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Dynamic Motor Drive: Optimizing Electric Motor Controls to Improve Efficiency

Dynamic Motor Drive: Optimierung der Steuerung von Elektromotoren zur Verbesserung der Effizienz

Abstract

Electrification of transportation cuts reliance on fossil fuels, mitigates climate change, and eliminates tailpipe emissions. Given that the amount and cost of energy consumed by electric vehicles will soon rival those of fossil fueled vehicles, the efficiency of electric energy usage will become as critical as that of legacy energy sources.

Improving the efficiency of battery-electric vehicle powertrains is key to improving the viability of this solution. Although the peak efficiencies of electric motors equipped with rare earth magnets exceed 90%, practical drive cycles and powertrain architectures frequently operate outside of the peak efficiency speed/load region. At 10% of the maximum torque of an electric vehicle, efficiency is more commonly 70-85%. In addition, the most efficient electric motors use magnets with large content of Neodymium or Samarium, both of which are expensive and have limited sources of supply.

Tula's control architecture – called Dynamic Motor Drive (DMD®) – mitigates the light-load efficiency losses of electric motors while simultaneously reducing or eliminating the reliance on rare-earth materials. By using the DMD pulse density strategy for electric motor control, inverter losses and core losses are mitigated. At high loads, experiments have proven efficiency improvements of 2% on induction motors, with more improvements possible at lighter loaded conditions. These gains project to 2.5% efficiency improvement in the WLTP. Those improvements enable reduced battery size and increased range while lowering total energy consumed, and do not require hardware changes to the motor or vehicle.

This work will detail the controls methodology used to achieve those gains, the optimization of motor design for this new control paradigm, and the experimental results of that system in use.

Kurzfassung

Durch die Elektrifizierung des Transportsektors wird die Abhängigkeit von fossilen Kraftstoffen reduziert, die Klimaveränderungen verringert und die Emissionen von Verbrennungsmotoren eliminiert. Zukünftig wird der Wirkungsgrad für die Nutzung der elektrischen Energie an Bedeutung gewinnen. Voraussetzung ist, dass der Energieverbrauch und die damit verbundenen Kosten von Elektrofahrzeugen die gleiche Bedeutung erlangen wird wie bei den fossil angetriebenen Fahrzeugen.

Die Verbesserung des Wirkungsgrades von batteriebetriebenen Elektrofahrzeugen ist entscheidend für deren Machbarkeit. Die maximalen Wirkungsgrade von Elektromotoren mit Seltenerd-Magnetwerkstoffen sind größer als 90 %. Bei ausgeführten Antriebsstrang-Architekturen und realen Fahrzyklen wird der Elektromotor häufig außerhalb des wirkungsgradoptimalen Kennfeldbereiches (Drehzahl/Last) betrieben. Der Wirkungsgrad des Elektromotors beträgt bei 10 % des maximalen Drehmomentes lediglich 70 bis 85 %. Des Weiteren besitzen die Magnete hocheffizienter Elektromotoren einen hohen Bestandteil von Neodym oder Samarium, beide sind sehr kostspielig und haben eine limitierte Verfügbarkeit.

Tulas Strategie zur Regelung der Elektromotoren – mit dem Namen Dynamic Motor Drive (DMD) – vermeidet die Wirkungsgradverluste bei niedriger Last und reduziert oder eliminiert die Abhängigkeit von den Seltenerd-Werkstoffen. Zur Regelung des Elektromotors wird eine neuartige Puls-Dichten-Strategie eingesetzt. Dadurch werden die Wechselrichter - und Magnetkreis Verluste vermieden. Bei hoher Last, haben Versuche mit Induktivmotoren eine Wirkungsgradsteigerung von 2 % Punkte nachgewiesen. Größere Verbesserungen sind bei kleinerer Last möglich. Im WLTP-Zyklus betragen die Verbesserungen 2,5 % Punkte. Durch

den geringeren Energieverbrauch kann die Batteriegröße reduziert und die Reichweite vergrößert werden.

In dem Beitrag werden sowohl die konstruktiven Maßnahmen zur Optimierung des Elektromotors beschrieben als auch die neuartige Regelstrategie anhand von Versuchsergebnissen im Detail erläutert.

Electric Vehicles are the future of Transportation

To reduce the negative impact of automobiles on the world, hundreds of organizations worldwide have undertaken enormous research efforts over the past decades. These efforts have culminated in production automotive engines that now can exceed over 40% brake thermal efficiency (Matsuo, Ikeda, Ito, & Nishiura, 2016). Proposed stringent Euro 7 standards of permissible emissions, if implemented and met, could dramatically reduce the level of toxic pollutions emitted from future automobiles. This presumes, of course, compliance through the full life of the vehicles, and excludes the reality of vehicles that are not always maintained and are commonly tampered with. The United States Environmental Protection Agency (US EPA) estimates that 10% of diesel vehicles in the United States have removed or disabled portions of the exhaust aftertreatment system. (United States Environmental Protection Agency, 2020) These vehicles produce toxins at levels that can be thousands or millions of times those permitted by law.

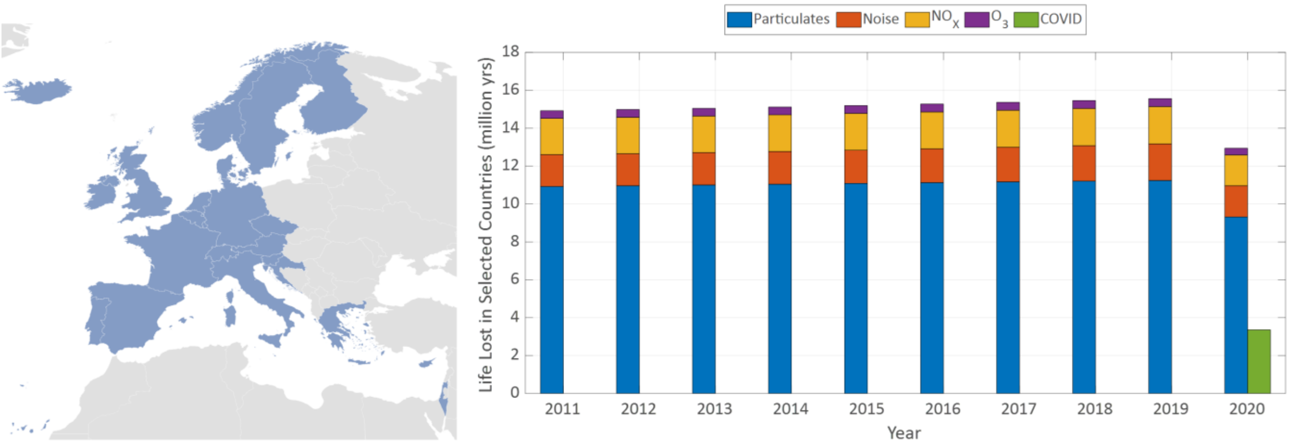


Figure 1: Years of life lost in selected European countries annually due to automotive pollution. Countries for which the data is projected are shown at left

Emissions of the automotive fleet have come to forefront in recent years as the world continues to learn about the negative impact of pollution. Large-scale research from many instances have concluded that the pollution caused in whole or part by automobiles are responsible for millions of years of life lost when considering large scale population. Particulate emissions have been the subject of recent research; Vohra, et. al, concluded that PM emissions caused an additional 10 million deaths worldwide annually. (Vohra, et al., 2021) The World Health Organization (WHO) estimated that in 2012 air pollution was responsible for 7 million premature deaths, including 600,000 in Europe alone. (Satterley, 2015) Lelieveld, et. al, concluded that air pollution caused over 790,000 excess deaths annually in Europe alone. (Lelieveld & Münzel, 2019) Toxicity is not limited to chemicals; either; the World Health Organization concluded that vehicular noise pollution caused in large part by combustion engines was responsible for over one million years of life lost annually in western Europe. (Fritschi, Brown, Kim, Schwela, & Kephalopouls, 2011) Caution should be observed when comparing these estimated numbers directly, but nevertheless, to emphasize the enormous loss of life caused by combustion engines, the authors have extrapolated them across the recent decade and compiled them into Figure 1. For contrast, the enormous number of years of life lost from COVID-19 in 2020 are shown in comparison. (Pifarré i Arolas, et al., 2021)

It is quite clear: we need a vaccine for combustion engines.

CO_2 emissions

Climate trends are now annual increases in temperatures and anomalous trends in weather events. These massive changes in climate are driven by greenhouse gas emissions. Atmospheric CO2 levels are shown in Figure 2. It is clear the increase in atmospheric CO_2, soon to reach an increase of 50% over prehistoric levels, is a recent and man-made phenomenon.

