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Traction motors for electric vehicles: Maximization of mechanical efficiency – A review

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HIGHLIGHTS

- Challenges and opportunities to maximize the overall efficiency of traction motors from a mechanical design point of view.
- Overview of various types of losses in traction motors with their mathematical formulation and minimization strategies.
- State-of-the-art transmission systems used in EVs, and their comparison based on vehicle performance and efficiency.
- Driveline configurations to exploit the maximum efficiency and their impact on the vehicle performance.
- Thermal Management Schemes pertinent to Mechanical design changes and their influence on overall efficiency.
- Material and Additive Manufacturing advances to enhance the overall efficiency of traction motors.

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ABSTRACT

With the accelerating electrification revolution, new challenges and opportunities are yet emerging, despite range anxiety is still one of the biggest obstacles. Battery has been in the spotlight for resolving this problem, but other critical vehicle components such as traction motors are the key to efficient propulsion. Traction motor design involves a multidisciplinary approach, with still significant room for improvement in terms of efficiency. Therefore, this paper provides a comprehensive review of scientific literature looking at various aspects of traction motors to maximize mechanical efficiency for the application to high-performance Battery Electric Vehicles. At first, and overview on the mechanical design of electric motors is presented, focusing on topology selection, efficiency, transmission systems, and vehicle layouts; Special attention is then paid to the thermal management, as it is one of the main aspects that affects the global efficiency of such machines; thirdly, the paper presents a discussion on possible future trends to tackle ongoing challenges and to further enhance the performance of traction motors.

1. Introduction

Climate change is widely acknowledged as severe issue of global concern [1], and road vehicle emissions are a key factor and a major cause of global warming: road transportation accounts for about one-fifth of the total EU emissions,[1] and the figures are similar for the US.[2] The automotive sector makes use of a significant amount of petroleum [2], which is detrimental to human society's long-term growth. Therefore, automotive industry is undergoing a paradigm shift from conventional internal combustion engine (ICE) vehicles to more environmentally friendly solutions to meet the targets set out in article 2 of the Paris Agreement [3]. As per the Fit for 55[3] legislative packages proposed by the EU Commission, the targets for reducing CO2 emissions for new cars have been increased to 55% from 37.5% by 2030. Moreover, a 100% CO2 emissions reduction target by 2035 for new cars has been enforced. Battery electric vehicles (BEVs) are experiencing a rise in popularity due to technological advancement and feasible

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[1] https://www.europarl.europa.eu/news/en/headlines/society/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics, accessed 29/11/2022.

[2] https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions, accessed 29/11/2022.

[3] https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition accessed 27/06/2023.

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Nomenclature

ρ	Fluid density around the rotor
C_f	Friction coefficient
w	Rotor speed
r	Rotor radius
L	Axial length
I	Current flowing through the conductor
R	Resistance of conductor
η_g	Overall gearbox efficiency
η_b	Efficiency of all bearings
η_{ng}	Efficiency of individual gears, and m is the number of gears
η_d	Overall efficiency of differential efficiency
η_{bd}	Overall differential bearings efficiency
η_{nd}	Differential gear efficiency
η	Total efficiency of transmission
η_{CV}	Efficiency of all constant velocity joints

Abbreviations

2WD/4WD	2-wheel drive/4-wheel drive
AC	Alternative Current
ACEA	The European Automobile Manufacturers' Association
ACIM	AC Induction motor
AM	Additive Manufacturing
BAAM	Big area Additive Manufacturing
BJP	Binder Jet Printing
CLEPA	European Association of Automotive Suppliers
CVT	Continuous variable transmission
DC	Direct Current
DMD	direct metal deposition
DMLS	DMLS-direct metal laser sintering
EM	Electric motor
ELU	Environmental load unit
EV	Electric Vehicle
FDM	Fused Deposition Modeling
FFF	Fused filament fabrication
IM	Induction Motor
IPMSM	Interior Permanent Magnet Synchronous Motor
IWM	In-wheel Motors
IWMG	In-wheel Motors with Gearsets
LEV	Light Electric Vehicle
LOM	Laminated Object Manufacturing
LPBF	Laser powder bed fusion
MM	Multi-Material
NEDC	New European Driving Cycle
PM	Permanent Magnet
PMAR	Permanent Magnet Assisted Reluctance
PMSM	Permanent Magnet Synchronous Motor
PMVM	Permanent Magnet Vernier Motor
SLM	Selective Laser Melting
SMC	Soft Magnetic Materials
SPM	Surface Mounted magnets
SRM	Switched Reluctance Motor
SynRM	Synchronous Reluctance Machine
UDDS	Urban Dynamometer Schedule
WRSM	Wound Rotor Synchronous Motor
WECL	Winding Eddy Current Loss

implementation plans at a mass level. According to the European Automobile Manufacturers' Association (ACEA), China currently dominates BEV market ahead of Europe and US, but forecast suggests that the European market will catch up in 2025 and eventually surpass other regions by 2030.[4] The advancement primarily focuses on key components such as batteries, traction motors, and power electronics.[5] The rapidly growing electric vehicle market is creating a significant demand for traction motors across various global regions and different vehicle categories [4,5]. These are praised for their simplicity and efficiency compared to ICE, fuel cells, solar, and other renewable options[6].

The powertrain system plays a crucial role in enabling high-performance in BEVs. Powertrain design is a multi-disciplinary task that encompasses mechanical [7], thermal [8], magnetic [9], and electrical domains [10]. This review paper aims to present key developments in the Mechanical design of BEV's powertrains, with a specific focus on those features, challenges, strategies, schemes, and critical aspects that impact mechanical efficiency. Furthermore, it introduces important insights about future trends and promising research topics in this area.

ICE run on low thermodynamic efficiency: while traveling at cruising speed, the vehicle utilizes just 25% of the energy the fuel produces [11]. The Paris Climate Agreement's[6] overall emission reduction objectives target can be mostly met through BEVs provided that the environmental footprint is monitored i.e., renewable energy sources are utilized for Electric Vehicle (EV) production [12]. There is still great room left to uplift efficiencies of individual components of the BEVs powertrain components such as the battery, traction motors, mechanical transmission, and power electronics [13,14].

Electric motors (EM) replace the ICE in BEVs and therefore must accomplish all the requirements for a power plant in a vehicle; they should operate in a wide torque and speed range enabling high performance.[7] EM must be able to deliver high overload power; higher torque at low speed for starting and climbing; moderate power at high speed for cruising; and function as a generator during braking [15,16]. High power density [kW/m^3] [17], torque density [Nm/m^3] [18], specific power [kW/kg] [19], Extensive and highly efficient operational range,[8] low vibration and noise [20,21], high reliability[22], and high performance-to-cost ratio[9] are required. Different KPIs such as peak power, torque, speed range, construction, compactness, geometry, and weight distribution of the motor are considered.

Efficient operation and thermal management of EV traction motors are indispensable for optimizing their performance and extending their lifespan [8,23–25]. It is imperative to thoroughly investigate a variety of thermal management techniques, including convection cooling, heat conduction, and hybrid solutions [7], as these methodologies exert a direct influence on both efficiency and sustainability. Within BEVs, the interplay between thermal management of traction motors and mechanical performance is evident. Maintaining these motors within their ideal temperature range is pivotal to maximize power output, minimize

4 Interactive map – Electric vehicle purchase incentives per country in Europe (2021 update) - ACEA - European Automobile Manufacturers' Association accessed 29/11/2022.

5 CLEPA – European Association of Automotive Suppliers accessed 29/11/2022.

6 https://unfccc.int/sites/default/files/english_paris_agreement, accessed 29/11/2022.

7 "'Wheels of fortune? A new age for electric motors.'" https://www.bbc.com/news/business-49958457, accessed 29/11/2022.

8 https://www.just-auto.com/interview/finding-the-edge-of-ev-efficiency-through-motor-and-driveline-technologies, accessed 22/06/2022.

9 https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/making-electric-vehicles-profitable, accessed 22/06/2022.

energy losses attributable to heat dissipation and consequently enhance the overall range of BEVs [26]. Furthermore, it is critical to delve deeply into innovative strategies and cutting-edge technologies that seamlessly integrate and synchronize thermal and mechanical elements to drive the continuous advancement of electric mobility.

The organization of the work is as follows: Section 2 focuses on the mechanical design aspects of EMs, covering motor type selection, various types of losses, transmission systems, and vehicle layouts. Section 3 addresses the critical topic of thermal management in EMs, discussing effective techniques for controlling heat generated by EM through the means of innovative cooling systems. And Section 4 highlights emerging trends and research gaps in the field, exploring evolving materials for EMs, advancements in additive manufacturing, and identifies areas that require further investigation.

2. Mechanical design

This section presents the state-of-the-art of mechanical design strategies and schemes adopted to optimize the functional requirements and increase the overall mechanical efficiency of traction EM. Different motor topologies presented in studies and patents are analyzed, using efficiency maps under different operating conditions, incorporating transmission to improve the performance. Different vehicle layouts are presented as well with focus on mechanical efficiency.

2.1. Topology selection of electric motors

As a promising solution, there is a wide range of motor types available [2,7,14,15,27,28], mainly classified as AC, Switched Reluctance Motors (SRM), and DC motors as shown in Fig. 1.

EVs were initially based on DC traction motors [29] since they showed reasonable torque versus speed performance curves, maximum torque at low speed, a wide constant power speed range, and ease of controllability.

DC motors are still relevant in Micro-mobility transportation such as bikes, mopeds, trikes, and other low-powered (up to 10-30 kW) vehicles [22]. On the other hand, there is a restriction on maximum speed due to commutators, and DC motors generally have lower efficiency and power density for higher speeds [13,14]. Moreover, the contact between brushes and the commutator in DC motors causes wear and friction issues, and at high speeds maintaining such contact becomes challenging, with brushes potentially bouncing off, leading to sparks and the risk of overheating or melting the commutator [7]. Brushless motors, on the other hand, offer greater reliability, dynamic accuracy, and efficiency. For these reasons nowadays AC motors are preferred for high-performance and high-power applications [30]. The prevalent choices for EVs in the AC category are Permanent Magnet (PM), Induction (IM), and Wound Rotor Synchronous (WRSM) motors [31]. 2020's market share of these motor types in BEVs and plug-in hybrid electric vehicles (PHEVs) is shown in Fig. 2a.

Fig. 2 shows that between 2015 and 2023, PM motors dominated the electric car market, consistently exceeding a 75% market share [32]. However, concerns arose due to China's control of the rare-earth magnet supply chain[10] and soaring prices in 2021.[11] To mitigate these concerns, European automakers like Renault and BMW adopted wound rotor motors,[12] while Audi and Hyundai[13] opted for induction motors (IMs). Tesla's 2023 announcement of a rare-earth-free PM motor highlighted the industry's shift toward alternative magnetic materials like ferrite magnets, with challenges to overcome for mass adoption [32].

SRMs are typically classified as AC motors in the field of electric vehicles as the torque generation relies on the variation of magnetic reluctance [33]. The operating principle of SRMs involves the rotor aligning with the path of minimum reluctance in response to alternating magnetic fields, typical of AC motors [34]. Although SRMs share similarities with DC motors in construction [35], their operational characteristics and control strategies align more closely with AC motors. Variable frequency AC drives are commonly used to drive SRMs, allowing precise control over phase excitation and synchronization. Input power supply can be AC [36] or DC [37].

The comparative analysis and investigation of IMs and PM motors within the automotive sector persist as a productive avenue for scholarly research [38]. The discussion surrounding these technologies remains relevant, as shown in Fig. 3, particularly within the automotive industry.

Automotive is actively striving to enhance efficiency [39], power density [40], cost-effectiveness, minimize the use of rare-earth materials [41], implement advanced control strategies [42], and compactness [43] to drive further advancements. For instance, researchers can delve into optimizing rotor designs [7], investigating novel magnet materials [44], and exploring innovative cooling techniques [45] to enhance motor performance. Moreover, there is a need for studies focused on cost reduction, customization of motor technologies for specific applications, and addressing integration challenges [46] with emerging automotive technologies [47]. By pursuing these research areas, scholars can contribute to the growth and success of electric vehicles in the automotive industry while expanding the body of knowledge in this field.

PM motors are by far the widest motors used in EV applications, as they provide higher efficiency, power density, torque density, and specific power compared to most of the others. Moreover, PM motors have the majority of patents registered, and the highest improvement rate compared to other topologies [48]. A number of researches have been found comparing the performances of different types of motors [2,11,13,15,49–51], and the following findings and trends have been deduced:

- Although IM is employed in some EVs, [50] underlines that in the coming years, their market share is not expected to change significantly, due to their lower power density and mechanical efficiency compared to PM motors, as shown in Fig. 4, as manufacturer have to consider a trade-off between peak efficiency and performance curve over a wide speed range [49].

- The area of concern for IM is the efficiency at low-speed, which is relatively low compared to other topologies [52]. At the same time the academic community conjures the prospect of IM if mechanical, core, and iron losses are reduced [53]. IMs have a simpler construction compared to PM motors [54], which translates to reduced complexity, lower maintenance requirements, and enhanced durability. These factors contribute to improved longevity and cost-effectiveness. The inherent characteristics of IMs, such as high starting torque and better thermal management, make them suitable for demanding driving conditions [55]. IMs exhibit excellent performance in applications requiring high torque at low speeds [56], making them ideal for heavy-duty vehicles, stop-and-go traffic, and off-road driving scenarios. Line Start PM motor [57], employs an induction rotor cage and powerful internal magnets to enhance

[10] https://www.reuters.com/markets/commodities/world-battles-loosen-chinas-grip-vital-rare-earths-clean-energy-transition-2023-08-02, accessed 27/09/2023.

[11] https://garnet.it/en/rare-earths-and-ferrite-price-trend-june-2021, accessed 27/09/2023.

[12] https://europe.autonews.com/automakers/renault-valeo-work-together-next-gen-e-motors, accessed 27/09/2023.

[13] https://www.businesskorea.co.kr/news/articleView.html?idxno=120210, accessed 27/09/2023.

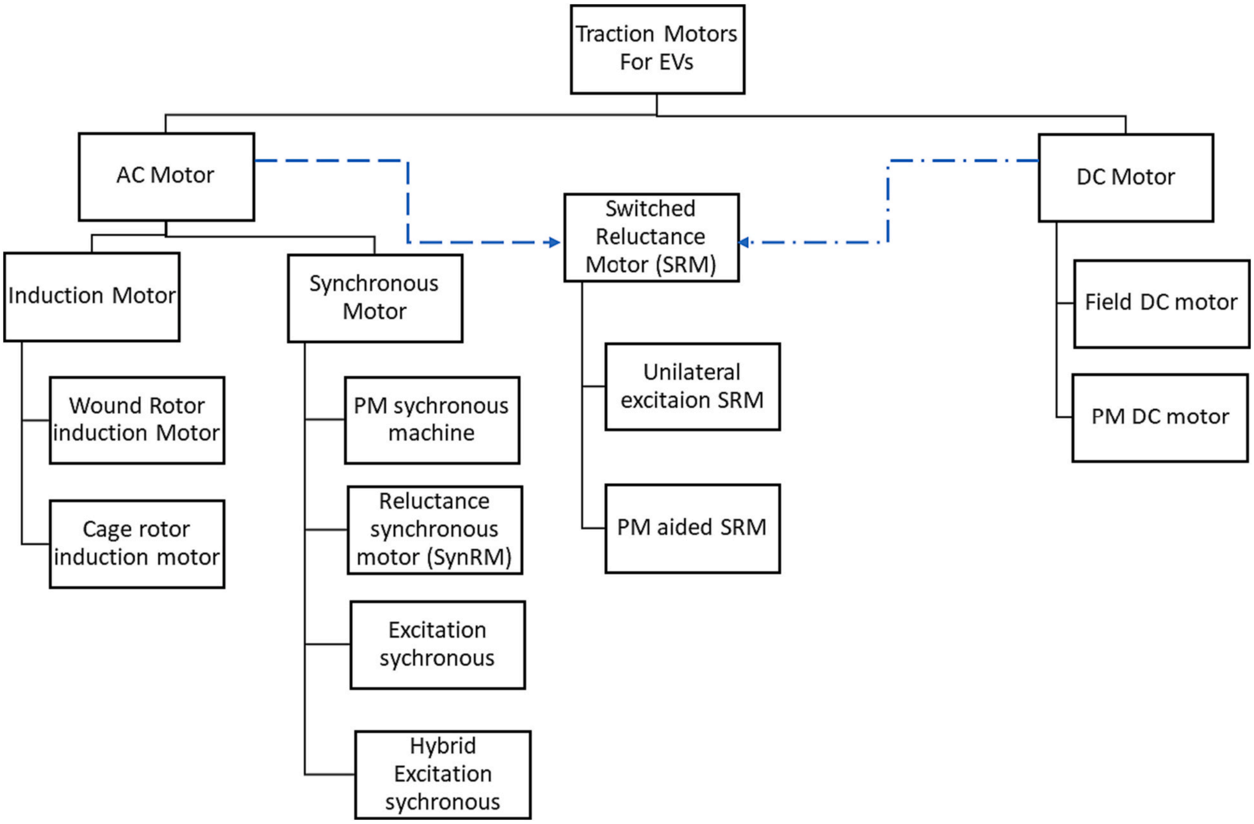


Fig. 1. Classification of electric motors for EVs based on power supply. Adapted from [2].

