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Evaluation of Current Developments in Battery Electric and Hybrid Vehicle Electric Traction Motors

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Abstract
An overview of current design trends for electric traction motors in electric vehicles—primarily battery electric and fully hybrid vehicles—is provided in this study. The main automakers from the past ten years—Jaguar, Tesla, Toyota, BMW, Nissan, General Motors, and Audi—are the subject of this study's permanent magnet traction motor analysis. This study's primary focus is on electromagnetic motor design, but it also covers the motor's mechanical characteristics and current developments in magnetic materials. In addition, the performance metrics including power density, motor speed, and field weakening are assessed and contrasted. Last but not least, performance and design trends for traction motors are also discussed. The objective is to showcase the most recent advancements.
Keywords- Permanent magnet motors, electric traction motors, electric cars, and rotor design

I. INTRODUCTION

Due to government initiatives to subsidize the purchase and operation of these vehicles as well as stricter regulations to reduce pollutant and CO2 emissions, sales of electric vehicles (xEV), primarily battery electric vehicles (BEVs) and plug-in hybrid vehicles (PHEVs), are drastically increasing. Global annual sales of cars with electrified drivetrains are expected to rise from 2.8 million units in 2019 to a third of the market in 2025, or about 35 million vehicles, according to predictions [1]. Larger sport utility vehicles (SUVs) and luxury electric cars will come equipped with two or more electric traction motors; as a result, the production of electric traction motors will rise annually from approximately 3 million units in 2019 to over 45 million units within necessitate various mass production facilities, material usage, and design strategies. From a commercial standpoint, the majority of automakers and For the electric traction motors, vendors select permanent magnet machines, which can be either an interior permanent magnet motor (IPM) or a permanent magnet assisted synchronous reluctance motor (PMaSynRM). Even if some manufacturers also utilize induction motors and externally stimulated synchronous machines, the permanent magnet motor will continue to play a prominent position in the industry for the foreseeable future. Consequently, the sole subject of this study will be permanent magnet motors.This study initially provides a summary of how traction motor performance characteristics and electromagnetic design have changed over the past ten years. The emphasis will be on the rotor lamination designs, in addition to the essential information on functionality and operating ranges. Additionally, noise reduction technologies and winding configurations are covered. The traction motors of the following automobiles are examined for this study: Nissan Leaf (2010), Chevy Volt Gen 1/Opel Ampera (2010), Toyota Prius Gen III (2010), Tesla Model 3 (2017), Jaguar I-pace (2019), Chevy Bolt (2016), BMW 225xe (2016), BMW i3 (2013), and Nissan Leaf (2010). The motors' essential mechanical and electromagnetic properties are benchmarked. Lastly, a prediction for motor designs and material trends in the future.

II.OVERVIEW OF TRACTION MOTOR

2010 saw the release of a number of new full hybrid cars, and ever since, sales of xEVs have sharply surged, rising from a few thousand to 2.8 million units. in 2019 [1], [2]. The specifications for the traction motors and their design also underwent a major modification as a result of this rise. An overview of the performance statistics for the traction motors under investigation is provided in Table I. This information is derived from the provided references as well as from our own disassembly and benchmarking of these motors. The motors under examination exhibit a broad spectrum of performance metrics, including power, torque, and speed, and vary in terms of geometric parameters and arrangements, such as the number of slots and poles, skewing, magnet arrangement, and so on. Keep in mind that care requirements depending, among other things, on the outside temperature and how long the motor can run at this output until a power reduction kicks in. Additionally, these values may be constrained by further elements of the electric power train, like the battery or the inverter. In terms of winding architecture, all but three of the 10 motors under investigation employ a slot per pole per phase number of q=2. Winding configurations with 48 slots and 8 poles or 72 slots and 12 poles are the most prevalent. Every motor in a hybrid car, with the exception of the single traction motor, has a dispersed winding.

