eTransportation 6 (2020) 100080

Contents lists available at ScienceDirect

eTransportation

journal homepage: www.journals.elsevier.com/etransportation

Low-cost high-performance ferrite permanent magnet machines in EV applications: A comprehensive review

Patrick Chi-Kwong Luk*, Hayder A. Abdulrahem, Bing Xia

Electric Power and Drives Group, Power Engineering Centre, Cranfield University, Cranfield, MK43 0AL, UK

ARTICLE INFO

Article history:
Received 1 July 2019
Received in revised form
24 July 2020
Accepted 20 August 2020
Available online 6 September 2020

Keywords:
Ferrite PM machines
Traction motors
Non-rare-earth machines
Rare-earth metal supply chain
Electric vehicles

ABSTRACT

Ferrite-based permanent magnet (PM) machines have been developed for many applications due to their highly desirable features such as low costs and stable supply chain. More recently, partly driven by the rapid uptake of the electric vehicle (EV) market, and partly due to the uncertainty of the supply chain of the rare-earth metals that are key components of the EV traction motor, there have been considerable interests in developing alternative solutions to rare-earth based PM motors. Due to their intrinsic low magnetic flux and prone to demagnetization, ferrite PM motors have not been previously considered for the more stringent EV applications. Hence, there is a growing body of research studies in addressing these challenges by deploying novel design strategies with varying proportions of ferrite materials, and with varying degrees of success. To date, there is a lack of comprehensive literature review of this class of evolving and yet highly promising electric machines that will offer a viable and sustainable alternative to EV traction applications. This paper aims to fill this gap and to provide a dedicated overview of these machines with a focus on their credentials as the 'traction motor of choice' in future EV markets.

© 2020 Elsevier B.V. All rights reserved.

1. Introduction

Ferrite-based permanent magnet (PM) machines, with their distinctive advantages such as high efficiency, low costs and stable supply chains, have been extensively used in many applications ranging from low power actuation to air-conditioning, and from electrical appliances to industrial automation. Together with induction motors, these low-cost electric machines consume a significant percentage of all electricity produced, and form the key parts of numerous high efficiency energy conversion systems. On the other hand, rare-earth based PM machines have entrenched the electric vehicle (EV) market due to their high power and torque density since the invention of the NdFeB permanent magnets in late 1980's. These PM machines, consisting of rare earth metals neodymium and dysprosium, have been the traction motor of choice by delivering superior performance under stringent driving conditions [1–4]. In energy efficiency applications, statistical data shows that considerable energy can be saved by just simply replacing old inefficient machines [5] with rare-earth ones. According to Ref. [6], the capital cost difference between highly efficient rare-earth based PM machines and less efficient induction machines would be paid back through operating cost savings in less than 2.5 years at 50% percent duty cycle. The appeal of these rare-earth PM machines has been significant. However, with the prospect of an imminent rapid uptake of the EV market worldwide and continuous healthy growth in wind generation, hence strong demands of high power-density and high-performance machines in the foreseeable future, there have been increasing concerns about the volatility of the costs of the rare-earth metals, and more importantly, the security of their supply chains in the long run. As shown in Fig. 1 [7], there had been global price hikes of rare-earth metals between 2011 and 2012, resulting in many rare-earth PM manufacturers and organisations seeking for strategic changes to mitigate the risk due to instability of the rare-earth supply chain. Although the price has returned to a relatively stable level in the past few years, the long-term prospect is still very unclear. Importantly, the adverse environmental impacts from the mining of the rare-earth metals, and absolute scarcity of some of heavy rare-earth metals, are becoming the new driving forces to develop alternative electric machines with less and no rare earth PM materials [8–10].

However, the challenges of developing high performance non-rare-earth machines are significant. The induction machine (IM) is one of the non-magnet solutions with simple and robust

* Corresponding author.
E-mail address: p.c.k.luk@cranfield.ac.uk (P.C.-K. Luk).

https://doi.org/10.1016/j.etran.2020.100080
2590-1168/© 2020 Elsevier B.V. All rights reserved.

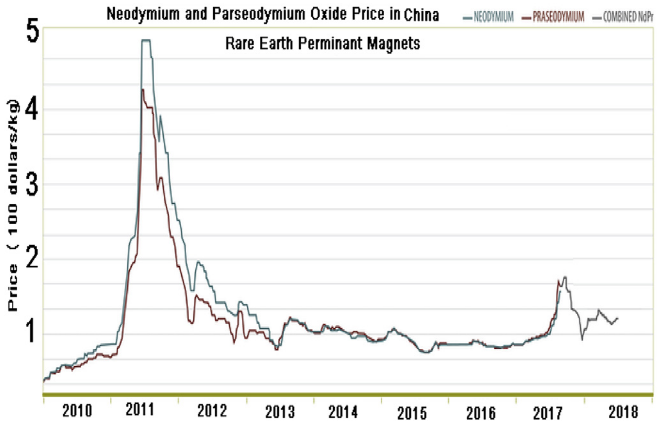


Fig. 1. Price trends of rare-earth materials [7].

structure. However, the efficiency of IMs is generally 3–4% lower than PM machines due to the higher stator magnetization current and considerable copper losses in the rotor cage bars [11]. Reluctance machines are another solution without using any PM material, but the large torque ripple and low power factor restrict the use for high performance applications. On the other hand, ferrite magnet machines have been drawing increasing attentions for the design of high-performance motors. With the merits of abundant raw material resources, low price, stability to corrosion and temperature, easy manufacture and very high electrical resistivity [12–14], ferrite magnet has been considered as a potentially ideal component for high performance PM machines. However, one key drawback of ferrite PM is the much lower residual flux density and energy product compared with its rare-earth counterpart, as illustrated in Fig. 2.

Another drawback is the risk of demagnetization due to its low coercivity, measured on the H-axis in A/m, which makes it far more prone to permanent demagnetization than NdFeB and SmCo. One of the first adoptions of bonded NdFeB to replace ferrite resulted in an impressive 50% weight and volume reductions [15]. However, the studies also show that output characteristics could be greatly compromised by 'retrofitting' rare-earth with ferrite PMs by simply increasing the amount of ferrite PM within an original rare-earth based design envelope. High performance applications such traction EV motors differ from the more conventional and benign applications that have endeared ferrite motors [16], in terms of high-

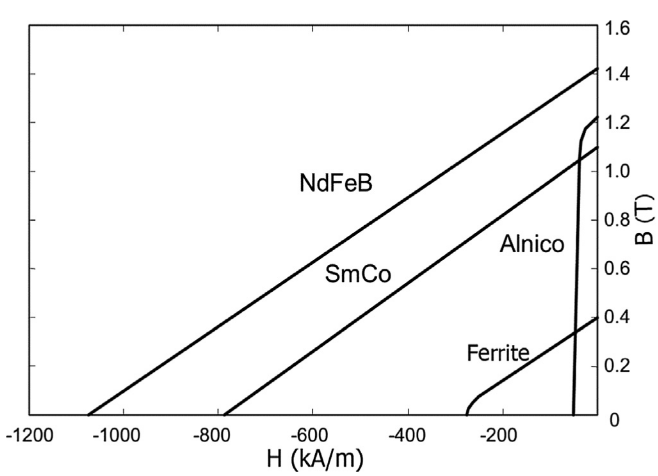


Fig. 2. Comparison of BH curves among different PM materials.

power density, wide speed range and demanding drive cycles operating at hazardous conditions. Subsequently, there has been a growing body of literature in relation to design methodologies of high-performance ferrite PM machines aiming to maximize the torque capability and to mitigate demagnetization [17,18]. However, there is a lack of review literature that offers a systematic study of these new ferrite-based PM machines that offer a low-cost alternative to high performance applications. This paper aims to fill this gap and to provide a comprehensive overview of the machine focusing on its credentials as the 'traction motor of choice' in future EV markets.

