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Efficiency Improvement of Automotive Traction Systems by Dynamic Motor Drive

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Abstract: Tula Technology has developed Dynamic Motor Drive (DMD) technology to optimize the efficiency of electric powertrains while avoiding the use of rare earth magnets. Similar to the concept of Dynamic Skip Fire (DSF), which is operating in vehicles with internal combustion engines, DMD intermittently operates the motor at high efficiency to seamlessly deliver torque while minimizing losses at low loads. Simulation results show it is possible to reduce the energy consumption of an Externally Excited Synchronous Motor (EESM) by 2 to 3.2% in WLTP and MCT drive cycles.

Keywords: Efficiency, electric vehicle, motor control.

1. Introduction

Electrification is progressing at a staggering pace in the automotive industry. More and more automakers have pledged to phase out development of Internal Combustion Engines (ICEs) and move forward to all-electric solutions as early as the 2030s. This will be a revolutionary change in the history of the automobile.

Nevertheless, Electric Vehicles (EVs) still face various technical challenges. The most notable ones are system efficiency and implementation cost. Increasing the efficiency of EV powertrains plays an important role in reducing grid load, decreasing pollution from electricity generation, and extending the driving distance per charge. However, improvements to efficiency over the past decade have focused on technologies that increase rare earth metal usage.

Although motors with large amounts of rare earth material have extremely high levels of peak system efficiency – above 90% or even 95% – the efficiency at lower loads, frequently encountered during EV operation, is often below 70%, which results in downgraded overall system performance.

Moreover, sources of economically recoverable rare earth metals are concentrated in only a few locations worldwide. Among them, Neodymium and Dysprosium are of critical importance and risk. Although these materials have equipped some of the roughly 10 million EVs in use today, it is unlikely to be an adequate and affordable solution in the future when the entire 1.4-billion-unit automotive fleet consists of EVs. In the next decade, the demand for these metals is estimated to more than double [1, 2]. Although future prices of rare earth magnets are not yet known, the price of equipping an electrical vehicle with these magnets may make these vehicles impractical to own for large portions of the population. We cannot rely exclusively on rare earth metals in the future.

2. Dynamic Motor Drive

The concept of Dynamic Motor Drive (DMD) is shown in Fig.1. With conventional control, the maximum energy efficiency is achieved at 25 to 30% of full load operation. As can be seen, the efficiency of conventional control falls off dramatically at low loads. In contrast, under DMD operation, torque is delivered intermittently at the load that achieves highest efficiency.

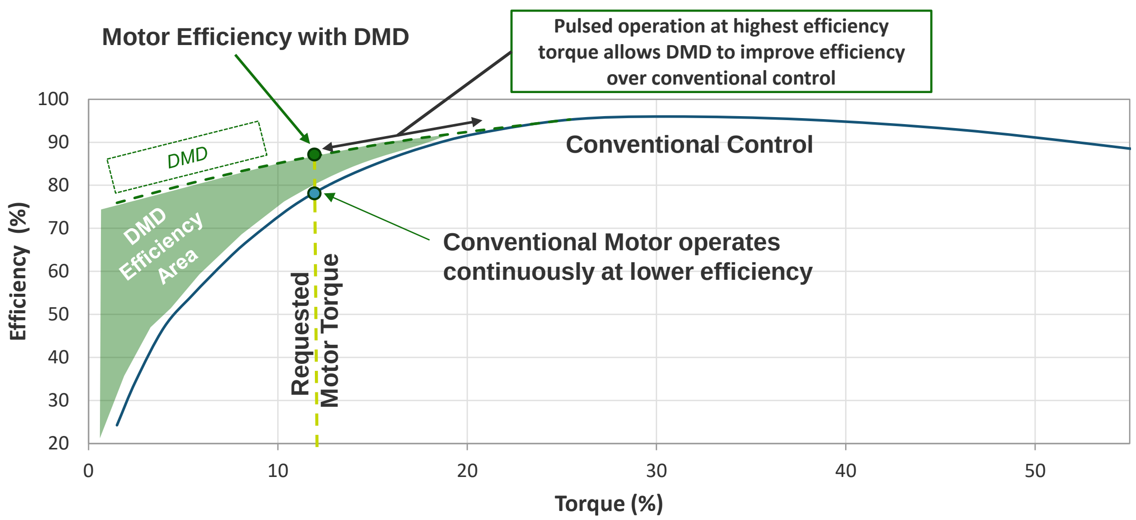


Fig.1 A typical motor system efficiency characteristics at a constant speed.

