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Review

Technical Roadmaps of Electric Motor Technology for Next Generation Electric Vehicles

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Abstract: This paper provides a consolidated discussion and proposes significant measures in improving and advancing the performance of synchronous machines employed in electric traction applications designed for passenger electric vehicles (EVs). The paper quantifies the discussion on improving the power density (kW/kg) and efficiency (%η) of the machine with the commercially available solutions in terms of new design architectures, advanced emerging materials, and adoption of additive manufacturing (AM) technologies. New challenges and opportunities are identified for the optimized machine designs having the potential to meet the global standards while keeping the cost under control. This paper provides an overview of current trends, an introduction to innovative technologies, and changes in existing manufacturing practices to achieve high-performance electrical machines with improved fault tolerance capabilities and reliability. Thereby meeting the standards for the next generation of electric vehicles.

Keywords: additive manufacturing (AM); electric drive technology (EDT); electric traction drive system (ETDS); electric vehicle (EV); fault tolerance; heavy rare-earth (HRE) materials; net-zero carbon emissions; synchronous motors

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1. Introduction

The transitional developments in adopting all electric vehicles (EVs) as a mode of mobility demands electric drive technology (EDT) to enhance, improve, and provide better operational capabilities for electric traction drive systems (ETDSs) [1]. This could potentially be achieved through the smart or additive manufacturing (AM) of electric traction machines—mostly synchronous motors—and employment of new advanced materials to attain high-power density ETDS with optimized inverter designs [2,3]. The automotive councils of the US [4] and UK [5] have set their vision and targets to advance ETDS by overcoming the number of existing issues and challenges. These include cost, which aims to make electrification more affordable and can possibly be achieved by optimizing the $/kW cost of the motor, inverter, converter, and on-board charger. The set target for the optimized cost is $6 per unit kW power (the baseline is for a 100 kW electric machine and a 100 kW Power Integrated Module (PIM)). Secondly, improving the performance, which refers to an increase in power per unit volume, while reducing the weight/volume of the components. The reduction in volume offers the integration of cooling parts within the current vehicle architecture. Third is the efficiency—which aims to provide value to the customer through a longer EV range, higher MPG (miles per gallon), and/or MPGe (miles per gallon equivalent) ratings. Finally, it is the reliability, which includes the fault tolerance capability of an ETDS to provide longer maintenance scheduling/service to the vehicle. The fault tolerance is defined as the ability of a system to continue its operation without

interruption, even if one of its components fails. The newly developed ETDS should thus be competitively equal to or better than conventional petroleum-powered vehicles, taking reliability aspects into consideration [6–8]. Additional challenges include reduction in manufacturing costs to have mass-market adoption, reducing or removing the dependency on materials (such as rare-earth elements) whose supply chain is unpredictable, minimizing the material waste, and lastly, enabling the possibility of reusing/recycling the material after use (keeping environmental impact into consideration) [9,10].

The following subsection illustrates the set targets of electric drive technology for the automotive councils of the US Department of Energy (DOE) combined with the UK Advanced Propulsion Centre (APC).

1.1. Electric Drivetrain Targets—Automotive Councils of the US and UK

The US DOE, in collaboration with the US Council for Automotive Research, has developed roadmaps for 2025 and announced distinct targets in 2013 and 2017 for the electric passenger vehicles listed in [6,8]. On similar lines, the UK APC in 2020–2021 has provided the UK Automotive Council roadmaps for 2035, setting up a target of net-zero emissions by 2050 [5]. The aim is to achieve a highly efficient and cost-effective passenger vehicle through a 100 kW electric traction drive and a 100 kW inverter [7]. For a 100 kW electric traction motor drive, or ETDS, the set target is to achieve 33 kW/L power density with 300,000 miles for a 15-year lifetime, and for a total cost of $6 per unit kW. This, when compared to 2020 goals [6], exhibits an 88% volume reduction and a 25% reduction in cost. The power density and mileage also double with the new set targets. For an inverter, a 100 kW integrated design with 100 kW/L power density at a cost of $2.70 per unit kW is expected [8]. This again, when compared to 2020 goals, represents an 87% volume reduction and an 18% reduction in cost [9,10]. While for a motor, the power density target of 50 kW/L at a cost of $3.30/kW is set, which constitutes a reduction in volume and cost of about 89% and 30%, respectively, when compared with 2020 goals [10,11]. The ETDS technical targets for 2025, which aim to reduce the production cost of power electronics and electric motors to $6/kW, are presented in Table 1. This is further bifurcated into two separate tables as electric motor and power electronic components as shown in Tables 1 and 2, respectively.

Table 1. Electric Traction Drive System * (ETDS) Targets (US DOE) [7–9].

Year	2020	2025	Reduction in Cost and Volume
Cost ($/kW)	8	6	Cost reduction—25%
Power Density (kW/L)	4.0	33	Volume reduction—88%

* For 100 kW electric machine and 100 kW Power Integrated Module (PIM).

Table 2. Electric (Synchronous) Motor Targets [7–9].

Year	2020	2025	Reduction in Cost and Volume
Cost ($/kW)	4.7	3.3	Cost reduction—30%
Power Density (kW/L)	5.7	50	Volume reduction—89%

The Automotive Council of the UK [5] and all other councils, including the European Union (EU) [12,13] align and stand in agreement with these targets. Tables 1–3 therefore serve as a benchmark to bring any advancement in the design and development of ETDS to improve its performance. Since the ETDS comprises the integration of both electrical machines and power electronics converters [14–16], as shown in Figure 1, this paper would, however, cover the comprehensive discussion on the electrical traction machines/motors only. The traction motor referred to in this study is synchronous machines.

Table 3. Power Electronics Targets [7–9].

Year	2020	2025	Reduction in Cost and Volume
Cost ($/kW)	3.3	2.7	Cost reduction—18%
Power Density (kW/L)	13.4	100	Volume reduction—87%

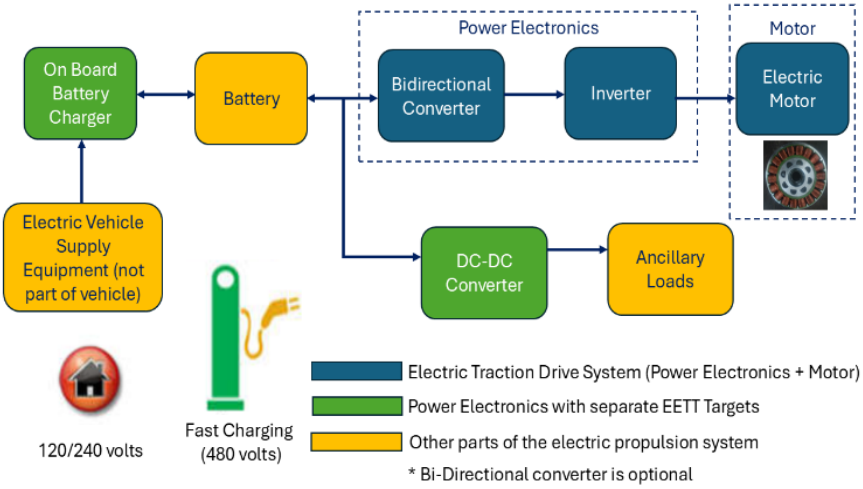


Figure 1. Component of electric traction drive system (ETDS) [7].

The detailed study on power electronics and thermal management systems (TMS) is currently under development and shall be presented in a future submission as an extension to this paper.

Objectives and Scope of the Paper

An EV propulsion motor requires a high torque/power density, reduced weight/volume of the machine, high efficiency to extend the battery range, and eventually low operating/manufacturing costs [16–18]. Most of the required demands are met by the existing traction motors, like interior permanent magnet (IPM)-based synchronous motors having adaptable modular designs [19,20]. However, the challenge in higher operating costs raises concerns because of the premium price and scarcity of dysprosium (Dy) fed heavy rare-earth (HRE) metals. There are continuous efforts made to design the IPM-based traction motors with no or reduced heavy rare earth (magnet) materials to match the existing performance of the currently used motors in today's battery-operated EVs [21]. This would also mitigate the problem of rotor demagnetization faults occurring in rare-earth magnets at temperatures below 100 °C. On these lines, the following sections shall focus on three way-forward steps: Section 2 would discuss (i) new machine designs and architectures, Section 3 will present (ii) advance materials, and Section 4 would cover the discussion on (iii) additive manufacturing (AM) technologies for the development of electric traction motors (synchronous motors). In addition, Section 5 illustrates the new emerging trends in the design and manufacturing of advanced ETDS, thereby finally making a comprehensive conclusion in Section 6.

2. New Designs/Architectures of Electric Traction (Synchronous) Motors

For the electric traction machines aiming for high power density and efficiency, advanced design architectures are found to be one of the possible solutions. Comprehensive rotor and stator designs solve maximum machine limitations and losses [18–20]. For the optimum machine design, the ratio of slots per pole per phase is a unifying factor [16,20] that comprises several motor design limitations with respect to maximum fundamental frequency (f_{max}) and high-speed losses [20,21]. Usually, the electric traction motors are

either radial or axial type machines [16–18]. In radial machines [20], the magnetic flux is perpendicular to the axis of rotation, while in the axial flux motors [22,23] the magnetic flux is parallel (to the rotation axis) and possesses a shorter flux path. Both machines have their own benefits over each other.