Various machine configurations with different PM materials were investigated and compared in a number of more recent studies [19,21–24]. Based on the literature, the following four categories of ferrite machine solutions will be discussed in the subsequent sections:

- Conventional PM machines. They have similar structure as the rare-earth machine but with larger amount of ferrite PM;
- PM assisted synchronous reluctance machines (PMASynRMs). Their structures originate from synchronous reluctance machines (SynRMs) with PM in the flux barriers;
- Spoke-Type PM machines. They use flux focusing techniques to achieve similar airgap flux density and torque density as rare-earth machines;
- Other types. These are not widely studied in the mainstream research of ferrite machines.

2. Conventional *Pm* machines with ferrite materials

Conventional structure PM machines adopt similar configurations as rare-earth ones by using ferrite instead of NdFeB PM. Due to the low residual flux density of ferrite, usually larger amount of PM was used to increase the flux density. Even so, the power density of ferrite machines is still very low compared to its rare-earth counterparts. As a result, ferrite machines with conventional structures are mostly used in low-cost and low-power applications such as electric assisted bicycles [25], pumps [26] and fans [27]. According the location of PM poles, they could be further divided into surface-mounted PM (SPM) and Interior PM (IPM) machines.

S. Pal in Ref. [28] studied the different performances of surface-mounted PM (SPM) machines with exactly the same machine geometry but different PM materials of ferrite, SmCo and NdFeB respectively, and the ferrite machine can only achieve 36% torque of SmCo and 31% that of NdFeB, due to the low residual flux density of ferrite. P. Sekerak in Ref. [29] optimized ferrite SPM design and obtained a final design with slightly larger size but only 60% torque of rare-earth one. To increase the airgap flux density for SPM ferrite machines, one method is to use much larger amount of PM material. A.M. Mihai et al. in Ref. [30] and S. Laurit et al. in Ref. [31] considered rare-earth PMs as the best solutions for wind power generator, in terms of overall weight and size, and also in terms of price. This could be caused by extra cost on the housing and foundation structure for wind power system due to the larger size and weight. However, for small low cost machines, because the original design of electric and magnetic loads is low, it is easier to achieve the required torque output in these applications. Gyeong-Chan Lee et al. in Ref. [32] showed that ferrite SPM machines with larger size were less than half the price of NdFeB for pump applications, though the cogging torque due to ferrite was much higher. H. Kim et al. also achieved same output characteristics with ferrite when compared to NdFeB for small water pump motors. J.A. Krizan et al. also indicated in Ref. [33] that SPM machines with lower energy PMs can still be competitive with machines adopting higher energy PMs if the machine designs were optimized specially for each PM material, with the advantage of low price.

In spite of larger amount of ferrite used in SPM machines, the airgap flux density still could not achieve that of rare-earth ones [30]. Thus, the stator yoke thickness could be reduced in order to increase the slot area for installation of more armature conductors to increase the electric load and power output [20], as shown in Fig. 3. In this case, under the same current density, the copper loss would increase and the overall efficiency would drop. In H.R. Bolton's study, over 10% of efficiency difference was found between rare-earth and ferrite SPMs [20]. In Ref. [34], copper loss of the ferrite generator was almost 3 times that of NdFeB with the same outer diameter, and thus the ferrite machine suffered 7% lower efficiency. And with 30% larger diameter, the efficiency of the ferrite motor was still 1% lower compared to the NdFeB motor in Ref. [35]. R. Gupta et al. in Refs. [27] proposed a ferrite SPM machine with radial- and Halbach-magnetized magnets to increase the flux density and improve the efficiency. Though 1.5–2.4% of higher efficiency could be achieved, these magnetization styles, especially the Halbach-magnetization would bring in extra costs in manufacturing.

D. Woo et al. and H. Kim et al. in Refs. [36,37] proposed another way to increase the flux density in armature flux linkage by applying the structure of longer rotor than stator, which is called an overhang configuration. With this structure, the leakage flux loss would be offset at the end of the lamination cores, and thus the performance of the machine can be improved. With 3 mm overhang, up to 6.8% increase in load torque can be achieved. However, 3D analysis would be required for this type of machine for accurate predictions at the design stage, which will increase the computational time and cost. Moreover, since the overhang was exposed to end of the stack where the reluctance of the magnetic path was much higher, the overhang was under higher risk of demagnetization.

Outer-rotor structure, with a larger airgap diameter, is able to increase the torque, and thus can improve the performance of the machine. I. Petrov and J. Pyrhonen in Ref. [38,39] presented outer-rotor low cost ferrite SPM machines of 4.7 kW and 50 kW respectively for automotive applications. High efficiency of 93.4% was achieved. But the torque density per volume obtained by Petrov was low compared with Prius rare-earth IPM machine, 14 Nm/L versus 80 Nm/L of Prius.

With PMs buried inside the rotor, the magnetic airgap length can be reduced and higher flux density can be achieved with IPM machines. H. Kim et al. in Ref. [40] concentrated on the magnet pole shape optimization to increase airgap flux density and reduce the cogging torque. Y. Im in Refs. [41] focused on the rotor rib shape optimization using response surface methodology to improve performance of ferrite IPM. However, the improvements are still far from the requirements of high torque density applications. B.N. Chaudhari et al. in Ref. [42,43] presented an IPM design using combined circumferentially and radially magnetized PMs to increase the flux density and rotor saliency, as shown in Fig. 4. However, since the magnet poles were not sinusoidal distributed in the rotor, there would be a high content of harmonics in the airgap flux density, which would affect the overall performance of the machine.

Although in small-scale low power density applications, by using much larger amount of PM material, ferrite machines can achieve similar torque output at the expense of lower efficiency compared to their rare-earth counterparts [44,45], it is almost impossible to accomplish the design goal for high power range with sizing constraint [46]. To conclude, due to the low residual flux density of ferrite materials and the large magnetic airgap length of SPM machine, SPM ferrite machines are not likely to fulfil the requirements of high torque density and efficiency for high performance automotive traction applications. This explains why ferrite machines for high performance applications are invariably designed with the IPM configuration, which provides flux enhancing effects [22–25].

3. *Pm* assisted synchronous reluctance machine (Pmasynrm)

PMASynRMs are derived directly from SynRMs, as illustrated in Fig. 5. By adding proper amount of PM materials into flux barriers in the SynRM rotor lamination, the torque density, power factor and efficiency of the PMASynRM can be improved, which makes it a

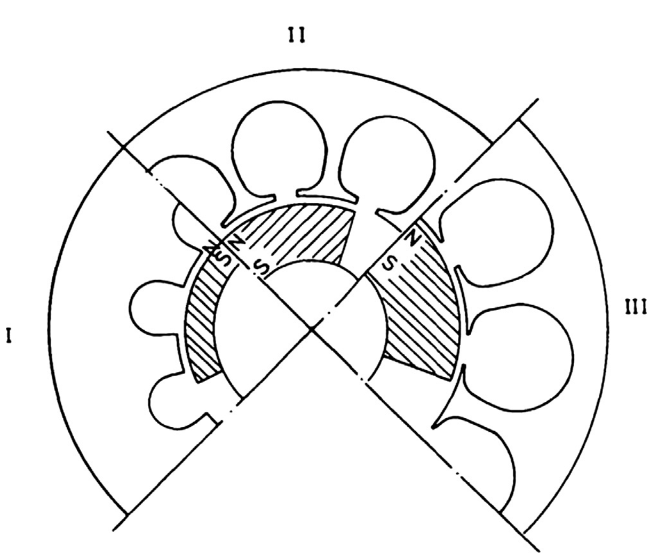


Fig. 3. Design consideration with more PM material, thinner stator yoke and larger size [20].