TABLE I OVERVIEW AND PERFORMANCE VALUES OF THE STUDIED MOTORS [3]–[13]

	Jaguar I-Pace	Tesla 3	Chevy Bolt	BMW i3	Nissan Leaf	Toyota Prius IV	BMW 225xe	Audi A3 e-tron	Chevy Volt Gen 1	Toyota Prius III
Market introduction	2019	2017	2016	2013	2010	2017	2016	2014	2010	2010
Vehicle Type	BEV	BEV	BEV	BEV	BEV	Hybrid	Hybrid	Hybrid	Hybrid	Hybrid
Peak Power / (kW)	147	202	150	127	80	53	100	75	110	60
Peak Torque / (Nm)	348	416	360	250	280	163	180	330	390	207
Max Speed / (rpm)	13000	18100	8810	11400	10400	17000	14000	6000	9000	13500
No Poles	8	6	8	12	8	8	8	16	12	8
No Slots	48	54	72	72	48	48	48	24	72	48
Max. motor frequency / (Hz)	867	905	587	1140	693	1133	933	800	900	900
Skewing	Rotor skew	Rotor V-skew	No skew	Rotor lin.-skew	No skew	No skew	Stator skew	Rotor lin.-skew	Rotor V-skew	No skew
Winding type	Hairpin	Distributed	Hairpin	Distributed	Distributed	Hairpin	Distributed	Concentrated	Hairpin	Distributed

III. Performance characteristics of the motor

Figs. 1 and 2 provide a summary of the motor performance values concerning power, speed, and torque. The nominal speed, also known as the base speed, is displayed in Fig. 1 over maximum torque. It is evident that the nominal speed range is often between 2500 and 6000 rpm, and the peak torque values are typically between 150 and 450 Nm.

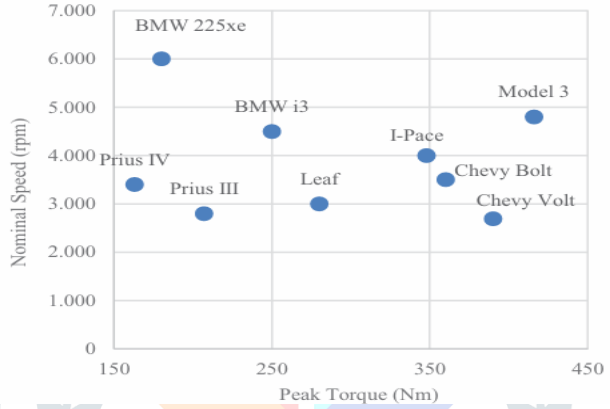

Figure 1: Overview of nominal speed over peak torque for the motors under investigation.

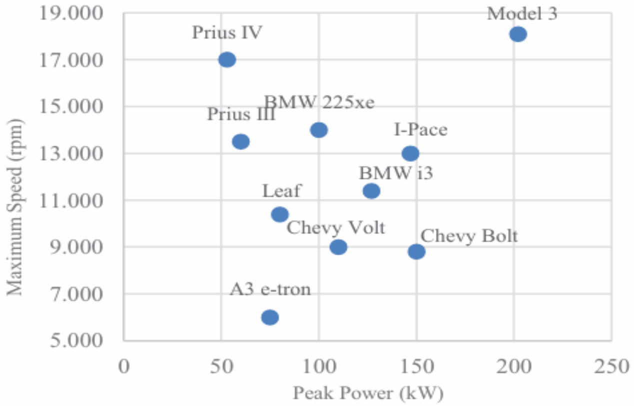

Fig. 2: Overview of the investigated motors' maximum speed over peak power.

To compare the maximum motor ratings, Fig. 2 displays the maximum motor speed over the peak power. As can be observed, this figure's motor configuration differs from Fig. 1's. This is because the motors have varying constant power-speed ranges, and as a result, varying field weakening capacities. Additionally, this demonstrates how the torque-speed characteristic can vary significantly even between motors with comparable peak powers. In terms of power density, the motors are compared in Fig. 3 for both power per weight (kW/kg) and power per active volume (kW/liter). Here, the active motor core length without end windings and the minimum outer stator diameter define the active volume.