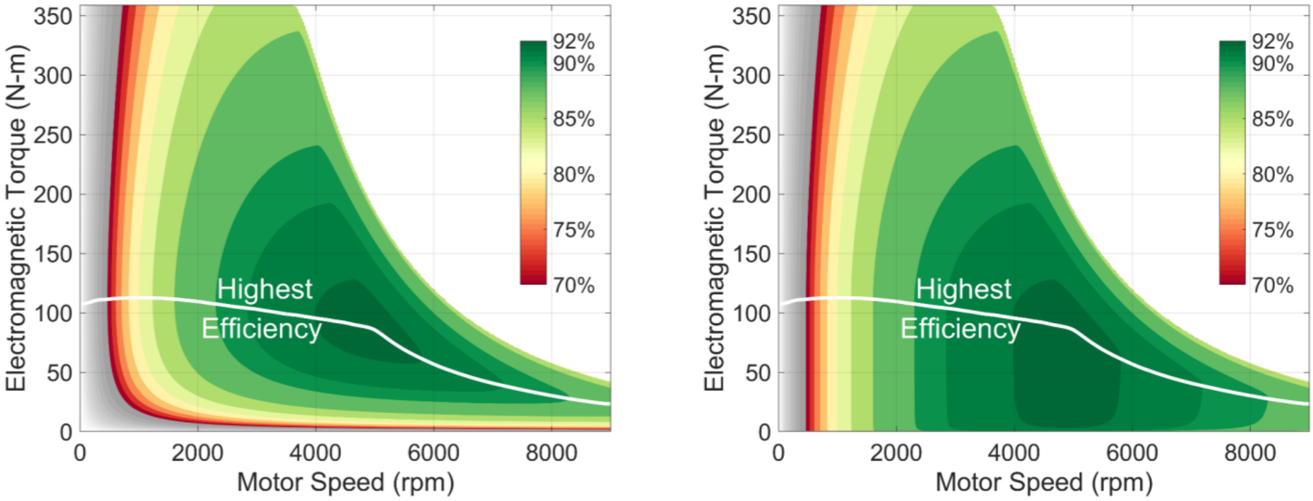


Fig.2 Improved electrical efficiency at low loads from conventional control (left) to DMD (right).

In the example given in the figure, working at a torque request of 12% load is achieved by operating at the more efficient 24% load, but with a 50% duty cycle. This allows the overall efficiency, even at low loads, to approach the levels only previously possible at high loads on the drive cycle.

The resulting motor efficiency is shown in Fig.2 for a 142kW EV powertrain. Efficiency of conventional operation, shown at left, is significantly worse at low loads when contrasted with DMD, shown at the right. For reference, the torque of most-efficient-operation for every motor speed is indicated by the overlaid white line. Torque requests at loads below that line can be improved with DMD. In practice, this means that for most vehicle operation, torque requests below 100 Nm can be improved with DMD. For a large portion of operation during the drive cycle, gains of over 5 or 10% are possible.

3. Loss Analysis

The effectiveness of DMD depends on the relationships between torque, current, and system losses. Detailed discussion can be found from previous publications [3, 4] but are broadly summarized in Fig.3. In the figure, as an illustrative example, conventional operation is contrasted with a motor operating with a simple 50% duty cycle square wave of load.

For most power losses in a motor control system, the relationships with motor current can be categorized into two types: losses that linearly proportional to current, and losses that are quadratically proportional to current. For instance, inverter switching losses are linear, while copper losses and eddy current losses are quadratic. Conduction losses of power switches combine both linear and quadratic terms, while hysteresis losses are nearly linear at low loads and are closer to quadratic at high loads.