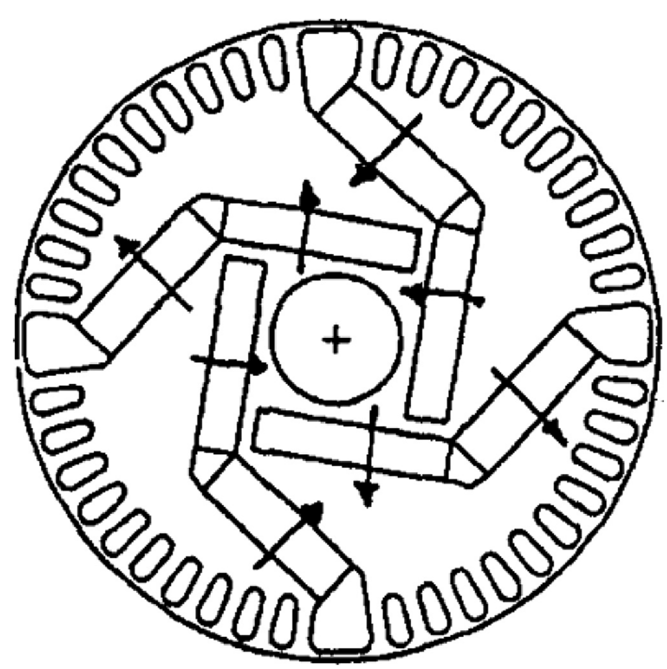


Fig. 4. The rotor design with combined circumferentially and radially magnetized PMs [42].

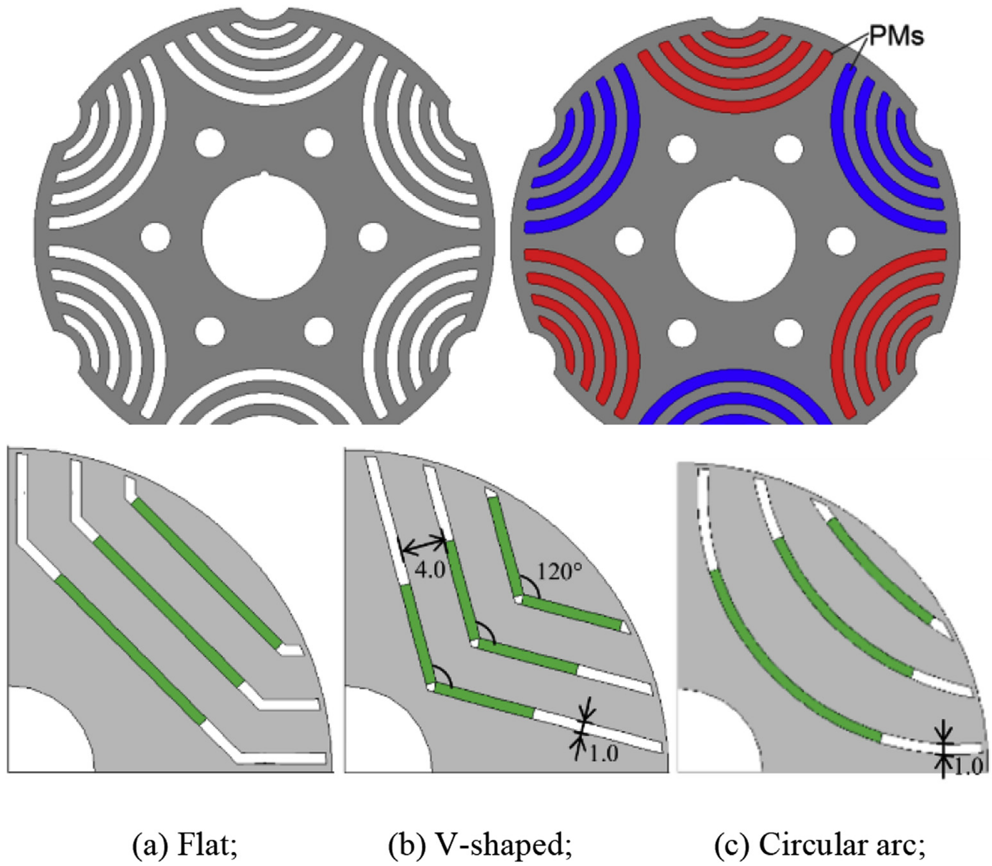


Fig. 5. Configuration of SynRM and PMASynRM rotor [116].

potential solution for ferrite IPM design [47–49].

E. Armando in Ref. [50] also pointed out that with even a small amount of PM, not only the torque output but also the constant power speed range could be improved greatly compared with SynRM design for washing machines. However it is not always the case that more PM results in higher torque. The main component of the torque for PMASynRM is still reluctance torque, and rotor design with too much PM can affect the thickness of barrier ribs and thus affect the saliency. D. Prieto et al. in Ref. [51] investigated the influence of the thickness of inserted PM poles, and suggested more PM materials could improve power factor, but also might cause significant decrease in torque output. M. Barcaro and N. Bianchi in Ref. [52] optimized the length and thickness of PMs, and proved that with similar rotor structure, reduced PM thickness can still attain similar performance, though with a slightly lower power factor. A 40 kW traction motor was presented with 26 Nm/L torque density [53], but it was still inferior to NdFeB IPM machine.

The shape of the PMs and flux barriers also showed great importance to the PMASynRM design. S. Musuroi et al. in Ref. [54] presented a V-shape ferrite PMASynRM since it has simple flux barriers and rectangular PM poles. K. Hayakawa et al. investigated the influence of different flux barrier shape, as shown in Fig. 6, and results revealed that circular arc structure could substantially improve the maximum torque and power output with three flux barriers [55]. It should be noted that ferrite PM was brittle especially when large thin arc shape was used. Y. Matsumoto et al. in Refs. [56] proposed a structure cutting the third flux barrier into three parts, so as to reduce the mechanical stress on the rotor. But due to the flux leakage in the ribs, demagnetization could be observed the PM edge near the ribs. When taken massive production in consideration, long arc shape PMs were more expensive to produce and difficult to assemble. Thus, rectangular segmented PMs were proposed in place of arc shaped magnets for easy manufacturing and assembly [57,58]. Though there was about 4% decrease in the torque output, both the amount of ferrite and manufacturing cost were reduced. 220 Nm of torque and 45 Nm/L of torque density were achieved with a current density of 15 A/mm^2. While with a 1/5 stacking length prototype machine, maximum current density of 7.5 A/mm^2 was tested and about 18 Nm maximum torque was achieved.

PMASynRM with 3 flux barriers is the most common configuration for the rotor design, which appears to be a good compromise between complexity and saliency. However designs with higher number of flux barrier were also adopted in some research works. M. Paradkar et al. in Ref. [59] presented a 55 kW EV motor with 4 flux barriers and about 105 Nm of torque was achieved with a torque density of 19.6 Nm/L. But the mechanical stress was not considered during the design, which was very important to insure the mechanical reliability especially at maximum operational speed, which was 14,000 rpm in the study. Y. Jeong et al. in Ref. [60] proposed a design with 5 flux barriers to gain a higher saliency, and 212 Nm of torque and 25Nm/L of torque density were achieved. Mechanical analysis was carried out to make sure the realization at high speed operation, at 11,000 rpm.

Researchers also found the saturation bridges, pitch and angle of flux barriers could affect the machine performance. Since the saturation bridges provide flux path for PM flux leakage and d-axis flux, both PM torque and reluctance torque could be reduced. H. Cai et al. in Ref. [61] proposed a design with all the bridges removed and yielded 8% increase of overall torque. However, the lamination

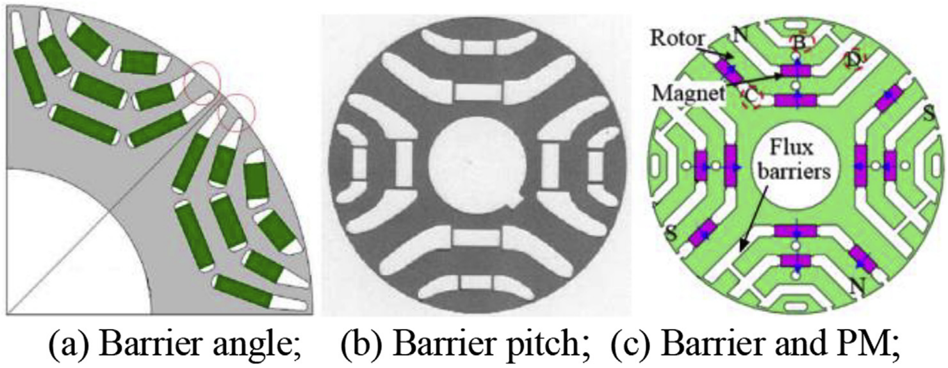


Fig. 6. Rotor shape of flat, V-shape, and circular arc flux barrier and PM poles [55].

rib layers would be completely detached from one another and thus the assembly of the rotor would be an issue to insure the rotor robustness during high speed operation. A torque level of 258Nm was achieved with the same frame size and operating conditions in simulation, which was 85% that of the benchmark. But in the laboratory experiments, the prototype machine was only tested to about 130 Nm. As a variant of reluctance machines, PMASynRMs inherit the drawback of large torque ripple. N. Bianchi optimized the pitch and angle of flux barriers to reduce the torque ripple while keeping the same average torque [62], and H. Cai et al. minimized torque ripple by 35% by adjusting the width of flux barrier opening [61]. Asymmetrical rotor configurations were proposed in Refs. [62–64] to further reduce the torque ripple and augment overall torque, as shown in Fig. 7. However, the harmonic content was dramatically increased for both the flux distribution and back EMF, which would have negative effects on the machine loss.