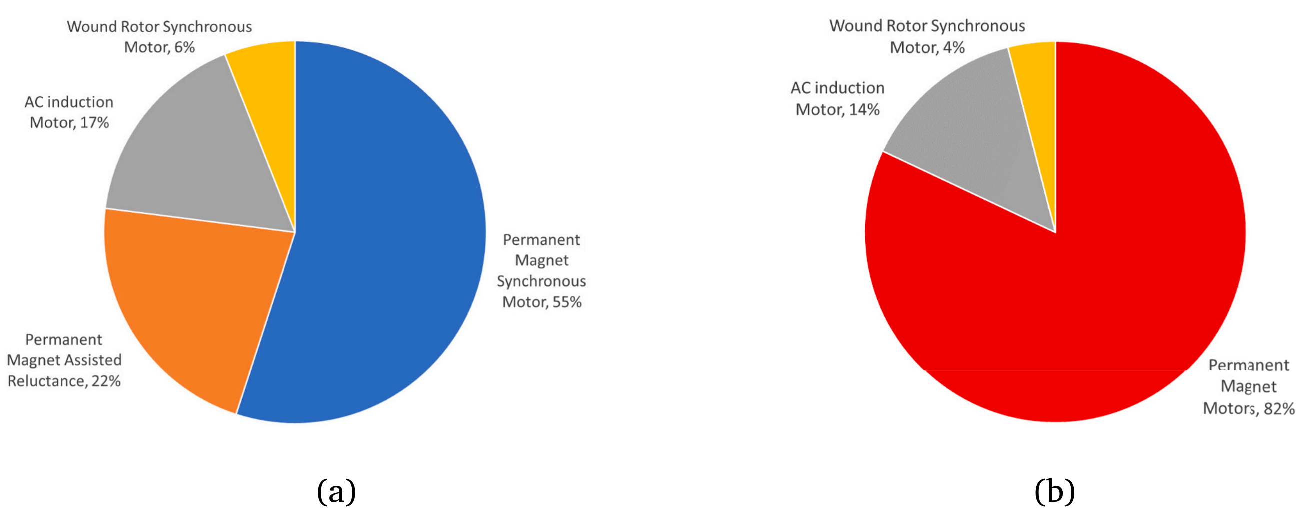


Fig. 2. Distribution of different AC traction motors in BEV and PHEV in 2020 (a) and 2023 (b). Data extracted from IDTechEx [31,32].

efficiency by eliminating rotor losses. This technology can operate at true synchronous speed without slip, or the need for a feedback device, or specialized drive controls. In [57] distinctive operational characteristics, application considerations, and advantages of utilizing adjustable frequency power with Line Start PM motor are discussed. Furthermore, a comparison is made between Line Start PM motor and other technologies. Overall, the case study illustrates significant power savings achieved by replacing an existing induction motor with a Line Start PM motor in a cooling water pump application, operated with an adjustable speed drive. The results indicate that Line Start PM motor, when appropriately applied, can yield substantial energy savings and improved efficiency.

- The major market of PM motor consists of is that of synchronous and assisted reluctance (PMAR) motors, the latter exploiting the gains of combining the magnet type with reluctance motors. Both manifest high-power density, high power factor, high efficiency, and wide speed range, which are the reason for their dominant (77%) market share as seen in Fig. 2(a). Among all PM topologies, IPM is pursued by OEMs due to higher efficiency, power density, torque density, high power factor, and sturdy packaging among other choices [2,58].

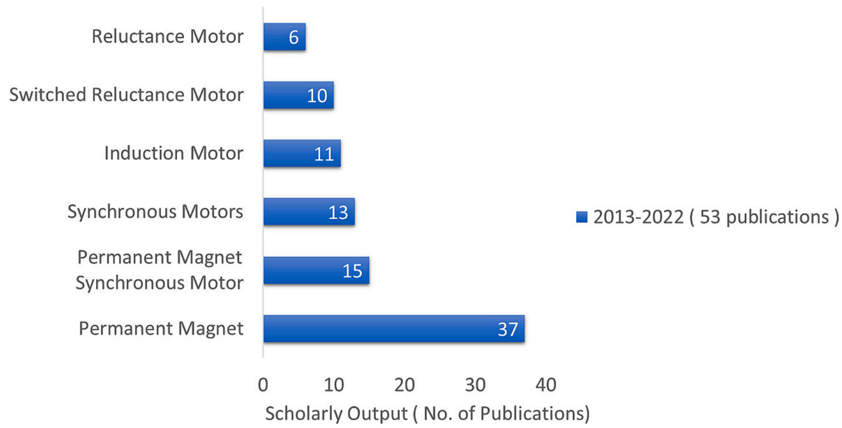
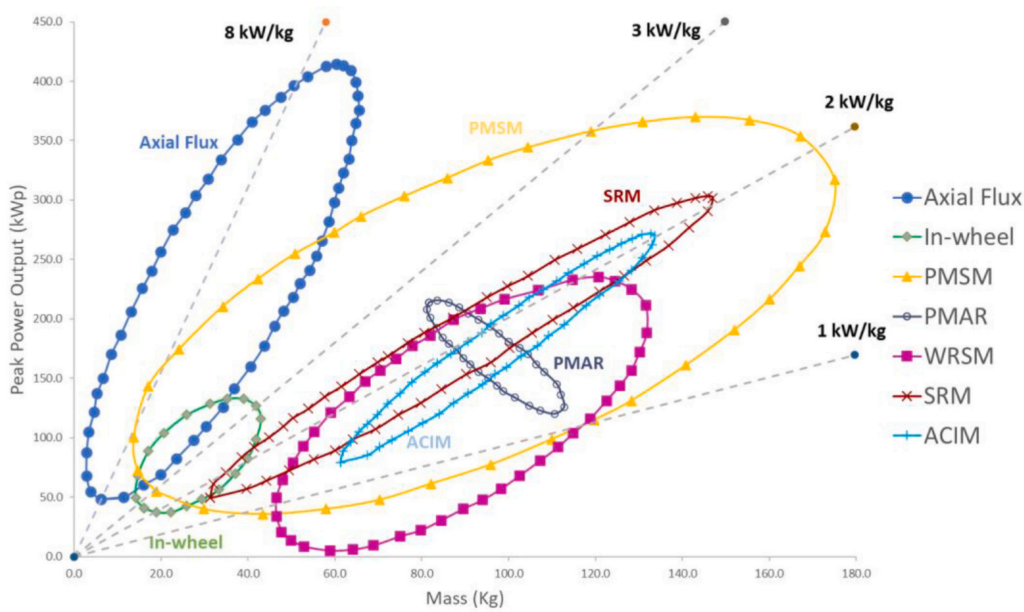


Fig. 3. Keyphrase relevance, according to motor type based on 53 out of 130 publications.



ACIM	*AC Induction motor*
PMAR	*Permanent Magnet Assisted Reluctance*
PMSM	*Permanent Magnet Synchronous Motor*
WRSM	*Wound Rotor Synchronous Motor*
SRM	*Switched Reluctance Motor*

Fig. 4. Power-density comparison of different motor types currently used in EVs, the x-axis represents Mass in kg and the y-axis is Peak Power Output (KW) Data extracted from IDTechEX [31].

- WRSMs are gaining popularity in the automotive industry for several compelling reasons. Firstly, they are highly efficient [59], leading to longer driving range and reduce emissions. Secondly, WRSMs offer precise control [60] over speed and torque, enhancing vehicle performance and safety. Lastly, WRSMs can generate high torque even at low speeds [60], making them ideal for swift acceleration in electric vehicles. These motors also have a wide constant power speed range, eliminating the need for an additional transmission system. Their straightforward design and low rotor inertia result in rapid responsiveness. While challenges [59] like noise, vibrations, and complex electronics have limited their use in electric vehicles, WRSMs are now gaining popularity as a solution to reduce reliance on rare-earth metals and overall costs [61], positioning them as a promising choice for future automotive applications.
- SRMs eliminate windings, slip rings, and PMs on the rotor, building the opportunity to eliminate rare-earth metals and reduce the cost. They exhibit considerably great power density and reliability as reported in [2]. Moreover, high torque at low speeds and a wide constant power speed region can be obtained. This wide speed range eliminates the use of an additional transmission system. Due to its simple structure and low rotor inertia, the SRM has fast dynamics; NVH and intricate electronics issues hinder their extensive commercial application in EVs [15,53]. Currently, the implementation of SRMs for traction purposes in commercial vehicles remains absent. However, research community strongly advocate for the adoption of SRMs to alleviate the prevailing dominance of PM and Induction Motors [62].
- Axial-Flux motors, shown in Fig. 5, can be classified based on the number of stators and rotors as shown in Fig. 6 and have the utmost

Fig. 5. Representation and implementation of axial-flux traction motor in Vehicle. https://electrek.co/2018/05/03/axial-flux-electric-motors-more-ev-power-smaller-package/,accessed 29/11/2022.

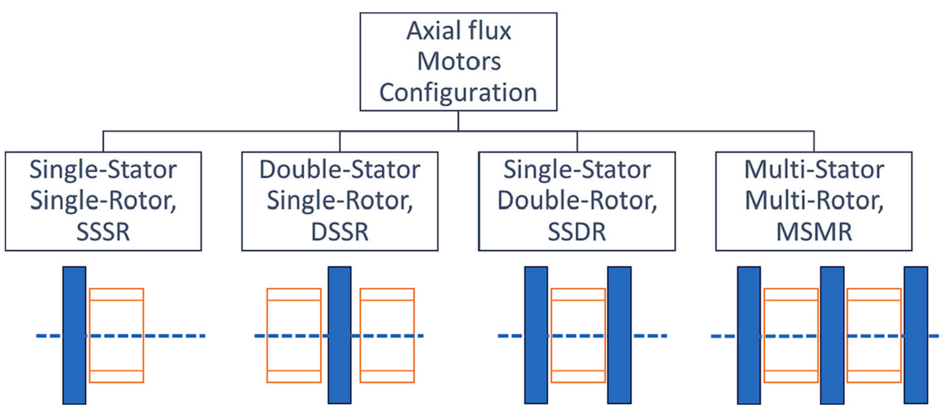


Fig. 6. Different axial-flux motors configurations based on number of stators and rotors.

potential to offer the highest torque, power density, and efficiency (greater than 96%) as demonstrated by YASA[14] and General Motors prototypes [13].

- Their light and compact design lead to high-power density, specific power, and torque density solutions make them desired choice for high-end OEMs [63]. Moreover, low-cost production is possible by eliminating complex multiple windings with a segmented armature and fewer material use. Nevertheless, implementation in the automotive industry is hindered due to the high complexity and high powertrain supply chain overhauling costs.[15] And complex structure hinders the optimization process due to the high simulation time required to mimic 3D electromagnetic and transient behaviour [64].

  In a recent patent [65], inventor introduces a novel design of a radial and axial flux motor that incorporates integrated windings to effectively combine radial and axial magnetic fluxes, thereby enhancing both efficiency and output power. The motor's rotor core integrates lateral and ceiling permanent magnets, while the stator core is equipped with corresponding windings. By harnessing the synergistic effects of integrated windings and perpendicular magnetic flux directions, the motor achieves notable improvements in efficiency, minimizing losses, and optimizing power consumption. This innovative design holds significant potential for advancing motor technology in various applications.
- In-wheel or hub motors are traction motors that unveil unprecedented vehicle dynamics performance in terms of longitudinal performance [66,67], tractive effort [66,68], torque vectoring-[69,70], anti-skid control [69], and regenerative braking [71]. Together, these advantages create the tipping point for Original Equipment Manufacturers (OEM) acceptance of in-wheel-motor technology [72]. In [66], the technical challenges of unsprung mass and brake integration are addressed [73], and commercial implementation is shown in the Protean PD18 vehicle [74]. They are the best candidate for LEVs since they allow more volume saving [75]. However, little development has been conducted to address the largescale implementation of these motors. Furthermore, in-wheel motors can be employed with (IWMG) or without gearsets (IWM-direct drive). The IWMG technology enables a broad spectrum of gear ratios, thereby optimizing torque and speed parameters to enhance both acceleration and climbing capabilities. Additionally, it contributes to improved motor efficiency by operating within the optimal speed range, leading to enhanced power transfer and energy utilization [76]. However, it is important to note that the adoption of IWMG introduces additional weight and size, which may potentially affect vehicle handling and necessitate periodic maintenance due to gear wear. Ongoing research endeavours are focused on refining and advancing IWMG technology to facilitate its wider implementation in future vehicle designs.

In Fig. 7, the authors provides a qualitative comparison of various traction motor topologies for automotive use. The goal is to aid in selecting suitable motor topology for traction motor application. Using a 1 to 5 scale (1 = low, 5 = high), the authors assess attributes. This overview results from the references presented in this section and personal experience. Note that this qualitative comparison may not cover all factors for specific applications.

[14] https://www.yasa.com/, accessed 29/11/2022.

[15] https://www.schaeffler.com/en/media/dates-events/kolloquium/digital-conference-book-2022/edrive/, accessed 29/11/2022.

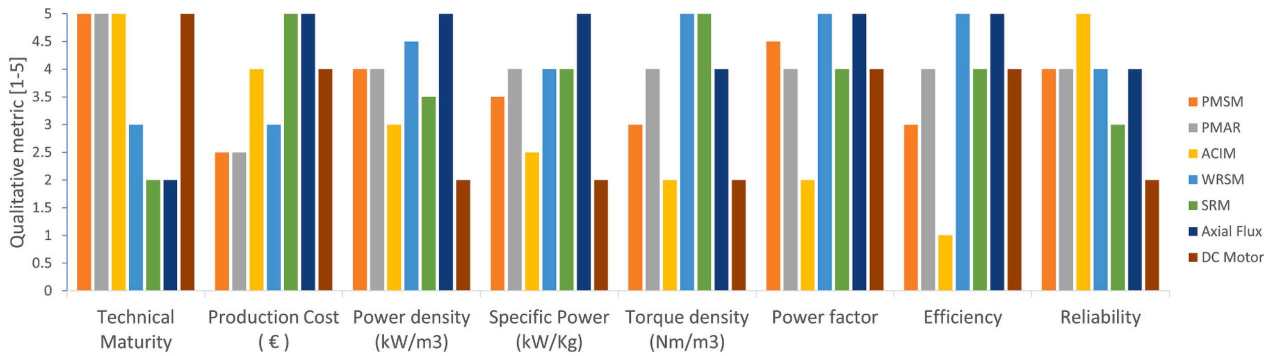


Fig. 7. Qualitative Comparison of different attributes of traction motor topologies for automotive applications.

2.2. Losses

2.2.1. General losses

Existing motor efficiency standards are only defined for single-speed applications. International Electrotechnical Commission (IEC) categorizes single-speed motor efficiency into categories named IE1, IE2, IE3, and IE4 [78]. However, currently, no efficiency regulation exists for motors designed for electric, and hybrid electric vehicles, requiring high efficiency over a wide range of torque and speed, i.e., it is needed to further extend IE levels.