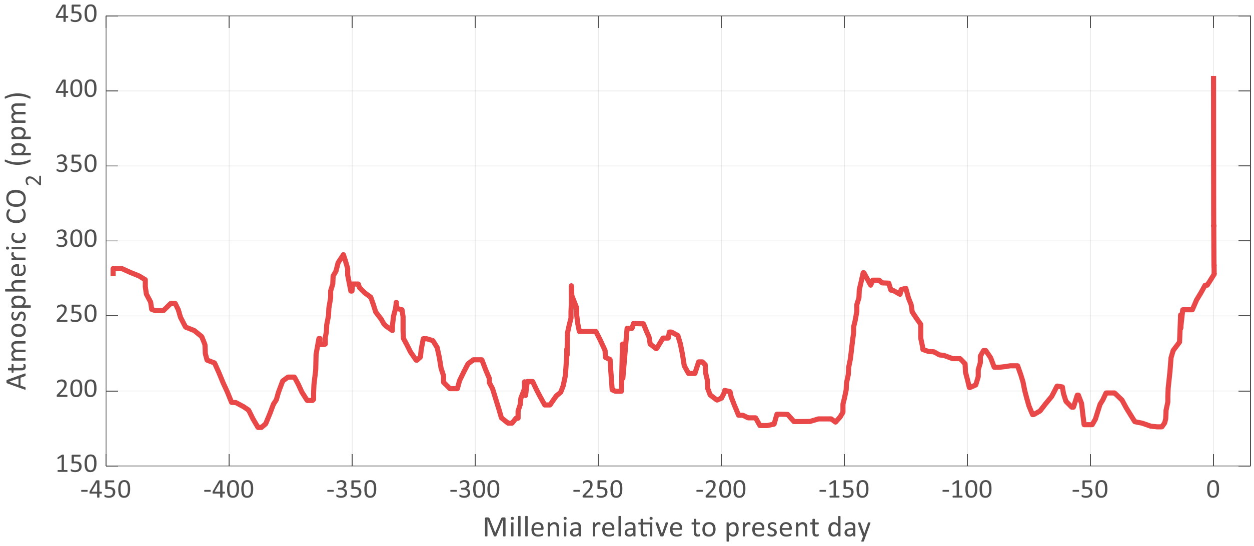


Figure 2: Atmospheric CO_2 over the last few hundred millennia, with enormous increase shown in the last century (NASA, n.d.)

A large portion of those CO_2 emissions are due to the transportation sector. To reduce or eliminate this impact, it is instructive to understand the sources of this unprecedented increase in CO_2 emissions. To that end, Volvo has published a valuable life cycle analysis of their new XC40 for both the conventional engine version and the battery electric version. (Egeskog, Hagdahl, Krewer, Råde, & Bolin, 2020) The authors from Volvo did a commendable job publicizing and emphasizing, through both analysis and graphics, the importance of charging a vehicle from a grid that is largely free of power derived from fossil fuels. Tula has added to that analysis the alternatives of a Toyota Prius Eco Hybrid and a XC40 EV recharged on a grid where incremental power demand is keeping coal power online. Those results are contrasted in Figure 3.

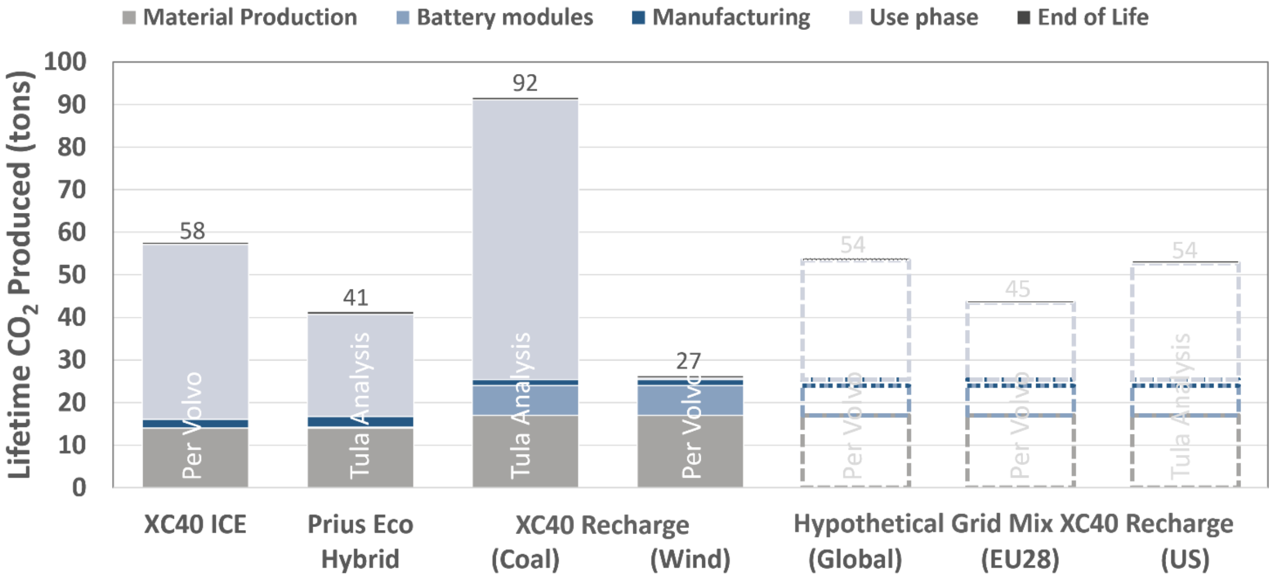


Figure 3: Life Cycle Analysis of greenhouse gas emissions, separate analysis from Volvo and Tula

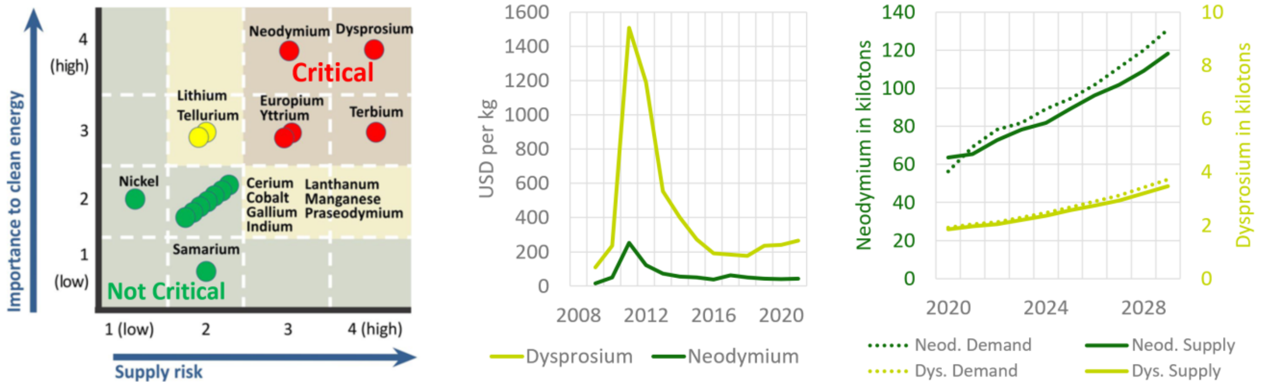
The electrical grid and automotive fleet must, of course, be optimized in conjunction. Electricity is probably the most fungible product that can exist. Although we might be tempted to simplify assumptions by using a grid-averaged levels of CO_2 per kW-hr, society can neither build nor retire an “average” electricity plant. We should therefore concern ourselves with the ‘marginal’ electricity plant – in other words, the electricity plant that is the most in need of being closed. As such we need to consider that every increase in grid power demand makes removing coal powered plants from the grid even more difficult. In order to forestall coming disasters in climate, we need to build renewable and carbon-free power plants and retire coal powered plants, while simultaneously converting the automotive fleet to run on this new carbon-free electricity.

It will not be easy. An average coal power plant producing 600MW will support the charging of approximately one million electric vehicles, and in so doing will generate an additional 38 megatons of CO_2 compared to a fleet of hybrid vehicles. If a large fleet of electric vehicles stresses the grid to the point where coal power is maintained, those electric vehicles will be responsible for over twice the CO_2 production of a fleet of efficient hybrids. Unfortunately, in 2019, the latest year in which data is available, over 17 gigawatts of new coal power plants were approved. (IEA, 2020) In just one year, the world has begun building new coal power plants that will annually output three times the amount of electricity required to power the entire worldwide electric vehicle fleet that has been produced over the past few decades. Moreover, these new coal power plants, and the coal power plants approved in future years, are expected to be online for decades. The challenge to bring electric vehicles online while simultaneously eliminating massive polluters from the grid has somehow become even more critical. Every action possible must be taken to mitigate the impact of electric vehicles on our world.

It is quite clear: we need to improve the efficiency of electric vehicles.

Rare earth metals

One of the key methods that has been used to improve the efficiency of electric powertrains is to increase the content of rare earth metals. Although this strategy is effective in producing efficiency gains for some of the roughly 7 million electric vehicles in use today, it is not likely to be an adequate solution for a 1.4-billion-unit automotive fleet. It is not clear that mining and recycling can produce the rare earth metals required for an electric vehicle fleet two hundred times larger than the current one.



DOE Medium-term (2015-2025) Criticality Matrix Historical Price of PM RE Elements Demand and Supply Forecast of PM RE Elements

Figure 4: Supply Risk, historical price, and projected future demand of rare-earth metals

Sources of economically recoverable rare earth metals are concentrated in only a few locations worldwide. In Figure 4, the left panel rates the importance and risk of each of these metals; among them Neodymium and Dysprosium are considered to be of critical importance and risk (U.S. Department of Energy, 2011). The center panel highlights the historical volatility of rare earth metals (Statista, 2021), and the right panel shows that the demand in the next decade for these metals will increase by a factor of 248% and 215% respectively (Adamas, Spotlight On Dysprosium, 2018) (Adamas, Rare Earth Elements: Small Market, Big Necessity, 2019). Although rare earth metals will be a key enabler of our vehicle conversion, we cannot rely exclusively on rare earth metals being affordable in the future.

Tula has introduced Dynamic Motor Drive to improve EV efficiency

Tula Technology, a company formed in San Jose, California in 2008, has been working to improve the efficiency of the automotive fleet since its inception. Tula's Dynamic Skip Fire (DSF®) was introduced on General Motors' products in 2018, and Tula has successfully navigated from a small startup into a profitable entity in series production. Tula recognizes that it is critical to reduce the negative impact the automotive fleet has on the world, even for powertrains that are based on batteries and electric motors. To that end, Tula has been working to optimize the system efficiency of BEV's algorithmically and has successfully developed the concept of Dynamic Motor Drive (DMD®).