Ferrite PM has higher temperature stability than rare-earth and can operate at around 250 °C. However, the residual flux density is much lower compared with rare-earth, which makes ferrite PMs quite vulnerable to demagnetization when facing directly to the armature reactive field. Some recent papers have put in evidence that the electric loading must be limited, and the flux barriers must be shaped properly to avoid demagnetization. T. Tokuda et al. in Ref. [65] suggested that the outer layer was more prone to demagnetization than the inner layers as the armature reactive field was stronger. Thus, the thickness of different flux barriers was rearranged, and the out layer would be thicker to resist demagnetization while the inner layers can be thinner to maintain constant flux path width. By fillet smoothing the magnet edge, tapered flux barriers and center ribs, noticeable decrease in

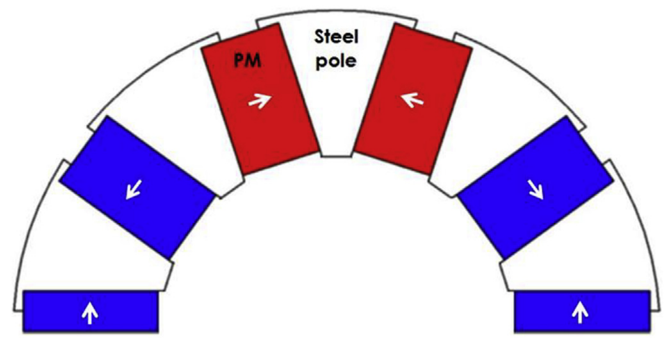


Fig. 8. Rotor design to reduce demagnetization of PMASynRM [66,67].

demagnetization could also be achieved [66,67], as shown in Fig. 8. The works on demagnetization present some guidance and methods on the design to avoid demagnetization. However no systematic approach was proposed. A. Vagati et al. developed an analytical methods to offer options and restraints in the design of rotor barriers to improve the robustness against possible demagnetization [68].

To conclude, PMASynRM machines mainly rely on the reluctance torque component and usually have a lower operating power factor and efficiency. Higher number of flux barriers can increase the rotor saliency, but it also complicates the rotor structure.

4. Spoke-type Ipm machine

To obtain high performance ferrite PM motors with similar

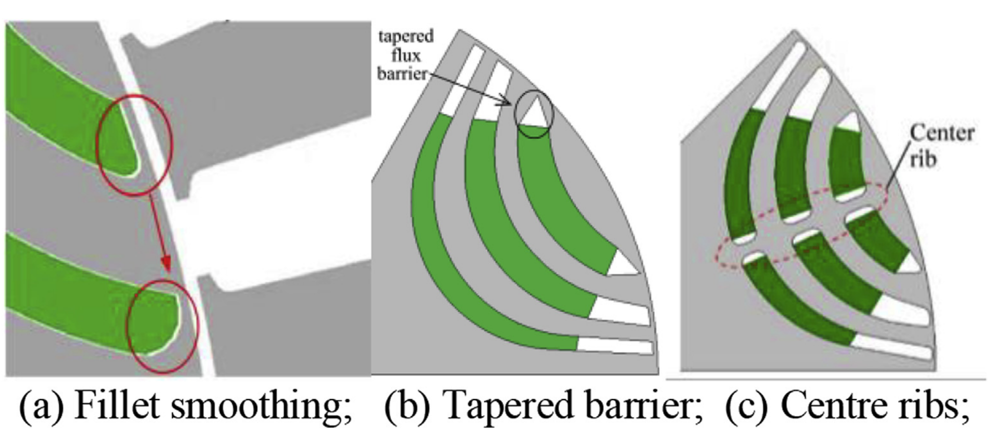


Fig. 7. Asymmetrical rotor configurations for PMASynRM [62–64].

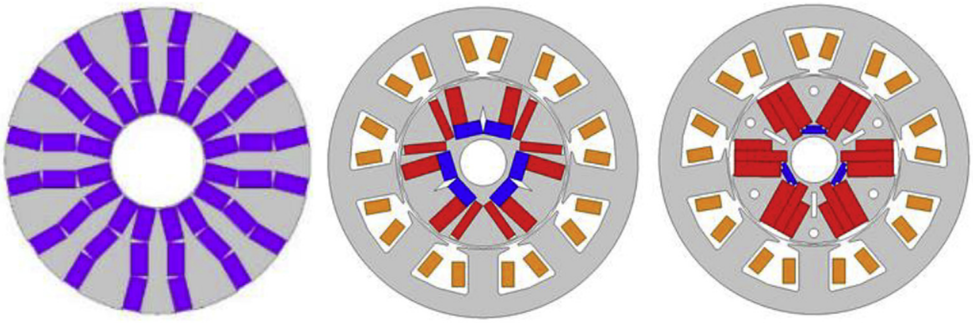


Fig. 9. Rotor configuration of a typical spoke-type machine [71].

torque density as rare-earth machines, many researchers investigate the ‘spoke-type’ structures, also known as ‘flux squeeze’ configuration, which concentrates the fluxes from the PM to achieve approximately the same air-gap flux density as the rare-earth machine, as shown in Fig. 9.

A. Isfanuti et al. in Refs. [69] compared surface NdFeB and spoke-type ferrite machines for low power applications, and found that the same torque can be achieved with high efficiency but higher torque ripple for low cost ferrite machines. Eriksson and Bernhoff in Ref. [70] evaluated the spoke-type wind generators of the same power range with ferrite and NdFeB PMs, and revealed that ferrite generators would be 50% heavier with only 30% of PM cost. E. Spooner et al. proposed a modular design of ferrite spoke-type wind generators for easy assembly and low manufacturing costs [71]. S.J. Galioto et al. investigated the potential of spoke type ferrite machines for high speed traction applications in Ref. [72]. Although the torque density achieved was only 65% of a benchmark NdFeB one, it was significantly advantageous in terms of cost and efficiency at high speed. F. Demmelmayr et al. in Ref. [73] proposed an outer-rotor spoke-type design. However, larger amount (5.7 times) of PM was used and thus outer diameter was enlarged by 26% to achieve same power as a rare-earth one. To compensate the low residual flux of ferrite and reduce the consumption of rare-earth, hybrid PM arrangements with both ferrite and rare-earth PMs were presented in Ref. [74]. Though the amount was reduced, rare-earth PM was still necessary for the design. Another issue that should be paid special attention to is the cross-demagnetization between strong rare-earth and weak ferrite PMs.

To maintain similar airgap flux density, various designs are proposed to use more PM to enhance the PM excited field. K. Kim et al. in Ref. [75] proposed a ferrite spoke-type design with an 13 mm axial overhang and the air-gap flux density was increased by 33%. I.C. Chabu et al. obtained 55% increase in the working flux passing through the airgap by applying an 44 mm axial overhang. W. kakihara et al. in Refs. [76] also applied an 6 mm rotor overhang and an 6 mm PM overhang, the torque output was improved and PM demagnetization rate was reduced. Large rotor overhang would certainly increase the amount of PM and rotor lamination, and the overhang PMs were not fully utilised since considerable parts of the flux would not go through the airgap directly but became leak flux. Axially magnetized PMs were used at each side of the rotor to enhance the flux focusing effect [77–79]. Both surface-mounted and spoke type PMs were used for the design of a ferrite axial flux machine, and the airgap flux density was significantly increased [77]. However, the amount of ferrite used is usually doubled or even tripled to add axially magnetized PM poles. Moreover, due to the existence of axial flux, soft magnetic composite (SMC) cores were necessary because of the 3-dimensional (3D) flux distribution, which would increase the material costs.