A common approach used to evaluate the efficiency of a traction motor is using the so-called Efficiency maps: charts in which the efficiency of the motor is given in the torque-speed plane, as illustrated in Fig. 8 and Fig. 9.

These charts are widely used as measuring tools to assess and compare the performance of EVs over the torque-speed envelope and are built employing dedicated test benches. Various losses in traction motors are described in Fig. 10, data acquired from [24,80].

The framework for optimal design requires the identification and analysis of the major loss components aiming at their reduction in the widest possible speed range. The copper, iron, permanent magnet, and converters losses are related to the electrical and magnetic dissipation in traction systems [79]; transmission system losses will be discussed in the next section. As shown in Fig. 10 apart from conductive and core losses, only around 50% of the existing literature has focused on exploring the various sources of loss in the drivetrain of an electric vehicle (EV), encompassing all mechanical and electrical components.

Losses in traction motors vary from one operating point to another, due to the different contributions of loss sources, conductive, converter, PM, core losses, and mechanical losses, which independently vary with speed and torque. Also, the efficiency depends on the architecture of the motor, and each type provides the best efficiency at different operating points [79]. An example of this is presented in [79], where efficiency maps of IPMSM and IM are shown in Fig. 8 and Fig. 9, respectively; it can be seen that the former offers higher efficiency in a wider range of torque-speed.

The reduction in efficiency at low speed in IM is due to the rotor bar losses whereas on the contrary, in the field weakening region, IMs offer higher efficiency at a higher speed due to the mitigation of the conductive and core losses [81]. Above a certain speed, the windage and friction losses become dominant, and the efficiency of IMs starts to decrease [79,81]. At the same time, PMSM losses increase with speed because of the iron and permanent magnet loss increase too. Additionally, conductive losses escalate due to the rise in the d-axis current in the field weakening region [82]. All main loss components other than mechanical losses are tabulated in Table 1.

2.2.2. Mechanical losses

The basic theory is reported in [14,83]. Here additional both general and specific questions are dealt with. Generally, mechanical losses comprise windage (due to air drag between stator and motor), friction (due to load couplings), bearing (due to wear and tear of ball bearings), and stray losses (due to sudden load transients and mainly depend on the speed), mainly depending on mechanical speed, shaft radius and length, and ambient conditions. Mechanical loss is given as [84] (Mack's model),

$$P_M = \pi \rho C_f w^3 {r_{rot}}^4 L \tag{1}$$

where ρ and C_f are fluid density around the rotor and friction coefficient, respectively; additionally, w, r, and L are rotor speed, radius, and axial length, respectively. Investigations have pointed out that both mechanical and stray losses are directly influenced by the speed and power of the motor [85]. It is pertinent to mention that some studies [86] have disregarded the impact of mechanical losses citing insignificant contributions, but as per [87], at high speeds, these cannot be neglected.

As illustrated in Fig. 11, the bearing losses are slightly influenced by the temperature, but speed is instrumental. As per [87], if the maximum efficiency of a traction motor is 90%, the mechanical loss is about 12% of the total losses at high speeds.

As mentioned in [49] and Chapter 11 of [88], motor mass increases structural loads and contributes to the loss of mechanical energy of the vehicle. As shown in Fig. 12, a 1% percent of reduction of mass bolsters 1% of mechanical energy into the system. Meanwhile, the impact of 1% aerodynamics improvement and enhancement of tire properties provides 0.3% and 0.4 % of mechanical energy savings, respectively. Therefore, operating at the highest efficiency is tantamount to reducing energy demands and thus, ultimately, lower battery mass in BEV[89].

2.3. Transmission systems

It is visible from Fig. 8 and Fig. 9 that traction motors are able to provide constant torque from zero to peak point speed but the addition of mechanical transmission system can improve the overall efficiency of powertrain, especially at lower efficiency regions of low torque and speed [90]. The same viewpoint is shared in [14,91], where the maximum speed of traction motor and the gear ratio of transmission are considered as the critical design parameters to achieve maximum speed and efficiency of powertrain. It is therefore imperative that different transmission layouts be explored to further enhance the efficiency of a BEV's powertrain. The studies have propelled to the forefront these state-of-art transmission system schemes to maximize the overall mechanical efficiency of traction motor in Electric vehicles:

- Single stage transmission
- Multi-stage transmission
- Continuously variable transmission (CVT)
- In-wheel motor transmission

The first three transmission systems, as shown in Fig. 13, all employ in-body architecture where a transmission system is mounted on the

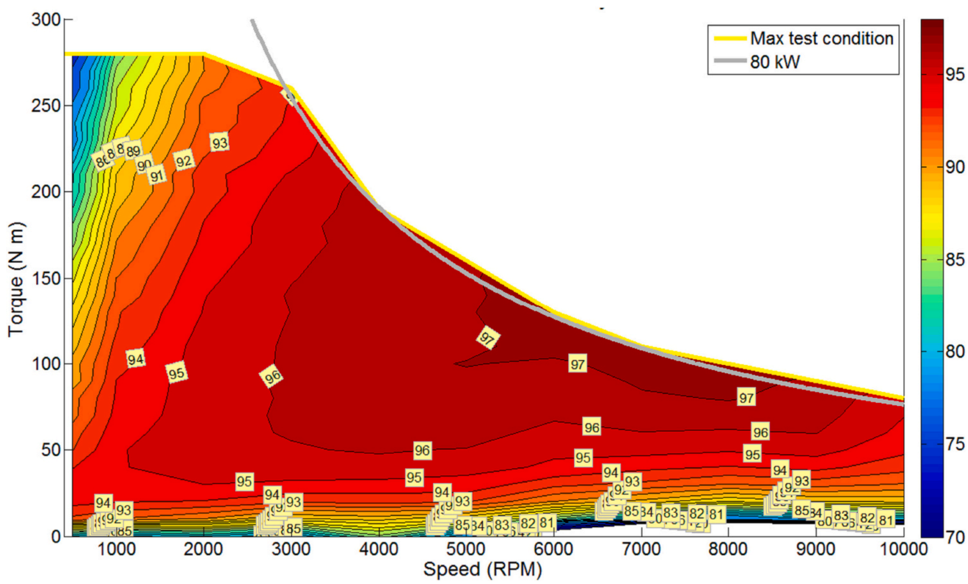


Fig. 8. Torque-speed curve and Nissan LEAF (IPM) motor efficiency map, with a DC bus voltage of 375 V [77].

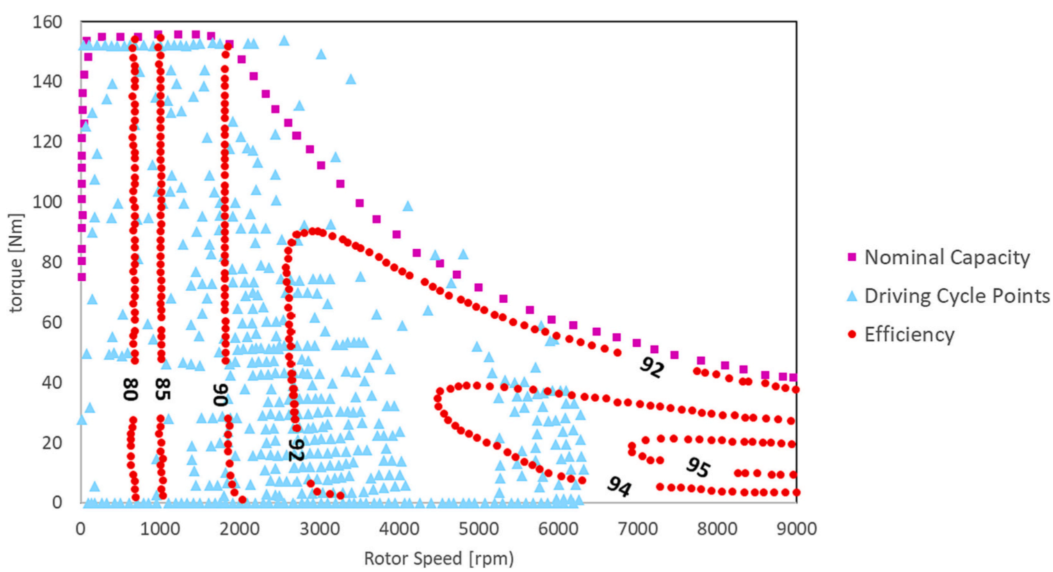


Fig. 9. Induction motor efficiency contour and the UDDS driving cycle operating points in the torque-speed envelope, permission granted to reproduce [79].

chassis and used to bring the power from the motor(s) to the wheels through drive shafts. Gearbox, dog clutches, synchronizers, differential (set of planetary gears), and drive shafts are the essential components in transmission systems.

Transmission efficiency is determined by gear power losses, bearing power losses, sealing power losses, and other power losses such as oil pumps [91]. Despite rising the number of gears augments the mechanical losses due to friction, the overall efficiency of the motor is higher since it functions in the field weakening region, where it is the most efficient [79].

Overall gearbox efficiency can be calculated as follows,

$$\eta_g = \eta_b \prod_1^n \eta_{ng} \quad (2)$$

where, η_g is overall gearbox efficiency, η_b is the efficiency of all bearings, η_{ng} is the efficiency of individual gears, and n is the number of gears. Further, the torque reaches the wheels through the differential i.e., a final drive that divides the torque between the right and left wheels,

$$\eta_d = \eta_{bd}\, \eta_{nd} \quad (3)$$

here, η_d represents the overall efficiency of differential efficiency, η_{bd} is overall differential bearings efficiency and η_{nd} is differential gear efficiency. Therefore, the total efficiency of transmission η is given as,

$$\eta = \eta_g\, \eta_d\, \eta_{CV} \quad (4)$$

where, η_{CV} is the efficiency of all constant velocity joints including drive-shafts and propellor shafts. It should be noted that the bearing efficiencies are a function of temperature and speed and are dependent on bearing type and size, bearing arrangement, lubricant viscosity, and supply [92]. Usually, rotational speed in transmission systems is lower than that of rotor therefore the impact of bearing efficiency impact is smaller on the transmission side.

It is clear from Eq. (2) that single-speed transmission systems offer the best efficiency in a wide range of driving operating conditions. However, according to [93–95], the multi-speed transmission improves

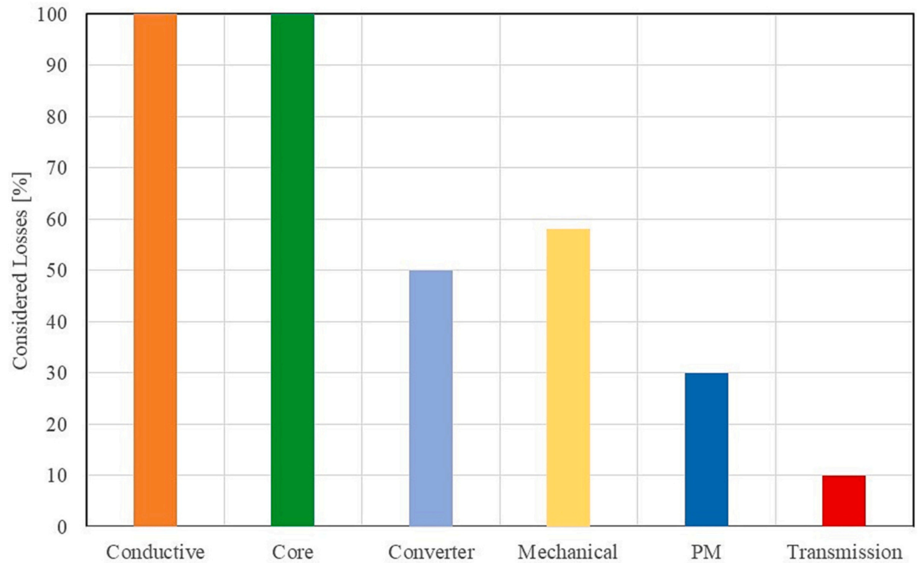


Fig. 10. Statistical findings arise from the examination of documented studies investigating the effects of different types of losses on the electric motor over a period of three decades, specifically from 1992 to 2021 [79].

Table 1
Sources and dependencies of loss components of traction motor [41,34].

Loss component	Source	Estimation/Dependence
Core	Eddy current and hysteresis	Steinmetz and Bertotti's equation. Core losses vary with frequency and flux density. The dependence on eddy current and hysteresis is also incorporated.
Converter	Power converters including both DC-AC and DC-DC (switches, buck-boost converters, semiconductors, etc.)	Shaft Speed, temperature
Permanent Magnets	Eddy current flowing in magnet	Variation of the rotor speed characterizes the PM loss. At higher RPMs, eddy current losses increase exponentially. The number and placement of magnet segments.

system efficiency (the motor can operate in the most efficient regions) and driving performance by decoupling the launch, top speed, and other driving conditions from the motor speed and torque. At the same time, increasing the number of reductions comes at the cost of extra weight, lower transmission efficiency, and higher overall manufacturing cost. Additional losses are provided by clutches, synchronizers, and additional gears. In [93], dual-clutch transmission is employed in multi-stage transmission systems which yields better driving performance as the number of gears are increased but eventually, transmission efficiency drops down as shown in Table 2. Additionally, the effects of transmission design on electric performance in different driving cycles are discussed in [94–96] and underline the advantages of additional gears.

Another conceivable transmission technology to incorporate with traction motors in BEVs[16] is CVT, which gives, in theory, an infinite number of possible ratios. It is currently utilized in ICE vehicles but due to efficiency losses in torque converter at constant driving and unusual engine behaviour, this technology is not that successfully employed in Europe [88]. Nevertheless, the removal of ICE strengthens the justification of CVT [93,97]. Furthermore, considering the possibility of replacing the torque converter with servo-electromechanical mechanisms, as illustrated in Fig. 14, has the potential to enhance the efficiency of the system [98].

The efficiency of CVT mainly depends on input torque and speed ratio as shown in Fig. 15.

The top red curve represents the variation in the efficiency of pulleys according to speed ratio. It is observed that an increase in the influence of input torque on the component could be found [93]. Also, the comparative results presented in [79,90,95,99] show that greater efficiency and hence better energy consumption is achieved in the case of CVT than multi-speed transmission in some driving cycles.

On the contrary, in the in-wheel architecture, as depicted in Fig. 16 and Fig. 17, the motors directly mounted to the hub of the wheel.

This construction provides great mass and volume reduction and eliminates additional components for power transfer [69]. However, it is suggested in [79,100] that the use of an additional reduction gear makes the motor operate in the field weakening region, hence with the highest efficiency. NSK and Protean electric[17], with inner and outer rotor structures as shown in Fig. 16 and Fig. 17 respectively. Have recently developed some innovative In-Wheel-Motors (IWM), implying the immense potential of this architecture. Moreover, from the control point of view, IWM architectures are easier to implement and provide better drivability due to smooth torque control [69,101]. Another benefit of this architecture is the reduction of overall noise levels inside the cabin. Nonetheless, such gains come at the cost of higher unsprung mass and an increase in the mass of driving elements (hence overall vehicle's inertia) [68,69,101]. The arguments for overcoming these challenges are comprehensively discussed in [66,102,103].

The research conducted in [101] approves that IWM architecture drastically reduces the losses in the drivetrain in contrast to in-body architecture. The extra increase in the investment cost with four drive modules can be overlooked by the fact that there is lower load on batteries and hence a greater life cycle is achieved.

The Permanent Magnet Vernier Motor (PMVM) offers advantages like gearless operation i.e. replace mechanical gear sets with an electromagnetic reduction gear, the specific harmonics in the airgap work as the same gear function. But they face limitations, including lower torque

[16] https://www.bosch-mobility.com/en/solutions/transmission-technology/transmission-cvt4ev, accessed 29/11/2022.

[17] Homepage - Protean: Protean (proteanelectric.com), accessed 29/11/2022.