Dynamic Motor Drive Control Strategy

The concept of Dynamic Motor Drive, shown in Figure 5, is to intermittently operate the electric motor only at the highest possible electromagnetic efficiency. When requested torque is below the torque that produces highest electromagnetic efficiency, an algorithm pulses the electric motor at conditions similar to those used to generate the higher efficiency. In the example shown, optimal efficiency is at 34% of peak torque, and requested torque is at 19% of peak torque. The controller will therefore operate at the optimal efficiency point roughly 19/34 = 56% of the time.

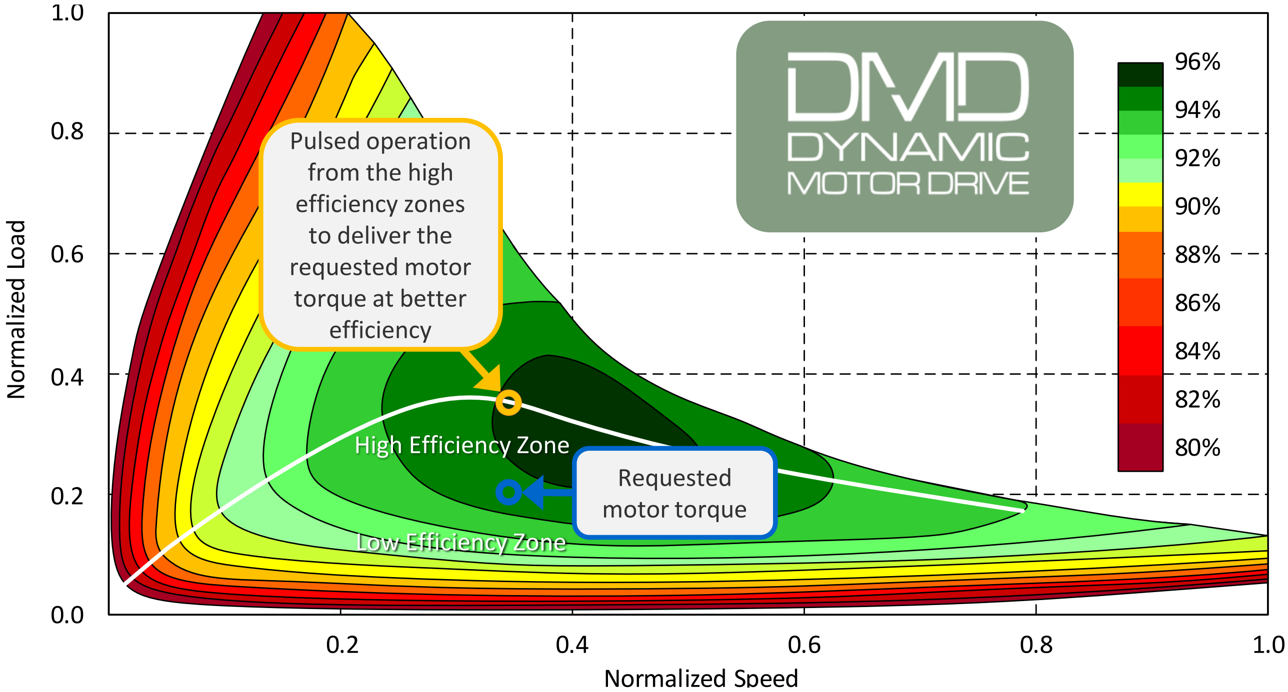


Figure 5: Concept of Dynamic Motor Drive

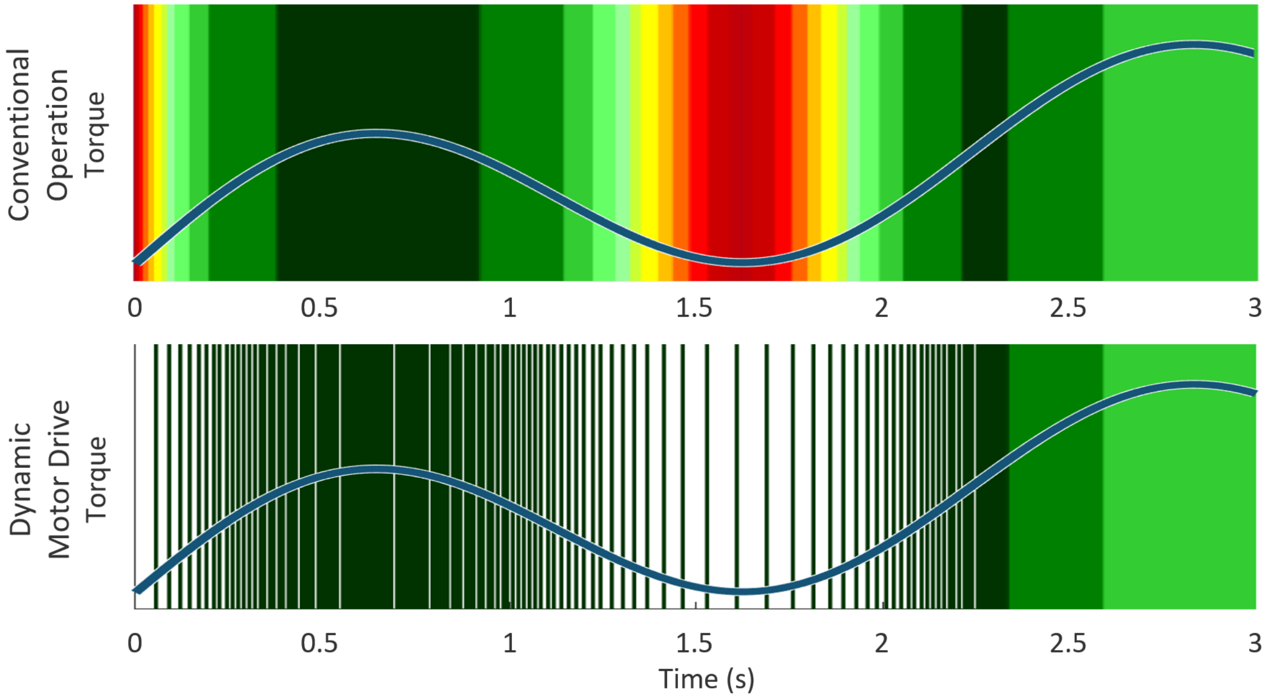


Figure 6: Torque Modulation of Dynamic Motor Drive

To meet the torque demanded in a very transient system, this strategy must be capable of quickly changing torque levels. To eliminate the noise and vibration that such a system might generate, the frequencies and amplitudes of pulsation must be carefully controlled. The strategy used is shown conceptually in Figure 6, which contrasts Dynamic Motor Drive with a conventional control strategy. At low loads, conventional control strategies have poor efficiency in generating electromagnetic torque. Alternatively, pulsing the motor intermittently with dynamic motor drive allow the motor to operate at the motor with optimal efficiency.

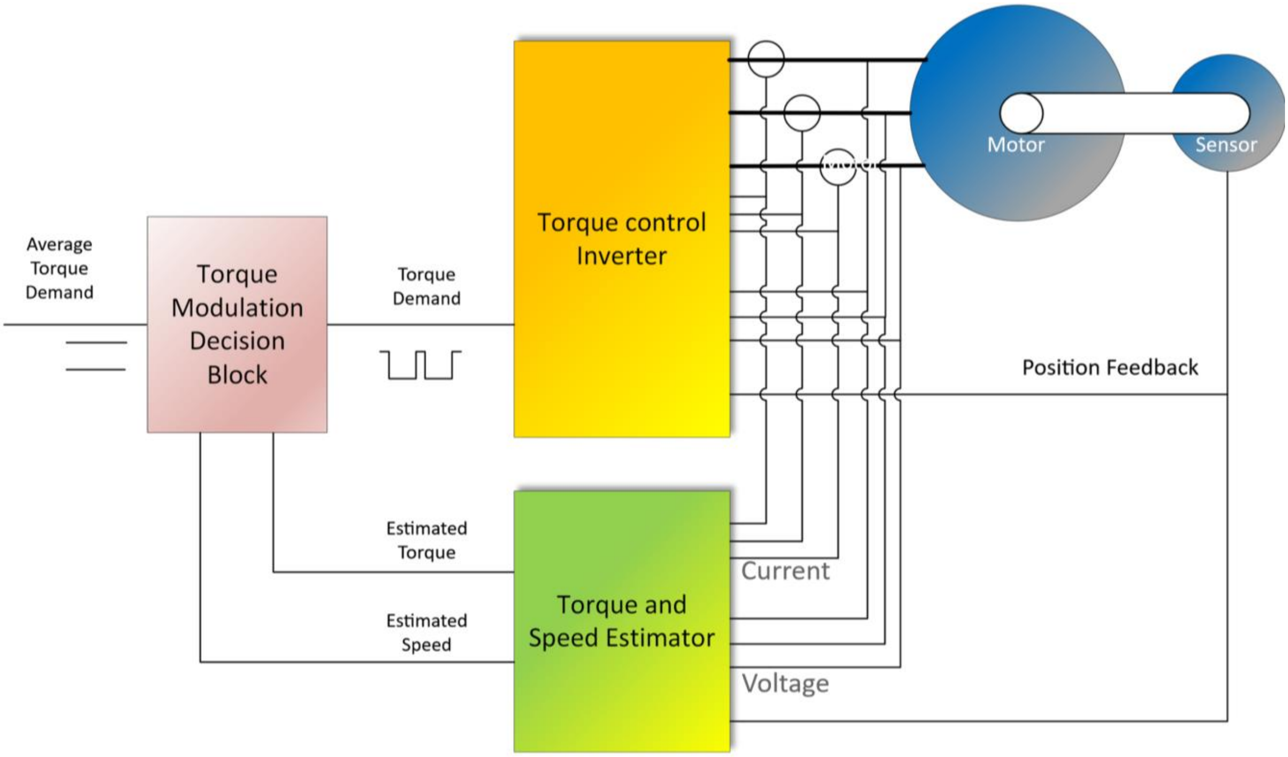


Figure 7: Simplified Torque Decision Control Schematic

A block diagram is shown in Figure 7 which describes the control architecture at a high level. A torque modulation decision block determines whether to drive the motor, the frequency of modulation, and the modulation waveform. The figure represents that modulation waveform as a square wave oscillating between the torque that delivers peak efficiency and zero torque; the actual waveform to provide peak efficiency and performance is calibrated into the modulation decision block. The torque demand is sent to a conventional torque controller, using algorithms that are standards in the industry. Torque and speed estimators similar to those use in conventional systems provide feedback to the control blocks. Estimations of position and speed can be used in lieu of physical sensors.