The relationship between torque and current differs with motor topologies. For Surface-mounted Permanent Magnet motors (SPMs), torque is proportional to stator current, as expressed in (1).

$$T = pK_e i_q \tag{1}$$

For an SPM at 50% duty cycle operation, the current employed during DMD's intermittent operation is double the peak current that would have been required for conventional motor operation. As a result, the average value of losses that are proportional to current remains the same, but that of losses that are quadratic to current doubles. The net result is, for SPMs, gains are not expected to be found.

In contrast to SPMs, Synchronous Reluctance Motors (SynRMs), utilizing reluctance torque instead of magnetic torque, have a quadratic relationship between torque and stator current.

$$T = p(L_d - L_q)i_d i_q = p(L_d - L_q)i_s^2 \sin\delta \tag{2}$$

At the same 50% duty cycle, the peak current increases by only 41.4%, which leads to no change in copper losses. But for losses proportional to current, like switching losses and some part of conduction losses, they are reduced when DMD is utilized.

Another example is Externally Excited Synchronous Motors (EESMs), which have current on both stator and rotor sides. For simplicity, suppose there is no reluctance torque,

$$T = pL_m i_f i_s. \tag{3}$$

The total copper loss of stator and rotor is

$$P_{cu} = R_s i_s^2 + R_r i_f^2. \tag{4}$$

In maximum-torque-per-ampere (MTPA) control, also known as minimal-copper-loss control, the first derivative of total copper loss satisfies condition (5).

$$\frac{dP_{cu}}{di_s} = 0 \tag{5}$$

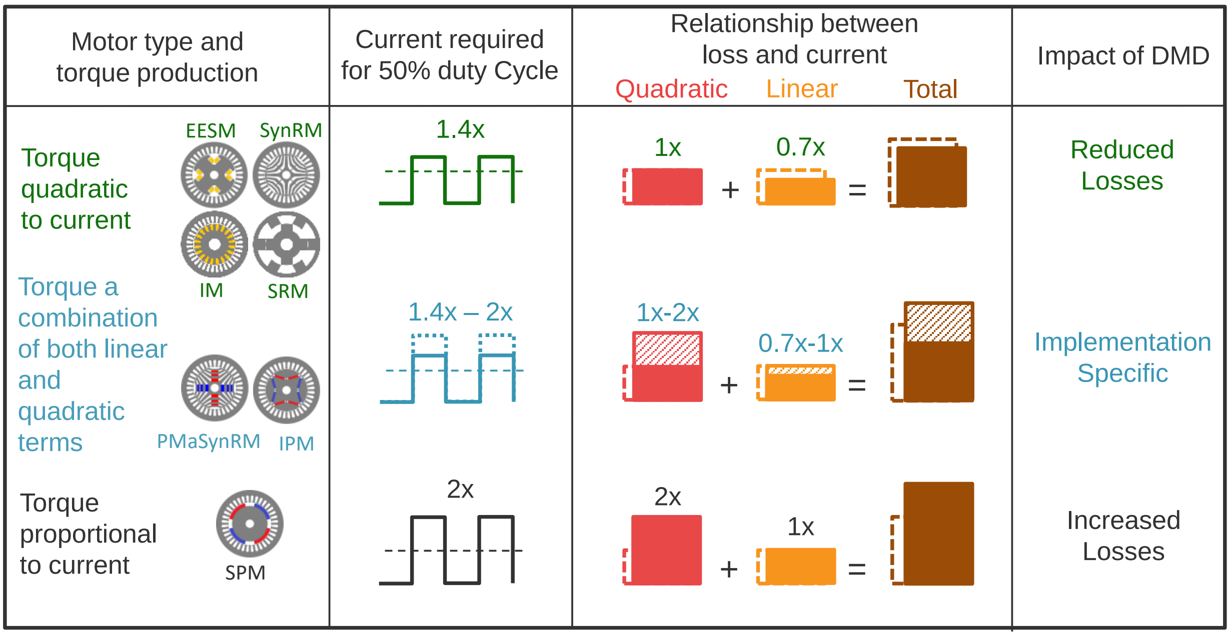


Fig.3 Efficiency improvement possibility of different motor topologies.

