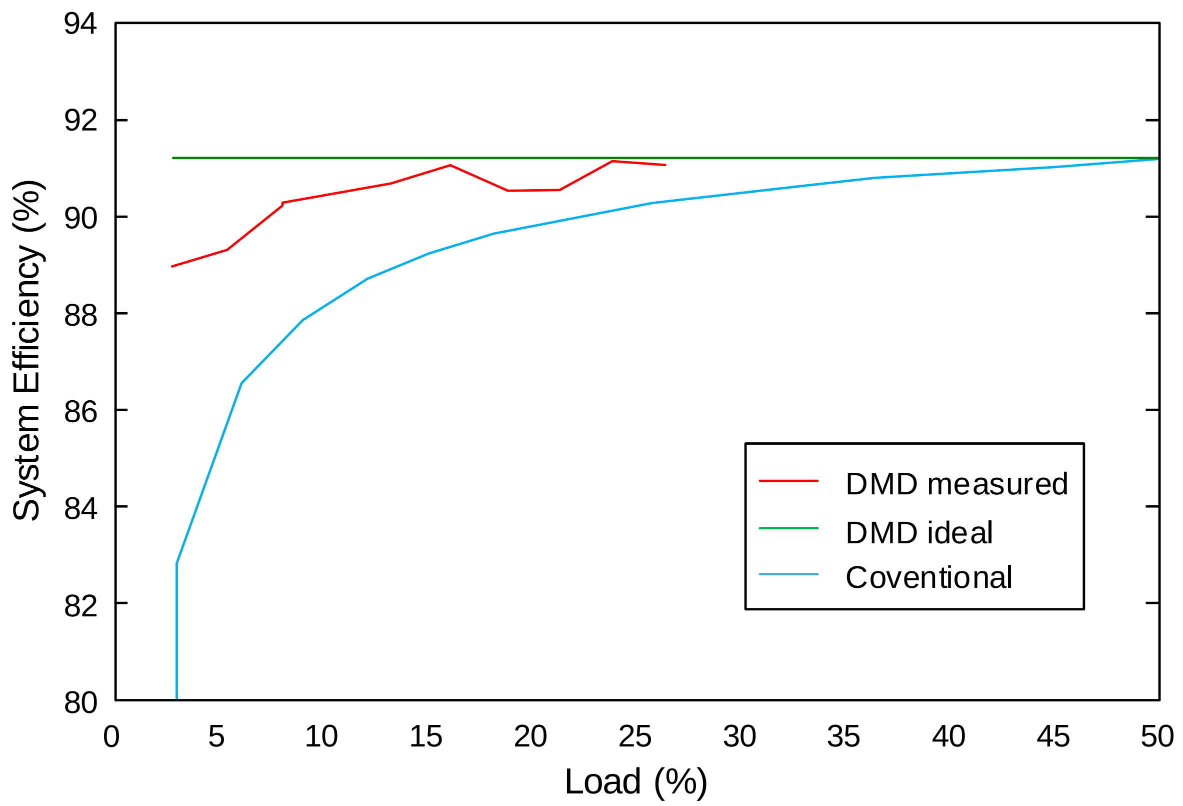

Switching modulation waveform phase between 0 and 180 degrees every 3 cycles

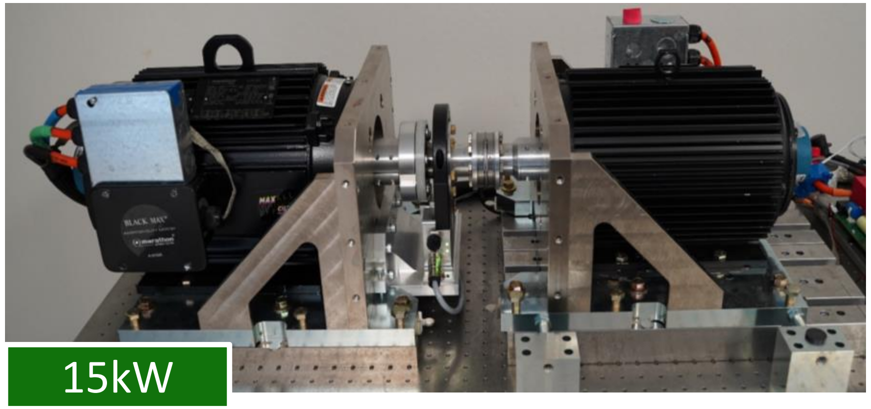



Changing torque modulation