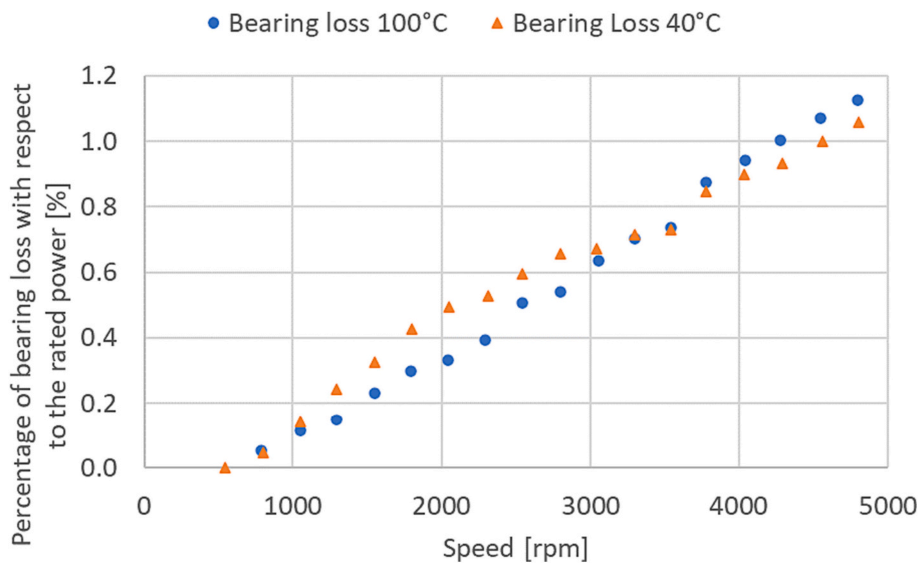


Fig. 11. Effect of speed on percentage bearing loss to the rated power [%] at 40 and 100° centigrade, data extracted from [87].

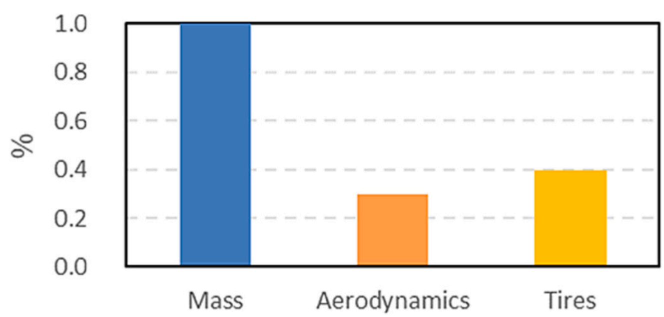


Fig. 12. Percent savings of mechanical energy by improving 1% of different vehicle aspects, data extracted from [88].

compared to other topologies using mechanical gears [104]. A concept of pseudo harmonic transmission ratio (PHTR) in permanent magnet vernier motor (PMVM) for IWMG is presented in [104]. The validation is done with the aid of FEA models of two motors as shown in Fig. 18, PMSM (with mechanical reduction gear) and PMVM (with harmonic gear reduction).

It is deduced that even though high energy loss occurs in harmonic transmission and, higher torque can be produced under different conditions as shown in Fig. 19. Despite the torque of PMVM is lower than that of PMSM plus mechanical gear, additional space is provided due to the removal of mechanical gear.

PMSMs are known for their excellent power factor characteristics, typically close to unity. The power factor of PMSMs remains high and stable across a wide range of operating conditions, which is a significant advantage. PMSMs have a simpler control structure compared to PMVMs, contributing to their high power factor and overall efficiency. Like flux switching and flux reversal motors. PMVMs, on the other hand, may have a lower power factor in entire operating area [105] than non-flux modulating topologies due to their unique flux modulation characteristics. However, advanced control strategies [106] can be employed to optimize their power factor, especially in demanding operating conditions, to achieve higher efficiency. PMVMs rely on surface-mounted magnets (SPMs), which are not ideal against

Table 2
Multi-speed dual-clutch transmission efficiency [21].

Transmission type	1-speed	2-speed	3-speed	4-speed
Overall Efficiency	0.93	0.86	0.83	0.80

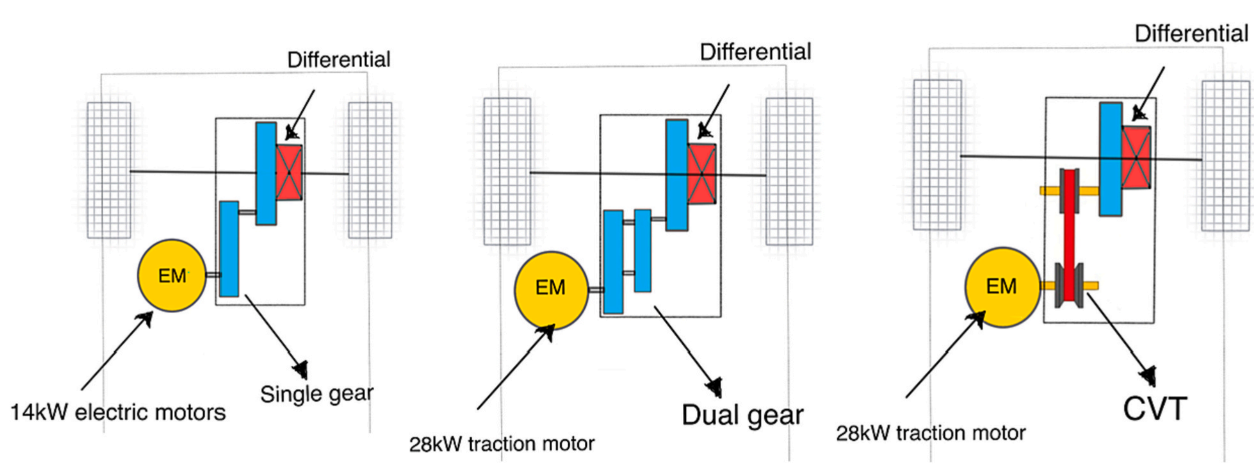


Fig. 13. Illustration of several types of transmission systems prevalent in electric vehicles (left) single-speed transmission (center) two-speed transmission and (right) CVT transmission.

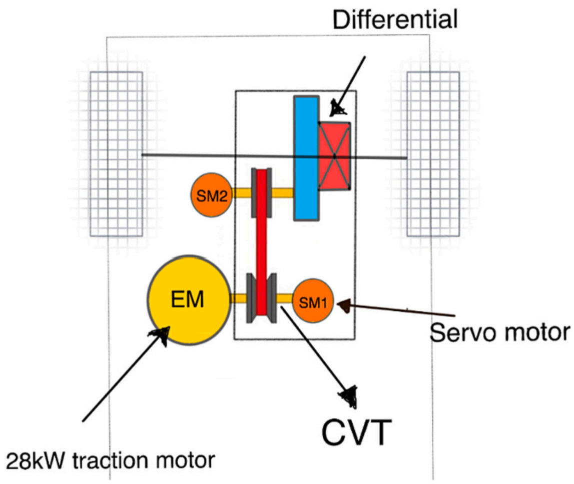


Fig. 14. Motor-Assisted CVT.

demagnetization. Additionally, reluctance torque, often used to achieve a wide constant power speed range, cannot be effectively utilized in PMVMs [106]. PMVM, as stated in [107] suffers from higher winding eddy current loss (WECL) therefore, the adoption of PMVM and other flux modulation technologies faces challenges related to lower power factor and eddy current losses. Comparing eddy current losses between PMVMs and PMSMs is complex and depends on specific design and optimization. Factors like core material and shape, and operating conditions influence losses [108]: both designs can achieve low eddy current losses which ultimately depend on implementation and application. However, the authors suggest that their significance is poised to increase when higher speed mechanical transmission systems become the norm in the EV sector.

The pursuit of maximizing mechanical efficiency in EVs has driven the exploration of various transmission system schemes. Potential options include single-stage, multi-stage, CVT, and in-wheel motor transmissions. Single-speed transmissions exhibit high efficiency across diverse conditions, while multi-speed transmissions enhance system efficiency and driving performance. CVT shows promise for EVs through servo-electromechanical mechanisms, offering improved efficiency. Despite the advantages of electronic or magnetic transmission systems, such as flexibility in gear ratios and regenerative braking, the established efficiency, reliability, cost-effectiveness, serviceability, and compatibility of mechanical transmission systems make them the current preferred choice for electric vehicles. However, in-wheel motor architecture reduces drivetrain losses but poses challenges related to maintenance, added unsprung mass, and volume constraints. Further research is needed to optimize transmission systems and advance the efficiency of EV powertrains.

2.4. Vehicle layouts

Several studies have been found promoting the need to investigate various vehicle architectures and layouts to maximize the efficiency of the overall vehicle [14,83]. The selection of a particular layout is majorly influenced by vehicle constraints such as type of vehicle [109], modularity [110,111], cost, performance [88], mass [112], ride and comfort [113], control [114], thermal management [8], etc. In this section, different vehicle layouts from different studies will be presented with an emphasis on the efficiency and performance of the vehicle.

The architecture presented in [115] is based on a two-motor two-axle configuration realized in the EU AMBER-ULV project as shown in Fig. 20 and Table 3.

The solution enhances the total tractive effort at the whole speed as opposed to a single drive of the same power rating. Due to the power split, the load requirement at each axle is reduced hence low voltages are needed for the battery packs. This solution also helps to eliminate a complicated BMS and assures safety due to lower voltages but at the cost of many control issues in the energy, traction, and stability management

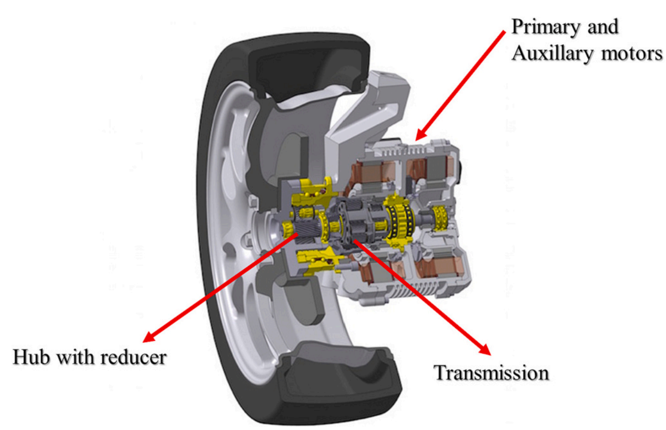


Fig. 16. In-wheel drive unit: Adapted from NSK in-wheel motor with reduction gear (planetary gears), with interior rotor.
NSK World's first transmission-equipped wheel hub motor (nskeurope.com), accessed 29/11/2022.

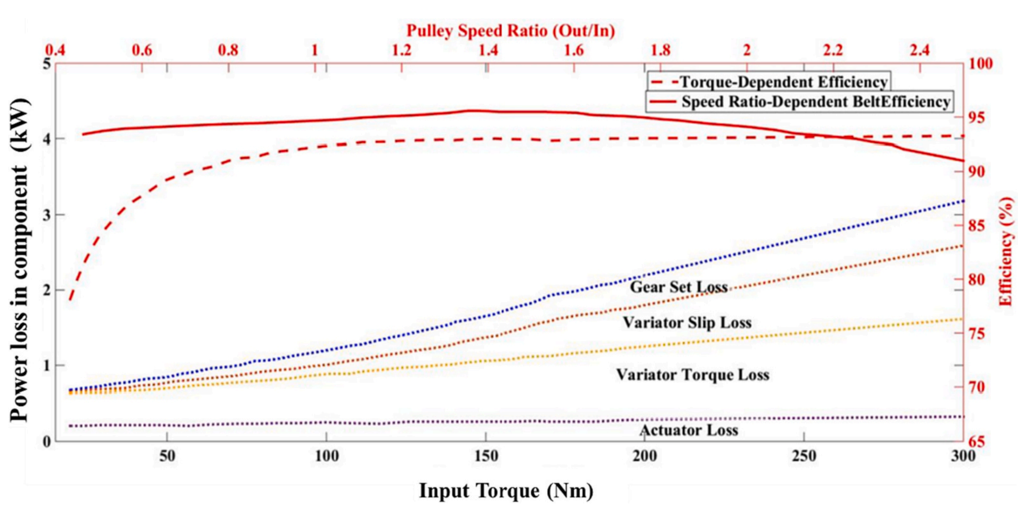


Fig. 15. The variation of the losses and efficiency in CVT, source [93].

Fig. 17. Protean Pd18 in-wheel motor design with exterior rotor.
https://www.emobility-engineering.com/protean-pd18-inwheel, accessed 29/11/2022.

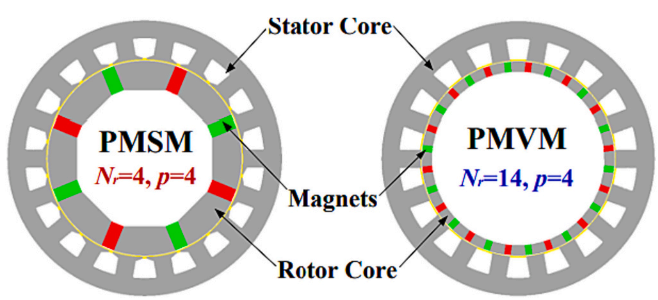


Fig. 18. The FEA models of PMSM and PMVM with the same stator tooth number, permission granted to reproduce [104].

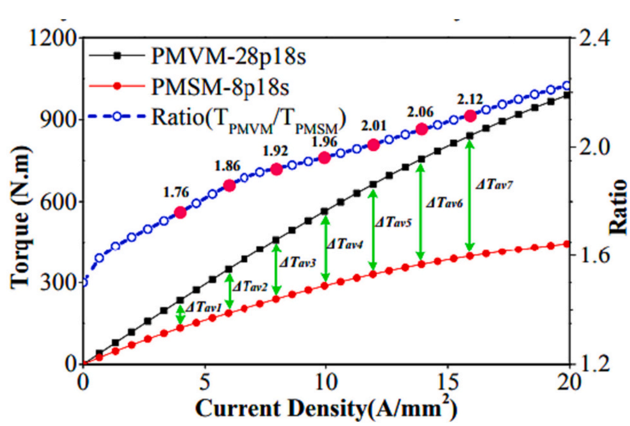


Fig. 19. Torque vs. current density curve comparison of two models, permission granted to reproduce [104].

of the vehicle[115].

A more comprehensive analysis of single and dual in-body motors (2WD and 4WD) with single-speed and 2-speed transmission is accomplished in [116] as shown in Fig. 21.

The comparison was based on a 28-kW power and mass of the vehicle ranging from 820 kg (single speed 2WD) to 870 kg (2-speed 4WD) on i)

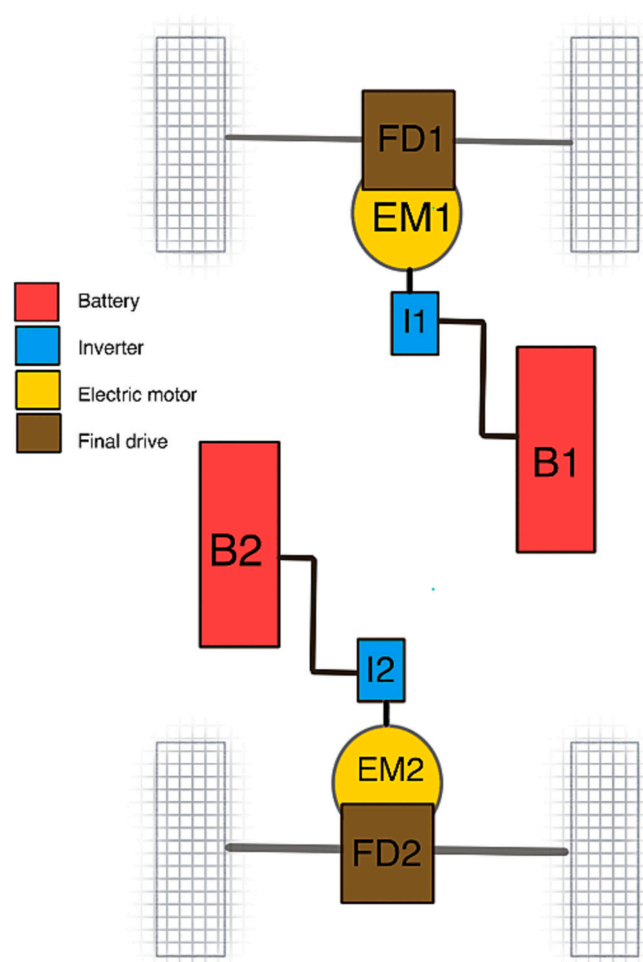


Fig. 20. Two-motor, two-battery, and two-axle powertrain realized in the EU AMBER-ULV project.