By solving (5), it is possible to find out the relationship between torque, stator and rotor currents as follows:

$$T = pL_m\sqrt{R_s/R_r}\,i_s^2 = pL_m\sqrt{R_r/R_s}\,i_f^2. \qquad (6)$$

This is true only when the motor operates within linear region with no magnetic saturation. It should be noted that even in cases where reluctance torque exists, a similar conclusion can still be achieved although more complicated mathematical deductions are necessary.

Similar to SynRMs, EESMs are characterized by having a quadratic relationship between torque and current in the MTPA region. With this relationship, DMD is also effective to substantially reduce the losses of EESMs.

Other motors, such as Interior Permanent magnet motors (IPMs) and Permanent Magnet Assisted Synchronous Reluctance Motors (PMaSynRMs), combine both magnetic torque and reluctance torque. Torque for these types of motors is a function of both current and the square of current. The ratio between these two factors determines the extent to which DMD can improve efficiency.

From the analysis above, it is known that DMD is most effective for motors without magnets. These types of motors do not contain rare earth metals, and as such eliminate the supply chain volatility inherent in the use of rare earth magnets. On average, since May of 2019, Dysprosium has increased in price by 3.5% every month, or approximately 50% annually [5]. The difficulty in sourcing these magnetic materials is expected to continue indefinitely and will limit the industry's ability to produce high efficiency powertrains across the automotive fleet. Eliminating the use of rare earth metals is an enormous advantage in securing the ability to produce future vehicles. And DMD is an effective way to make up for the efficiency loss due to the removal of magnets.

4. Vibration Suppression Strategy

All vehicle developments have strict constraints on vibration to ensure customer comfort and acceptance. For EVs, this vibration often comes from the torque ripple, a periodic increase and decrease of output torque as the motor shaft rotates. The amplitude, frequency, and phase of the torque ripple are decided by spatial flux distribution and rotation speed. Two exemplar frequencies are shown in Fig.4(c), the first and sixth order harmonics. The torque ripple is not controlled, and thus the vibration induced by it cannot be avoided. This is particularly critical at very low speeds when there are minimal other sources of noise and vibration that could potentially mask operation. At those conditions, the relative kinetic energy of the system means that even modest ripples in torque result in high amplitudes of vibration.

In contrast to the torque ripple that is a common problem in EVs today, DMD algorithms offer control of pulsing strategies, which helps to eliminate perceptible vibration. The modulation frequency of DMD is selectable independently from rotor or vehicle speed. Two factors can be considered. The first is human sensitivity, which is usually between 0.2Hz and 20Hz as shown in Fig.4(a). The second is resonance, which varies from vehicle to vehicle but can be measured by tests. Fig.4(b) shows the Frequency Response Functions (FRFs) of seat track and steering wheel for a