frequency randomly between 4 Hz and 40 Hz

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

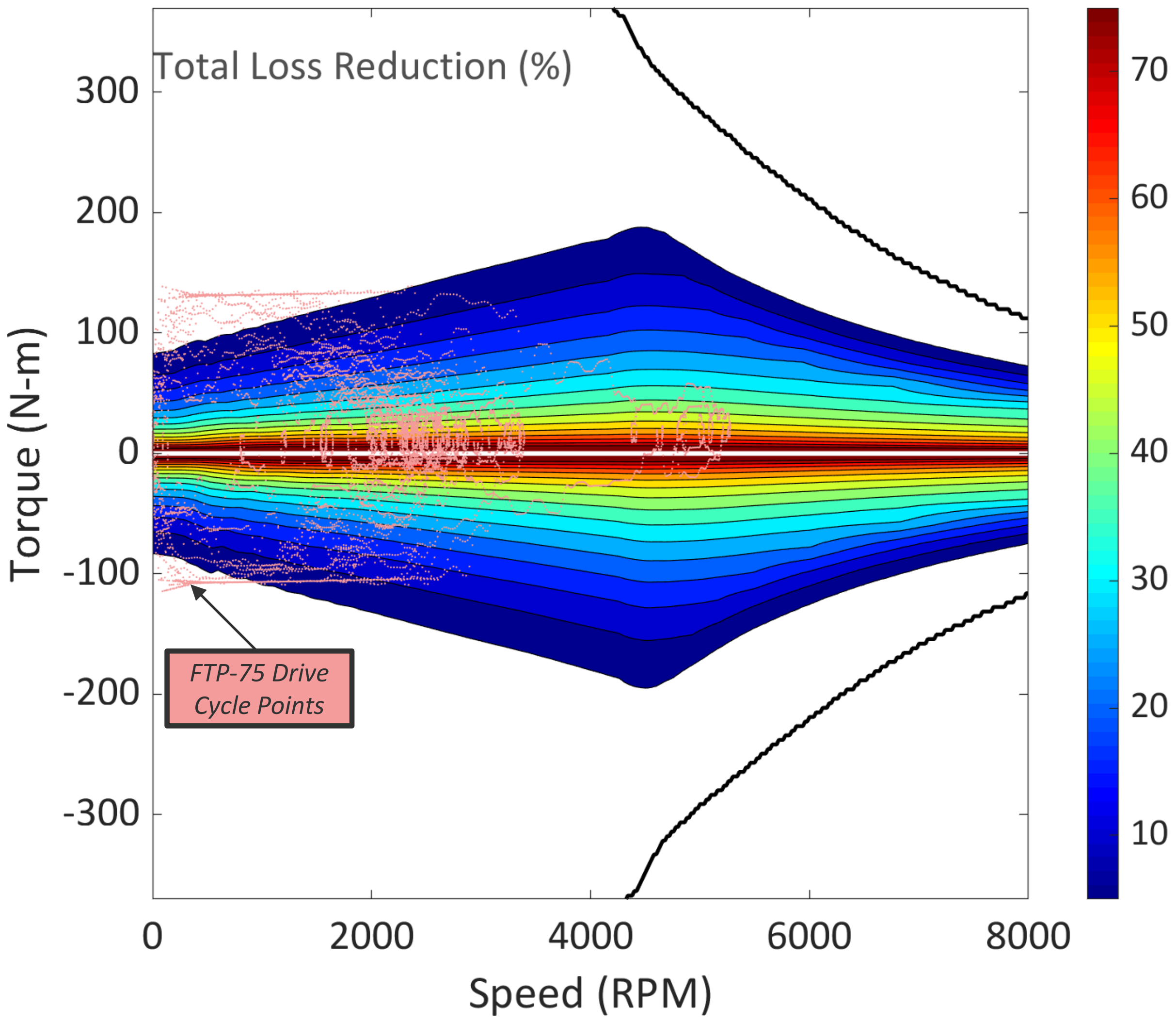
# Test Results of Efficiency Improvement of 15kW SynRM