Table 3
Vehicle performance for different Layouts [116].

Layout	Top speed (km/h)	Acceleration time (s)		
		0-30 km/h	0-50 km/h	0-70 km/h
single speed 2WD	78.7	3.1	5.4	9.1
2-speed 2WD	103.2	2.7	6.0	9.6
single speed 4WD	78.7	3.1	5.5	9.3
2-speed 4WD	103.2	2.4	5.7	9.4

the urban part of the New European Drive Cycle (NEDC), i.e., for four repetitions of the so-called ECE-15 cycle, and ii) the Japanese 10–15 mode test cycle (J10–15), and the results show that the 4WD layout reduces the energy consumption during driving cycles compared to the conventional 2WD layout [116]. Two motors per axle enhance active safety through the implementation of continuous yaw moment control plus better energy efficiency in cornering. At low torque operation, the predominant factor is the mass hence the best energy consumption comes from a single-speed 2WD layout. However, the single speed 4WD is more energy efficient along the driving cycles. This layout does not require complicated controllers or actuators, it can be regarded as an effective architecture in terms of drivability, acceleration, gradeability, and overall efficiency [116].

Somewhat similar layouts are proposed in [90] as shown in Fig. 22, however, the architecture is based on 2WD (only one axle) with a special case of installing planetary gear sets in transmission in dual motors.

The concept of the dual motor is illustrated to be highly efficient by maximizing the torque utilization factor of motors. The proposed dual motor layout does not contain any shifting mechanism and hence does not compromise drivability and other performance parameters. Dual motor configuration is realized in two approaches, speed split as shown in Fig. 22(c), and torque split in Fig. 22(d). Efficiency analysis yields that dual motor layouts have better efficiency as compared to single motor ones. Dual motor with Planetary gear transmission proves to be the most efficient but the arrangement is overly complicated. This result is also supported by a similar study used to optimize Simpson [117] planetary gearset-based dual-motor powertrains in EVs, which also suggests that further increasing the operation modes in this type of configuration does not bring any significant improvement in powertrain energy efficiency [118].

Moreover, the comparison between in-body motor (mounted on the chassis) with 2WD and IWM has been made in [68,101,102]. As stated earlier, the centralized layout is the most inherent solution due to commercial maturity and ease of adaptability in the existing ICE vehicle chassis. Nevertheless, the effectiveness of IWM cannot be overlooked even in presence of some obvious drawbacks [102]. Related the comparison made in [68] shows that consumption-wise, the centralized motor is regarded as the winner, but only a slight difference exists with IWM but additional machine elements are a drawback.

Moreover, it is interesting to mention the architecture used by Rimac Automobili,[18] which uses four independent motors, inverters, and gearboxes mounted on the body. In addition to Rimac, a few other hypercar companies utilize similar configurations to capitalize on torque vectoring and electronic differential while maintaining a low unsprung mass.

A new solution of utilizing hydraulic motors in in-wheel configuration is proposed, which is termed to be most suitable for off-road conditions due to their reliability, sturdiness, and agility even though it is too expensive and constraint to low speeds. On the contrary, simulation results conducted in [101] indicate that 4WD in-wheel motors reduce the overall losses in the drive system as compared to single motor and transmission.

Moreover, a better range of 6% is also achieved in the WLTC driving cycle. The increase in the unsprung mass does not have a substantial influence on forces applied to the vehicle body but affects the road holding [113]. The impact of tire pressure has an appreciable influence on comfort and rolling resistance, having too low tire pressure (∼ 1 bar) results in a 20% of increase in rolling resistance. Finally, distinct architectures for IWM are presented in literature and the most prevalent choice is that with a single motor on each wheel. This configuration ensures a flexible [119] convenient and easy solution for the electrification of traditional vehicles [69]. References used for all these layouts and transmission systems are tabulated in Table 4.

In general, the research findings discussed in this section and summarized in Table 5, that emphasizes the importance of considering vehicle constraints, modularity, cost, performance, mass, comfort, and thermal management when selecting an optimal layout for EVs. Various layouts, such as the two-motor two-axle configuration and single/dual in-body motors with single-speed or 2-speed transmissions, have been extensively investigated for their efficiency and performance characteristics. The findings highlight the unique advantages of different layouts, including improved tractive effort, reduced energy consumption, enhanced safety, and drivability. However, it is essential to recognize that each layout has inherent limitations, such as increased control complexity, additional machine elements, and higher costs. Comparative assessments among in-body motors, in-wheel motors, and hydraulic motors further demonstrate their respective strengths and limitations. To advance EV efficiency, the research community should consider these findings and strive to explore innovative vehicle layouts that address the challenges associated with each system, while aiming for modular or scalable architectures.

3. Thermal management of electric motors

Adequate thermal management systems are essential to ensure traction motors operate in the most efficient regions at high speed i.e., avoiding critical temperatures [23]. Besides, not only extreme temperatures decrease the efficiency, but also harm the components, affecting their durability and life cycle [8,24,45,120]. In the case of electric motors, the choice of the thermal management system is dependent on the operating power, type of motor, transmission system, and the layout to be deployed. Generally, as shown in Fig. 23, thermal management techniques for electric motors can be divided into convection cooling and heat conduction enhancement. Hybrid thermal management techniques are the combination of cooling methods, like convection, with heat conduction.

Inside convection cooling, air and liquid cooling options are present, while heat conduction enhancement implements high thermal conductivity materials/components to uplift thermal performance. The overall comparison of these technologies is illustrated in Fig. 24. An interesting strategy is shown in, where diverse thermal management techniques are employed for a target component such as stator and rotor since temperature distribution, space requirements, and the criticality of these components are different [25].

Air cooling methods are the best choices for mass savings: Also, a smaller number of components provide easier assembly [24]. Regardless, their applications are quite restricted due to unsatisfactory thermal efficiency at elevated temperatures, acoustic pollution due to turbulent airflow, and difficult and costly maintenance for open-loop layouts [25,120]. External natural air cooling is mostly dependent on the number and geometry of fins: the higher their number, the higher the efficiency, but at the cost of increased weight and volume [23]. In the case of internal airflow, the objective is to reduce the airflow resistance, Thus, decreasing pressure drop and increasing air flow velocity. Moreover, better performance can also be achieved by optimizing fan parameters [24].

As mentioned in [120], fitting a fan externally at the shaft is quite popular to decrease rotor, winding, and PM temperatures but this solution is detrimental to the efficiency and the power density of the

[18] Home - Rimac Automobili (rimac-automobili.com),accessed 29/11/2022.

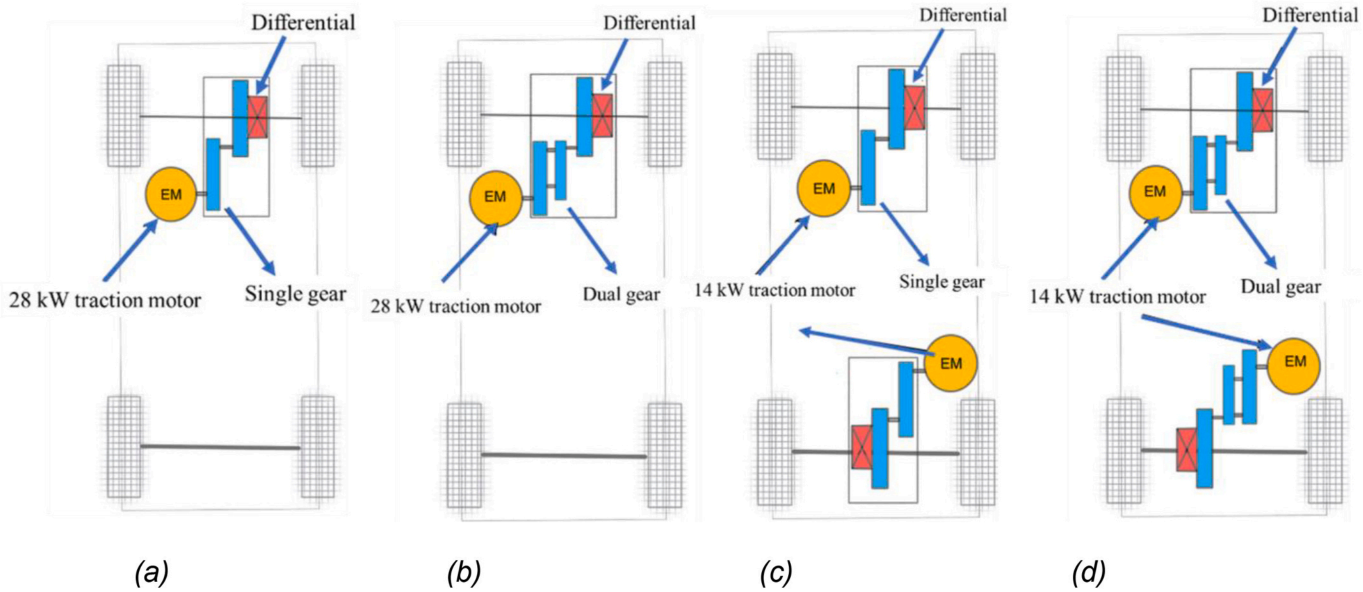


Fig. 21. One (a and b) or two (c and d) electric motors, coupled with single-speed (a and c) or 2-speed (b and d) transmissions [116].

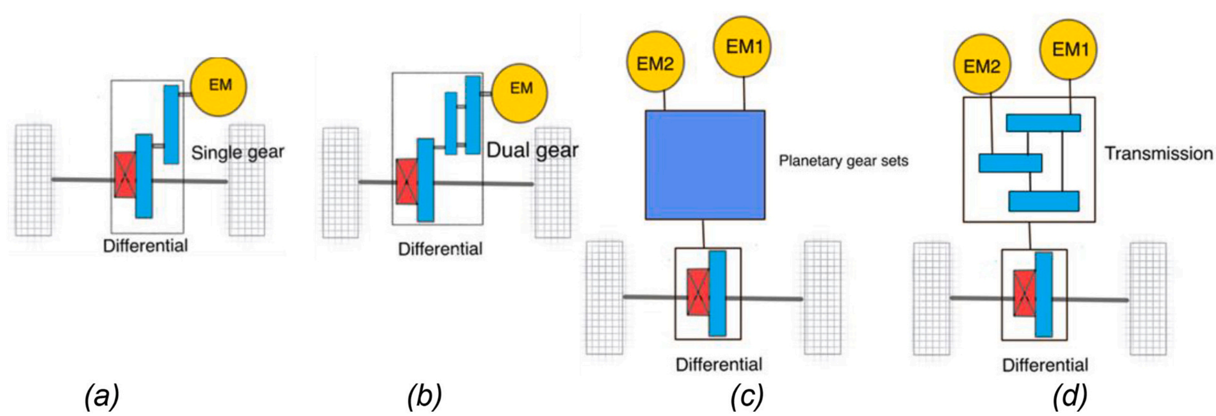


Fig. 22. Powertrain Layouts (a) single motor 1-speed, (b) single motor 2-speed, (c) Dual motor with planetary gear transmission, (d) Dual motor with parallel axle transmission adapted from [90].

Table 4
Tabulated references for transmission systems and vehicle layouts.

Reference Number	Single speed transmission	2-Speed transmission	CVT In EVs	In-wheel Motors	Hydraulic motor
[68]	✓	✓	×	✓	✓
[90,94,96,116]	✓	✓	×	×	×
[115]	✓	×	×	×	×
[102]	✓	✓	×	✓	×
[93,95]	✓	✓	✓	×	×
[35,66,69–71,100,101,103]	×	×	×	✓	×
[79,99]	✓	✓	✓	✓	×
[97]	×	×	✓	×	×

motor. Additionally, open, and closed loop (sealed) air-forced cooling systems are presented in [24], but both incur windage losses and poor performance in terms of rotor cooling. As shown in Fig. 25, an increase of more than 100% of the heat dissipated is found in oil spraying than in reference condition (air), therefore, air-based cooling is only applied if the occurring heat losses are low. Since the shift is toward high-performance traction motors, liquid cooling is currently the more obvious choice [45,121–124]. Air cooling is favorable for high-speed electric motors[25] especially for cooling rotors and water-cooled rotors may be prone to unfavorable phenomena of cavitation.

In liquid cooling, especially when applied to both the rotor and stator, there are typically increased friction and hydraulic losses compared to air cooling. However, liquid cooling is preferred due to its superior characteristics, such as better specific heat and higher convective coefficients [25]. Currently, water and oil are used in liquid-based cooling systems for traction motors. Convection heat transfer through jackets is by far the utmost conducive method for liquid cooling of electric motor stator. Literature suggests that increasing the cooling passages (up to an extent), optimizing the geometry of water jackets, decreasing pressure drop along the channels, and boosting the flow rate

Table 5
Comparison of transmission systems and vehicle layouts attributes for electric vehicles.

Attribute	Single-speed transmission	2-speed transmission	CVT	In-wheel motors	Hydraulic motor
Efficiency	High	Good	Good	Varied	Varied
Complexity	Low	Moderate	Moderate	Moderate	High
Drivability	Good	Good	Good	Good	Limited
Acceleration	Good	Good	Good	Good	Limited
Power Split Capabilities	No	Yes	Yes	Yes	No
Energy Consumption	Competitive	Competitive	Competitive	Competitive	Higher
Vehicle Mass	Lower	Moderate	Moderate	Varied	Higher
Control Complexity	Low	Moderate	High	High	High
Cost	Lower	Moderate	Moderate	Varied	Higher
Unsprung Mass Impact	Low	Moderate	Moderate	High	High
Terrain Suitability	On-road	Varied	On-road	Varied	Off-road

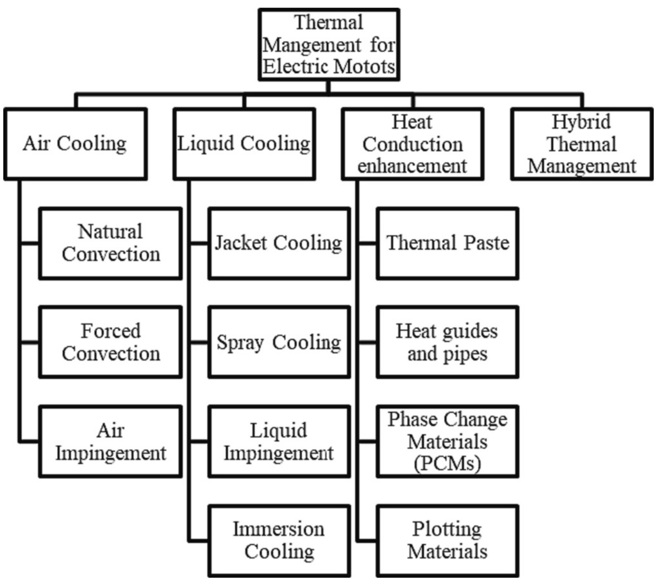


Fig. 23. Thermal management techniques for electric motors.

of coolant improve the heat transfer. The simulation-based result obtained in [125] through multi-objective topology optimization of water jackets in PM-SynRM, predicts an 80% decrease in system pressure drop and an 11% increase in thermal dissipation. Contemporarily, water as a coolant is more predominant than oil since lower power is required for fluid recirculation. On the contrary, water (generally it is mixed with glycol) has concerns such as corrosion, sealing, and insulation [120]. Moreover, oil can be used as a dielectric fluid and independent cooling passages can be avoided [25]. Also, a comparison of different liquid-based cooling systems for PMSM presented in [121], suggests that the highest continuous power is achieved when windings are cooled with oil.

It is argued by several authors that the most effective heating method is to keep the heat sink not far from the heat sources. Therefore, as shown in Fig. 26, oil spraying results in the best cooling scheme, especially when combined with water jacket cooling and applied to end windings [120]. The viewpoint is strongly supported by several authors in [24,25,52,124] and shortcomings such as uneven temperature distribution and complexity are also highlighted. However, as mentioned in [124], appropriate coolant selection and optimizing spray nozzle parameters will overcome these limitations.