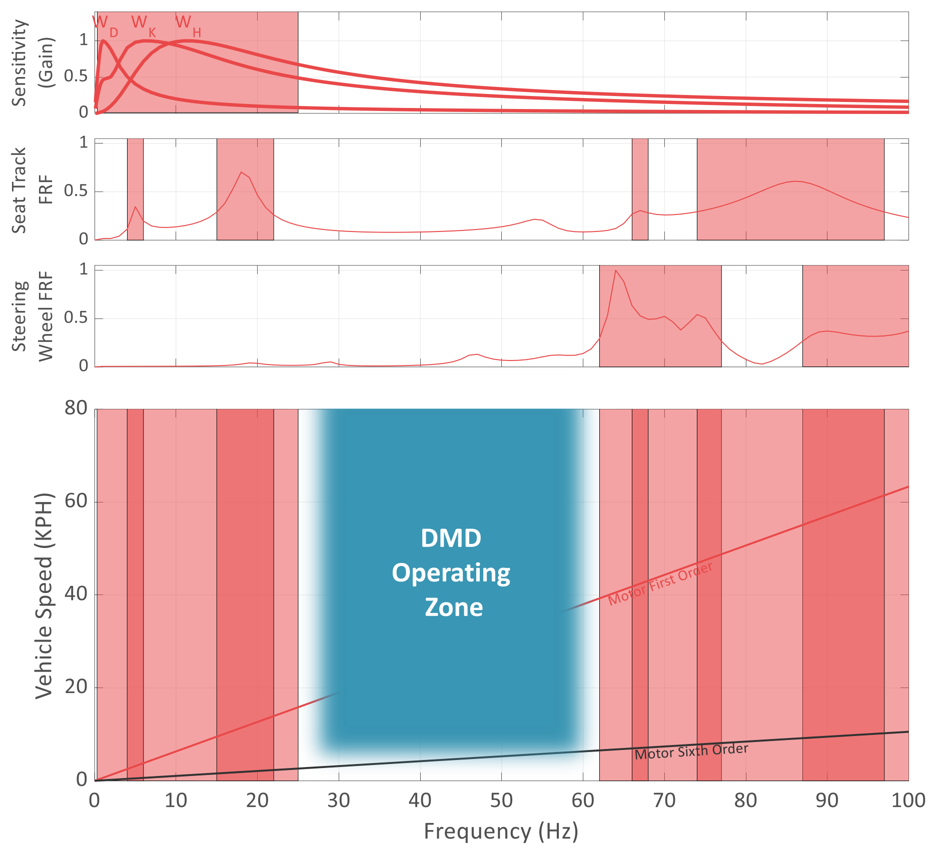


Fig.4 DMD algorithms operates while avoiding resonances and perceptible vibration. (a) top: human sensitivity gain; (b) middle: frequency response functions at seat track and steering wheel for a 2020 Chevrolet Bolt; (c) bottom: DMD operating zone.

2020 Chevrolet Bolt. For both limitations, areas highlighted in red must be avoided. Fortunately, even given these restrictions, there is a generous area in which DMD can operate as shown in blue on Fig.4(c).

Furthermore, it is possible to operate DMD only at the vehicle speeds, torque amplitudes, and operating frequencies at which vibration will not be felt by the passenger. As shown in Fig.4(c), DMD operation is excluded below 10km/h, which avoids the extremely sensitive region of very low speeds.

5. Optimal Motor Control

Selecting DMD modulation frequencies of 20 to 60 Hz requires careful management of transient motor torque. As DMD repeatedly cycles torque on and off to minimize total energy consumption, performance during the transition becomes critical for cumulative efficiency. This, in turn, requires rapid ramping of motor torque between on and off states, as well as a good current tracking to the MTPA curve during the transient. To meet all these requirements, a current control with fast response speed becomes vital.

A current controller's response speed is generally determined by several factors: battery voltage, time constant of the winding circuits, sampling rate, and the controller's cutoff frequency. Nevertheless, even with these physical limitations, it is still possible to obtain the expected DMD control response for most vehicular traction motors, as there are several advantageous factors for control of DMD with electric motors.

First, DMD is primarily used at low loads in the low to medium speed region. Under this condition, there is generally enough DC bus voltage margin for appropriate current control.

Second, for the traction motors that are most suitable for DMD strategy, stator windings usually have time constants which do not hinder fast current response speeds.

Third, the state-of-the-art microcontrollers used for vehicle traction purpose have sampling frequencies several orders of magnitude faster than DMD modulation frequencies. DMD usually operates between 20 and 50Hz, while the microcontrollers on the inverter commonly operate at 10kHz. With such a high rate, even conventional Proportional-Integral (PI) controllers can be implemented with a cutoff frequency of 500Hz. For microcontrollers operating at a slower clock speed, strategies like deadbeat control and direct torque control can be used to achieve the required current response.