The type of modulation employed is determined by the motor type. Due to the high time constants to create magnetic fields in induction motors, only the torque current (i_q) is modulated. The magnetizing current (i_d) is selected based upon efficiency and inverter bus voltage. For motors without magnetically induced back-electromotive force (BEMF), the inverter can intermittently be disabled as part of the modulation strategy, which reduces the losses even further. For motors equipped with magnets, the magnetizing field needs to be maintained in the field weakening area to keep the motor BEMF within the limitation of the inverter bus voltage. Below the field weakening threshold, the inverter may be turned off for the additional saving in inverter losses. The strength of this strategy allows DMD gain to be achieved with any motor type.

Figure 8 shows a sample torque control and voltage required to reach a nearly-square-wave torque waveform at a nominal 15Hz. In this example, duty cycle is approximately 50%, so commanded torque for the near-square-wave can reach twice of nominal.

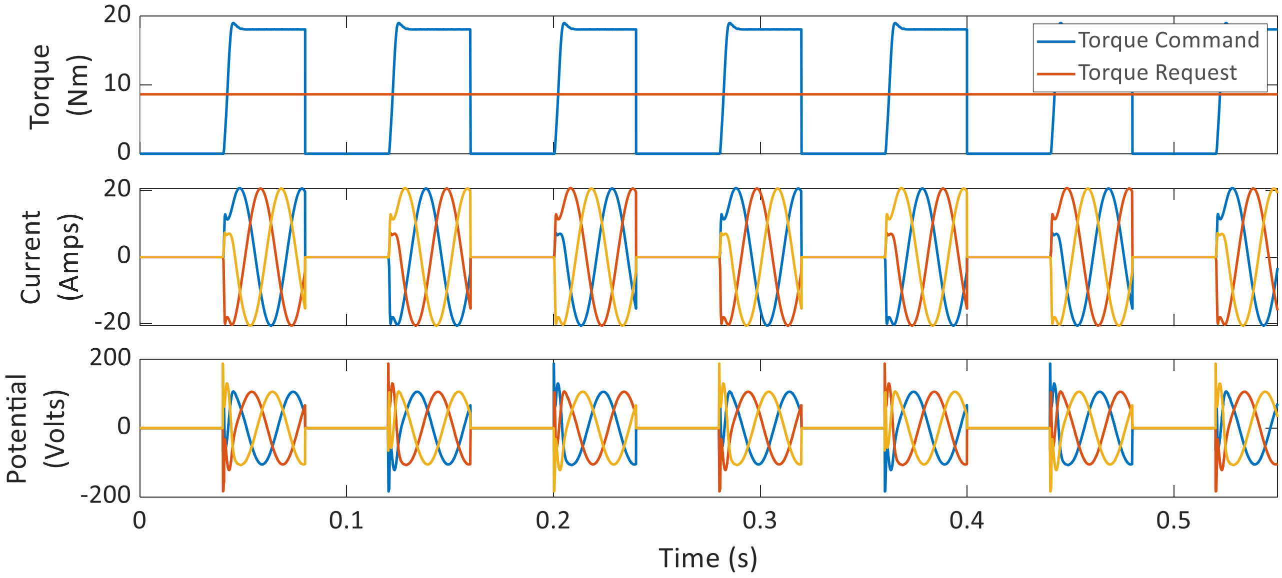


Figure 8: Example of torque, voltage, and current waveforms of Dynamic Motor Drive

Experiments Validate the Dynamic Motor Drive Concept

For initial proof of concept testing, Tula selected to evaluate performance on a Marathon Y543A induction motor. This motor allowed quick testing on a benchtop dynamometer, and the installation is shown in Figure 9. The motor is capable of a maximum continuous torque of approximately 20 N-m, and a maximum continuous power of approximately 3.8kW. Although the inverter used was designed to be flexible, it represents conventional technology. It uses Silicon Carbide FETs, the modules of which are rated to 1200 Volts (breakdown) and 50 Amps. The inverter is controlled at frequencies between 18 and 40 kHz. FET actuation is achieved through a CREE Six Channel SiC MOSFET driver board (CGD15FB45P1) controlled by a TI Delphino processor (F28379D). Custom software was created to avoid restrictions imposed by conventional controllers and allow quick changes in the drive state of the conventional hardware used.

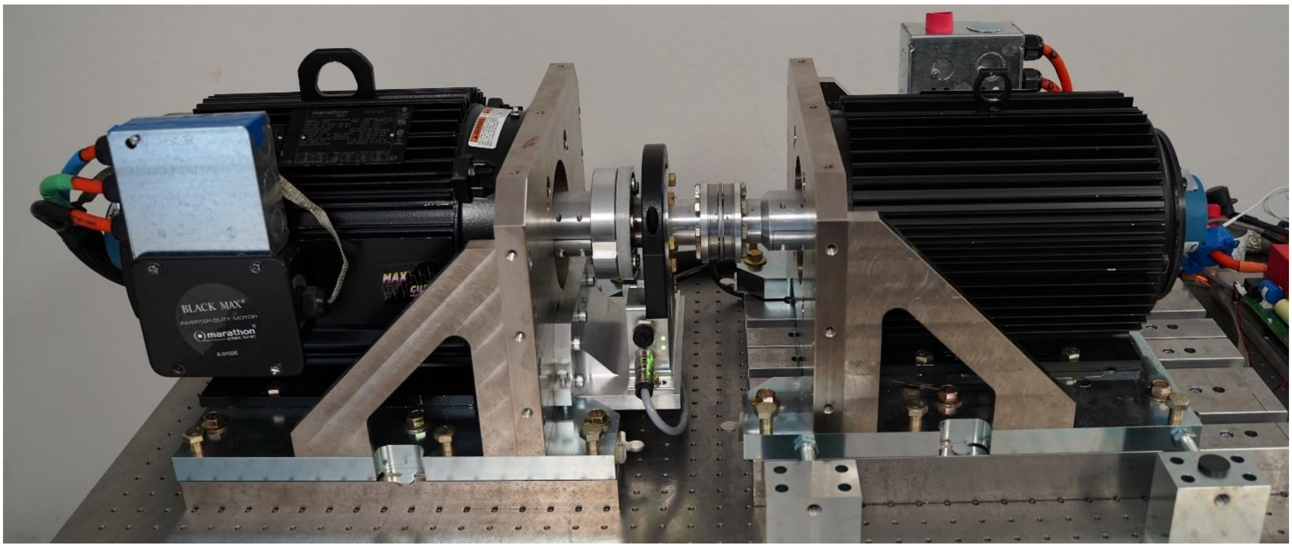


Figure 9: Experimental setup for small motor testing

Tula conducted efficiency measurements of this motor by measuring output power through torque and speed with an HBM torque meter. The voltage and current input to the inverter allowed calculation of input power. Measured system efficiency is shown in Figure 10. Peak efficiency of the baseline system (inverter and motor) is around 90%. Tula chose 1150 RPM and 18Nm as a mid-high load reference point to conduct testing; at that condition, baseline efficiency is approximately 88%.

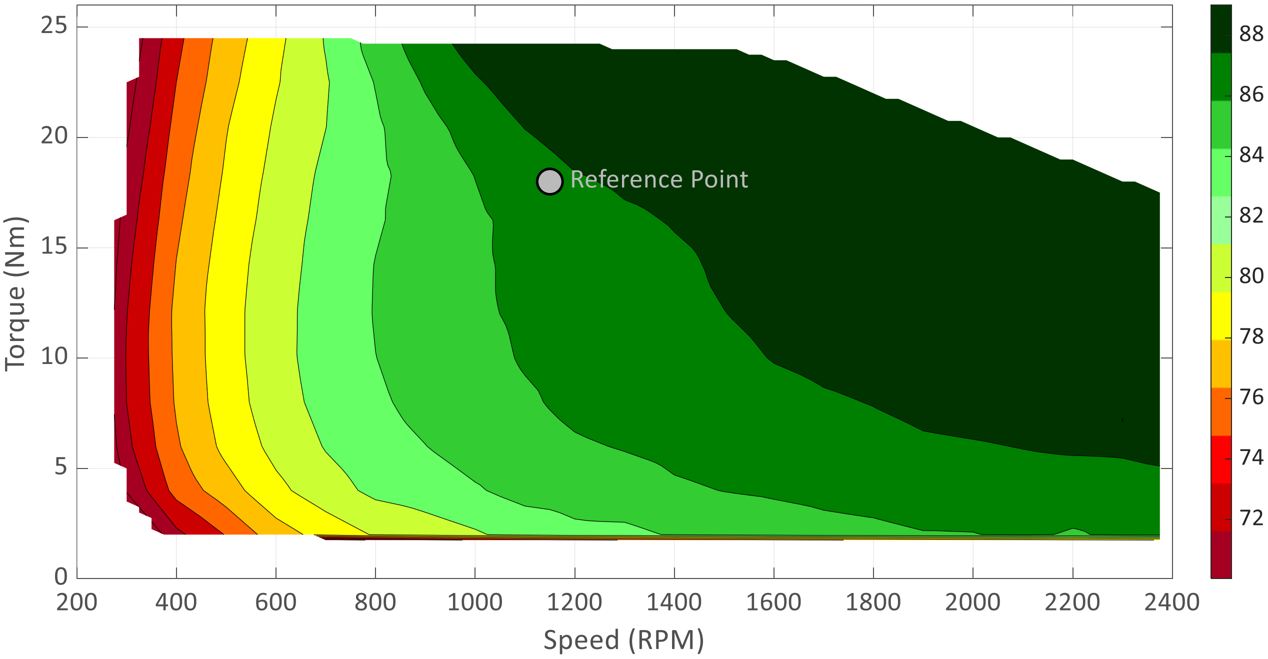


Figure 10: Marathon induction motor system efficiency

For DMD testing, the control architecture and calibration required dramatic changes in motor drive current waveforms. One such modified waveform is shown in Figure 11. Although it is an unconventional waveform for what is nominally a steady condition, the waveform was achieved with the conventional inverter described previously.