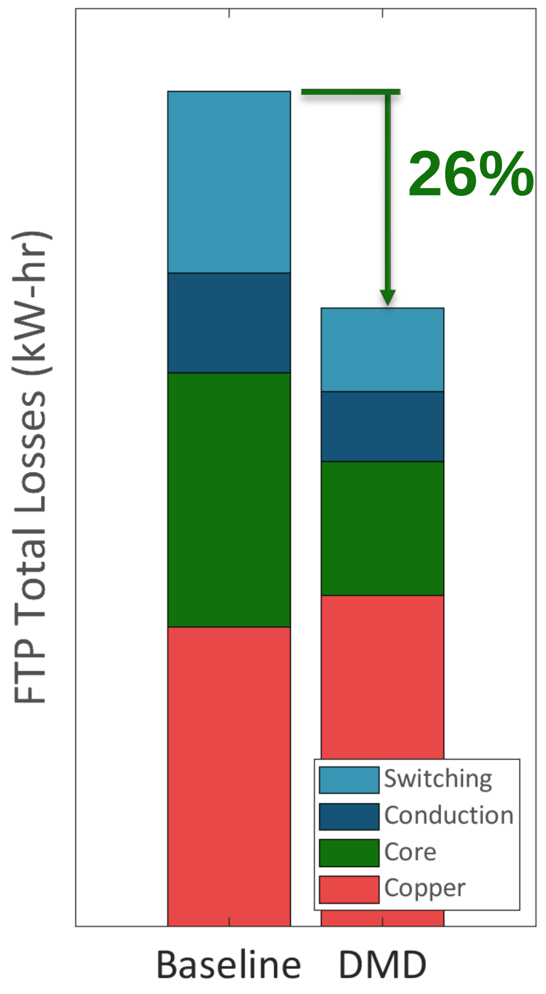



- Up to 7% efficiency improvement is verified at low loads with initial controller
- Advanced controller is under developing to narrow the gap to ideal values

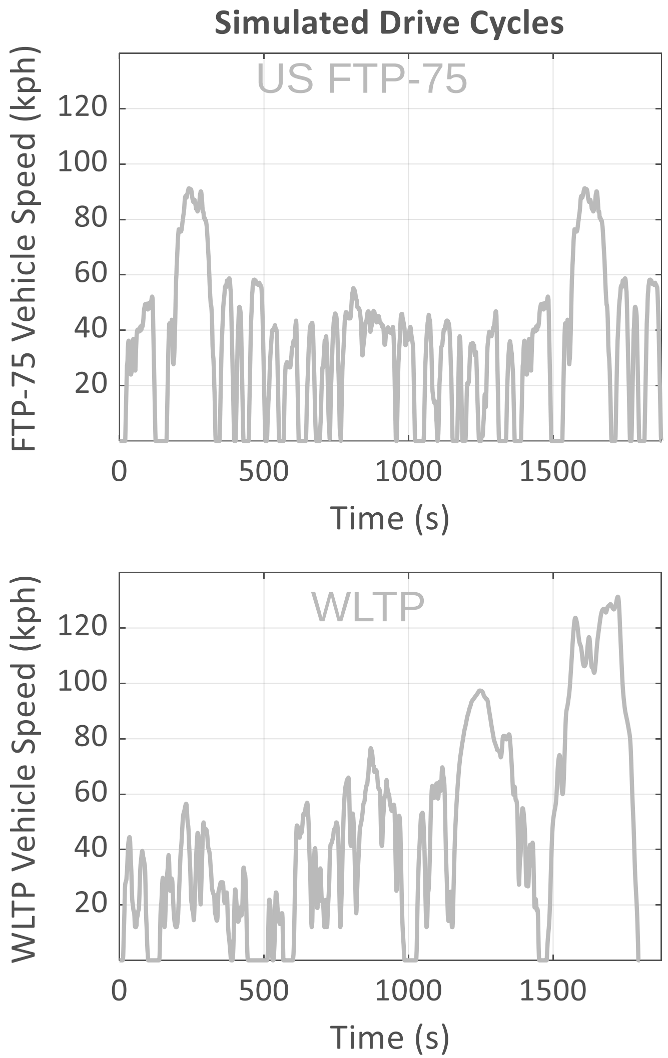
# Simulation Results on Efficiency Improvement