Presently, the trend is to improve the heat transfer in a localized manner i.e., hybrid cooling methods that target spots that attain higher temperatures and employ heat conduction enhancement methods [24,123]. Slot winding, end winding, rotor shaft, bearings, and rotor magnet are some of these critical spots [52]. Out of these, the rotor magnets attain the highest temperature and represent the most critical section. Fig. 27 shows how improving the stator or rotor cooling can decrease the overall losses in continuous power. A comparative analysis based on heat transfer performance at different critical locations is performed in [52] among 18 different cooling concepts. The results suggest that the combination of a rotor shaft with spray cooling the end windings by radial rotors spray cooling, an outer cooling jacket and stator oil flushing showed an 18% average improvement of heat dissipation overall motor components.

An innovative liquid cooling topology that supersedes Tesla and BYD cooling systems as shown in Fig. 28 is discussed in [45]: air gap cooling cavity and heat conduction at the shaft cooling chamber is used at the rotor, while fluid enters the stator core cooling jacking by the stator core oil channels. Moreover, the stator winding fixed cooler is designed in a way to avoid in-homogenous cooling intensity, and additional stator winding rotary coolers are incorporated to tackle NVH issues.

Several studies for instance [31,124,126], have promoted the idea of substituting conventional round bar windings with hairpin windings as illustrated in Fig. 29. This replacement results in better thermal performance due to greater head dissipation area.

Microchannels, heat guide plates, and heat pipes are some auxiliary solutions that can provide additional heat transfer paths. As mentioned in [24], heat guide plates can reduce the temperature by 40% at critical spots and heat pipes have the potential to drop the peak temperature by 60 °C. It is reported in [122] that a 47% increase in overall heat transfer coefficient is obtained when compared to the natural convection of the motor surface.

Thermal management of centralized motors is easier than IWM and IWMG, since these latter usually consist of integrated motor drives, and the heat exchange becomes quite difficult in a such compact setting [123]. It utilizes the shared cooling system to optimize thermal management for maximum efficiency, as well as a modular arrangement for improved fault tolerance[127]. Technology and principle-wise thermal management systems are the same across IWM and centralized systems, but the packaging is a decisive attribute. For IWM, the packaging approaches can be radial or axial, subject to traction motor topology, and shared or dedicated cooling of the motor can be performed. Accordingly, mechanical, and thermal designs should be separate and in the vicinity of each other to achieve effective design for highly integrated IWM, which makes hybrid design the preferred methodology. The evidence presented thus far supports the idea that individual motors should have a dedicated thermal management system and a more sensitive electronic system should be cooled first [123]. Moreover, optimization of cooling channel configuration has shown 8% and 6.4% cooling performance improvement of the bearings and resolver, respectively [128].

It is pertinent to mention that YASA has patented their axial flux IWM design with liquid evaporative cooling scheme [129]. Evaporative cooling, as seen in patents like SU-955379 and U.S. Pat. No. 5,394,040, involves a hollow shaft cooling the rotor by evaporating refrigerant inside. Vapor condenses in an external housing, releasing heat. These systems are passive and sensitive to temperature and pressure changes. Maintaining ambient pressure is ideal to avoid seal stress, but it may

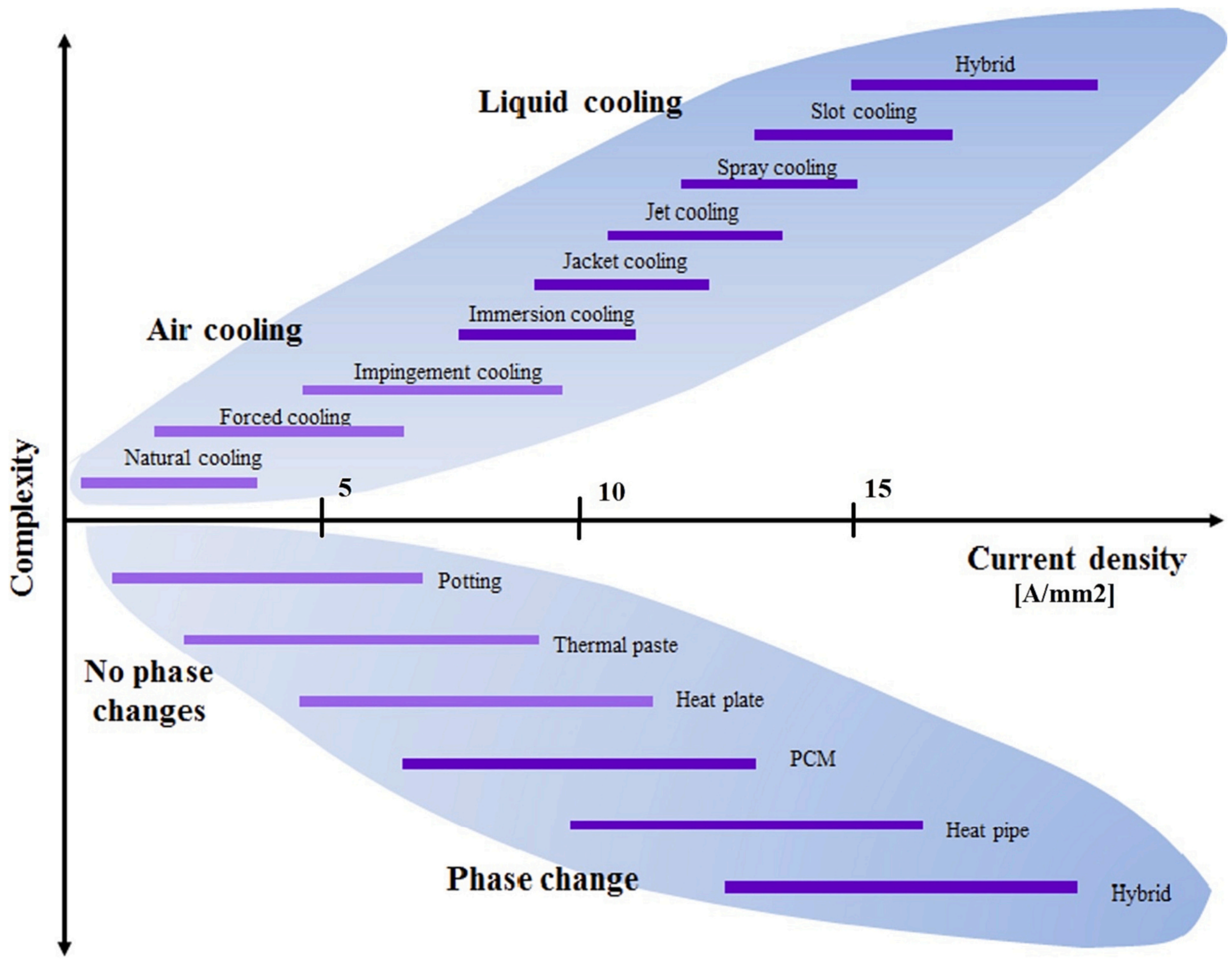


Fig. 24. Comparison of different thermal management technologies [24].

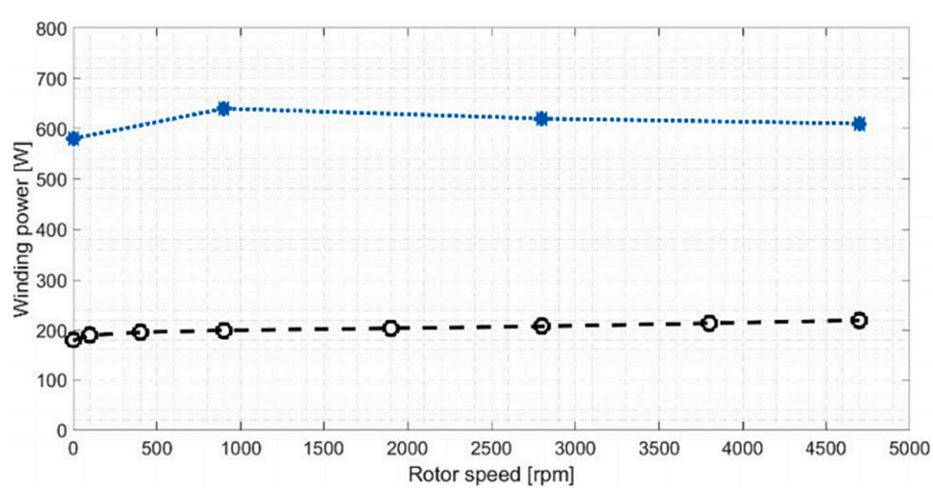


Fig. 25. Effect of rotor power on winding power for relative max oil flow rate, black dashed line represents heat dissipation in reference condition (air) and the blue dotted represents heat dissipation with oil spraying [88]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

impact cooling efficiency. Alternatively, the cavity may contain only the working fluid, resulting in sub-atmospheric pressure at ambient conditions, requiring pressure reduction measures. YASA's cooling system encloses a sealed chamber with a cooling medium that turns to vapor on contact with heated stator coils, transferring heat as it condenses on the stator housing. Rotation of the rotor enhances cooling with airflow. The chamber contains less than 25% liquid, maintaining ambient pressure for seal integrity and cooling efficiency. Pressure regulation can be added if needed.

In practice, the thermal management of traction motors is always associated with that of the batteries, inverters, HVAC, etc., and therefore the contribution due to the integration of these components should be

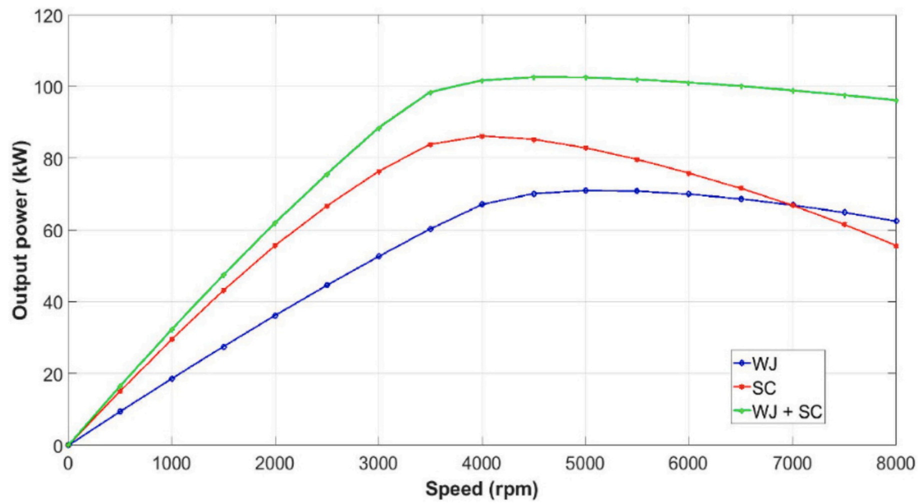


Fig. 26. Output Power of an electric motor comparison with and without oil spraying, where WJ is Water Jacket cooling and SC is spray Cooling [120].

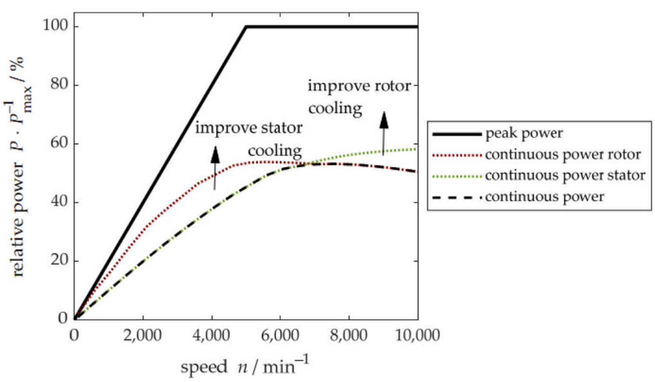


Fig. 27. Percentage peak power and continuous power of a PMSM, limit temperatures at stator windings or magnets were considered [121].

considered [8,24]. Table 6 summarizes key attributes of the thermal management schemes presented in Section 3.

References used to gather trends and attributes for these schemes are tabulated in Table 7

4. Future trends

This section delves into the significance of materials and additive manufacturing in improving the mechanical efficiency of traction motors in electric vehicles (EVs). It examines the influence of material selection, explores alternative motor types, and presents weight reduction concepts. The importance of thermal-efficient materials and advancements in additive manufacturing are emphasized. Additionally, future research directions and opportunities are identified, encompassing emerging trends, such as nanomaterials and active suspensions. This section offers valuable insights into the evolving field of materials and additive manufacturing, specifically tailored to high-efficiency traction motors in EVs.

4.1. Materials trends

A considerable amount of literature has been published discussing material advancement, and enhancing the magnetic, electronic, and thermal performances of traction motors[7,130]; however, very few

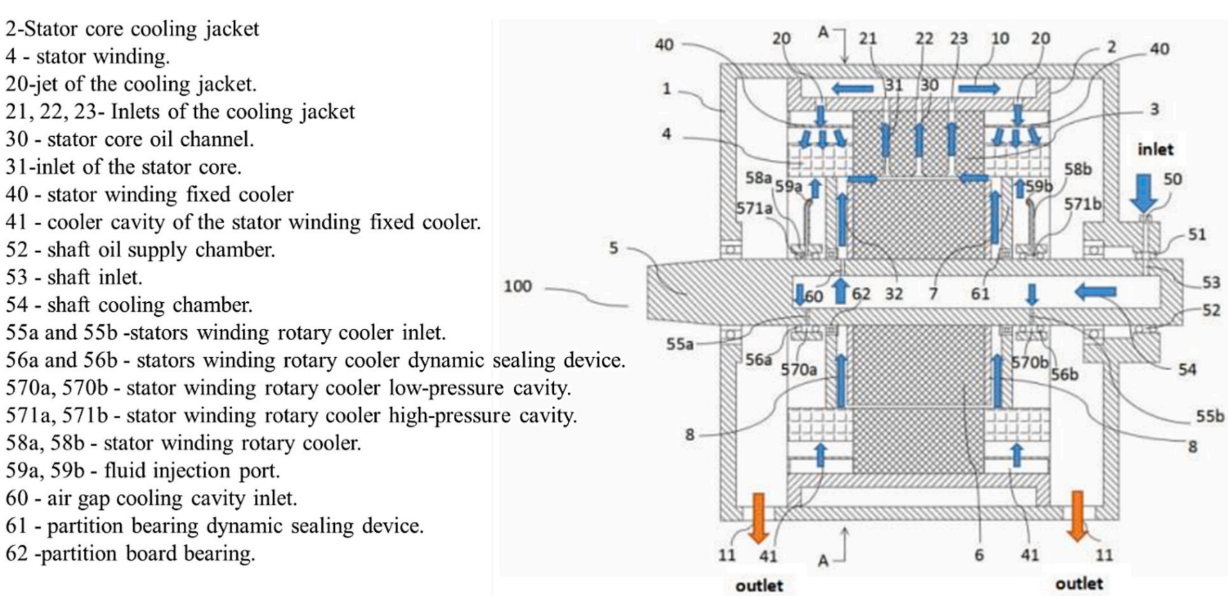


Fig. 28. Cooling system Concept adapted from [45].

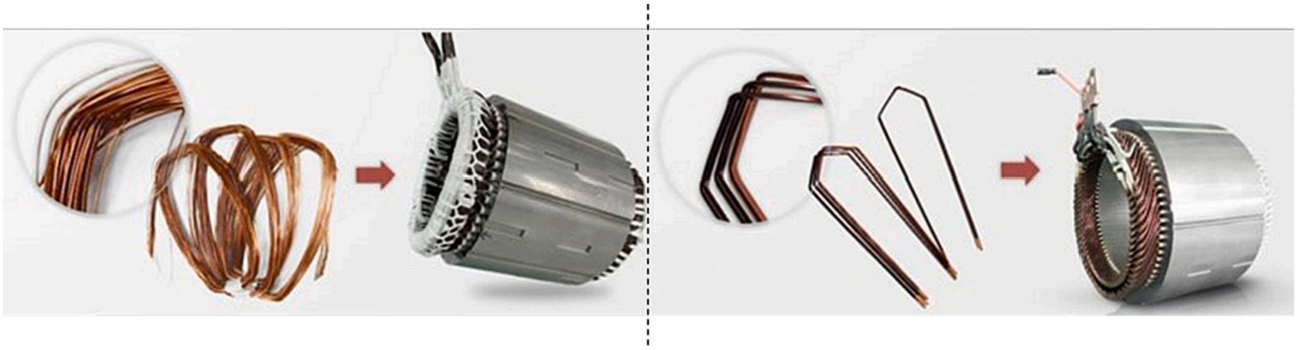


Fig. 29. Round bar windings (left) vs Hairpin windings (right).