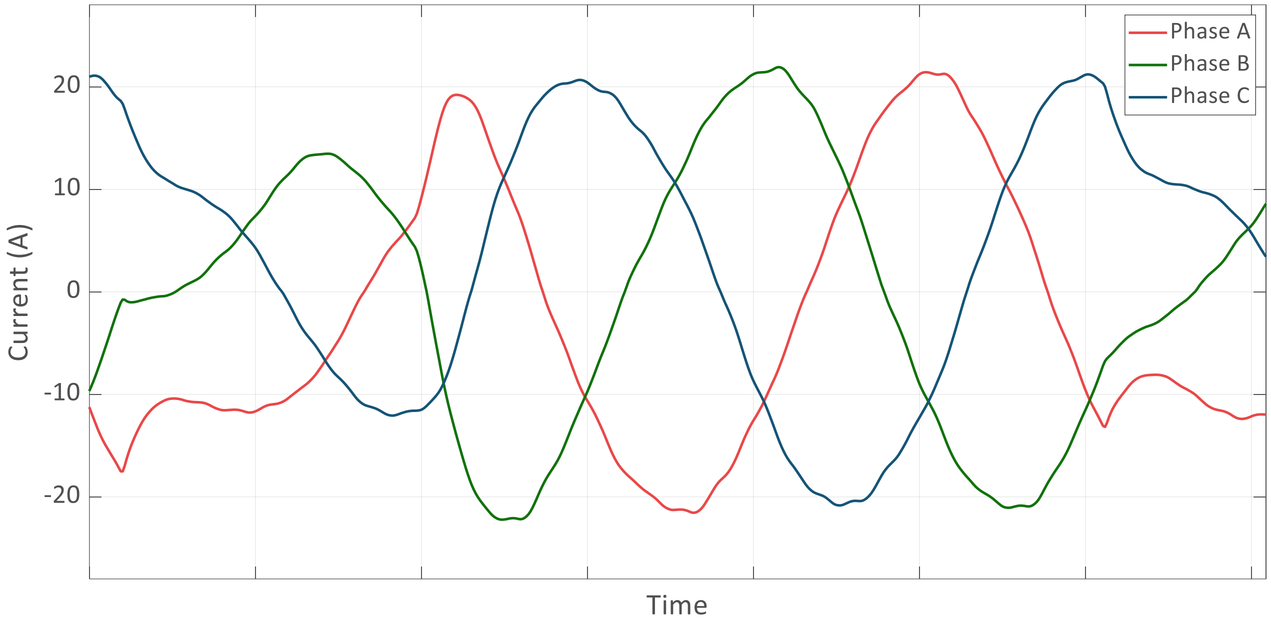


Figure 11: Instantaneous current trace of example DMD torque control waveform

Many waveforms were attempted to optimize the efficiency, drivability, and noise of the system. The measured efficiency of those waveforms is shown in Figure 12. Several waveforms that were attempted improve efficiency only when induced at frequencies that are inappropriate for automotive use – results of those inadequate waveforms are shown in grey. In contrast, the preferred algorithm is shown in green and has substantial improvements in efficiency in the frequencies that appropriate for automotive use.

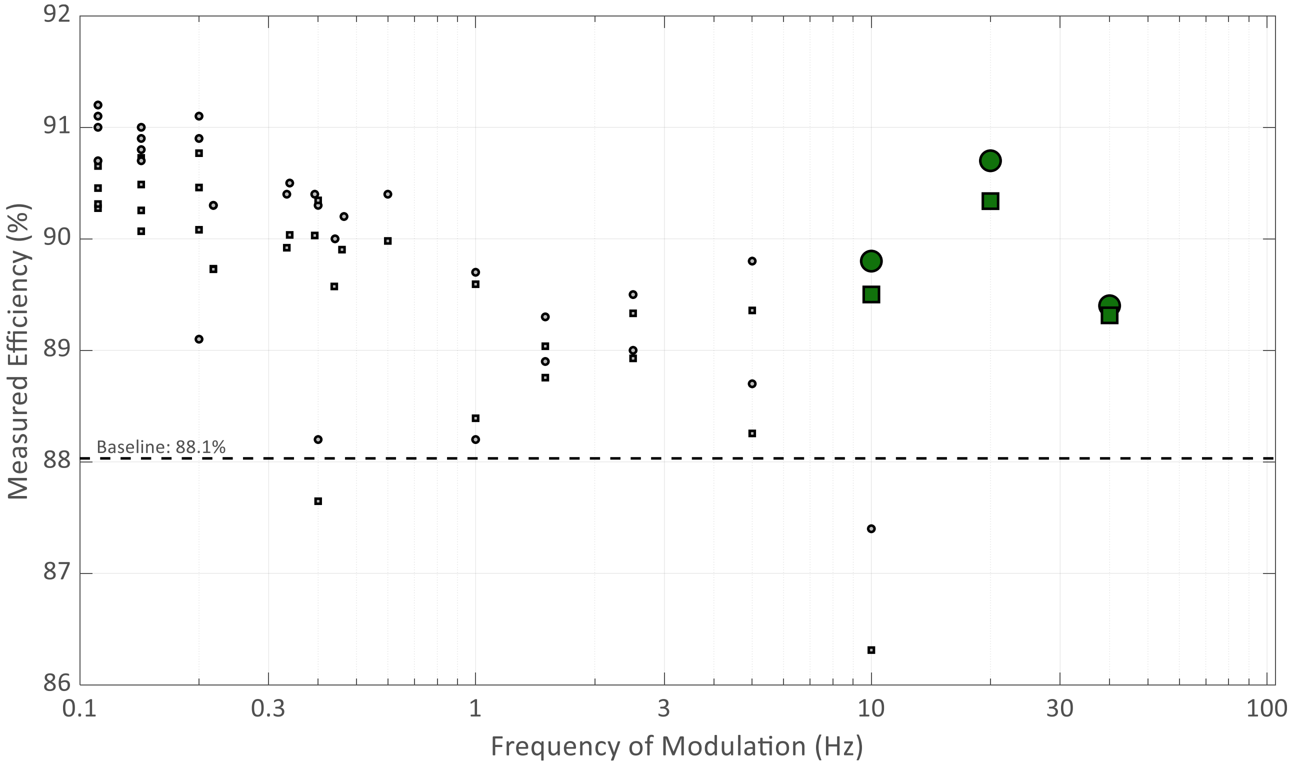


Figure 12: Experimental results validating efficiency gain of Dynamic Motor Drive. Points relevant to automotive use highlighted.

Optimizing the gain possible with Dynamic Motor Drive

Motor Selection

Having proven that gains are possible with DMD, a pertinent question to answer is how DMD control methods might impact motor selection and design optimization to maximize system efficiency. To understand that optimization process, it is instructive to understand that the gains of Dynamic Motor Drive come from three fundamental areas.

1. Inverter losses are reduced; in the optimal case, by turning the inverter off during the low torque periods of the waveform. This is only feasible if the unpowered BEMF is lower than the inverter bus voltage.
2. Copper losses can be reduced, but the change in copper resistance losses depends strongly on motor type. Reductions are only found in motors that need significant levels of current before torque is produced. This relationship of current and torque can be seen in maximum torque per amp (MTPA) curves, but in practice, this means that synchronous reluctance motors generally will have reductions in copper losses and surface permanent magnet motors (with linear torque characteristics) will have increases in copper losses.
3. Core losses are reduced by periodically turning off magnetic flux in the motor. This only gives appreciable improvement in motors that rely less on permanent magnets. Each motor type and even every motor design will have a unique combination of gains with DMD.