For integrated traction motors, comparing the motors based on volume is more equitable than comparing them based on weight because the housing designs vary greatly (e.g. the motors of the Toyota Prius are integrated into the gearbox rather than having its separate housing, and some motors have a dual side axle shaft, clutch, or gear set built into the rotor design. This explains why the two power density values in Figure 3 differ from one another. Power is directly correlated with torque and speed, and the motor's torque grows linearly with the active length of the motor and essentially squares the airgap diameter. The makers make every effort to maximize the spinning speed of the motor because they want the motor's volume to be as compact as feasible. However, surpassing tensions in the rotor laminations and the bearing design limit the maximum rotational speed and, consequently, the rotor surface velocity. Additionally, when speed increases, so do iron losses and the switching frequencies used by inverters due to the higher electrical frequency.

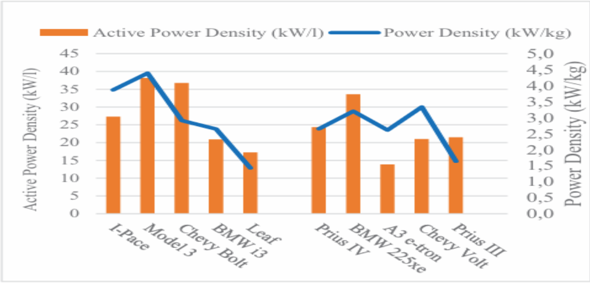

Figure 3: Gravimetrical and volumetric power density comparison.

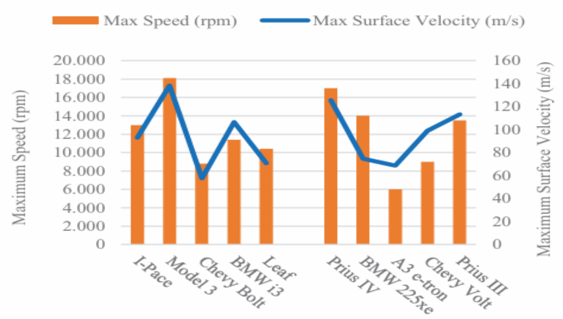

Figure 4: Rotor speed and surface velocity comparison.

The graphic in Figure 4 compares the maximum rotational speed (left axis) with the corresponding rotor surface velocity (right axis). Observing the rise in power density during Figure 3's depiction of the last ten years and Figure 4's speed increase make it evident that, particularly in the case of battery-electric cars, an increase in rotor speeds is primarily responsible for the improvement in power density. Modern motors may rotate at over 17,000 rpm and achieve surface velocities of over 120 m/s. Only advancements in the materials used for the lamination sheets and the bearings made these accomplishments possible. Some manufacturers offer product series that are specifically designed for xEV applications in order to boost the mechanical strength of lamination sheets. With the same rotor design arrangement, these sheets' higher silicon content usually boosts the material's yield strength and allows for faster speeds [14]. In addition, because of higher electrical fundamental frequencies, the lamination thickness in more recent motors has also been lowered to lessen eddy current losses. Table I shows that the motors reach frequencies exceeding 1000 Hz at maximum rotational speed. These high frequencies are raising the demands on the switching capability of power electronics in addition to sharply increasing eddy currents (which rise with frequency squared). Currently available motor designs typically have a lamination thickness of the cage and lubrication are what prevent the bearings—traction motors typically use deep groove ball bearings—from being further increased in rotating motor speeds. In particular Bearing manufacturers offer novel cage materials that increase the maximum rotational speeds for electric traction applications. To decrease the weight of the cage and extend its potential operating range, new polyamide cages—possibly with or without glass fiber reinforcement—are being developed in place of metal cages. The weight of the permanent magnet material in the rotor is another crucial performance factor. All motors under investigation make use of neodymium-iron-boron (NdFeB) magnets. To obtain the weight of the permanent magnets is calculated per motor peak power for a fair comparison of the motors, and Fig. 5 shows the result. The magnet material consumption is indicated by the unit of measurement, grams per kilowatt, although it does not account for the permanent magnet grade or the high rare earth content. As a result, there may be large differences in the magnets' strengths and costs throughout the motors.