For more cost-effective ways of increasing PM excited field, more ferrite was inserted by making full use of the space inside the rotor. I. Seo et al. presented segmented spoke type poles with certain angles [80], as demonstrated in Fig. 10(a). By adjusting the angles of the segmented PMs, larger amount of PM material could be inserted, and open-circuit flux density was improved. Moreover, cogging torque could be reduced by optimized design. However, this uneven PM distribution would bring in unwanted harmonics. H. Kim et al. in Ref. [81,82] presented a ring-type assistant pole in the inner rotor part to increase the torque density with 3.8%. Wing-type and wing-shaped spoke-type configurations were proposed to place more and more PM poles in the rotor [83,84]. Compared to spoke-type only structure, the airgap flux density could be enhanced by 25%, as depicted in Fig. 10(b) and (c). Slightly higher torque output was also achieved compared to the initial rare-earth IPM machine. These designs utilised most of the space in the rotor to house the PM poles, so the assembly of rotor with more PM than steel lamination would be an issue. Moreover, although the wing-shaped spoke-type machine maximized the PM torque, the reluctance torque was significantly reduced. Thus, these structures may not be very practical nor material-effective for industrial use.

Other than PM torque, reluctance torque is also a very important component in total torque production. Increasing the rotor saliency with spoke-type structure would be more effective. W. Kakihara et al. in Ref. [76] proposed a 50 kW ferrite machine with air holes and triangular cut-outs to increase the salient pole ratio and up to 80% torque of Prius rare-earth motor was achieved with same frame size at the current density of 20 A/mm^2. Auxiliary radial magnetized poles were applied in between two spoke-type main poles to increase flux density as well as reluctance torque in Refs. [78,85]. An improved spoke-type design was proposed by dividing each of the conventional spoke-type pole into two parts shown in Fig. 11(b) [86,87]. The reactance torque could benefit from this design and an 25 Nm/L torque density was achieved. However, there are still more room to develop a rotor design sustaining certain airgap flux density and higher rotor saliency. B. Xia et al. in Ref. [88] proposed a novel design with multi-layer configuration for traction applications. The reluctance torque was maximized with acceptable PM torque component, and the final design was able to deliver up to 95% of the Prius rare-earth IPM machines as shown in Fig. 11(c). W. Fei et al. further investigated the influence of the number of layers on the machine performance, and shown that two-layer configuration was the most cost-effective design compromise in terms of performance and rotor complexity [89].

To fully utilize the machine space and gain higher torque density, a 3D trench airgap configuration with double-stators was proposed in Ref. [85] to increase flux density, as illustrated in

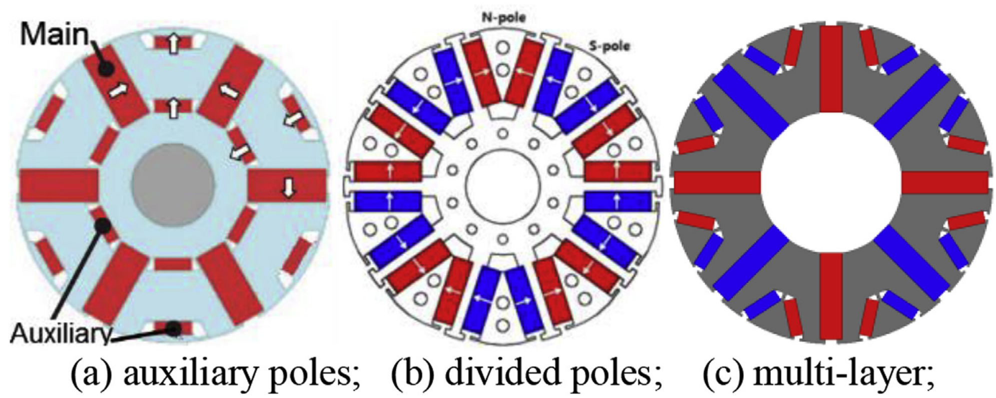


Fig. 10. Ferrite spoke-type design with more PM poles.

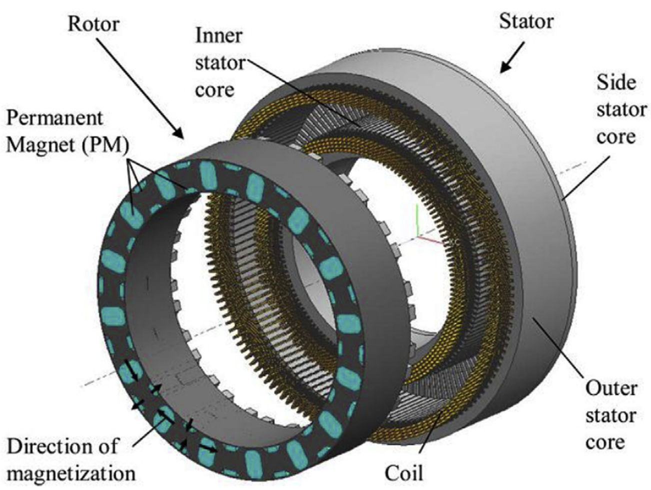


Fig. 11. Spoke type designs to increase rotor saliency [78,86,88].

Fig. 12. The proposed machine consisted of double stators and a spoke type rotor with side rotor poles sandwiched in between. Comparable torque density with rare-earth machines could be achieved. However, double-stator structures required larger amount of copper to increase the power density, which resulted in relatively low efficiency level (similar to IMs). Moreover, the complex structure would increase the manufacturing cost and therefore may not be suitable for mass production.

Compared with PMASynRM, spoke-type suffers higher risks of irreversible demagnetization [23]. Occurrences of demagnetization were reported in many of the papers reviewed here. In Ref. [78] the demagnetization was below 0.5% and thus could be negligible. Though demagnetization occurred in Ref. [90–92], no solution was presented. In Refs. [86], the main pole was divided into two parts, a flux path was created for armature active field, so the demagnetized area was reduced. Usually the edge of the PM poles suffered higher risk of demagnetization. K. Kondo et al. cut the edge end with chamfered-style [85], while a deeper PM insertion and overhang methods were applied in Ref. [76].

To conclude, spoke-type ferrite PM machines have the potential of achieving higher torque density and torque factor than PMASynRM with lower torque ripple. However, the electromagnetic loading of spoke-type motors needs to be designed very carefully due to the higher risks of irreversible demagnetizations.

5. Other types of ferrite machines

There are many other works proposing ferrite PM machines for various applications with different motor configuration, such as flux switching, claw-pole, Vernier-type and axial flux machines, to name but a few. Below we attempt to describe the key ones that attract more interests among researchers.