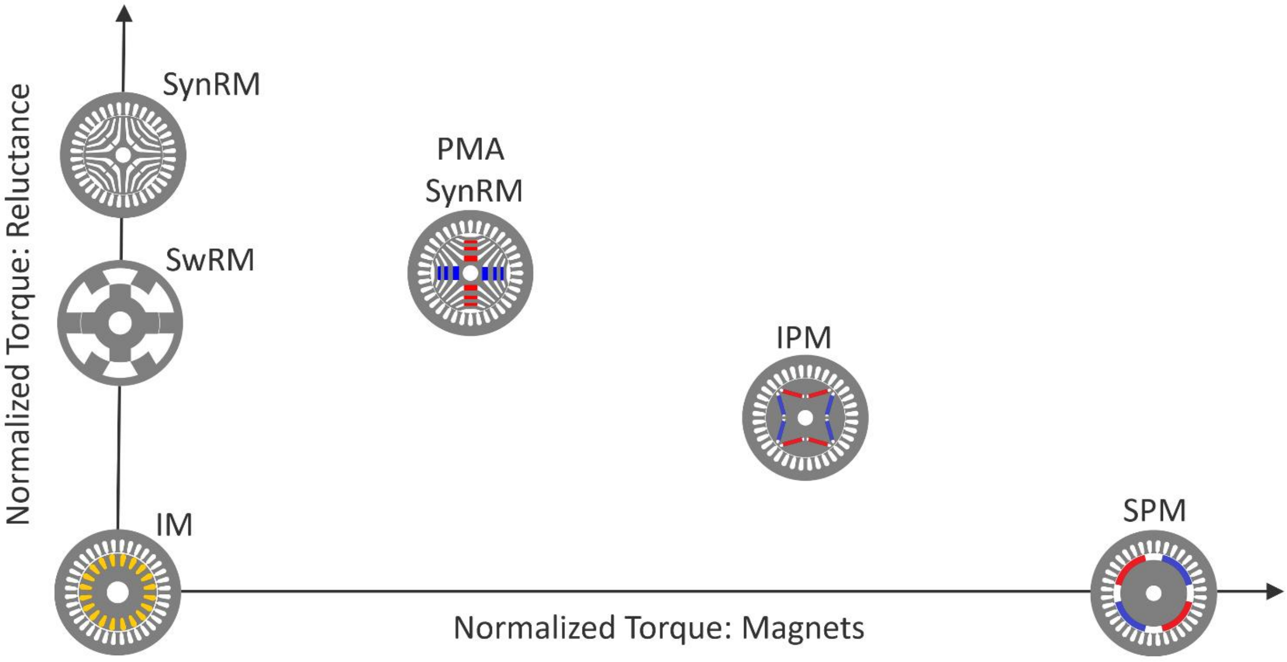
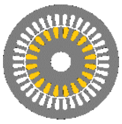


Figure 13: Relative reluctance torque and magnetic torque of selected motor types

Figure 13 contrasts the reluctance torque and magnetic torque of six common motor types.

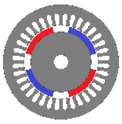
Induction Motors



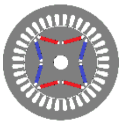
Induction Motors (IM) have no magnets and are a good candidate for DMD. There is a challenge in implementing DMD on Induction Motors – the rotor current takes a relatively long time to build a field sufficient to support the torque demand. Tula has solved this problem by maintaining the field current and only modulating the torque generating current. Such a control strategy does not allow for the inverter to be turned off but does allow for a faster DMD modulation response at the cost of losses during the zero-torque modulation period.

Wound Rotor Induction Motors (WRIM) are more efficient motors than the normal induction motor as the rotor current does not have to pass through the stator winding with the associated losses. This type of motor is expected to have the same problem of building up the magnetizing current and as such we should maintain a constant field resulting in the same performance as the IM but with less opportunities for DMD gain.

Permanent Magnet Motors



Surface Permanent Magnet (SPM) motors rely exclusively on magnetic torque. They are not easily field weakened and therefore tend to have nearly constant maximum torque regardless of speed; torque is directly proportional to the applied torque current. For these motors, doubling the current doubles the torque but quadruples the copper losses, which means that modulation of torque will increase copper (I^2R) losses. During the inverter off period, inverter losses are zero, but there will still be core losses due to the magnetic flux.

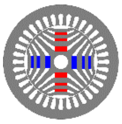


Internal Permanent Magnet (IPM) motors rely upon both magnetic torque and reluctance torque. As the magnetic flux cannot be turned off, DMD gains will be limited to a reduction in inverter losses below base speed. As permanent magnet motors do not rely as heavily on electrical current to create magnetic fields, the improvements possible will be proportionally less than alternative motor designs. Gains will be maximized in IPM's for designs that have larger proportions of reluctance torque rather than magnetic torque. DMD can maintain the efficiency of those designs while reducing the reliance on rare earth metals.

Reluctance Motors

Synchronous Reluctance Motors (SynRM) do not contain any permanent magnets and generate torque solely from magnetic reluctance. They do not suffer from the delays in magnetic field creation that induction motors face. As these motors do not generate BEMF when the motor is not energized, DMD gain can be maximized. In these motors the torque production is not linear to applied current in a manner that can increase DMD gain. Overall, this motor is a good candidate for the application of DMD.

Synchronous Reluctance Motors do suffer from a poor power factor, resulting in higher currents being required to produce torque. As DMD mitigates the losses this additional current incurs, a synchronous reluctance motor controlled with DMD algorithms will provide a motor with improved efficiency without requiring rare earth metals.



Permanent Magnet Assisted Synchronous Reluctance Motors (PMA SynRM), similar to IPMs, use both reluctance and magnetic torque to improve the power factor. In practice, motors can combine any combination of reluctance and magnetic torque; common motor types are shown in Figure 13. This motor type sits between the SynRM and the IPM motor based upon percentage magnetic torque, as SynRM's use zero magnetic torque and SPM's use magnetic torque exclusively. Similarly, DMD gain would be between the SynRM motor and IPM motors. As the magnetic flux requirements are lower, these motor types can enjoy the enormous advantage of eliminating rare earth metals. The magnetic content will generate a BEMF and as such a mixture of strategies are required to maximize the potential DMD gain. In summary, synchronous reluctance motors offer promising possibility when paired with Dynamic Motor Drive.

Like synchronous reluctance motors, Switched Reluctance Motors (SwRM) also use reluctance torque exclusively. Time constants will also be relatively small, and some of the same algorithms used to mitigate torque waveforms in DMD could be used to mitigate the noise increases in switched reluctance motors through selective frequency shifting of the radial force that creates the noise. Efficiency gains are expected to be similar to those achieved with synchronous reluctance motors.

Motor Design

The motor design process is very similar to conventional motor design process, using the same steps and tools; but the compromises made during design should recognize that operation at low electromagnetic torque levels will be avoided algorithmically. In addition, the DMD motor should be designed with full consideration of operation under modulation noise and torque levels, as poor noise performance and/or torque ripple will preclude DMD operation.

Tula has gone through the process of creating a Synchronous Reluctance Motor design that has been optimized for DMD. After the motor design was conceptualized, it was created and evaluated in the electromechanical simulation software package ‘JMAG’. In JMAG, a finite element analysis (FEA) mesh was created, and magnetic flux and various losses were calculated. This was an iterative process in which over 2000 iterations of motor designs were evaluated prior to building the most promising candidate design. That design is shown in Figure 14, and shows the cross section of the rotor, the FEA mesh used, and resulting flux lines and flux density of the FEA.

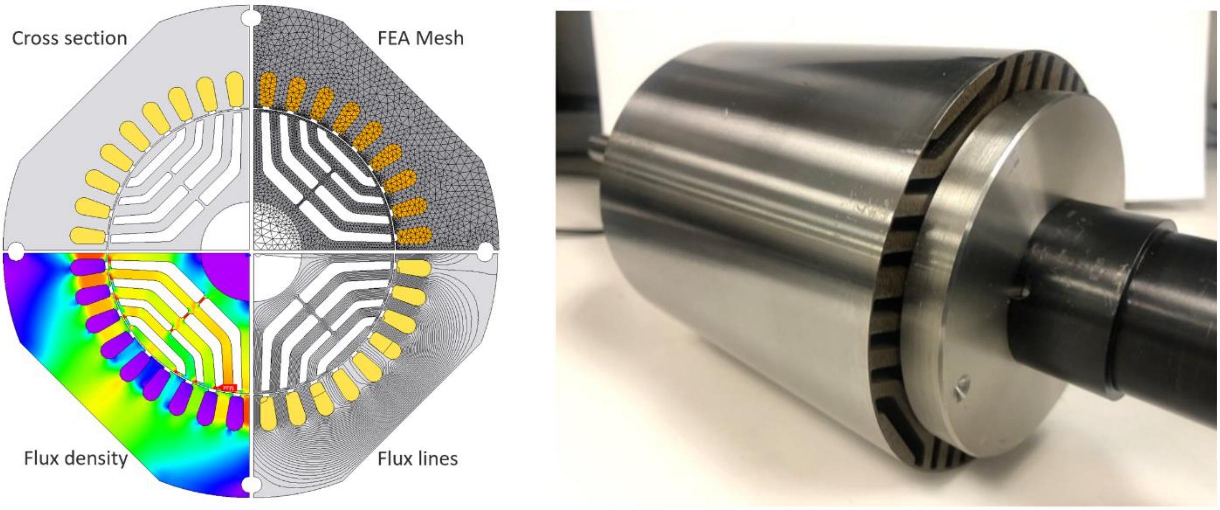


Figure 14: Left: Synchronous reluctance motor cross section, FEA mesh, flux density, and flux Lines.

Right: Prototype assembled synchronous reluctance rotor

Understanding Requirements for Transparent Operation of DMD

In order to determine the efficiency gains that might be possible in an electric vehicle, Tula has purchased two Chevrolet Bolt EVs to implement Dynamic Motor Drive algorithms in-vehicle. To allow control of the electric motor, extensive modifications need to be made to bypass the conventional controller. To that end, the inverter has been outfitted with controllers capable of operating the inverter and outputting the currents and voltages required with DMD’s pulse-based strategy.