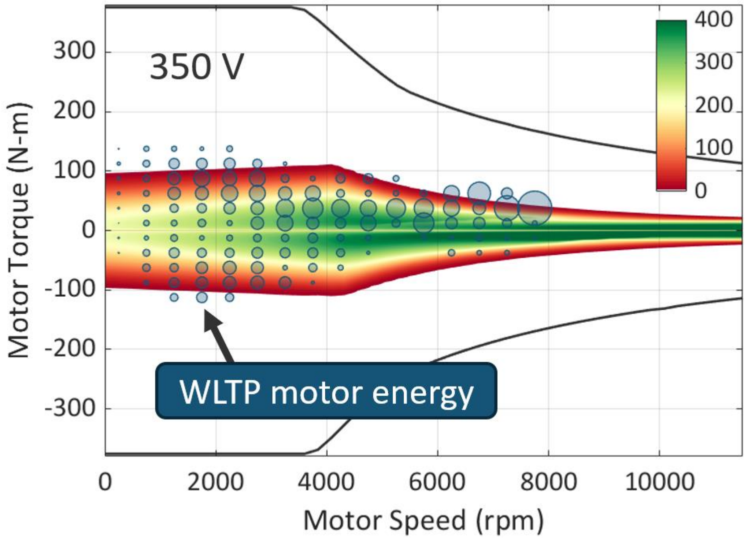
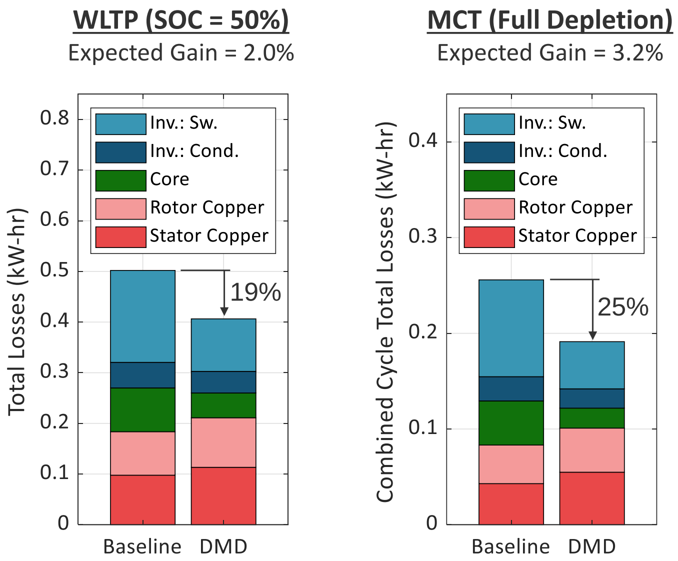


Fig.5 Simulation results of DMD loss reduction in Watts at 350V battery voltage of an 142kW EESM and energy consumption of the motor and inverter system in the WLTP drive cycle.



(b)

Fig.6 Loss breakdown and reduction amount of DMD in the WLTP and MCT drive cycles.

For the above reasons, it is possible to deliver the required transient performance, and achieve the desired DMD modulation frequency.

6. EV Range Improvement

To verify the efficiency improvement made possible with DMD, a simulation study was conducted for an EESM as the traction drive of a 1760 kg subcompact battery EV. Motor parameters are summarized in Table 1. Electrical losses in the motor and inverter were determined using a finite element analysis (FEA) model. Losses at different speed and load conditions with and without DMD operation are compared in Fig.5 with loss reductions by DMD shown as the colored area.

Table 1 Motor Parameters

Parameter	Value
Peak torque	374 Nm
Peak power	142 kW
Peak speed	12,000 rpm

Furthermore, drive cycle simulations of the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) and the US Multi-Cycle Test (MCT) were carried out. Energy consumption on the WLTP is overlaid in Fig.5(a) as circles. The bigger the area of a circle, the