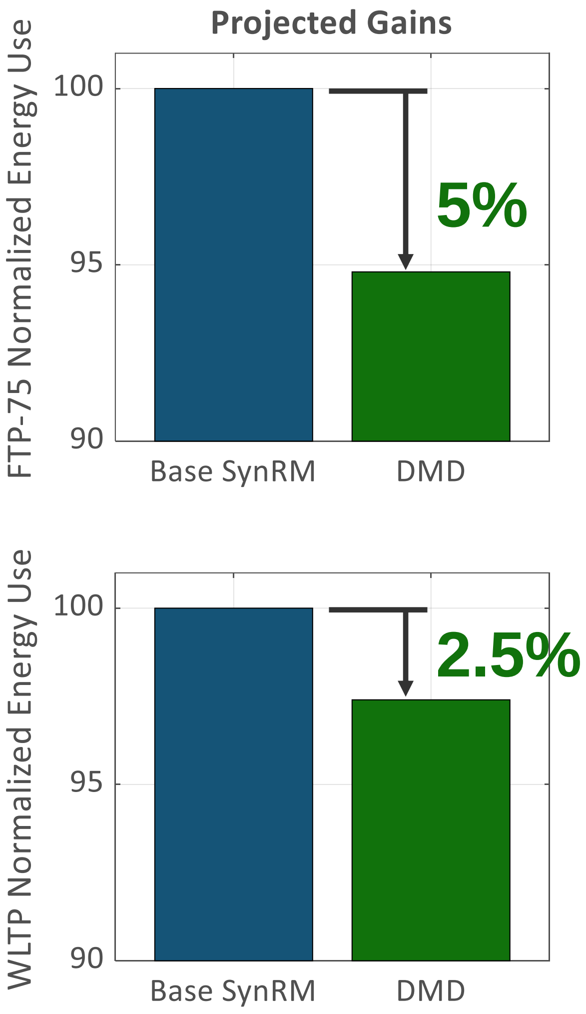



Drive cycle losses are reduced by 26%

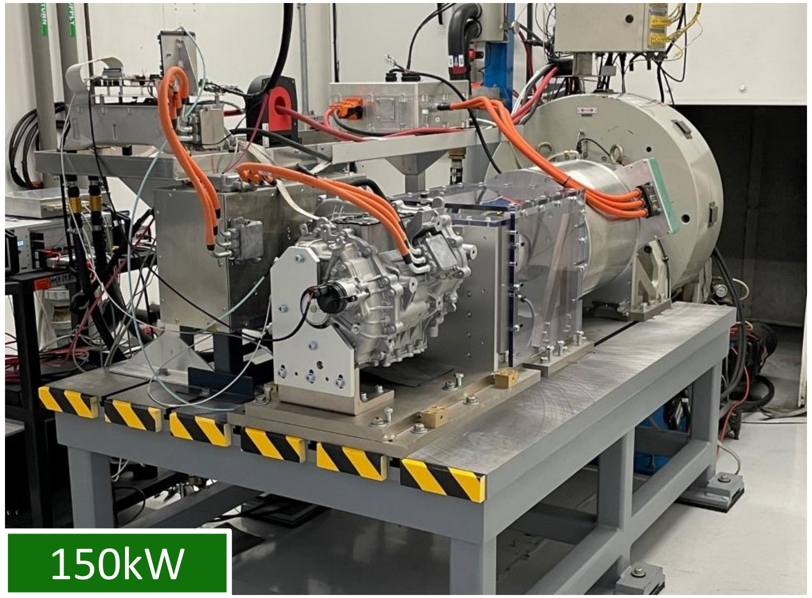
# Simulation Results on Efficiency Improvement




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

# Future Plan on Full-Sized Traction Motor Test




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