Most of the traction motors employed in EV applications are of radial architecture. These motors include AC induction machine (IM), switched reluctance motor (SRM), and permanent magnet-based synchronous machine (PMSM). Asynchronous AC induction machines (IM) and PM-based synchronous motors are mostly used in on-road EVs. Since the scope of this paper is limited to the PM-based synchronous machines used for traction drive applications, the discussion would focus on PMSM only. PM synchronous machines are classified into interior permanent magnet (IPM) and surface-mounted permanent magnet (SPM) synchronous machines [16–18], as shown in Figure 2.

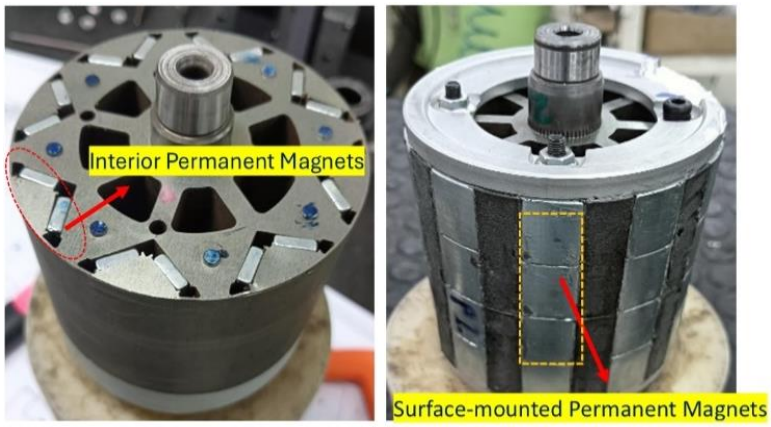


Figure 2. IPM- and SPM-type synchronous traction motors used in EV applications. (The motor pictures are taken from the research laboratory of Varroc Engineering Limited (VEL), Pune, India).

Among these two types, the IPM synchronous motor is most preferred. The IPM machines employ neodymium (Nd)–iron (Fe)–boron (B) magnets, which deliver higher power/torque density and efficiency in comparison to AC induction machines. This is the vital reason for employing IPSM in traction motor drives, although their cost is higher than IM [24,25]. However, there are several ongoing research efforts to design the IPM machines either with a lower/non-heavy rare earth magnet material or replace them with new advanced materials to match the performance of the current EVs [21,26]. There is a complete section on advanced materials to be discussed later in this paper.

The choice of employing flux machines in the traction motor drives (for EVs) is gaining wide interest [22,23]. Axial flux machines have their own benefits and are typically suitable for applications where the axial length is a constraint. The radial flux machines usually have an axial length larger than their diameter, while the axial flux machine has a significantly higher diameter when compared to its axial length. The designs of both radial and axial flux machines are optimized for EV applications. However, the new research is inclining more towards the employment of axial flux machines due to their compact size, less weight, high torque-to-weight ratio, and higher power density with improved efficiency [27,28].

It may be observed in [29] that for a given design space, the axial flux machines seem to have a lower active volume than the radial flux counterparts. It is also concluded from the studies of [27–29] that though for the same motor rating, both the radial and axial flux machines produce approximately the same torque within a specified envelope; however, the axial flux machine has a comparatively lower active mass than the radial machines. Therefore, more torque/power density can be derived from the axial architecture, which is receiving wider preference in EV applications. In addition, due to the flat architectural

design, heat dissipation is better in axial flux machines, which further enhances their efficiency. Hence, the benefits of employing axial flux motors over radial machines are aimed at increasing power and torque density and having a compact structure for system integration [29]. For more detailed technical designs and comparisons between radial and axial flux machines, papers [27–29] can be referred to. However, the inferences drawn from these studies [22,23,27–29] are included in Table 4, weighed in terms of power density (kW/kg), efficiency (%η), and cost ($/EUR/INR).

Table 4. Performance comparison between radial and axial flux machines [22,23,27–29].

Parameters	Power Density (kW/kg)	Efficiency (%η)	Cost ($/EUR/INR)
Traditional Radial Flux Machines	Can be optimized to have higher power density	Efficiency is limited due to design constraints	Cost is less due to simple designs and well-established manufacturing technology
New axial flux motor	Have more power density than the traditional flux machines	More efficient due to design flexibility and more efficient than the traditional radial flux machines	More cost due to complex design structures and emerging manufacturing technology, which requires high cost

With significant developments in design and topology, the axial flux machines have been further advanced to flux-switching machines (FSM) which gives higher performance in terms of torque density and efficiency. The FSM differs from conventional axial flux machines in terms of the direction of the magnetic flux path. In conventional flux machines, the magnetic flux is parallel to the motor's axis of rotation, while in an FSM, the magnetic flux is switched between different paths within the stator to generate torque. Thereby delivering higher torque density and providing controllability in the operation of the machine when employed as a drive system [21–23,26–29].

Conventional FSM usually employs rare-earth magnets, which inflict major challenges like heavy weight (due to the heavier mass of the RE magnets), limiting the torque and power densities of the machine. The alternative and countermeasure were the replacement of RE magnets with the high-temperature superconductors (HTS), which would enhance the torque-power density of the machine for wider speed ranges. In addition, there is also a significant improvement in its efficiency. The focus of employing HTS-based FSM is currently narrowed to aerospace and electric aircraft propulsion systems (under cryogenics) [22,23] only; however, with future advancements in motor technology, they may find suitability in high-range EVs as well. The developments in HTS-based machines are leading to the emergence of new superconducting (SC) materials belonging to the family of $REBa_2Cu_3Oy$ (RE stands for rare earth metals like yttrium (Y), gadolinium (Gd), europium (Eu) and others, while Ba_2Cu_3Oy refers to barium copper oxide). The basic structure of the REBCO tape is given in Figure 3 [30]. Among the most used SC materials employed in flux-switching machines, yttrium barium copper oxide (YBCO) is more preferred [30–32]. In addition, the employment of bismuth strontium calcium copper oxide (Bi2212) superconductor strand, which has a unique property for magnets possessing an exceptionally high magnetic field of 25T. Bi2212 is found more realistically suitable for all electric aircraft applications [33–35].

It is also comprehended from the literature [22,23,31,32] that the design of high-temperature superconducting FSM is mostly performed on a dual rotor with an air-core stator to avoid magnetic core saturation. This is being performed to reduce losses, obtain higher efficiency, and achieve incremental improvement in machine torque and power density (by increasing the torque and reducing the machine's weight). It is also reported in [33–35] that the employment of new superconducting materials (Bi2212) is found to be a more promising solution to advance the machine's performance with improved power

and torque density. However, the thermal management system (TMS) constitutes critical challenges. Superconductivity is a broad area, and therefore, the discussion is limited to this section only as it lies beyond the scope of this paper.

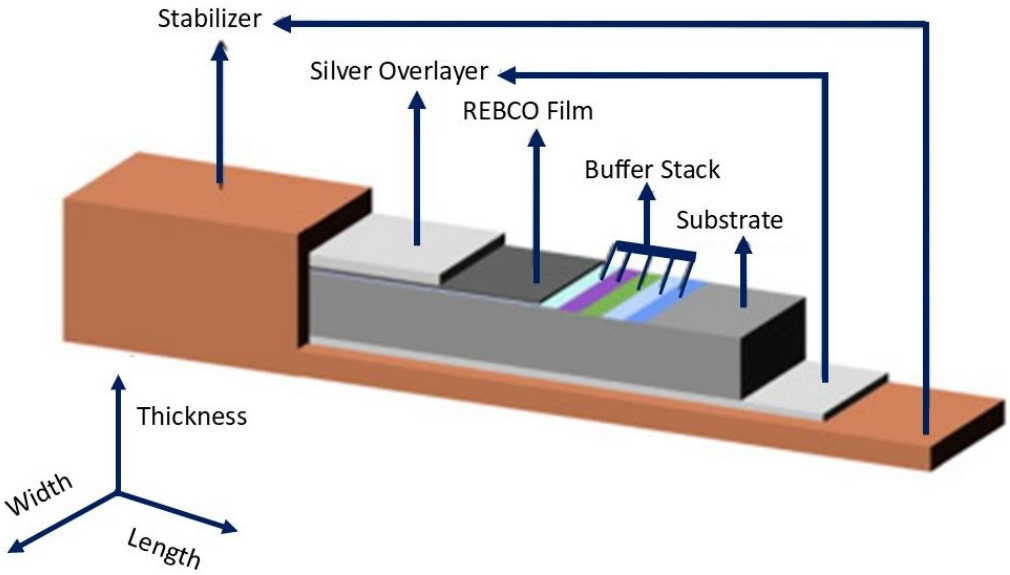


Figure 3. Basic structure of a rare earth barium copper oxide (REBCO)—high-temperature superconducting (HTS) tape [30].