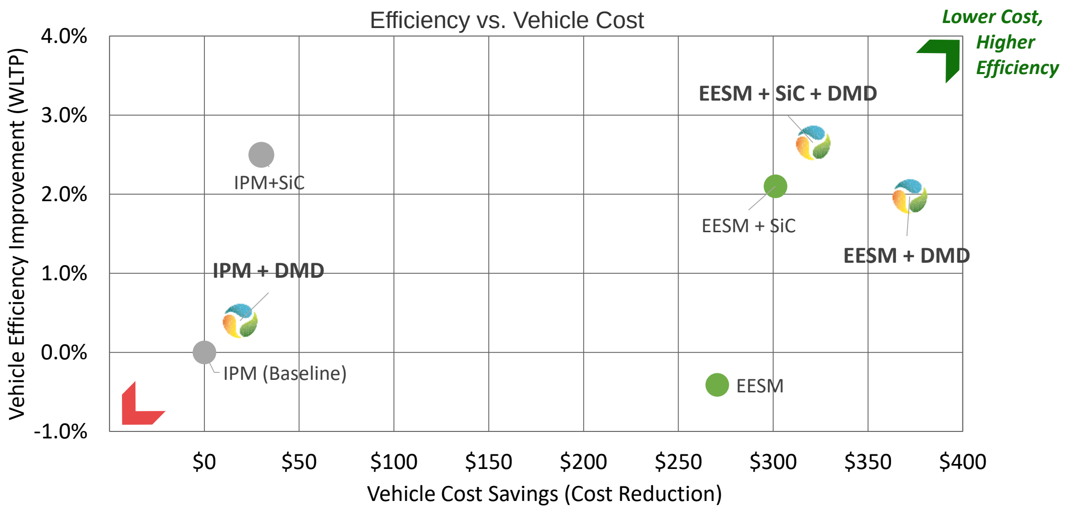


Fig.7 The impact of DMD on an IPM and an EESM for traction drives.

more energy consumed at that speed and load combination. Most operating points are covered in the DMD loss reduction area, implying the effectiveness of the DMD strategy.

The cumulative total loss and breakdown of each type of loss are shown as bar charts in Fig.6. A 19% reduction of losses was observed for the WLTP, and 25% for the MCT. In both cases, large cuts in motor core losses, inverter conduction losses and switching losses offset a slight increase in motor copper losses.

The reduced losses with DMD translate to cycle energy consumption reductions of 2% on the WLTP and 3.2% on the MCT. These are substantial considering they are the result of an easily implementable software strategy.

7. Summary

The impact of DMD on EESM is summarized in Fig.7. Powertrain costs are projected for a battery EV with a range of 400km. Battery size is scaled as appropriate to meet that range. The battery cost is assumed to be $130 per kWh of capacity, and magnet cost is the current 2022 price.

From the figure, it is seen that the EESM and DMD combination is far less expensive and more efficient than the industry standard IPM, with or without an inverter of silicon carbide (SiC) field-effect transistors (FETs). Clearly the benefits brought by DMD have twofold. For end users, it means less energy consumption, and thus cheaper utility bills. For manufacturers, it means less battery capacity for the same distance, and together with the magnet-free design, results in savings of several hundred US dollars on vehicle cost.

All these improvements are achieved with an easily implemented software change in conventional controllers operating with conventional inverters. This makes it possible to improve the efficiency of motors that are free from magnets, and thus significantly reduce the dependence on the rare earth metals that otherwise will limit our ability to electrify the automotive fleet.

8. References

[1] Adamas Intelligence: “Spotlight on Dysprosium”, 2018.
[2] Adamas Intelligence: “Rare Earth Elements: Small Market, Big Necessity”, 2019.
[3] M. Younkins, P. Carvell, J. Fuerst: “Dynamic Motor Drive: Optimizing Electric Motor Controls to Improve Efficiency”, 42nd Vienna Motor Symposium, Vienna, 2021.
[4] Z. Chen, P. Carvell, M. Younkins: “Optimizing Electric Motor Controls with Dynamic Motor Drive”, 30th Aachen Colloquium Sustainable Mobility, Aachen, 2021.
[5] Kitco Metals Inc.: “Strategic Metals”, online: www.kitco.com/strategic-metals/, accessed February 1, 2022.

9. Nomenclature

T: electromagnetic torque
p: number of pole pairs
K_e: back-EMF coefficient
i_d: d-axis current
i_q: q-axis current
i_s: stator current
i_f: excitation current
δ: current angle
L_d: d-axis inductance
L_q: q-axis inductance
L_m: mutual inductance
R_s: stator resistances
R_r: rotor resistance
P_{cu}: copper loss power