Table 6
Comparison of thermal management attributes for electric vehicle traction motors.

Attributes	Air cooling	Water cooling	Oil cooling	Integrated thermal management	Heat transfer enhancement
Efficiency at High Temperatures	Unsatisfactory	Effective	Effective	Effective	Varied
Maintenance Complexity	Complex & Costly	Low	Low	Low	Varied
Cooling Components	Fins, Turbulent Airflow	Water Jackets, Pumps	Oil Passages, Pumps	Complex Systems	Hybrid Methods
Power Density Impact	Detrimental	Low Impact	Low Impact	Low Impact	Varied
Friction & Hydraulic Losses	Low	High	High	Varied	Varied
Coolant Selection	Air	Water (with glycol)	Oil	Varied	Varied
Complexity	High	Moderate	Moderate	High	Varied
Optimization Potential	Limited	Moderate	Moderate	High	High
Additional Heat Transfer Paths	Limited	Moderate	Moderate	High	High
Specific Heat & Convective Coefficients	Low	High	High	High	Varied
Cooling Location	Rotor Cooling	Stator and Rotor	Stator and Rotor	Various Critical Spots	Localized Heat Transfer

Table 7
Tabulated references for cooling system alternatives for traction motor.

Reference number	Air cooling	Water cooling	Oil cooling	Integrated thermal management	Heat transfer enhancement
[8,24,25,120]	✓	✓	✓	✓	✓
[52]	✓	✓	✓	×	✓
[121]	×	✓	✓	×	×
[45,124]	×	×	✓	×	×
[122]	×	×	×	×	✓
[123,128]	×	×	×	✓	×

studies have investigated the influence of materials on mechanical efficiency.

Considering the scarcity and exorbitant cost of rare-earth metal as neodymium Fig. 30, researchers and OEMs are keen to reduce their consumption or completely substitute rare-earth metals [31].

Therefore, induction, wound rotors, switched reluctance and ferrite-based motors are going to be prime alternatives to PM motors [72,131]. Magnet manufacturers are striving to reduce the rare earth content of magnets while maintaining or improving their performance. One such example is Hitachi metals[19] which are manufacturing magnets using a novel process, which involves the diffusion of dysprosium into the magnet material in place of direct alloying [131]. Moreover, recycling and recovering is also deemed as a possible solution for cheap extraction of these materials, however, concerns related to quality and recurring usage are still to be resolved [132]. Other useful materials alternatives for these materials are iron nitride and manganese-based compounds but, commercialization is still a hindrance [131].

Materials selection is crucial to curtailing the mass of traction motors without compromising on their performance characteristics. This notion has been used to develop two different material substitution concepts to reduce the mass and rotational inertia in PMSM [133]. Copper wires in the stator have been replaced with aluminum ones in the first case, but the weight savings comes at the cost of the drop in maximum power, and eventually, the substitution fails to provide the same specific power. On the other hand, the second solution guarantees a 13% increase in the power-to-weight ratio by using a polymer as a substitute material for rotor lamination sheets without considering the mechanical or thermal stability of the motor [133]. Rotor lamination sheets perform important functions such as reducing the magnetic resistance and torque transmission between the rotor shaft and rotor yoke.

Materials for lamination has been dominated by silicon steel; however cobalt steel and cobalt-iron alloys are of interest due to their superior magnetic properties, leading to more efficient and compact motors [134]. However, they are more expensive than traditional silicon steel laminations, impacting manufacturing costs [135]. Additionally, concerns exist about cobalt's availability due to its rarity and its mining's and extraction's significant environmental impact [136]. Balancing its advantages with cost considerations is essential when considering their use in traction motors.

Materials for magnetic core are gaining prominence due to their critical role in determining losses in traction motors. A soft magnetic core (electrical sheet lamination) with high permeability and low core loss is required to render high performance. Therefore, non–oriented electrical steel (NOES) with optimum microstructure and texture is produced to impart high–speed in traction motors [137]. Performance analysis using FEA indicates that a 3.2% Si NOES after final annealing at 850 °C for 60 min provides identical output power with commercially available materials but with core losses reduction of up to 48.5% and an efficiency increase of 0.45%. Similarly, in [138], a comparison between three alternatives employed claw-pole, radial, and axial flux motors

[19] https://asia.nikkei.com/Business/Materials/Hitachi-Metals-developing-EV-motors-with-less-China-rare-earths accessed 29/11/2022.

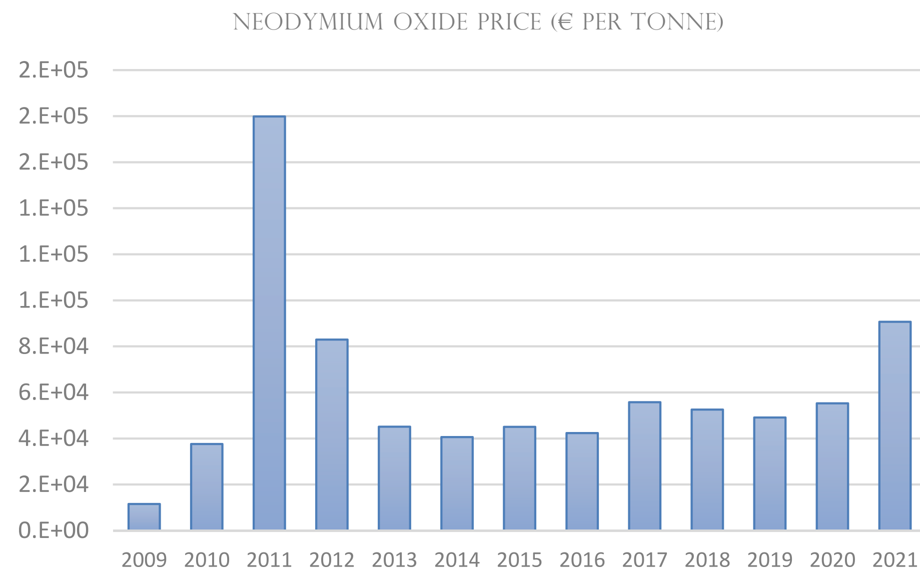


Fig. 30. Cost of Neodymium in the last decade. Source: www.statista.com/statistics/450152/global-reo-neodymium-oxide-price-forecast/.

reveal that a Soft magnetic composite (SMC) material with a medium magnetic permeability, electric resistivity, and hysteresis loss, achieved the highest efficiency and mechanical analysis also confirms the manufacturing feasibility. SMC materials, composed of iron powder particles held together by insulating materials, can play integral components in electric motors construction [139]. The material exhibits isotropic properties, which enables the creation of magnetic circuits featuring three-dimensional flux pathways. Additionally, the presence of an insulating layer between the iron powder particles serves to reduce losses stemming from eddy currents [140]., boosting power density in space-constrained applications. However, SMC materials have limitations, including reduced mechanical strength, lower thermal conductivity, high core loss at low frequency range [141],limited availability, higher initial cost, potential environmental concerns, and magnetic property variability. These characteristics can be improved as SMC materials offer design flexibility through powder processing [142].

Thermal-efficient materials are in high demand in the pursuit of high-speed traction motors. There are many potential replacement materials for enamel coatings on magnet wires, including ceramics, which have excellent thermal stability over a wide range of temperatures [143]. To further improve efficiency and reduce the temperature rise of the motor, resin rings mixed with magnetic powder are attached to the stator to improve efficiency and reduce the temperature rise [144]. The eddy current losses were reduced by 78%, while the temperature rise value was reduced by 30° compared with open slot motors (the conventional motors with an air gap between coils and permanent magnets). Moreover, efficiency was enhanced by 1.1% and 1.8%, compared to open and closed slot counterparts, respectively.

Potting materials as shown in Fig. 31 are generally used to fill air pockets between solid components in motors for heat conduction enhancement purposes.

Electric traction motors employ two main potting methods: end winding potting and global winding potting [145], vital for efficient thermal management [146], especially in motors with liquid cooling systems that often rely on housing water jackets [147]. However, this cooling approach can create temperature hot spots in windings due to the extended heat transfer path within the motor. Stator potting resolves the issue by creating a direct heat transfer pathway from hot spots to the motor frame, where coolant circulates. Global potting improves heat transfer further with high thermal conductivity resins. Selecting the right potting material for automotive traction motor cooling involves key criteria [145]: temperature resistance above 200 °C, thermal conductivity ranging from 0.5 to 5 W/m·K, appropriate viscosity (e.g., up to 12,000 mPa·s), compatibility with motor design (electrical properties, chemical resistance, adhesion, curing time, shrinkage control, mechanical stability), and resistance to environmental factors like moisture and chemicals. End winding potting offers versatility, as it doesn't require primary insulation, allowing for materials with superior thermal conductivity despite poorer electrical properties and higher viscosities. The authors in [147] have regarded the potting material encapsulation as an enhanced thermal cooling solution for the PMSMs.

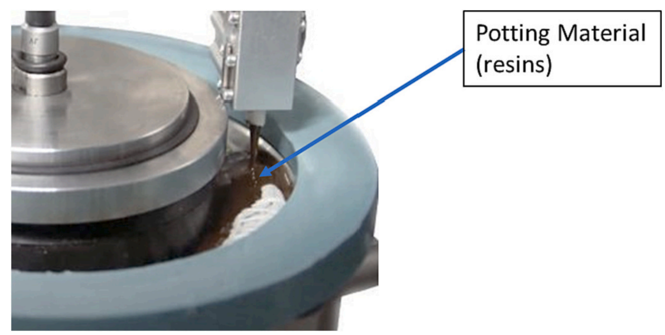


Fig. 31. Application of Potting material in traction motors as an encapsulant.

Studies such as [24,120,147], reveal a positive effect on power density and motor life due to their usage, particularly in end windings which are also depicted in Fig. 32.

Additionally, [24,120] purpose the application of Phase-change materials (PCMs) in thermal management systems, allowing prolonging the continuous operation of the motor by 50% and decreasing the peak temperature up to 8°. The excellent electric and thermal conductivity of graphene and other allotropes of carbon can make a significant difference in motor windings and motor thermal management [143]. Finally, promising material choices are tabulated according to their applications in Table 8.

4.2. Additive manufacturing advances

After reviewing the current materials trends, this section discusses additive manufacturing advancements that enable high-efficiency traction motors. Although additive manufacturing offers significant advantages, and major automakers are engaging in this technology, it has yet to be widely adopted [148,149]. There are several reasons for the low

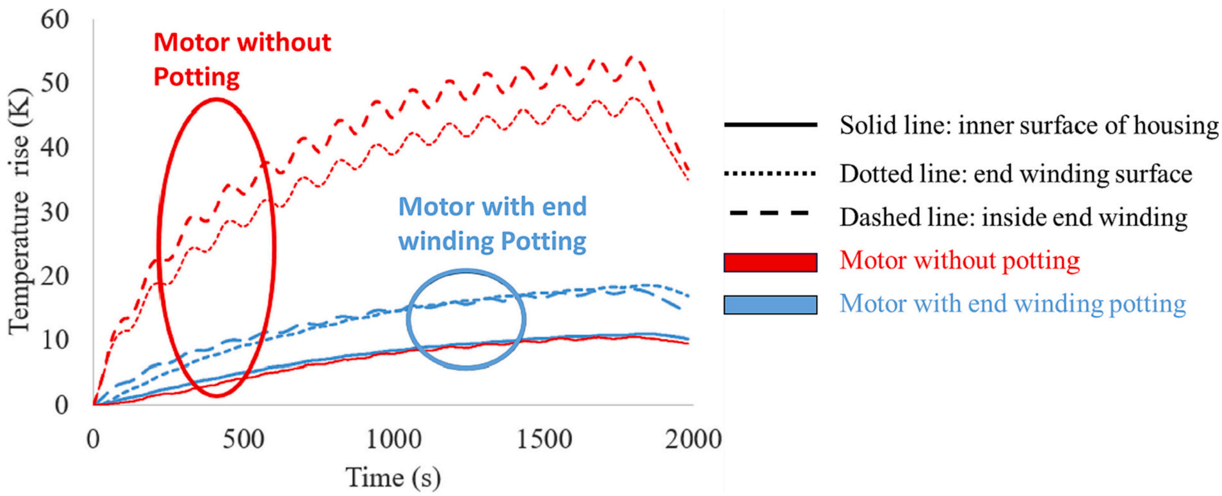


Fig. 32. Comparative analysis of temperature elevation during transient conditions between the reference motor and the motor employing end winding potting. Power fluctuates from 0 W to 500 W in 60-s intervals. Temperature sensor positions are indicated by distinctive line patterns [147].

adoption rate of additive manufacturing technology, including its high initial cost, long production times, inability to produce large single parts, multi-material printing issues [149] and the wide material composition of the modern automobile. Traditional automotive manufacturing processes used a wide range of raw materials, and some of the additive manufacturing processes may not support materials that are currently being used for manufacturing. Presently, 3D printers can support only up to a few materials at a time for a build. Most additive manufacturing techniques cannot support different materials for printing one single component. Another key area of concern is that additive manufacturing requires technical expertise from the stage of designing the product to the stage wherein the end component is removed for post-curing. Lack of skilled labour is a challenge hindering the adoption of this technology, especially among tier manufacturers across the globe.

However, there are certain claims by researchers stating plausible implementation of AM on a large scale. Most of the research on AM advances in traction motors has focused on the application of advanced AM materials at the part level and topology-wise. Table 9 summarizes state-of-art AM technologies employed in traction motors at the part level [143,149–151].

AM technology can make it possible to obtain excellent and customized desirable material properties, as presented in [148], where it is indicated that a small binder size is the key to the optimization of hard magnetic materials in the cold spray AM process. It is also argued that higher losses are incurred in cold spraying of SMC and FFF and they are still nascent to be used. However, SMCs are capable of being used in AM applications as demonstrated in [152] and [153], where an Laser Power bed Fusion (LPBF)-based SMC rotor is produced and tested for SRM, and powder metallurgy applications of SMCs are discussed, respectively. Furthermore, Metal-FeB composite permanent magnets can be produced by cold spray, achieving comparable properties to conventional methods without major defects [154].

A significant breakthrough can be achieved in the thermal management of traction motors through AM [123,143,149]. AM-produced hollow winding conductors have a larger effective area with the same active cross-section, therefore more current density is achieved. The capability to produce small tubes with thin walls up to 60 μm and manufacturing of the coolers implemented in special thermally

Table 8
Summary of material trends for traction motors.

Material	Design requirements	Promising choices	References
SOFT MAGNETIC MATERIAL	• High permeability and saturation • Low iron core losses	• Fe-SI • Fe-Ni • Fe-Co • Iron alloys with 1% aluminum and less than 0.5% Manganese • Amorphous iron • NOES	[137], [138,143]
CONDUCTING MATERIALS	• Good electrical • heat conductivity	• Copper • Aluminum • Graphene	[133,143]
HARD MAGNETIC MATERIALS	• Great residual magnetic flux density • coercive magnetic field strength, and energy density • Favorable mechanical features	• Neodymium-Iron Boron (NdFeB) • Iron-Nitride • Aluminum Nickel Cobalt (AlNiC) • Samarium Cobalt (SmCo)	[34,82,132,143]
THERMAL MANAGEMENT	• Temperature-resistant • High conductivity	• AlSi10Mg • Al-Ni • BeO • SiC • Graphene • Ceramics • Phase-change materials • Potting materials	[39,70,128,144]

Table 9
Part-wise AM advances traction motor.