There exists a lack of adoption of axial motors in EV applications; the technology is still rapidly evolving to market integration. Industries like Daimler and Renault have recently shown interest in axial motors and therefore initiated acquiring key players in this sector. While Daimler aims to acquire YASA and use its motors in AMG electric vehicles, Renault has collaborated with WHYLOT to use its axial flux motors in its hybrid electric vehicles starting in 2025 [36]. This indicates the growing adoption and promising performance of the axial motors in traction applications. Given the fact that the axial flux machines have straight flux paths, grain-oriented steels (in place of non-grain-oriented) can be used to advance and improve the motor efficiency, listed as one of the roadmaps of US and UK automotive councils given in [4,5]. In addition, the compact structure of the axial flux machines further removes the requirement for electrical steel for back iron, thereby significantly reducing the weight and improving the power density of the machines.

3. Advanced Materials for Electric Traction Motors

Advanced materials play a vital role in complying with new designs/architectures of the machine [26]. The developments in new materials and their suitability in electric traction motors are growing widely [37,38]. The employment of advanced materials even in the conventionally designed machines shows a significant enhancement in its performance, along with the improvement in its power density. The potential role of advanced materials in electrical machines can be applied in three major components, which include the core of the machine, stator windings, and rotor magnets. These are discussed subsequently.

3.1. Core of the Machine

To improve the magnetic properties of the core, new emerging materials are utilized for the development of stator and rotor cores in the form of laminations. Advanced improvement in the magnetic and chemical properties of electrical steel can reduce the core losses (eddy current and hysteresis), thereby improving the overall efficiency of the electric machine [39]. Currently the steel used in the commercial applications has a high silicon

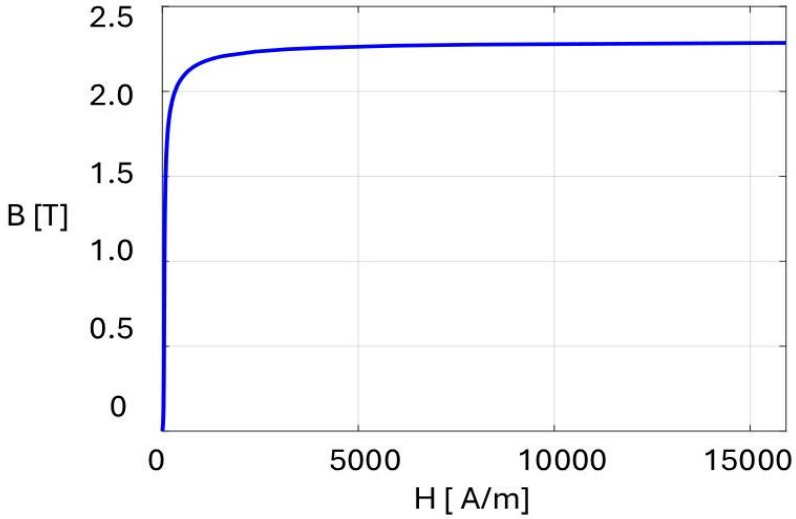
(Si) content of about 3.2 mass%, with a lamination thickness of 0.35 and 0.5 mm [38,39]. Further lowering the thickness range would increase the electrical resistivity of iron, thereby reducing the eddy current losses. The practice of increasing the mechanical strength of the steel by changing the average size of the grain is very much gaining popularity in the manufacturing industries. This is also referred to as the Grain Boundary Strengthening (GBS) [39,40]. It is based on the observation that grain boundaries lack the ability to overcome the dislocations. The stress concentration in the grain is affected by the number of dislocations occurring within the adjacent grain. This consequently activates the dislocation sources, which enables deformation. The yield strength increases with the accumulation of dislocations taking place inside the grains. Therefore, a reduction in the grain size would effectively result in a high yield strength [40,41]. Hence, for the next-generation electric machines, a high Si-content (6.5% Si) steel with a more reduced lamination thickness of about 0.25–3.0 mm is recommended [42].

The high Si content steel would even exhibit superior soft magnetic characteristics; however, it makes the steel more brittle both during the manufacturing of the steel and the processing of finished steel into motor laminations. This would consequently add more cost to the manufacturing process. The research thus opens avenues for the development of new soft magnetic cores using alloys containing silicon (Si), chromium (Cr), aluminum (Al), and manganese (Mn) [38,39,41,42]. Alloys of iron and nickel (Fe-Ni) are highly permeable and significantly possess low losses even compared to 6.5% silicon. The challenges with the Fe-Ni alloy are low saturation and premium cost. However, as reported in [38,39,42] the alloys with 48% nickel have competitive prices as that of 6.5% silicon.

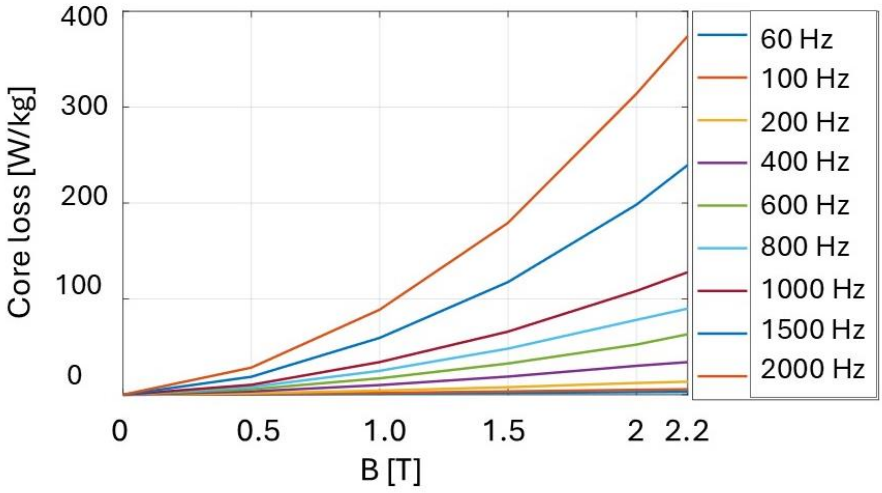
Another new lamination material, which is an alloy of iron and cobalt (Fe-Co) referred to as, *Permendur* (Hiperco-50) in [22,23,26,37,38] is a 49% cobalt, 2% vanadium, and balanced iron alloy, having exceptional mechanical strength. The Hiperco-50 has a maximum saturation flux density of 2.4 T (as shown in Figure 4) which finds its suitability in improving the power density of the machines. With the employment of Hiperco-50, the performance of the electric machines is significantly boosted, and the efficiency is improved due to reduced core losses as illustrated in [22,23,32,43,44]. But the high cost of the material restricts it to specific applications like aircraft.

Similarly, grain-oriented steels, which have high permeability, can be employed in modular and segmented machines [45–47] apart from flux-switching motors (where the magnetic flux path is unidirectional) for enhancing the motor performance and efficiency. However, while improving the permeability of a machine and reducing the grain sizes, the challenge of maintaining reliability at low manufacturing cost should be taken into consideration.

Some newly practiced approaches, which include dual-phase materials, seem to have a significant enhancement in the power density and efficiency of the machine [48,49]. Dual-phase materials have a characteristic feature of selectively controlling the magnetic properties at specific locations within the laminations of the core. These materials exhibit non-magnetic characteristics at the center pots and bridges of the laminations while maintaining strong magnetic properties in the other part of the rotor laminations. Since bridges of the laminations are the major sources of flux leakages, non-magnetic properties at these spots would eventually reduce the loss and consequently improve both the efficiency and power density of the machine. The challenges of these materials are lower saturation flux density and higher cost when compared to M19 electrical steel.



(**a**)



(**b**)

Figure 4. (**a**) Magnetic field (B-H) characteristics of Hiperco-50. (**b**) Iron losses of Hiperco-50 soft iron material at different frequencies [22].

From this discussion, all the potential advanced core materials are contemplated in Table 4, considering the relevant factors, which include magnetic permeability, μ (H/m); electrical resistivity, ρ (Ωcm); magnetic saturation, Bsat (T); and temperatures, T (°C). Further, the impact of these factors on the motor performance in terms of power density (kW/kg), efficiency (%η), and cost ($/EUR/INR) is also determined and given in Table 5.

Table 5. Advanced materials for the core of a machine.