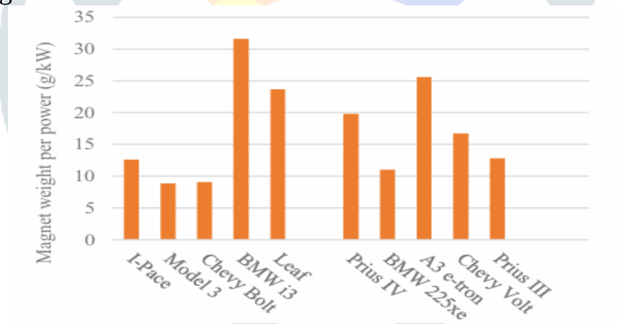

Figure 5 shows a comparison of the motors' peak output and total magnet weight.

IV.THE LAST DECADE SAW AN EVOLUTION IN MAGNETIC DESIGN

An overview of the various rotor designs of the traction motors under study is provided in Fig. 6. It is evident that every motor has buried magnets and guided magnetic pathways. Characteristics of the rotor, also known as flux barriers. This is to minimize the utilization of magnet material while simultaneously utilizing reluctance torque and attaining a wide range of constant power speed for field weakening operation. The magnets are often grouped in a single or double layer V-shape in rotor designs. However, there are also cars with flat magnet layouts (like the BMW i3 and Jaguar I-Pace) or cars that combine the two (like the Nissan Leaf). Firstly, by increasing the reluctance torque and decreasing torque ripple, the cavities in the rotor sheets around and below the permanent magnets improve the electromagnetic performance of the motor. However, as seen in the majority of modern designs, the chambers below the magnets are particularly for weight reduction and improved air cooling.