AM Appl.	Design requirements	Potential technologies	Comments
Core	• High magnetic permeability and saturation • Low hysteresis and eddy current losses • Mechanical properties	• SLM • FDM • LOM • DMLS • LPBF	• AM can provide solutions with increased ductility and optimal geometry. • Construction of radially unsymmetrical iron cores is easier. • The best material is Fe-Si alloys with higher silicon content. • DMLS approach can solve mechanical issues. • The lack of reliable inter-material insulation layers is a shortcoming compared to conventional processes.
Coils/ Windings	• Lower power losses • Low electrical resistivity • High conductor filling • Good magnetic, thermal, and mechanical properties	• DMLS • Multi-Material AM	• Non-conventional forms of windings are possible, with better heat-resistant insulation and the possibility to equip cooling channels • Multi-Material (MM) - AM can eliminate post-processing. • Good thermal characteristics of the resin-based insulation from MM-AM without losing mechanical strength. • Not possible to AM pure Copper or Aluminum. • Higher slot-filling factor possible.
Permanent Magnets	• High magnetic permeability, hysteresis losses, eddy current losses	• SLM • BJP • FDM • BAAM	• Optimal magnetic energy delivery with the least amount of waste. • isotropic or anisotropic properties can be modified/ created by controlling the grain structure.

conductive electrical insulators, allows effective cooling of windings. For iron core cooling, AM enables the realization of cooling jackets as a single unit, thus avoiding leakage problems due to mechanical integrity [143]. Besides, the ability to produce intricate shapes is used to enhance the thermal performance of housing, as shown in Fig. 33, providing additional mass reduction by 40% and increased rigidity of the structure.

Turning now to the topology level, the most promising AM applications in this regard are asymmetric designs, shape optimization, and modified properties [143,149]. Among the benefits of AM for PMSM is its ability to reduce mass, volume, and inertia and optimization the shape of the rotors. In the case of IM, a good diffusion bonding between the copper layer and the iron core will prevent the detachment of these components [143]. AM technologies can overcome the barrier of complex shapes for SynRM, as well as reduce torque ripple by a significant amount [57]. Finally, AM can be used to achieve an optimized structure for SRM to resolve torque ripples and noise. One interesting development presented in [151,155] is the introduction of multi-material 3D printers with an example in Fig. 34, which can further excel the

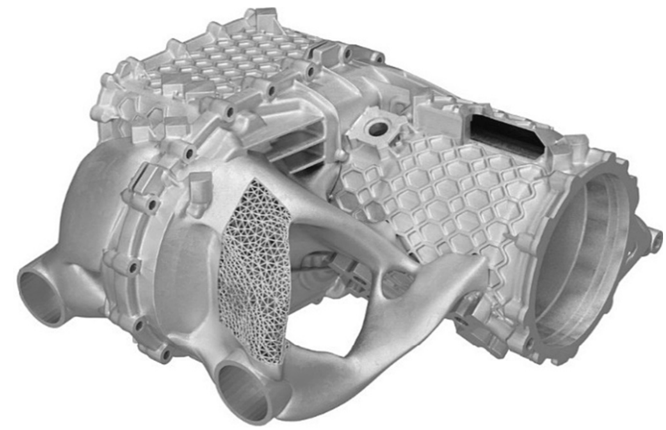


Fig. 33. Prototype for small-series production: Porsche electric drive housing from a 3D printer.
Porsche, "Prototype for small-series production: electric drive housing from a 3D printer; Press Release, accessed 29/11/2022.

application of AM in the coming days. Comparison of four metal AM techniques for electric motor is made in [156]: Powder-based methods like PBF and binder jetting offer high resolution but are slower and face safety concerns. In contrast, wire-based techniques like wire Directed Metal Deposition and joule printing are faster and cost-effective but may have lower resolution and post-processing needs. The paper showcases successful examples of metal AM in electrical machines, emphasizing the need for further research to tackle challenges and enable multi-material printing for improved performance.

Moreover, research in [157] investigates the potential application of additive manufacturing (AM) and asymmetric hairpin winding layouts to enhance the performance of electrical machines. The study focuses on exploring the viability of aluminum alloys, specifically ENAW6016 and A03830, as alternatives to copper alloys, considering their lower cost as shown in Fig. 35. Furthermore, according to [158], the Environmental Load Unit (ELU) underscores that the environmental damage cost for copper (131.0 ELU/Kg) is notably higher than that for aluminum (0.159 ELU/Kg), highlighting the potential sustainability benefits of choosing aluminum.

Finite element modeling demonstrates that ENAW6016 and A03830 exhibit reduced losses compared to pure copper as shown in Fig. 36.

Utilizing an analytical model and optimization algorithms, the research identifies optimal winding layouts that incorporate variable conductor cross-sections. By integrating AM and these optimized

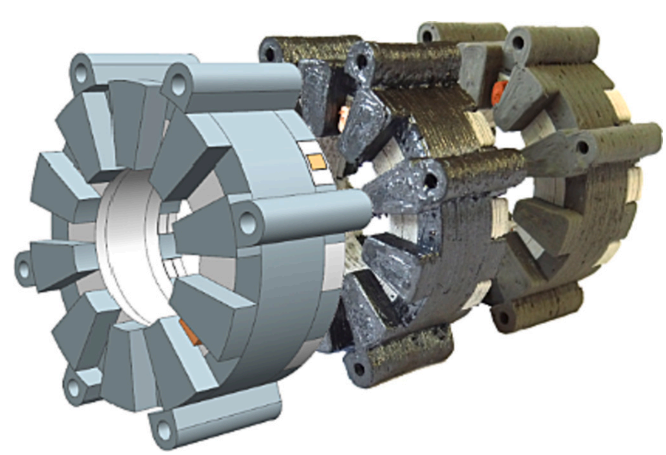


Fig. 34. Stator of the reluctance motor. Left: CAD model, middle: sintered stator, right: printed part before heat treatment.
https://www.tu-chemnitz.de/etit/ema/AMMM/, accessed 29/11/2022.

layouts, the study aims to enhance the overall efficiency of electrical machines, thus contributing to advancements in the field.

As stated in [159], Additive manufacturing holds significant promise for the future of mobility by enabling functional integration and higher power density in components. Continuous improvements in component quality and mechanical properties are expanding its application horizons. However, challenges remain in accurately estimating the costs of additive components due to fragmented cost analysis approaches that overlook comprehensive process chains. This research emphasizes the need for transparent and structured cost calculation methods in this context.

4.3. Research gaps/opportunities

This paper has comprehensively reviewed current novel trends to improve the mechanical efficiency of traction motors in EVs. Yet, the ever-growing demand for EVs suggests the following research gaps and opportunities to be explored (see. Fig. 37 for a pictorial representation):

- Switching to Axial and in-wheel motors is inevitable as both these technologies provide better power density and compact powertrain solutions [31];
- Archetype formation, platform sharing and modular and scalable architecture [110] are going to be key for OEMs as they will comprehensively reduce the design lead time and cost to form new solutions [160];
- Regenerative braking is a great solution to maximize the mechanical efficiency of EVs, novel control, and recovery strategies are required [71,93,96];
- High-Performance demands and lower mass requirements are shifting traction motors to high voltages, therefore related groundwork is required [58];
- Design processes and schemes are needed to synchronize distinct aspects and for achieving systematic flow [35,161–163]; especially co-designing electric vehicle components, known as concurrent engineering, enhances electric motor efficiency. It integrates batteries, optimizes thermal management, reduces weight, streamlines aerodynamics, and fine-tunes transmission and drivetrain components. This approach also incorporates regenerative braking and advanced control systems, collectively maximizing motor efficiency and improving overall electric vehicle performance.
- Artificial intelligence is used for novel design solutions and optimization of existing ones [96,164–168],
- As explained, the design of traction motors is interdisciplinary. Therefore, future research will be devoted to taking multi-physic design constraints into account [169]. One such example will be integrated thermal management systems, which will make use of heat recirculation to improve overall thermal efficiency [170,171];

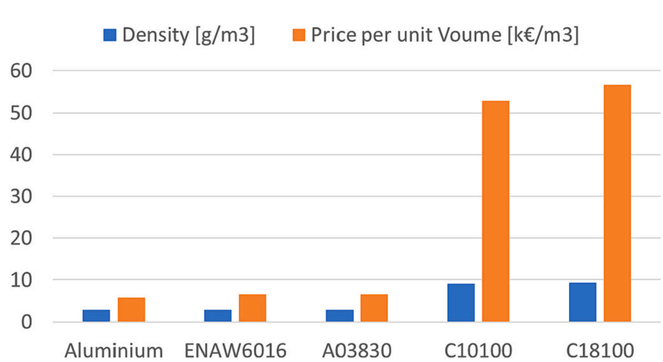


Fig. 35. Density and price per unit volume of the species identified in [157] are shown.

- Torque vectoring strategies for traction motors are necessary to upgrade driving performance and optimize the power requirements [172,173];
- With novel solutions coming up, the need to devise a testing method for validation purposes will be ever-growing [174];
- Nanomaterials are prospective material alternatives, but their application is still in the immature phase [175,176]. They can provide solutions with high material performance with additional weight and volume reductions.
- Developing a new generation of active suspensions will enable IWM and IWMG to be adopted[177].
- Hairpin windings present advantageous features that contribute to the improvement of mechanical efficiency in electric motors [178]. These windings facilitate efficient heat dissipation, thereby preventing overheating and maintaining an optimal motor temperature, which reduces the likelihood of performance deterioration [179]. Furthermore, since as stated in [180] hairpin windings provide the possibility to design smaller slot openings they can effectively decrease cogging torque, resulting in smoother motor operation and reduced mechanical losses [180]. Additionally, they enable a higher slot fill factor, allowing for a greater amount of copper mass in the stator[181]. This enhancement positively impacts electromagnetic performance, power density, and overall mechanical efficiency of the motor.

5. Conclusion

This paper reviews the state-of-art strategies to improve the overall mechanical efficiency of traction motors for the implementation of EVs. The strategies were explored through different aspects namely mechanical design, materials trends, and AM advances. The following conclusions are established.

- Based on a comparison of traction motor topologies according to design requirements, Axial flux, in-wheel, and SRM are the topologies that possess relevant potential.
- losses incurred in traction motors have been analyzed and their formulation shows that speed and temperature are the crucial parameters to be considered.
- Referring to transmission technologies compatible with traction motors, employment of transmission does widen the efficiency region of the motor, plus it also enhances the driving and range performance. It is foresighted that the role of multi-stage, CVT, and other novel transmission system solutions will be useful.
- The selection of an efficient transmission system is not enough, layout optimization allows the operation of the traction motor and transmission efficiently. The more independent the wheels are, the better driving performance is achieved, and overall optimization of efficiency is also guaranteed but cost and complexity have to be managed.
- The selection of thermal management systems for electric motors is entirely dependent on the maximum operating requirements. Liquid cooling systems performance is best suited for high-performance motors provided that the stator is cooled. The rotor should be preferably cooled with air to avoid unbalance due to bubbles in the cooling fluid (cavitation). The application of heat enhancement technology can also aid in reducing the temperatures.
- Materials are key to both the mechanical and thermal performance of traction motors. With the challenge to replace rare-earth metals and further enhance traction motor performance, novel materials are introduced to fulfil these demand requirements.
- AM technologies are still evolving to develop traction motors with better performance. Partwise, AM is likely to make an impact but on the topology front, it still needs technological advancements to reach the performance achieved by conventional production processes.

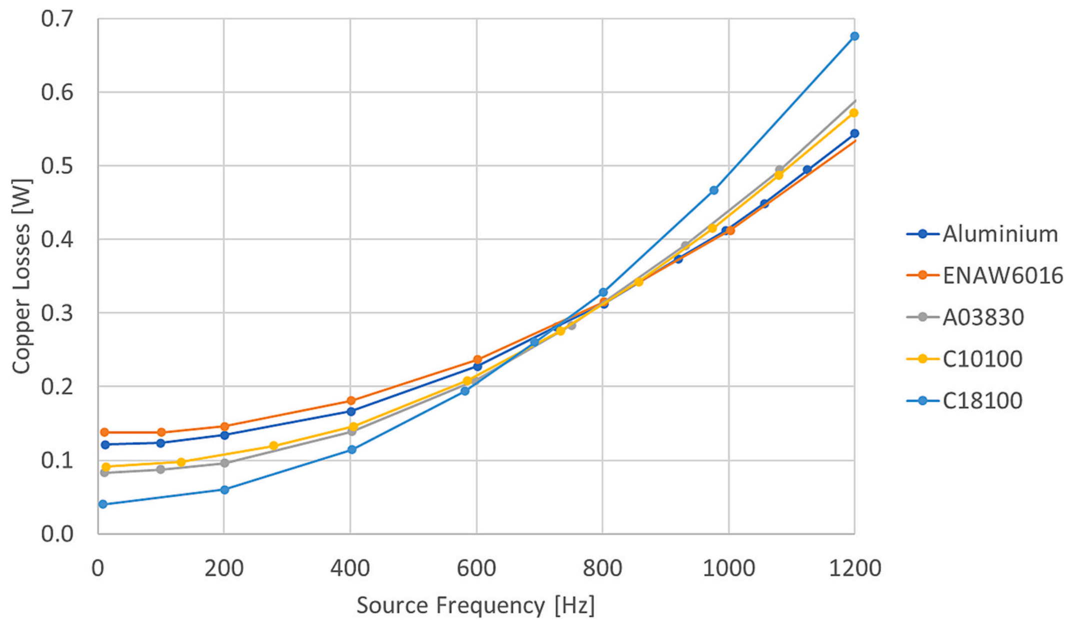


Fig. 36. Analyzing AC losses in conventional hairpin designs across a range of materials, while exploring their frequency-dependent behaviour [157].

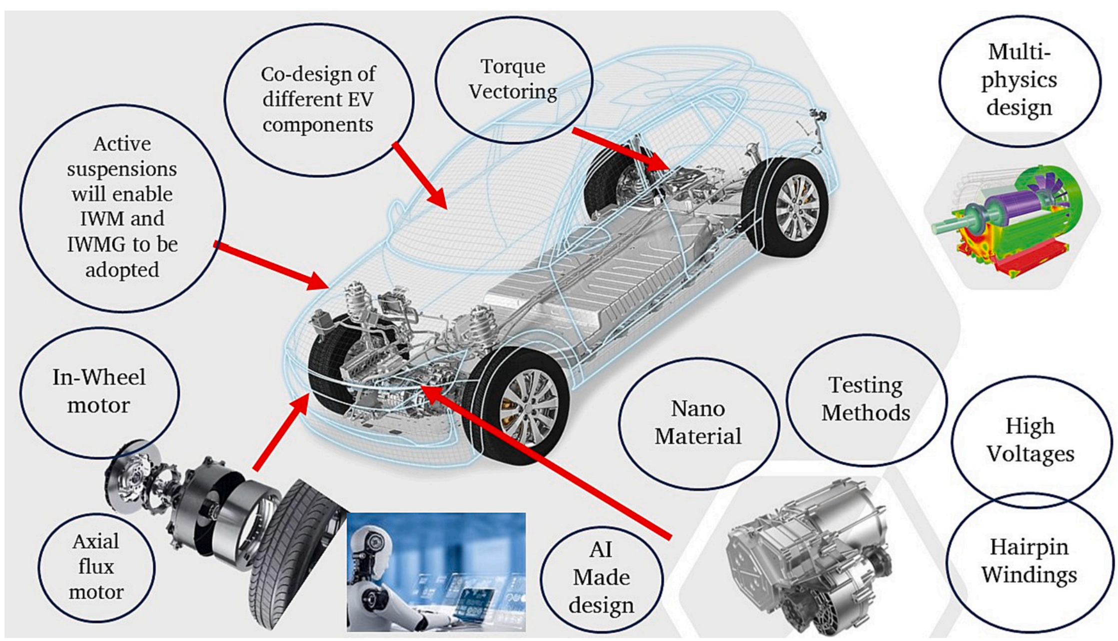


Fig. 37. Research Gaps/Opportunities to be explored.

CRediT authorship contribution statement

Massimiliano Gobbi: Writing – review & editing, Methodology, Funding acquisition, Conceptualization. **Aqeab Sattar:** Writing – original draft, Investigation. **Roberto Palazzetti:** Writing – original draft, Methodology, Investigation. **Gianpiero Mastinu:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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