Figure 15: Chevrolet Bolt used for Dynamic Motor Drive experiments

Perceptible vibration and noise need to be eliminated for automotive traction motors. To determine the benefit possible with Dynamic Motor Drive, the sensitivity of occupants to vibration and noise must be understood. Tula's approach, already in production with DSF, is to understand the frequency response function of a vehicle to a variety of inputs, and adjust the calibration to eliminate any perception of marginal response.

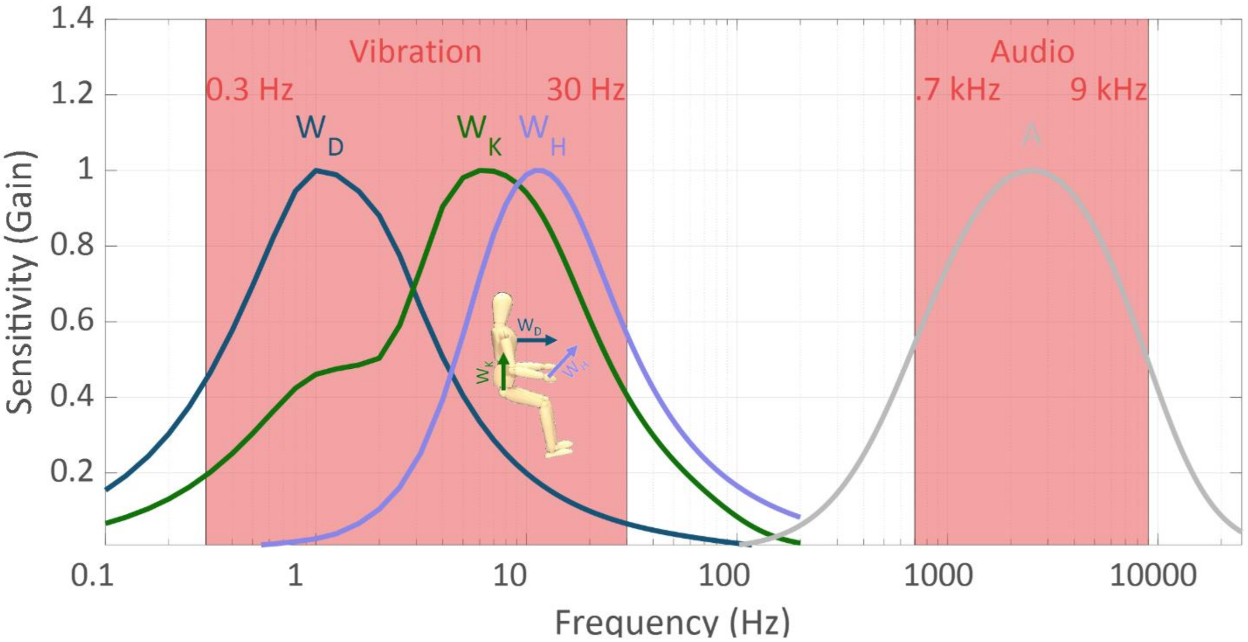


Figure 16: Human sensitivity to vibration, ISO 2631 and 5349, and audio frequencies, IEC 61672:2003.

Example sensitivities of a human to vibration are given in ISO 2631 and 5349 and are shown in Figure 16. Audio frequencies are represented by the A-weighting, given in IEC 61672:2003. Low frequency vibrations, between 0.3 Hz and 30 Hz, should be eliminated to minimize the disturbance felt by the occupants. In addition, audio frequencies between 700 Hz and 9 kHz are easily heard and should also be eliminated.

The tested frequency response function of the Bolt to a variety of relevant frequencies is given by an impact response test in Figure 17. The frequencies where human perception of vibration is high are highlighted in red. The seat track response is shown in the top plot, and the steering wheel is shown on the bottom plot. Frequencies at which the transmission is low in both seat track and steering wheel are highlighted in green. There are large areas of potential DMD operation between 25 and 40 Hz, between 48 and 52 Hz, and between 120 and 185 Hz. Fortunately, for electric motor control, the pulsing frequency can be decoupled from the rotational speed of the rotor, and there is wide latitude to select any of these frequencies for DMD operation.

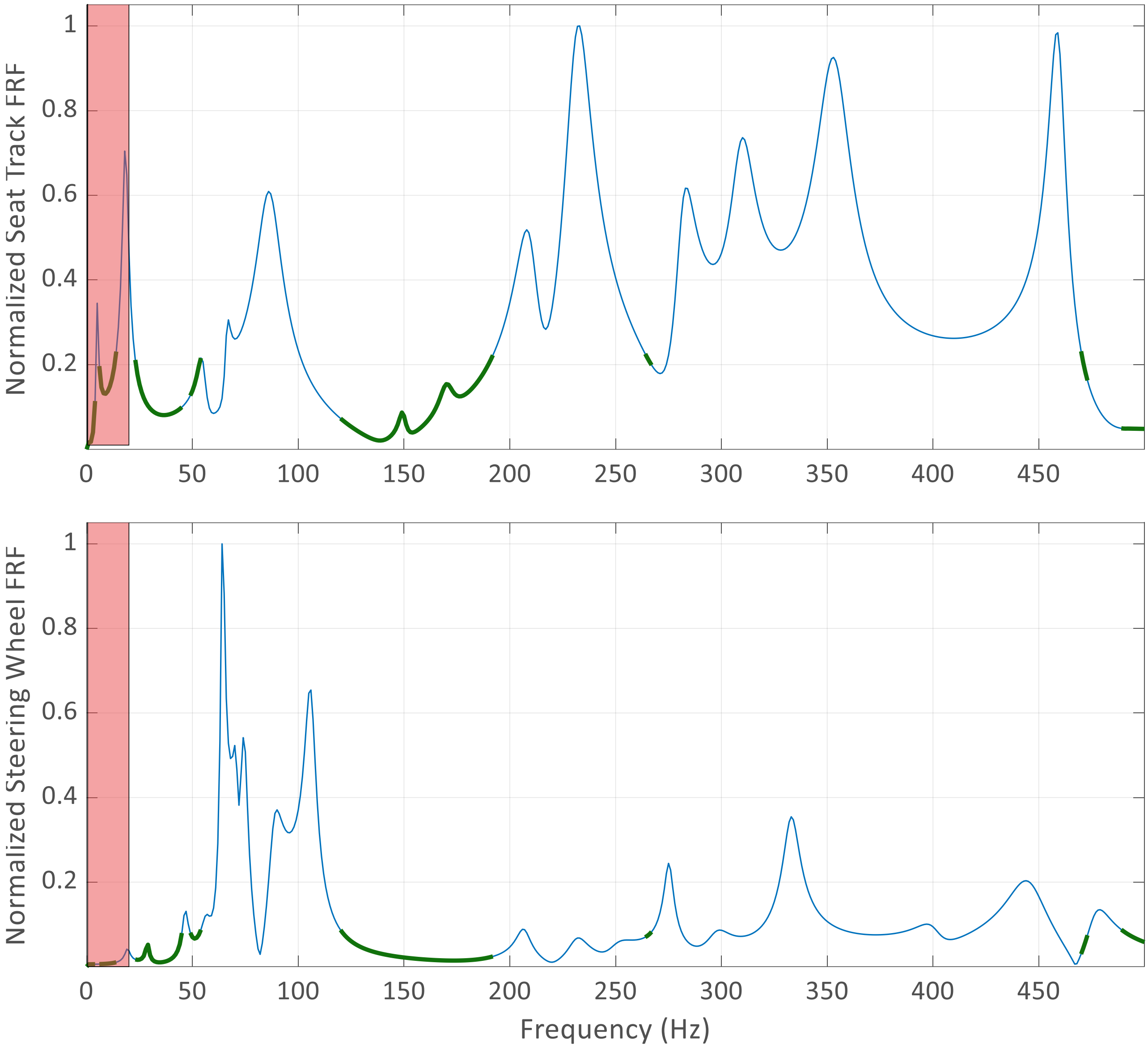


Figure 17: Frequency response functions of Seat Track and Steering Wheel, subjected to impact response

Electric Motor Results

To determine the various reasons for efficiency improvement made possible on a synchronous reluctance motor, Tula used JMAG software to estimate copper, core, inverter, and other losses. The copper, core, and inverter losses represent the largest losses and are shown in Figure 18. WLTC operating conditions are shown in a pink dot overlaying the contour. The cumulative total of WLTC losses is shown in bar charts on the left.