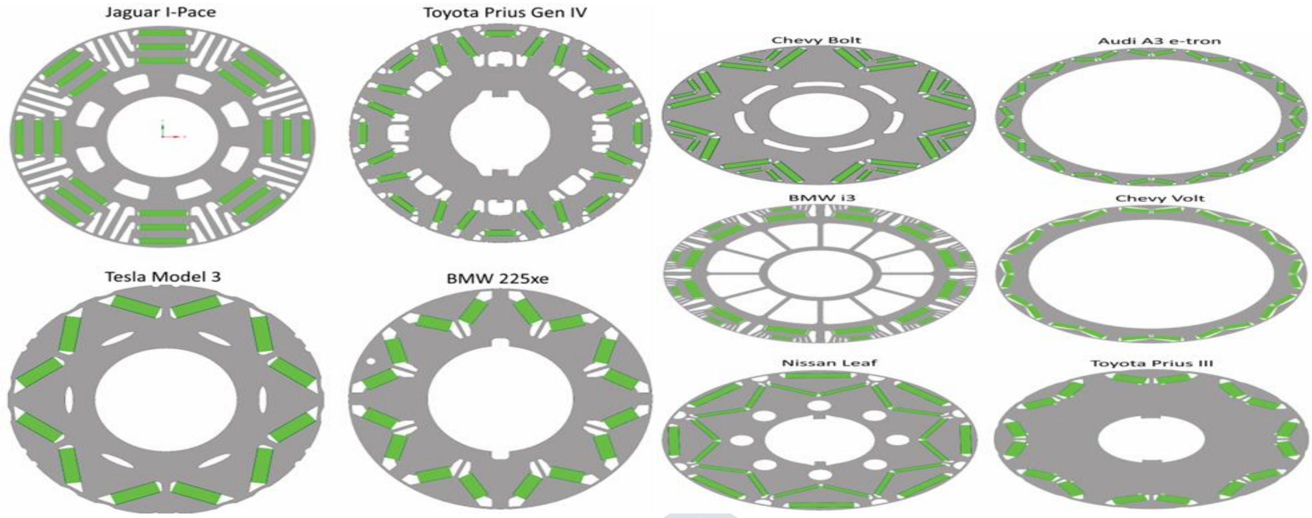

Figure 6 shows the rotor design geometries of the traction motors under study. The permanent magnets in green are not reliant on the direction of magnetization.

Acoustic and Noise-Reduction Features of Magnetic Design

Compared to industrial motors, noise is more significant in electric traction motors used in automobiles. Because electric motors often emit higher frequency noise excitations, passengers in BEVs without combustion engines are particularly susceptible to motor noise. As a result, in certain cars, sound insulation kits also cover the electric traction motors. Nevertheless, noise reduction in the motor itself is a favored approach over acoustic insulation with additional materials. Air gap harmonics caused by the layout of the stator slots and the rotor design are a major cause of noise and therefore acoustic issues. As a result, skewing or other features in the rotor surface and magnet pocket design are used in the stator or rotor design to reduce these harmonics. Table one complete stator slot is covered by the skew angle, which is usually linear in stator skewing. Because it is more economical, the rotor skewing is usually not as continuous as the stator skewing. basic permanent magnet forms, such as rectangles. Instead, the skewing is accomplished by a fixed stepping of the rotor stacks. This can be arranged in a V-shape or linearly from one rotor side to the other [15]. A typical linear rotor and stator skewing utilized in traction motors is depicted in Fig. 7.

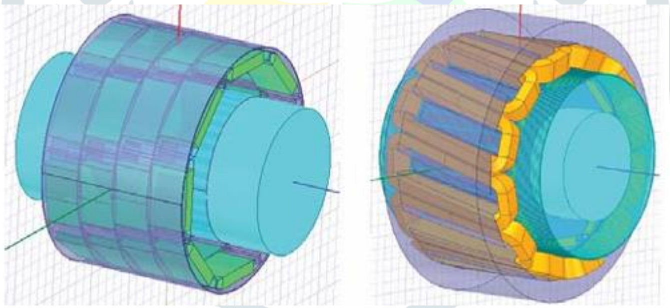

Figure 7 shows the linear skew of a PMSM's rotor (left) and stator (right).

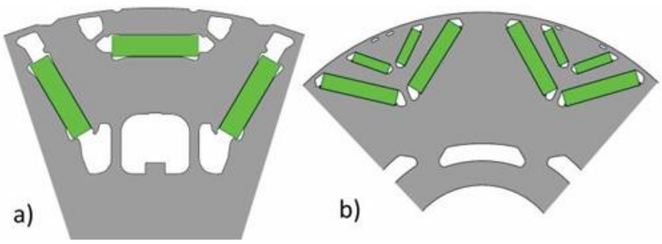

Figure 8: Torque ripple reduction features on the rotors of the Chevy Bolt (b) and Toyota Prius IV (a)

In addition to flux barriers and minor asymmetry in the rotor design, geometric elements on the rotor surface can also lower airgap harmonics. Reducing more harmonics through the modification of the relative airgap length in specific areas. As a result, the motor's noise level and overall harmonic spectrum are decreased. For example, these attributes are included in the tiny cavities on the rotor surface are lowering the harmonics in the airgap in the most recent Toyota Prius motor (see Fig. 8 a)). As seen in Fig. 8b) [3], [4], the Chevy Bolt motor, on the other hand, includes small asymmetric chambers above the magnets and asymmetric magnet alignments that vary between the poles.