5.1. Dual-rotor structures

Due to the low residual flux density of ferrite PMs, researchers intend to expand the active space to place more PMs to enhance the

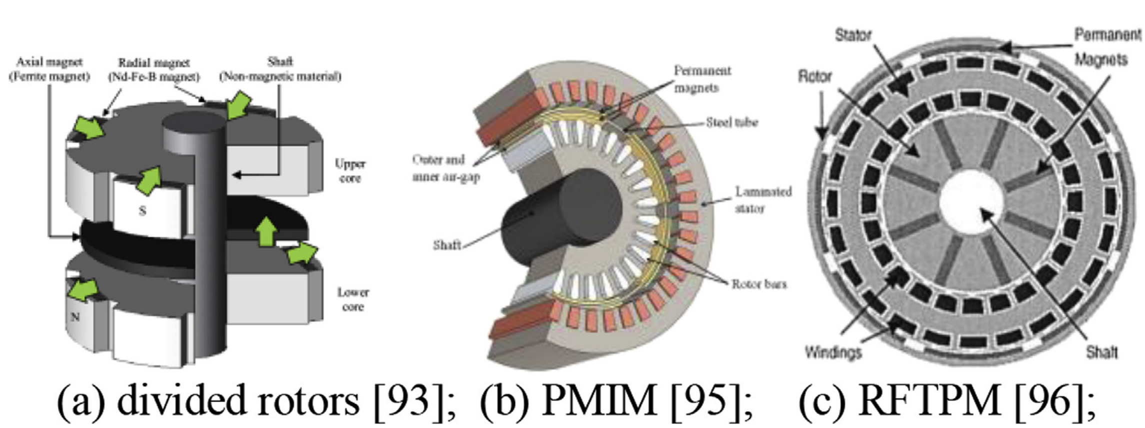


Fig. 12. Design model of double stator spoke-type machine with 3D trench airgap [85].

airgap flux density. A novel rotor structure consisting of upper and lower cores with an axially-magnetized ferrite pole was developed in Ref. [93,94] to reduce the use of rare-earth material, as demonstrated in Fig. 13(a). However, a key issue with this structure was that at the same circular position, the electrical phases of magnetic field from the upper and lower part were different. Thus two sets of armature windings would be needed to adapt the rotor structure. A. Gazdac in Refs. [95] presented a PM induction machine (PMIM) combining squirrel-cage IM and PM rotors, as depicted in Fig. 13(b). However, the IM rotor would have a slip from synchronous speed, and the two rotors rotated at different speeds. Hence, two set of bearings and connections were required for the two rotors. R. Qu et al. in Ref. [96] proposed a dual-PM-rotor toroidally-wound PM (RFTPM) machine to improve torque density and efficiency, as shown in Fig. 13(c). Inner rotor fully utilised the inner space and toroidal armature reduced end-winding lengths. Yet, ferrite SPM structure cannot generate enough airgap flux distribution, and the torque density (4.32 Nm/L claimed) was still too low for traction applications. By using dual-rotor configurations, the flux density could be improved to some extent, but the mechanical structure tends to be more complicated, which would increase the manufacturing cost.

5.2. Flux switching PM machines

Flux switching PM (FSPM) machines with both ferrite magnet and field windings in the stator were presented in Ref. [97,98], and good power density with acceptable efficiency was reported in Ref. [97]. A self-excited single-phase reluctance generator with small pieces of ferrite in between stator teeth was presented in Ref. [99], but the achievable PM excited flux density was too low, which resulted in low efficiency. A hybrid NdFeB and ferrite PM FSPM was investigated in Ref. [100] to reduce material costs. The torque density of hybrid PM was between that of NdFeB and ferrite only FSPMs, depending on rare-earth proportion. E. Hoang et al. and J. Zhang et al. in Ref. [101,102] presented a FSPM design capable of flux concentration, and very good flux weakening ability could be achieved with wide constant power speed range. However, the power density of ferrite FSPM machines was relatively low. In all, the low-energy ferrite PM apparently did not suit for FSPM since the space in the stator was quite limited to accommodate armature windings, stator teeth and PM poles. It should also be noted that the risk of demagnetization for ferrite FSPMs was high because the low magnetic energy PM would face directly to reactive field from the armature installed together with PMs in stator [22].

5.3. Claw pole machines

Claw pole ferrite PM machines with field coils were investigated in Ref. [103,104]. The hybrid-excited configuration compensated the lower flux density of ferrite compared with rare-earth. High torque output was achieved but the efficiency of 85% was relatively low due to high copper loss. In Ref. [105,106] segmented rotors with claw poles were proposed for easy power scaling up with existing designs.

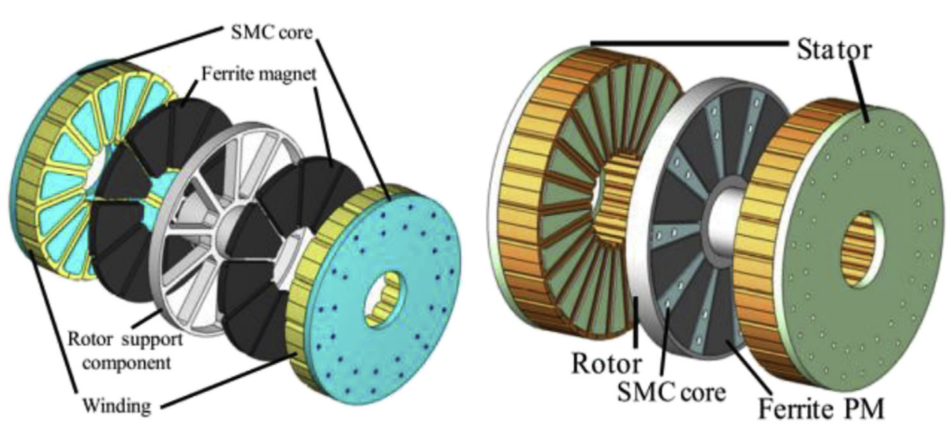
5.4. Axial flux machine

Axial flux PM (AFPM) machines are expected to have higher torque density and compact structure and are considered as a candidate for high performance applications. Z. Wang et al. in Refs. [107] presented a high speed AFPM ferrite machine with amorphous metal cores. Each of the stator teeth was a modular part using amorphous magnetic materials (AMMs) cut core for the ease in manufacturing. W. Zhao et al. proposed a spoke-type ferrite AFPM and 63.4 Nm of torque and 18.8 Nm/L of torque density were achieved [108]. But axial spoke-type machines could be more complicated to assemble than its radial counterparts. K. Chiba and K. Sone et al. in Refs. [109,110] proposed a double-stator single-coreless-rotor ferrite AFPM machine, as shown in Fig. 14(a) and the PM shape was optimized to reduce torque ripple. A torque density of 34.7 Nm/L and 14.6 Nm/L was achieved at the current density of 22 A/mm^2 and 11 A/mm^2 respectively. K. Sone in Ref. [111] indicated that the rotor core in the double-stator single-rotor AFPM machines would aggravate demagnetization in PMs. Thus coreless rotor could suppress irreversible demagnetization. In order to increase the reluctance torque of this machine design, S. Chino and T. Miura et al. in Refs. [112,113] proposed a SMC cores assembled in between adjacent PM poles to increase the salient pole ratio, as shown in Fig. 14(b). As a result, a maximum torque of 326.7 Nm at 22 A/mm^2, which was 37 Nm/L of torque density, was achieved in simulation, while the experimental result was 6.9% lower than predicted.

For AFPM machines, usually SMC cores are necessary due to the existence of 3D flux path. It surely would increase the material cost comparing to steel laminations. Moreover, the manufacturing and assembly of axial machines flux are also more complicated than radial ones.

5.5. Vernier machines

Permanent magnet Vernier machines (PMVMs) can deliver large



(a) coreless rotor design [109]; (b) with rotor cores [112];

Fig. 13. Examples of dual-rotor configurations.