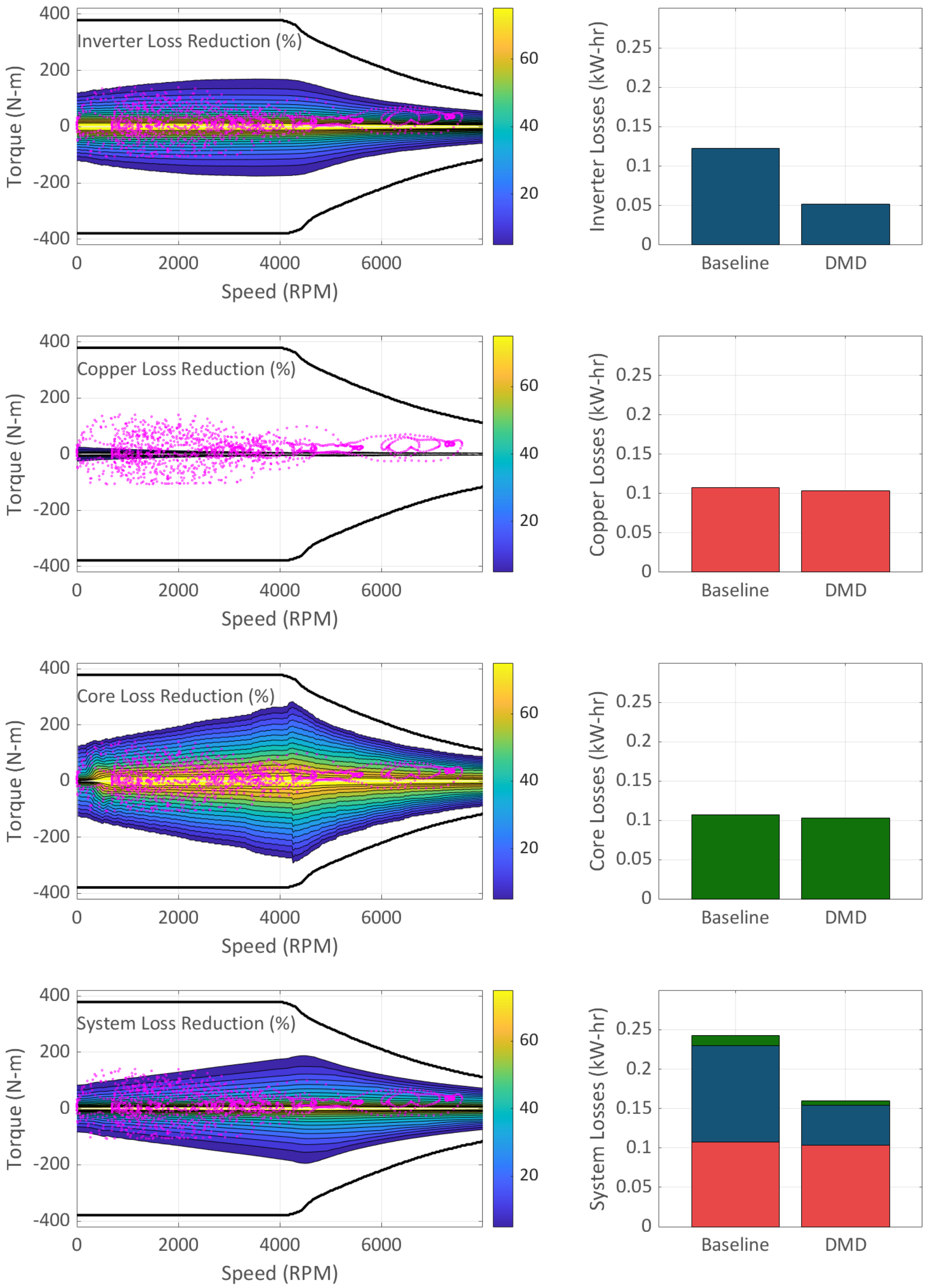


Figure 18: Reduction in losses under DMD. Percent of losses reduced is shown on the contour maps at left, and total losses on the WLTP for a synchronous reluctance motor vehicle application are shown at right.

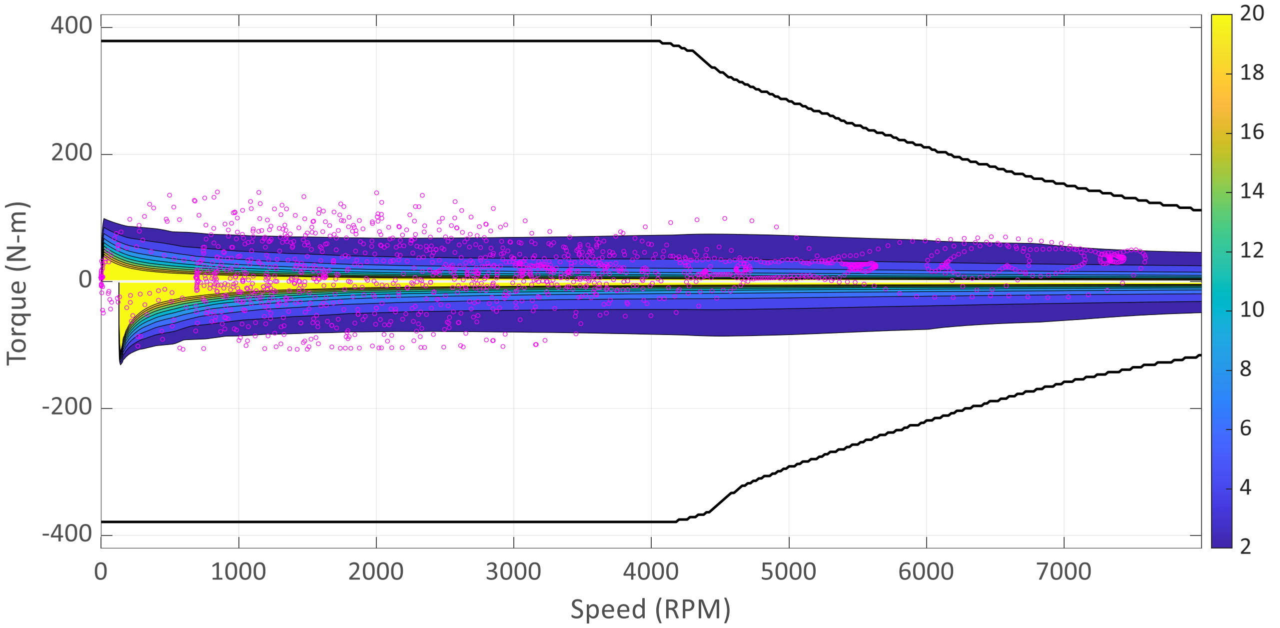


Figure 19: System efficiency improvements for DMD, overlaid with WLTP operating points

The overall efficiency gain as a function of torque and speed is shown in Figure 19. At torques of around 70 N-m and below, a gain of at least 2% efficiency is seen. At the lowest torques, improvements exceeding 20% can be seen. These gains are substantial considering they are the result of an easily implementable software strategy.

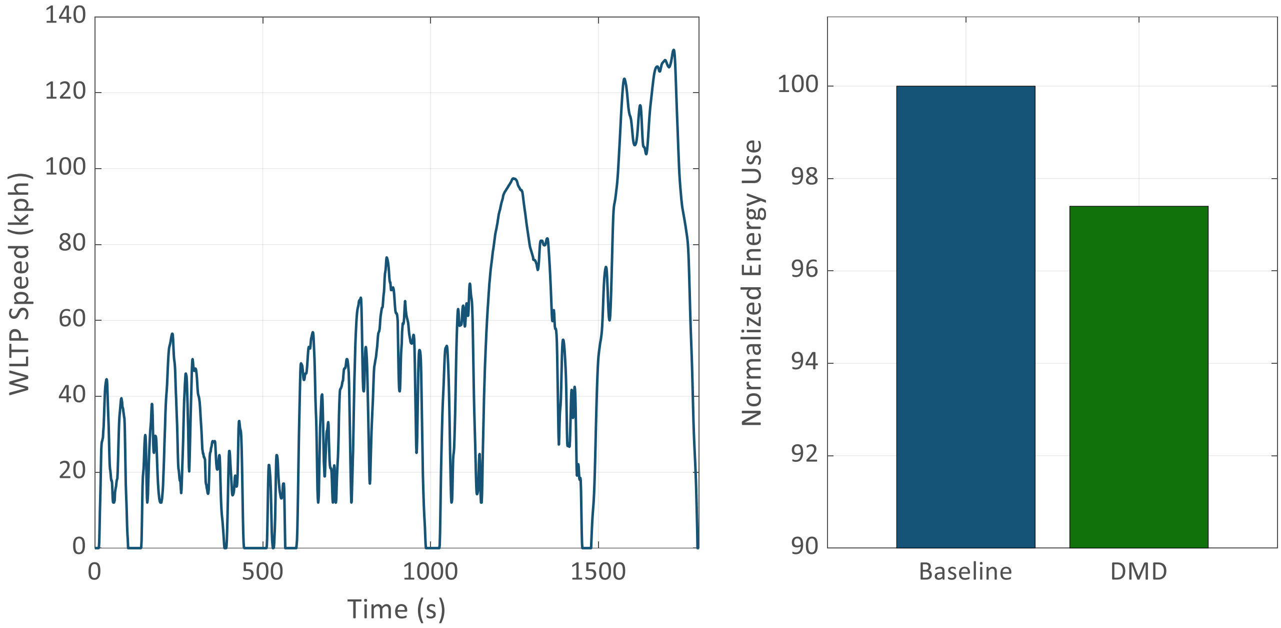


Figure 20: Relative energy usage on WLTP cycle

Drive Cycle Efficiency Improvements

These gains are translated into gains on the WLTP cycle in Figure 20. The total energy usage is reduced by 2.5% by implementing DMD electric motor control. This improvement allows for longer ranges or smaller batteries that will have a substantial impact on electric vehicles.

Tula’s Dynamic Motor Drive improves motor efficiency with software

Tula has experimentally proven the benefit of DMD on several motor types. Induction motors have experimental improvements of over 2% at high loads. Synchronous reluctance motors can see steady state gains of over 50% at lightly loaded conditions, which translates to 2.5% gain on the WLTP with current assumptions. Gains are anticipated to improve on the RDE as the algorithms used, by necessity, emphasize efficiency during torque transients.

These gains can be had with an easily implemented software change in conventional controllers operating with conventional inverters. With these improvements, it becomes easier to reduce or eliminate the rare earth metals that are currently required for the automotive fleet but are not yet available. DMD reduces or eliminates those sourcing problems while maintaining high efficiency operation.

Tula’s Dynamic Motor Drive technology will deliver high value efficiency improvement to the full spectrum of electrification technologies of the future. With DMD, induction motors and reluctance motors will have their efficiency improved. With DMD, permanent magnet motors will be less dependent on rare earth metals. The Tula team looks forward to optimizing performance with its partners and customers in the transportation, industrial, and power generation ecosystems.

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