Comparing Different Types of Windings

The winding designs of the motors under investigation are also displayed in Table I. Typically, the traction motors of fully hybrid and BEV vehicles feature distributed windings, frequently with 48 or 72 places available. Round wires (usually grade 2 wires, comparable to those found in industrial motors) or rectangular wires with four to eight layers per slot can be used to wind these distributed windings. Usually, hair-pin windings are the result of the rectangular wires. This indicates that every conductor is forced into the slots from one side and, on the other, bent before being welded together. When compared to round wire windings with copper fill factors, the hair-pin winding's main benefit is its huge copper fill factor (>0.7).

Field Weakening and Operational Ranges

For BEVs and parallel hybrid cars, the traction motors usually have a set gear ratio to the wheels. This that is, the maximum traction torque and, consequently, the vehicle acceleration are defined by the maximum torque at low speeds. Conversely, the maximum motor speed then sets a restriction on the maximum vehicle speed. Up until now, only high-end and race automobiles have been equipped with transmissions with two or more gears in order to optimize acceleration torque and top speed.

Traction motors employ field weakening operation, which is enhanced by the magnetic rotor design and the fact that they do not require the full torque across their whole speed range. material for permanent magnets [16], [17]. An overview of the field weakening range over the motor peak power is provided in Fig. 9, which is calculated as the maximum speed divided by the nominal speed. Evidently, every traction motor has a broad field weakening range of at least 2.5 and, in some cases, up to 5 times the nominal speed.

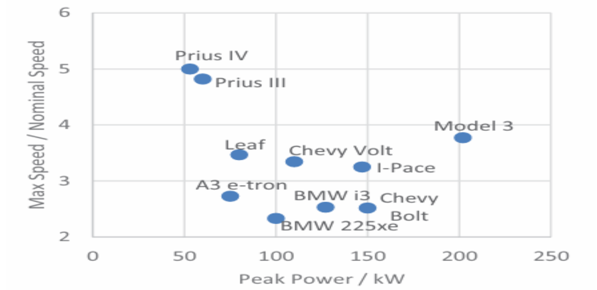

Fig. 9. Overview of field weakening range over peak power.

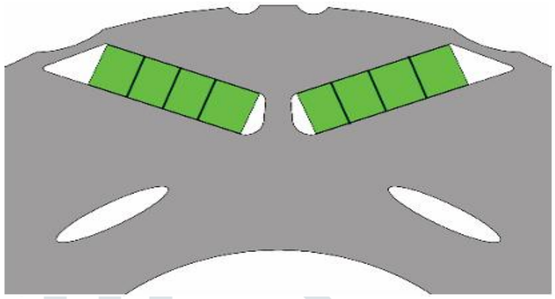

Figure 10. A Tesla 3 rotor segment with permanent magnets arranged radially to reduce eddy current loss.

Even if the electric traction motors' power density much increased, more may be done to make them even better. The US Department of Energy's goals specifies that, for a motor with a peak power of 100 kW, the power density must rise from the current approximate 35 kW/l to over 50 kW/l by 2025 [18]. It is anticipated that the maximum speed would rise even more, to 20,000 rpm and beyond, in order to accomplish this aim. The reduction of heavy rare earth content, the reduction of magnet costs, and the decrease in magnet volume are the next trends in traction motor advances [12], [19]. However, there is also talk about reducing eddy current loss inside permanent magnets. Buried magnets in the rotor can be constructed from several pieces in the magnet core as described in reference [20]. Lastly, [21] presents a method for changing the magnet size in an axial direction. This lowers the motor's magnet mass as well as, consequently increases the torque per magnet weight. Using this method, eddy current losses in the smaller portions would be the next logical step.

Conclusion

This study provides a thorough review of the evolution of the traction motor. Ten traction motors from fully hybrid and battery-electric cars are analyzed, and their technical traits and attributes contrasted. The thorough comparison of the rotor lamination design with the buried permanent magnets is the primary topic. The last ten years' trends are emphasized, and additional advancements are talked about. The information supplied ought to offer the motor designer with a general understanding of the state and future directions of traction motors in electric cars.

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