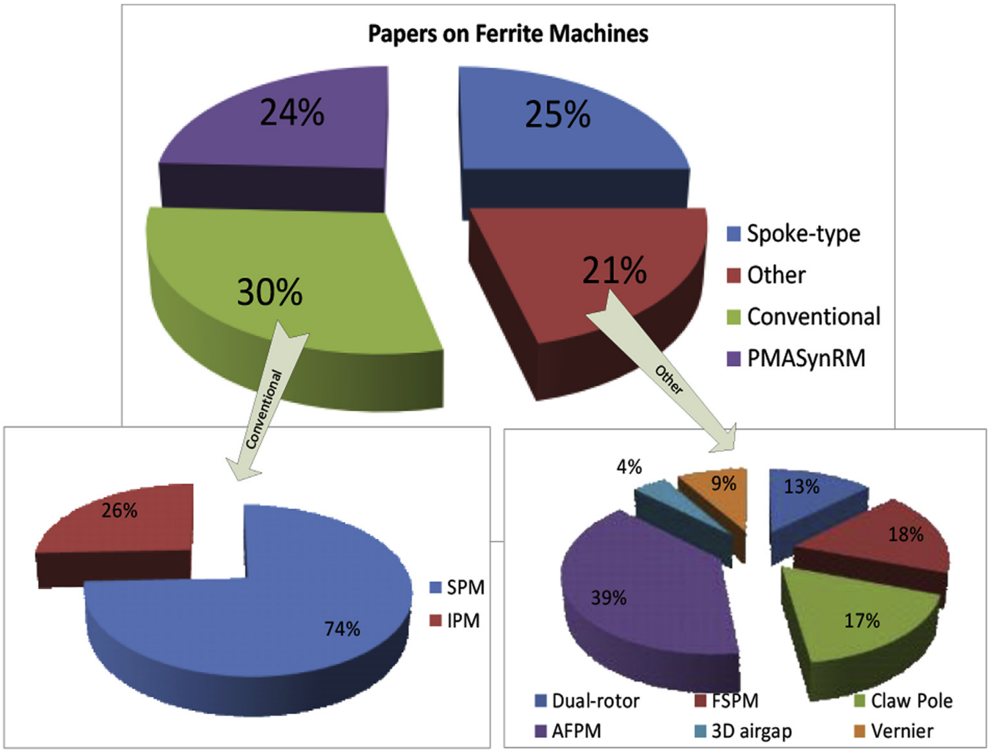


Fig. 14. Designs of double-stator single-rotor AFPM machines.

torque at low speed and are 'multi-polarized' in fewer slots than conventionally designed machines, and thus are considered for in-wheel machines for EV applications. R. Hosoya and K. Sato et al. in Refs. [114,115] presented a ferrite PMVM to accomplish high torque density design goals. A V-shaped PM outer-rotor configuration was applied and 58% of higher flux density was achieved in the airgap. For their final design, 510 Nm of torque was obtained, which was 25 Nm/L.

6. Comparisons

In the discussion here, the Prius 2004 rare-earth IPM machine is used as a benchmark to make some comparisons between the design from different categories and research groups.

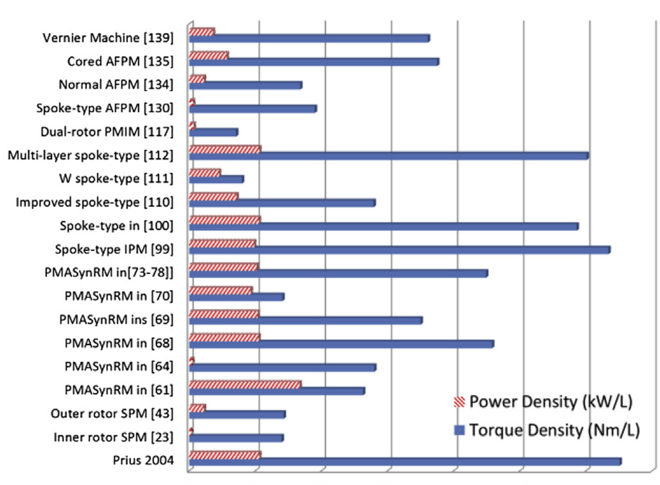


Fig. 15. The percentage of papers reviewed on ferrite PM machines.

Fig. 15 shows the number and percentage of papers reviewed in our current study and indicates the existing work on different machine structures and topologies. Though the highest number of papers on ferrite PM machines comes from the conventional category, some of them were published 20–30 years ago, and a large part were intended for low-power applications to reduce the material cost. To increase the power density, more PM material and larger size were the common solutions. However, due to the huge difference in PM properties, it is very difficult to realize the critical requirements such as high efficiency, high power density and small size for high performance traction applications. Nowadays, PMA-SynRM and Spoke-type IPMs are most attractive solutions with relatively mature technology to replace rare-earth machines. PMASynRM configurations descend from SynRMs with PM inserted inside the flux barriers to increase the torque production and power factor. Since the PMASynRM originates from reluctance machines, it has a high saliency ratio and depends largely on reluctance torque. Also, it can operate at wider speed range with better flux weakening ability. In terms of power factor and torque density, PMASynRMs are inferior to Spoke-type IPMs. On the other hand, spoke-type IPMs can potentially achieve approximately similar open-circuit flux distribution with rare-earth machines using flux focusing structures. As a result, higher power factor and torque density can be obtained. To achieve high torque density, reluctance torque is also a very important part for the overall torque. Thus, various improvements and modifications are needed to maximize the electromagnetic torque. Since the length of PM poles to pole pitch ratio is very critical to flux focusing effect, relative high pole number is preferred for spoke type machines. Because this flux focusing structure faces higher risk of demagnetization special attention should be paid during the design.

Among the Other types of machines, AFPM seems to the most popular alternatives for high performance EV applications.

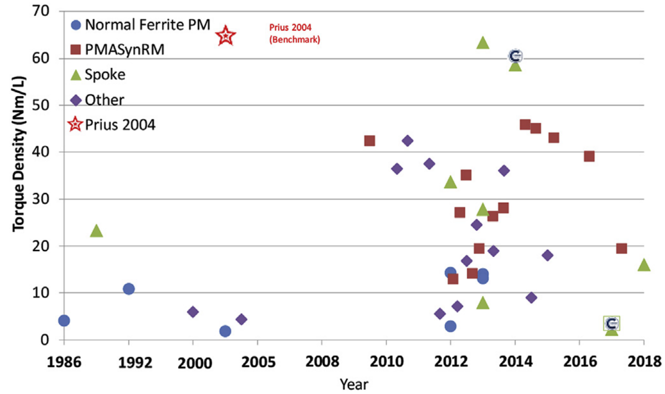


Fig. 16. Comparisons of power and torque density of ferrite machines in literature against Prius 2004 p.m.

However, larger outer diameters and pole numbers are preferable for this flat-shaped machine structure, which would raise the issues of loss and mechanical stress at high speed. For ferrite FSPMs, it is difficult to achieve the required torque density since there is not enough space to accommodate enough amount of PM to improve the flux density.

Fig. 16 and Fig. 17 show the developments of the torque and power density of typical machines of different machine types, with reference to Prius 2004 rare-earth IPM. Obviously conventional SPMs have the lowest torque density due to the low flux level. The highest among PMASynRMs is 45.8 Nm/L from Ref. [61]. Also in Ref. [67] a PMASynRM design achieved 44.9 Nm/L, which is also very promising for EV applications. Spoke-type IPMs have better torque densities, with the highest value of 63.4 Nm/L from Ref. [76]. A multi-layer spoke design in Ref. [88] also achieved a torque density of 60 Nm/L for traction applications. As for the other types of machines, AFPM, Claw pole and Vernier machines have similar torque density, at 37.5, 36.4 and 36.1 Nm/L respectively.

Most designs in the reviewed papers aiming for traction applications are between 200 and 300 Nm, except in the case of a high speed PMASynRM with 188 Nm, which could run at 14,000 rpm maximum, and the Vernier one with 400 Nm at 1350 rpm maximum. From the speed point of view, PMASynRMs are more suitable to run at a higher speed with better flux weakening abilities, and Vernier motors are usually for low speed operations. As for the current density, the design of high speed PMASynRM in Refs. [59] was easier to deal with the cooling issues since the highest current density is only less than 10 A/mm^2. On the other hand, the AFPM design had the highest current density of 22 A/mm^2, which would require a specially designed cooling system to remove the heat to avoid overheating.

7. Conclusion

This paper has aimed to provide, a most comprehensive review to date, on the current developments of ferrite PM machines, and has focused on the key issues of torque density and efficiency. The review is based on carefully grouping the considerably diverse body of works into four categories, namely conventional SPM/IPM machines, PMASynRMs, spoke-type machines and machines with other special structures or topologies.

For SPM machines, the airgap flux field excited by ferrite PM cannot exceed ferrite residual flux density, which is too low to achieve a high torque density. While for conventional IPM, there is not enough space for large amount of PM material. As for other types of ferrite machines, the technologies in both design and manufacturing are not quite mature yet, which may influence the mass production. Also, special materials sometimes are required for their instinctive design, e.g. SMC core for 3D motor design.