Parameters	Magnetic Permeability, μ (H/m)	Electrical Resistivity, ρ (Ωcm)	Magnetic Saturation, Bsat (T)	Temperature, T (°C)	Power Density (kW/kg)	Efficiency (% η)	Cost of the Core with the Given Materials ($/EUR/INR)
Si content: 3.2% to 6.5%	High	High	1.6–1.8	-	Improves	Higher than 3.2% Si	More than conventional
Fe-Ni alloys	High	-	-	High	Not much impact	More than Si content steel	More
Fe-Co alloys (Permendur)	High	-	2.4	High	Improves	Increases	More
Dual-Phase Materials	Medium	Same as Si	Low-1.6	Low	Improves	Increases	Relatively less

3.2. Stator Windings of the Machine

For an efficient electrical machine, the windings of the stator should have high electrical conductivity and better capabilities to withstand high temperatures without degrading the insulation. Due to this fact, copper (Cu) is mostly used as a material for motor winding. Though aluminum (Al), due to its lightweight and cheap cost, is a strong substitute for copper, its relatively higher resistivity ($\rho_{Al} = 2.65\,e-8$) than copper ($\rho_{\mathrm{Cu}} = 1.68e-8$) makes it occupy more cross-sectional area. Hence, more aluminum material is required. For the same current rating, the required area of conduction for copper is less than aluminum, and therefore, Cu is given priority for stator windings in traction motor drives. However, in applications like aircraft, where machine power density is a preferred priority, aluminum windings are heavily employed (aircraft propulsion motors). Some new approaches of using copper (Cu) clad aluminum (Al) windings (as reported in UK roadmaps) [5] with an objective of reducing motor weight have been widely explored. The high electrical conductivity and low mass of Cu-clad Al windings improve the power density and efficiency of an electrical motor. In addition, the cheaper cost of the windings makes the motor cost-effective.

The new developments in the areas of carbon nanotube (CNT)-incorporated copper (Cu) windings (shown in Figure 5) are also gaining interest for traction electric machines [50,51]. The high strength, low weight, and improved electrical and thermal properties of CNTs make them ideal for motor winding material and a strong replacement for copper and aluminum. There has been an inference drawn that the coating layer of CNT on both sides of copper enhances the percentage of electrical conductivity, which is much higher (~100 times higher current-carrying capacity) than the conventional copper [37,38,51–53]. In addition, the CNT incorporated Cu has less sensitivity to temperatures, which gives an advantage of maintaining high efficiency at higher temperatures [53].

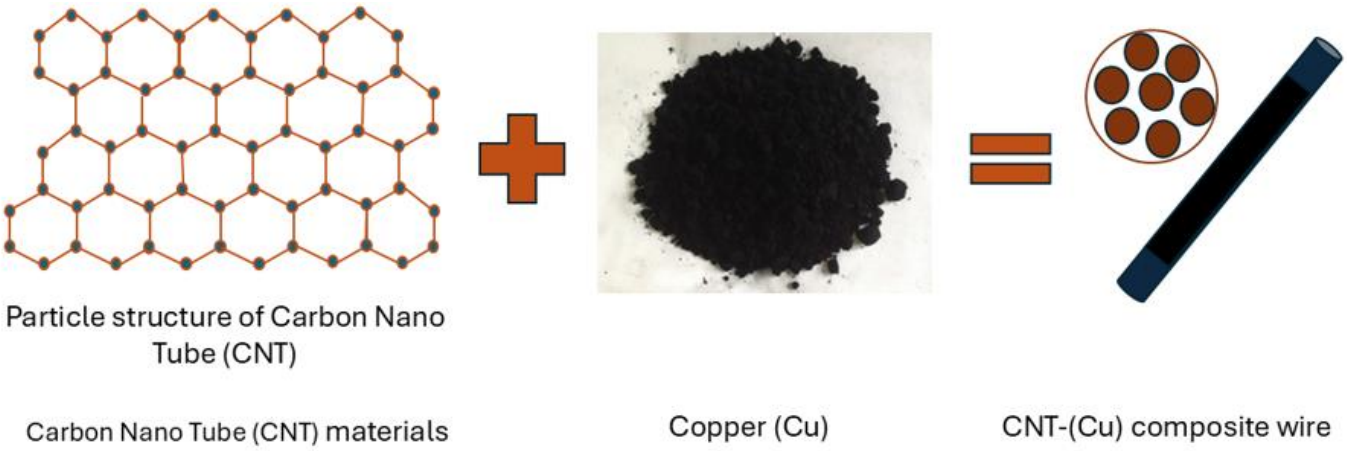


Figure 5. Concept of CNT-Cu composite conductor used for motor windings [50,51].

Another approach of adding graphene to copper for improving the electrical conductivity of the windings is demonstrated by US DOE-Pacific Northwest National Laboratory (PNNL) [54]. It is claimed by PNNL researchers that when an existing electrical grade of copper is added with eighteen parts per million of graphene, the temperature coefficient of resistance is reduced by 11% while the electrical conductivity remains unchanged (at room temperature). This increase in electrical conductivity of a copper winding by 11% is translated as a 1% gain in overall motor efficiency. The proposed concept, as shown in Figure 6, is pertinent for the manufacturing of electric motors, where maintaining or even improving the electrical conductivity can benefit efficiency. Figure 6a–c illustrates the transmission electron microscopy (TEM), and atom probe tomography (APT) results

from copper (Cu)-graphene (Gr) extrudate. Figure 6a,b shows the STEM image from Cu showing the Cu grain with C-rich nano-domains aligned in 111 planes. (b) APT results further confirm the enrichment of C in the matrix. Figure 6c shows the 2-D compositional map which is color-coded to indicate the enrichment of carbon by bright red color. The regions with a carbon content of 8 at% or higher can be seen to align in a direction that could be the [1 1 1] plane of the crystal.

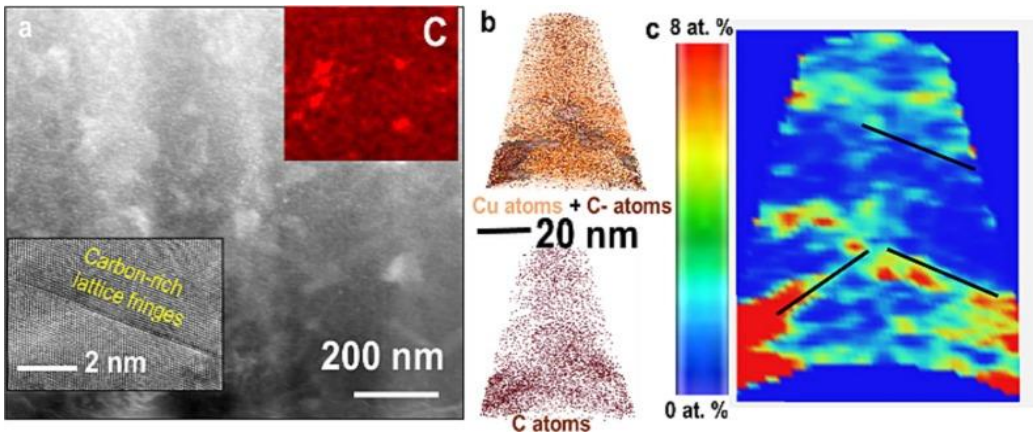


Figure 6. Concept of graphene-based CNT composite conductor developed for motor windings at *PNNL* [54].

Since the employment of CNT and graphene-based approaches is still in the developmental stages, it would require more time for these metal windings to become commercially scalable. But whenever they find accessibility in the market, it would effectively boost the performance of the electric machines in terms of power density and efficiency. From this discussion, all the potential advanced materials for the stator windings are contemplated and further summarized in Table 6 to see the impact on motor performance.

Table 6. Advanced materials for motor windings.

Parameters	Power Density (kW/kg)	Efficiency (% η)	Cost ($/EUR/INR)
Carbon Nano-Tubes (CNTS)	Improves significantly	Very High	More
Nano-Structured Interconnected Carbon Conductors (NICCs)	Improves significantly	Increases	More
Aluminum Windings	Improves	Not as good as copper	Less

Stator Windings Configuration

With the employment of new advanced materials in the electric traction motors, it becomes more important to change the physical configuration/arrangement of the stator windings for achieving the desired performance. The stator winding can be distributed or concentrated types as shown in Figure 7. Each of which has a merit and limitation of its own [1–3,16–18,55,56]. However, distributed windings are mostly preferred (by Toyota, Tesla, and Nissan) since they create sinusoidal airgap flux density, have minimum spatial harmonic contents, and have higher reluctance torque [16–18,36–38,55,56]. The distributed windings can themselves be either single-layer or double-layer windings. The double-layer winding arrangement nullifies the harmonic contents when compared to the single-layer winding and therefore is a widely practiced approach. The concentrated winding too has pronounced merits, which include the advantage of a higher fill factor, shorter end turn lengths, and a modular structure [55,56]. However, there are more unwanted spatial harmonics contributing to higher core and magnet losses of the machine, which draw

certain limitations [57,58]. But trade-offs can be made over the limitations if the resulting overall performance is better. Currently, the Honda Accord uses a concentrated winding motor [36].



(**a**) Distributed windings (**b**) Concentrated windings

Figure 7. Traction motor showing (**a**) distributed and (**b**) concentrated windings used in e-mobility systems (the motor pictures are taken from the research laboratory of Varroc Engineering Limited (VEL), Pune, India).

There is also significant progress in improving the slot fill factor of the machine, which eventually impacts its performance. Hairpin-type windings (as shown in Figure 8) provide higher slot fill factors, improving both power density and thermal performance of an electric traction motor [59]. The hairpin windings carry more current than the stranded wires and hence have greater advantages over conventionally used stranded conductor–based windings [60]. However, high-speed AC conductor loss limits the winding operations and applications [61]. But depending upon the requirement, the selective choice of winding can be made.

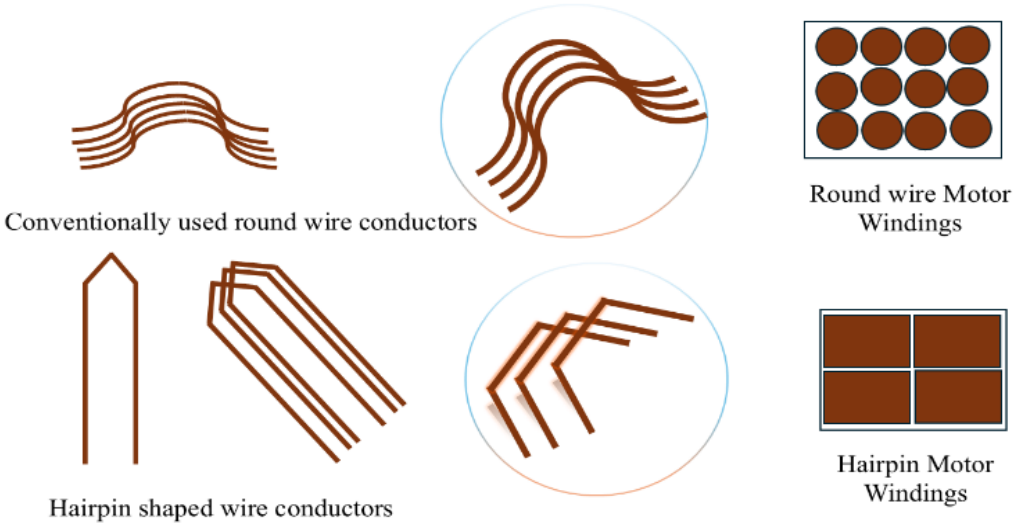


Figure 8. Comparison between round wire motor windings with hairpin-shaped windings [59–61]. The latter provides more slot fill factors.

3.3. Rotor Magnets of the Machine

Amongst all the available rare-earth materials, sintered neodymium–iron–boron (Nd-FeB) magnets are the preferred choice in the Permanent Magnet (PM) based traction motor drives [62,63]. NdFeB magnets have high energy density approximating to around 50 MGOe (Mega Gauss Oersted), and the addition of heavy rare earth elements (HREEs) such as dysprosium (Dy) and terbium (Tb) brings its magnet knee-point in the third quadrant of the B-H characteristics [63], thereby preventing demagnetization at higher operating

temperatures. Dy-enriched rotor magnets enable safe motor operations. But the premium price of HREE-enriched magnets leads to a cost challenge in the market. Several efforts and approaches are being made to advance the magnets, which include improving the PM energy product to 60 MGOe, which is beyond the conventional rating (50 MGOe), and the second approach is to use a lower level of rare-earth metals [64] in order to lower the cost of the magnets [65]. For both these approaches, new composite materials are being investigated in [66]. Some of the prominent rare-earth metals used in magnets are listed in Tables 7 and 8 [67].

Table 7. Light rare earth elements (LREEs) [67].

Light Rare Earth Elements (LREEs)			
Element	**Symbol**	**Atomic Number**	**Crustal Abundance ***
Lanthanum	La	57	39
Cerium	Ce	58	66.5
Praseodymium	Pr	59	9.2
Neodymium	Nd	60	41.5
Samarium	Sm	62	7.05
Europium	Eu	63	2.0
Gadolinium	Gd	64	6.2

* Crystal Abundance refers to parts per million (ppm) by mass, where 10,000 ppm is equal to 1%.

Table 8. Heavy rare earth elements (HREEs) [67].

Heavy Rare Earth Elements (HREEs)			
Element	**Symbol**	**Atomic Number**	**Crustal Abundance ***
Terbium	Tb	65	1.2
Dysprosium	Dy	66	5.2
Holmium	Ho	67	1.3
Erbium	Er	68	3.5
Thulium	Tm	69	0.52
Ytterbium	Yb	70	3.2
Lutetium	Lu	71	0.8
Yttrium	Y	39	33

* Crystal Abundance refers to parts per million (ppm) by mass, where 10,000 ppm is equal to 1%.

The automotive councils of the UK APC [5] and US DOE [6–8] discourage the dependency on internationally imported materials (magnets) whose supply chain is uncertain and the price is unstable. These include heavy rare-earth elements, like dysprosium (Dy) and terbium (Tb), which are used in the manufacturing of magnets for the PM-based electric traction motors.

This section therefore suggests suitable and possible solutions, based on the excerpts from [5–8,16–18,21,37,38]. This includes the minimum use or complete elimination of HRE contents from magnets (without degrading the performance), which would eventually lower the cost of PM machines employed in EVs [68,69]. Blending two rare earth materials is another constructive approach in the path to reducing dysprosium from the magnets. The authors in [21,70,71] have used the blend of two types of Dy-free magnets on an interior PM (IPM) motor based on the Nissan Leaf 2012. The two magnets used were of varying remanent flux densities. It was found that the blending of magnets/materials does not alone optimize the performance of the machine but requires physical variation in machine rotor geometry as well. The suitable and potential designs for rotor geometry have been discussed later in this section only.

There are also two commercially available magnets that support low dysprosium concepts in magnets. These are grain boundary diffusion (GBD)-based magnets [62,65,72] in which the edges and corners of the magnets are much richer with HRE content when

compared with the interior sections of the magnet and therefore provide stronger resistance to demagnetization. The other commercially available Dy-free magnets are NEOREC45mhf, which limits its operating temperature to 150–160 °C, making it more vulnerable to demagnetization above this temperature [16–18,21,70,71]. Similarly, adding cerium (Ce) and lanthanum (La) as a replacement for neodymium (Nd) can be another suitable alternative to neo-magnets as the former elements shield themselves from potential price spikes, even phasing out neodymium (Nd). There are ongoing efforts to design permanent magnets based on 100% recycled material that maintains high-temperature capability and high flux densities [16–18,37,38,69]. Bonded magnets [72,73] are emerging as another promising substitute to Dy-fed magnets. These magnets have a high energy product, high resistivity, and low eddy current loss. In addition, bonded magnets have good mechanical strength with high thermal stability. Bonded magnets are made of two components: hard magnetic powder and non-magnetic material serving as a binder. The hard magnetic powder includes permanent magnet materials such as NdFeB, SmCo, SmFeN, and ferrite. The non-magnetic binder is usually a polymer. They are also commonly referred to as polymer-bonded magnets. These magnets, though, have moderate energy products, but their coercivity (H_c) values (resistance to demagnetization) are high [73,74]. The bonded magnets find their applications in small electric motors, which have competitive potential when compared to lower energy product ferrites and AlNiCo magnets [73]. Some of the magnet materials that are found to be a suitable replacement for HRE are extracted from [16–18,38,66,68,70,72–75] and are listed in Table 9.

Table 9. Magnet materials found suitable replacements for heavy rare earth elements (HREEs) [16–18,38,66,68,70,72–75].

Magnet Materials	Operating Temperatures	Applications	Challenges	Opportunities
Iron ferrite magnets	Medium temperatures (up to 250 °C)	Lower-powered motor	Given the lower flux density, the magnets are considerably heavier and cannot act as a direct drop-in for NdFeB	Automobiles, washing machines, and electric fans
Samarium cobalt (SmCo) magnets	High temperatures (up to 500 °C)	48 V-based motors	Price premium	Considered more suitable for aerospace applications
Polymer-bonded NdFeB magnets	Low temperatures (up to 150 °C)	Both low- and medium-powered motors	Low energy product, susceptible to corrosion, and limited temperature stability	With improvement in performance, they find a suitable possibility of getting employed in EV applications

In addition, the automotive council of the UK Advanced Propulsion Centre (APC) [5] has compiled different grades of rare earth materials to draw some relevant conclusions and recommend suitable substitutes. Eventually the council concluded with five potential magnetic materials as alternatives and supplements to rare earth elements. They were ranked according to the possibility of being adopted alongside the sintered NdFeB magnets in EVs [5]. Figure 9 reflects the ranking of the magnetic materials (including the polymer-bonded magnets), which are possible substitutes and supplements to rare earth elements. The materials are ranked on a scale of 0–10, where 0 means not at all likely, 1–3 signifies the least possibility, 3–4 refers to a low possibility, 4–5 is the average, and 5–7 refers to a high possibility to be adopted. The scale of 10 signifies the extreme level of possibility for adoption.

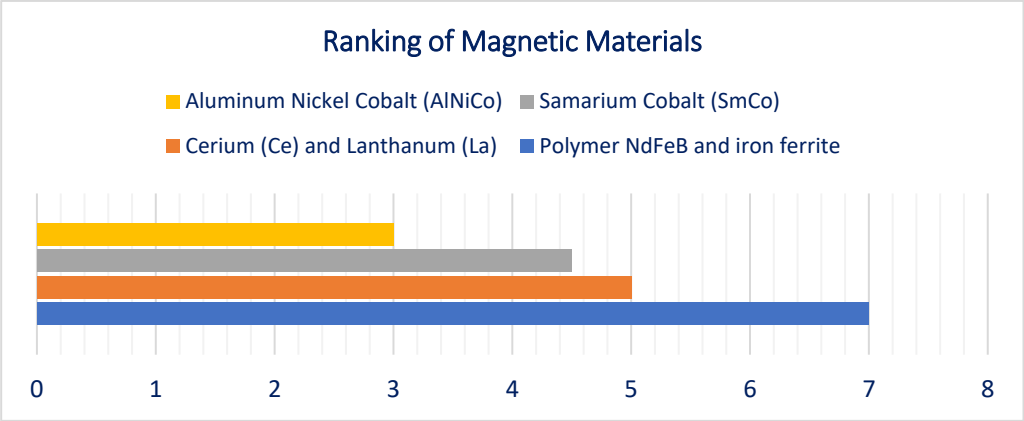


Figure 9. Ranking of magnetic materials (alternatives and supplements to rare earth materials) [5].

Since the permanent magnets contain expensive rare earth elements like Dy and Tb, considerable attention is being drawn to recycling these magnets. Several magnet recycling processes are developed and introduced in [75–77]. The aim is to recover the REEs both from the pre- and post-consumer magnet products. Recycling of Nd-Fe-B sintered magnets into bonded magnets is also reported in [78], where the nanocrystalline powders were obtained from the NdFeB scrap magnets. These nanocrystalline powders were then further used to prepare recycled bonded magnets. However, there still exist major challenges to practically establishing a strong claim.

From this discussion, all the potential advanced materials for rotor magnets are contemplated in Table 9, considering the relevant factors, which include magnetic permeability, μ (H/m); electrical resistivity, ρ (Ωcm); magnetic saturation, Bsat (T); and temperatures, T (°C). Further, the impact of these factors on the motor performance in terms of power density (kW/kg), efficiency (%η), and cost ($/EUR/INR) is also concluded and given in Table 10 [21,37,38,70,71].

Table 10. Potential advanced materials for rotor magnets [21,37,38,70,71].

Parameters	Magnetic Permeability, μ (H/m)	Electrical Resistivity, ρ (Ωcm)	Magnetic Saturation, Bsat (T)	Temperature, T (°C)	Power Density (kW/kg)	Efficiency (% η)	Cost ($/EUR/INR)
Dy-free Magnets	-	Medium	<1	Low	Increases	Decreases	Low cost
Polymer-bonded magnets	-	High	<1	-	Improves	Can be improved	Low cost
Blending of new magnets	Medium	Medium	~1	Low	Can be improved	Can be improved	Low cost
Iron nitride phases—the α″-Fe16N2	-	-	2T	-	Expected to be more	Expected to be more	Expected to be more

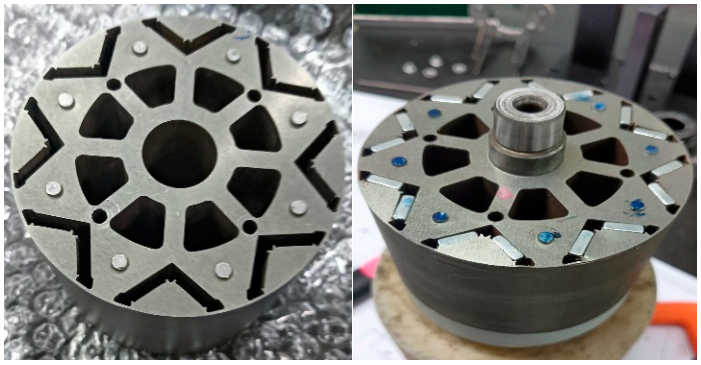
Rotor Design Configuration

As discussed earlier, the employment of advanced materials for magnets does not alone optimize the performance of the electric traction machine, but the change in physical rotor design geometry is necessitated. Among the available variants of rotor designs, the three variants are more popular for IPM-based electric traction motors. These include V-shape, double-V-shape, and U-shape rotor geometry. Each design has its own advantages and disadvantages as reported in the literature [1–3,16–18,21,26,37,38,70,71]. Amongst the three, V-shape rotor is widely used in traction applications due to reduced torque ripples, which give smooth machine operations delivering maximum efficiency. In addition, the heat dissipation is better when compared with other rotor slot configurations. However, the limitation of low corner speed and magnetic losses adds a challenge to this rotor slot shape. With the employment of double-V-shape rotor slot geometry, the machine torque and efficiency can be improved to the maximum. In fact, amongst all three rotor configurations, the double V-shaped rotor provides the highest torque density. However,

high heat dissipation, manufacturing complexities, and higher costs due to increased volumes of magnet material give it a drawback. The U-shape rotor configuration is a trade-off between the V and double-V-shape designs that offer some design flexibility and optimize the performance of electric machines. However, it has challenges in manufacturing magnets of that shape along with its assembly. This challenge can be circumvented by the employment of advanced manufacturing techniques, as will be discussed in the next section. Table 11 [22,23,27–29] shows the performance metrics of employing V, double-V, and U-shaped rotor slots in electric traction motors, while Figure 10 shows the V-shaped rotor design, which is mostly used in two-wheeler applications in Southeast Asian countries.

Table 11. Performance comparison of employing V, double-V, and U-shape rotors [22,23,27–29].

Rotor Slot Geometry	Torque Density	Efficiency (%η)	Merits	Limitations	Challenges
V-shape	High	High	Have higher power density when compared with U and double V rotors	Lower corner speeds	Increase in torque ripples and the magnetic losses
double-V-shape	Improved torque than V-shaped rotor. Highest torque density among the U- and V-shaped rotors	Improved efficiency when compared with U and V rotors.	High torque can be achieved at the cost of more magnet material	More losses	High heat dissipation. Manufacturing complexity. Higher cost due to increased volume of magnet material
U-shape	Improved torque but at the cost of more magnet material	Improved efficiency	Offers design flexibility	More magnet volume is required	High heat dissipation. Manufacturing complexity. Higher cost due to increased volume of magnet material



(**a**) (**b**)

Figure 10. (**a**) Physical geometry of V-shaped rotor design. (**b**) V-shaped rotor with magnets (the motor pictures are taken from the research laboratory of Varroc Engineering Limited (VEL), Pune, India).

This section has provided an overview of the potential role of advanced materials in building the components of electrical machines, which include the core, stator windings, and rotor magnets. Advanced soft-magnetic materials like high-grade Si-6% steel are promising core materials in improving motor efficiency by reducing the eddy current (core) losses. Similarly, the introduction of dual-phase magnetic materials at the bridges and center posts would certainly reduce leakage flux and improve motor efficiency. The highly conductive and lightweight materials for stator windings, like copper-combined-CNT conductors, are expected to improve both the power density and efficiency of the machine. Additionally, high-strength magnetic materials, bonded magnets, and new blends of dysprosium-free magnets would benefit the overall cost and performance of the machine. Lastly, the motor performance metrics based on different rotor slot configurations are also discussed, concluding with the benefits of each type depending upon the application necessity.

4. Additive Manufacturing (AM) Technology for Electric Traction Motors

In addition to advanced machine architectures/topologies and materials, advanced manufacturing technology is apprehended to have a meaningful impact on improving the design and performance of electrical machines [79]. These advanced manufacturing techniques are referred to as additive manufacturing (AM) technology, which is widely gaining prominence in the electric motor drives area of Industry 4.0 [80]. AM technology is defined as an industrial process that involves the creation of an object by the deposition of material in layers [79,80]. AM is a 3D printing technology developed in the late 1980s. Later it was advanced to Selective Laser Sintering (SLS), which employed lasers to sinter the powdered material into solid structures [81]. After the development of fused deposition modeling (FDM) or fused filament fabrication (FFF), the wide utilization of AM technology progressed in industries. Many companies, such as Rolls Royce, General Electric, and Boeing, have already adopted additive manufacturing technologies in producing high-performance parts for various applications, which include automobile vehicles [36,82].

AM is an enabling technology that simplifies the manufacturing of complex structures. It is a rapid process that expedites the iterations by enabling the provision of modifying the designs, customizing it, and further producing a unique, tailored product. This technology involves the process of joining materials and producing objects layer by layer from 3D models. AM is considered an essential component that is necessary for the wide transformation and improvement of the electric transportation sector. With the intensification of AM-based approaches in e-mobility systems, the production of EV components is being accelerated [79,82,83]. AM overcomes the limitations and challenges resulting from 2D laminations, thereby generating a new manufacturing trend in the design of EDT. The merits of adopting AM technology are reported in [84,85] where the motor power density is improved through the development of a high slot-fill factor winding and further optimizing the thermal performance of the machines (PMSM [84] and IM [85]). AM technology thus seems to provide feasible solutions for high power density motor-drive systems with improved performance and no or low waste with flexible design options. Smart/or AM technologies are adopted for the development of electrical machines through building of machine cores [83,86,87], stator windings [88–94] as well as rotor magnets [73–75,95–100], which are discussed subsequently.

4.1. Additive Manufacturing of Machine Core

The conventional practice of developing the machine core is through stacking the laminations of soft magnetic materials using varnish. Usually, steel with 3.5% silicon (Si) is used as the core material. The concept of using (steel) laminations was to reduce the eddy current and hysteresis losses during machine operations [1–3]. With the evolution of AM technology, the process of manufacturing machine cores became easy with the mass production of metal components with highly complex topologies [83–85]. However, due to the lack of laminations, the increase in eddy current loss was evident [86,87]. To decrease this loss, the resistivity of the conventionally used steel is increased through the increase in the percentage of Si content from 3.5% to 6.5%. It has been discussed earlier, in Section 3 that with the additional increase in Si content in steel, the material becomes harder and brittle, which adds another challenge in handling the printed steel. But with the adoption of advanced AM technology this, limitation could be circumvented, but it still needs to be proven.

In [86], the soft magnetic rotor core for a switched reluctance motor (SRM), with Si content less than 6% (Fe-5.0% w.t. Si), has been developed using AM technology shown in Figure 11. The motor performance was found to be promising for the lower speed operations when compared with the conventionally laminated rotor of the identical SRM.

However, the absence of laminations (and SMC with reduced %Si content) meant the eddy current losses were higher in the 3D-printed rotor, which eventually adds and opens the opportunities for improvement. Similarly, in [87], it has been observed that using the AM technology for the manufacturing of high-grade steel of 6% Si grade, there was the formation of cracks (due to an increase in the brittleness property of the high Si grade steel). However, there are possibilities for optimization and printing nearly fully dense, crack-free material (steel).

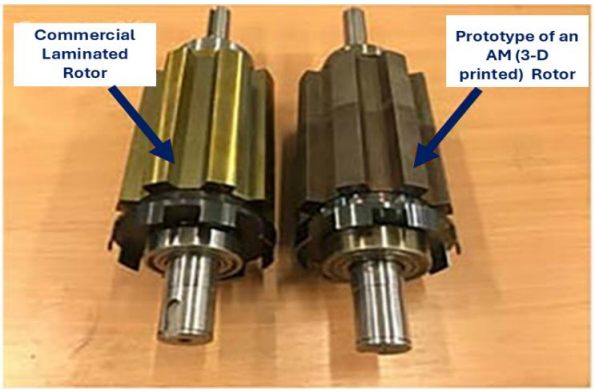


Figure 11. Commercially available laminated piece of an 8-pole SRM rotor (left-hand side) and identical 3D-printed/AM-built rotor (right-hand side) [86]—(image taken from [86] under the creative commons (CC) redistribution license).

AM technology can thus be leveraged in developing a machine core with a minimum printing duration. Additionally, the annealing parameters can be determined to achieve better quality of steel in terms of electrical, magnetic, and mechanical properties [83–87].

4.2. Additive Manufacturing (AM) of Stator Windings

Additive manufacturing (AM) of stator windings opens avenues for new designs of customized windings [88]. Earlier special tooling approaches were required for every individual design, which required both human efforts, time, and cost. Several advantages of employing AM technology in the development of stator windings/coils have been discussed in the reports of [4–10], which aim to significantly boost the power density and efficiency of the machine in order to meet the set targets of the e-mobility roadmaps for 2025–2030. There is ongoing research on the development of stator winding/coils of aluminum silicon and magnesium alloys commonly referred to as $AlSi_{10}Mg$ coils using AM technology [88,89]. Some of the advantages of using additively manufactured $AlSi_{10}Mg$ coils have been demonstrated in [89]. This includes low mass density—improving the motor power density—and low electrical conductivity—which minimizes windings AC losses at higher frequencies.

One of the most crucial features of AM is the provision of changing material properties while the material is under the manufacturing process. This enables AM to manufacture complex winding designs for advanced electric traction motors. One of the complex winding structures includes hollow conductors, shown in Figure 12. The objective of using hollow conductors is to integrate them with heat pipes to aid in effective cooling systems.

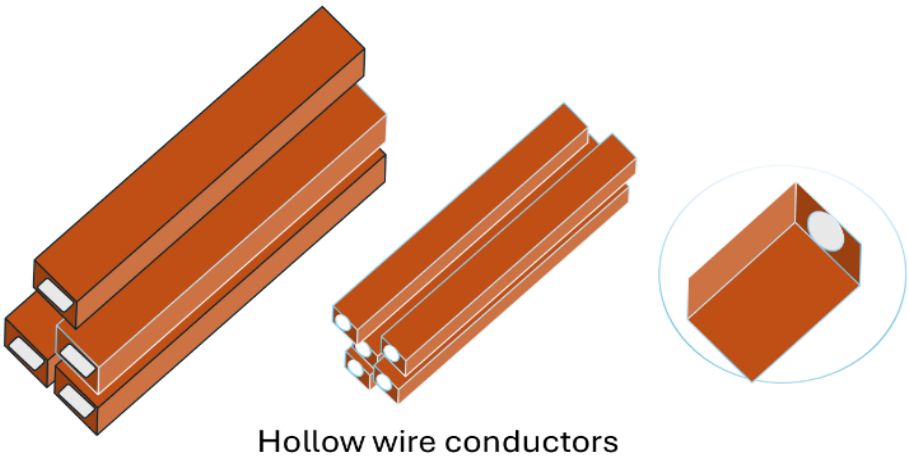


Figure 12. Concept of hollow conductors [37,38,90,91].

It has been presented in [90–92] where the winding shape is optimized within the slot to maximize the copper slot fill factor by keeping a solid cross-section in the end regions while the sides have a hollow cross-section. The provision of hollow conductors enables the integration of heat pipes on each end to increase the cooling effectiveness and consequently increase winding current density and electric loadings [92]. On a similar line [93], it discusses the in-slot cooling where the heat is removed by employing heat pipes inside the slot bottom paired with a heat guide to cover the empty area in the middle of the slot. The proposed concept improves the cooling performance of the windings/machine. Additionally, with the in-slot cooling concept, the slot current density can also be boosted consequentially. It is also demonstrated in [93] that it is only through the adoption of AM technology that the copper/aluminum combined-CNT windings can be manufactured, which increases the current capacity of the windings to a hundred times as claimed in [94]. The employment of CNT-based stator windings is one of the goals set by the US DOE in order to improve the power density and efficiency of the electric drive trains.

However, it is to be noted that the use of AM coils in electrical machines is an evolving practice, and therefore the impact of these coils on AC losses is still being explored. But with the current research status, the outcomes seem to be effectively promising.

4.3. Additive Manufacturing (AM) for Rotor Magnets

As discussed earlier, for the permanent magnet (PM)-based synchronous motor drives, usually neodymium–iron–boron (Nd-Fe-B) or samarium cobalt (Sm-Co) materials are employed as rotor magnets. NdFeB magnets are more prominent among these, which are widely used due to their high energy density and magnet stability, as illustrated in [16–18,24,37,38,62,63]. These magnets were traditionally manufactured using conventional sintering methods and required machining/tooling to give final geometrical shape and dimensions. The available manufacturing constraints limit the shape of the magnets to rectangular or circular cross-sectional in shape. However, with the introduction of AM technology, new net-shape magnets could be developed that do not require machining to give geometrical shape [95–97]. This minimizes the material waste and enables the possibility of reusing/recycling the unfused powder in subsequent processes of buildings, which made the magnets cost-effective [75–78]. In addition, it is also investigated at the laboratory level that AM can control the grain texture of the material to create isotropic or anisotropic properties in the magnet material [73,74]. Thereby improving the magnetic properties of the material in terms of high remanence, coercivity, and temperature stability. Further, the introduction of additively manufactured polymer-bonded magnets removes dependency on heavy rare-earth materials like dysprosium (Dy) and terbium (Tb). In [73–78,95–97],

the authors have reported different AM approaches that employ the concept of mixing isotropic powder with a polymer as shown in Figure 13 to produce bonded magnets using AM technology.

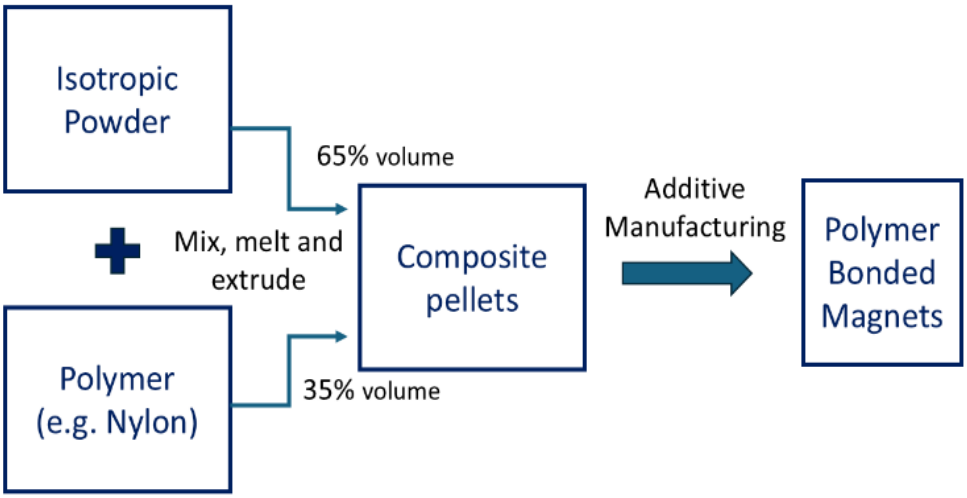


Figure 13. Process of producing polymer-bonded magnets using AM technology [73–78,95–97].

Some of the existing and hybrid AM approaches include extrusion-based big area additively manufactured (BAAM) bonded magnets [99], powder bed fusion (PBF) method-based magnets, which include (i) electron beam melting (PBF-EB) (ii) laser beam (PBF-LB) [100], respectively, and selective laser melting (SLM) method-based magnets [96], etc. The BAAM approach applied in [99] is the extension of additively manufactured polymer-bonded magnets discussed in [75–78]. With the employment of BAAM technology, higher energy density magnets can be manufactured, having a thousand times less eddy current losses. Similarly, with the AM approach used in [100], it was found that the permanent magnets produced by PBF-LB possessed superior magnetic properties when compared to extrusion-based techniques; however, there still exist some challenges that need to be addressed. In [96], it was reported that the printed $Nd_2Fe_{14}B$ grain was 1 µm, which resulted in better magnetic properties, enhancing machine performance. It is also estimated that using AM technology, rotor magnets can be integrated with cooling channels, which would further reduce the dependency on HREEs for thermal stability.

Therefore, the magnetic properties (energy density) of the printed NdFeB magnets are expected to increase in the coming years due to the new advancing capabilities offered by the AM. Hence, additive manufacturing of rotor magnets seems to be an essential change in manufacturing technology that is gaining wide interest from industries and the scientific research community.

It is observed from the above discussion that smart manufacturing, or additive manufacturing (AM) technology, has opened avenues for machine design and manufacturing solutions for electric drive trains. As per the scope of this paper, the discussion limits the employment of AM technologies for developing three major components of a permanent magnet-based electric machine, which include the machine core, stator windings, and rotor permanent magnets. At the present stages, these components are built separately and later assembled together; however, building a fully additively manufactured machine is still at the early stages for proof of concept [84]. For building a complete AM electric machine, it may require multiple AM technologies to include other components of the machine as well. The fully AM electric machines would then certainly outperform the conventionally built machines in terms of their mechanical, thermal, and electromagnetic performances. Additionally, AM-built machines also have a provision for changing the

material properties while it is still under the manufacturing process, which makes the technology more promising in building new ETDS components and products.

5. New Emerging Trends for Electric Traction Motors

In addition to the crucial transformation being introduced through the change in machine architecture, employment of advanced materials, and adoption of additive manufacturing processes, there are some proposed and ongoing developments in other related areas of EDT. These include [4–10,16–18,25,26,37,38,68,72,77,79,83,84]:

a. Reducing and removing wet processes in motor assembly—Wet processes introduce complexity into high-volume production assembly lines.
b. Removing resins, greases, additives, and bonding materials would improve motor production speeds and reduce the costs (apparently removing wet processes involved during motor assembly).
c. Employment of mechanically joint techniques to provide strength and save the cost of adhesives.
d. Adoption of hollow conductors with integrated cooling systems (to achieve high fill factors and efficient thermal management).
e. Employment of dual-phase materials to improve machine power density and efficiency.
f. Enhanced magnets manufacturing processes, which can lower eddy current losses (advanced extrusion-based AM technique).
g. Employment of superconducting magnets (GE's Freelium, Siemens DryCool, and Philips' BlueSeal magnets).
h. Employing bonded magnets (net shape, which do not require finishing and result in zero-waste magnetic materials).
i. Reversible Adhesives—Recycling of water-based adhesives achieved by changing pH. This would aid in detaching (disassembling) the machine parts again in strongly acidic or alkaline environments.

These concepts are still in the development stages but are expected to provide feasible solutions to the advanced electric motor drive technology. However, these new practices need to be practically proven to have a strong claim for improving motor efficiency and reliability while reducing the cost.

6. Challenges and Opportunities

This paper has provided a quantified discussion on improving the performance of electric machines in terms of power density (kW/kg) and efficiency (%η), while taking cost into consideration. For this, various possible and feasible solutions, like the introduction of new design structures, advanced emerging materials, and the adoption of additive manufacturing (AM) technologies, have been investigated. During this course of study, practical limitations and new challenges were also identified, which are addressed in this section. The viable steps in attenuating these challenges are also provided in order to boost the emerging technologies for improving machine performance.

The introduction of new design topologies has led to the development of radical machine structures that require AM-based technology for its production and manufacturing. It is evident from existing literature that though the AM-based technology allows the design of complex geometries, the process is costlier than the conventional processes. In addition, AM is a rapid process that saves manufacturing/processing time in producing a tailored product, but the procedures may further require post-processing like assembly and polishing (as AM produces rough surface products) [101]. This would demand additional labor, contributing to overhead costs per unit. An additional challenge would be the availability of technical expertise to manage and operate the equipment [102]. Since the

current market has a huge demand for technical expertise, the internal development of expertise additionally requires time and justification for the capital equipment.

Similarly, the introduction of new emerging materials like high silicon (Si-6%) steel and cobalt–iron alloys for soft magnetic machine cores; carbon nanotubes (CNT) for stator windings, and RE-free metals like polymer-bonded magnets for rotors, has a challenge for both material availability and manufacturing complexities [103]. Advanced, specialized, and customized manufacturing equipment is required, which adds significant cost to the production unit. Additionally, there is a lack of extensive knowledge and clearly defined specifications of material data, which makes the manufacturers hesitant to use the technology [104]. Another significant challenge is the environmental restrictions, which include proper disposition and recycling of the materials. If the failed prints/products are not disposed of properly, they can severely harm the environment. For example, polymer waste from failed prints and excess material may contribute to pollution if not handled correctly. Some materials used in AM printing are also toxic or non-biodegradable, posing further environmental risks [105]. Hence, it is required that the industries ensure proper waste management practices, such as recycling and safe disposal, to minimize these impacts. But again, these require additional costs and are quite expensive.

Another major issue with AM, as comprehended from the literature, is its ability to produce only small quantities of products, which is not suitable for large-scale production. This limitation arises because additive manufacturing is a relatively slow process. Therefore, when high-volume manufacturing or mass production is needed, AM may be inefficient and time-consuming compared to traditional manufacturing techniques [101,102,105]. However, a larger and greater numbers of printers may be required to circumvent this, which would additionally require changes in infrastructure.

There is no available technology in the manufacturing sector, which is devoid of challenges and limitations. However, the adoption of advanced and emerging technology depends on customer demand, market requirements, and industry specifications. There are several available opportunities that would boost and improve the AM-based technology in industries. The most significant amongst all is the rapid production of the products, which enables the industries to expedite the prototypes for validation. The layer-wise development of an object is an inherent additional merit of the AM-based approach, which minimizes material waste and saves the cost of the product. Moreover, with the growing research on material technology and material selection, the AM is now finding appropriate expansion in the manufacturing and production sector. Lastly, with the setting up of technical guidelines related to AM standards, it would further boost the manufacturing industry to develop radical machines using advanced materials employing AM-based technologies. Though at this time cost may be a crucial factor, with the adoption and evolution of growing technology, it would be normalized in a timely manner.

7. Conclusions

This study provides in-depth information on the potential role of new design architectures, advanced materials, and additive manufacturing of electric machines for the next generation of electric vehicles. The transition to advanced electric machines aims to bring significant improvement in machine performance with better operational capabilities at reduced cost. The introduction of new motor topologies provides viable solutions in reducing the volume and weight of the components, which improves the power per unit volume of the machine. The employment of advanced materials reduces motor losses, which eventually enhances the overall machine efficiency. With the evaluation of new designs and advanced materials, improvements in the fault tolerance capabilities and reliability of the electric machine drive systems are possible. The adoption of advanced

manufacturing approaches like additive manufacturing techniques, which include life cycle assessment and reduction in material waste, generates possible avenues for providing reasonable cost-cutting in the final end product. Additionally, the employment of rare-earth (RE) free materials would further reduce the exertion of the global supply chain, cost, and environmental impacts of advanced electric machines.

This paper makes an attempt to quantify the discussion and provide suitable solutions for improving the performance of electrical machines. The merit of each technology is accompanied by its potential challenge, followed by a remedy. Moreover, the authors have expressed a more balanced perspective by discussing viable opportunities and necessary trade-offs required in the adoption of these technologies for the next generation of electric vehicles.

As for future research directions, the given technology can be applied in the existing electric traction machines, where some aspects can be employed directly to investigate the impact on motor performance. It is more likely that the deployed technology would require additional developments such as design modifications, but eventually it will boost the motor performance in terms of power density and efficiency. Though at this time cost may be a crucial factor, with the adoption and evolution of growing technology, it would be normalized in a timely manner.

This paper apparently serves as a good reference in terms of literature, where the quantitative details for the advanced electric machines in terms of new design architectures, emerging materials, and advanced manufacturing techniques can be found.

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