The most promising structures to achieve high performance requirements for EV application are PMASynRM and spoke-type configurations, which make use of both PM torque and reluctance torque to improve high torque density. PMASynRMs maximize the rotor saliency and use PM to improve the power factor as well as torque density. Spoke-type machines adapt the flux-squeeze structure for flux concentration to compensate the low residual flux density of ferrite material, and meanwhile optimal design should be carried out to increase the salient pole ratio for higher reluctance torque. PMASynRMs have lower power factor and higher torque ripple, while spoke-type machines suffer more serious irreversible demagnetization and have a relatively small flux weakening ability. Some typical machines from existing works are chosen for an extensive comparison among different machine

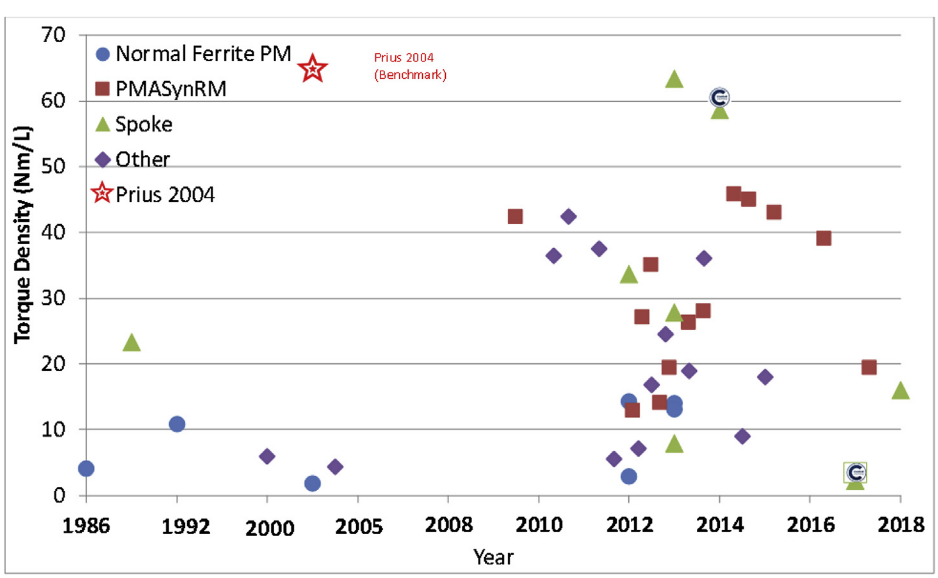


Fig. 17. Torque density of key typical ferrite PM machines against publication year.

structures. Some of the works offer very promising prospect for high performance EV applications, while some others may stay at the theoretical stage for a long time.

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.

Acknowledgement

This work has been funded by The Engineering and Physical Sciences Research Council (EPSRC) of the United Kingdom, under the Refs. EP/S032053/1 and EP/I038543/1.

References

[1] Chau KT, Chan CC, Liu C. Overview of permanent-magnet brushless drives for electric and hybrid electric vehicles. IEEE Trans Ind Electron 2008;55:2246–57.
[2] Yetiş H, Meşe E, Biyikli M. Design and comparison of ferrite based IPM and NdFeB based SPM synchronous motors for gearless elevator systems. In: 2018 XIII International conference on electrical machines. Alexandroupoli: ICEM; 2018. p. 635–41. https://doi.org/10.1109/ICELMACH.2018.8506825.
[3] Chen J, Gu P, Chen X. Application of Mn-Zn ferrite in permanent magnet brushless DC motor with high speed. In: 2018 Asia-Pacific magnetic recording conference (APMRC), Shanghai; 2018. https://doi.org/10.1109/APMRC.2018.8601052. 1-1.
[4] Zhu ZQ, Howe D. Electrical machines and drives for electric, hybrid, and fuel cell vehicles. Proc IEEE 2007;95:746–65.
[5] Bramerdorfer G, Silber S, Weidenholzer G, Amrhein W. Comprehensive cost optimization study of high-efficiency brushless synchronous machines. In: Electric machines & drives conference (IEMDC), 2013 IEEE International; 2013. p. 1126–31.
[6] Richter E, Miller TJE, Neumann TW, Hudson TL. The ferrite permanent magnet AC motor–A technical and economical assessment. IEEE Trans Ind Appl 1985;IA-21:644–50.
[7] Bloomberg. 'Prices of selected rare earth elements' Bloomberg. Available at: Subscript sennce, https://worldview.stratfor.com/article/geopolitics-rare-earth-elements. [Accessed 17 June 2019].
[8] Boldea I, Tutelea LN, Parsa L, Dorrell D. Automotive electric propulsion systems with reduced or No permanent magnets: an overview. IEEE Trans Ind Electron 2014;61:5696–711.
[9] Dorrell D, Parsa L, Boldea I. Automotive electric motors, generators, and actuator drive systems with reduced or No permanent magnets and innovative design concepts. IEEE Trans Ind Electron 2014;61:5693–5.
[10] Morimoto S, Asano Y, Kosaka T, Enomoto Y. Recent technical trends in PMSM. In: Power electronics conference (IPEC-Hiroshima 2014 - ECCE-ASIA). International; 2014. p. 1997–2003. 2014.
[11] Guan Y, Zhu ZQ, Afinowi IAA, Mipo JC, Farah P. Comparison between induction machine and interior permanent magnet machine for electric vehicle application. In: Electrical Machines and Systems (ICEMS), 2014 17th International Conference on; 2014. p. 144–50.
[12] Gould JE. Permanent magnets. Proc Inst Electr Eng 1978;125:1137–51.
[13] Deshpande US. Recent advances in materials for use in permanent magnet machines-a review. In: Electric Machines and drives conference, 2003. vol. 1. IEMDC'03. IEEE International; 2003. p. 509–15. vol. 1.
[14] Zhang S, Xu J, Junak J, Fiederling D, Sawczuk G, Koch M, Schalja A, Podack M, Baumgartner J. Permanent magnet technology for electric motors in automotive applications. In: *Electric drives production conference (EDPC)*, 2012 2nd International; 2012. p. 1–11.
[15] Hayashi Y, Mitarai H, Honkura Y. Development of a DC brush motor with 50% weight and volume reduction using an Nd-Fe-B anisotropic bonded magnet. IEEE Trans Magn 2003;39:2893–5.
[16] Grant E, Roszyk LM. Design consideration for permanent magnet motors in appliance applications, vol. I; 1968.
[17] Petrov I, Niemelä M, Ponomarev P, Pyrhönen J. Rotor surface ferrite permanent magnets in electrical machines: advantages and limitations. IEEE Trans Ind Electron July 2017;64(7):5314–22. https://doi.org/10.1109/TIE.2017.2677320.
[18] Knebl L, Ondrusek C, Kurfürst J. Ferrite assisted synchronous reluctance motor design, manufacturing and material influence on motor characteristics. In: 2018 18th International conference on mechatronics - mechatronika (ME); 2018. p. 1–6. Brno, Czech Republic.
[19] Richter E, Miller TJE, Neumann TW, Hudson TL. The ferrite permanent magnet AC motor—A technical and economical assessment. IEEE Trans Ind Appl 1985;IA-21:644–50.
[20] Bolton HR, Liu YD, Mallinson NM. Investigation into a class of brushless DC motor with quasisquare voltages and currents. IEE Proc B Elec Power Appl 1986;133:103–11.
[21] Richter E, Neumann T. Line start permanent magnet motors with different materials. IEEE Trans Magn 1984;20:1762–4.
[22] Bonthu SSR, Arafat A, Choi S. Comparisons of rare-earth and rare-earth-free external rotor permanent magnet assisted synchronous reluctance motors. IEEE Trans Ind Electron Dec. 2017;64(12):9729–38. https://doi.org/10.1109/TIE.2017.2711580.
[23] Montalvo-Ortiz EE, Foster SN, Cintron-Rivera JG, Strangas EG. Comparison between a spoke-type PMSM and a PMASynRM using ferrite magnets. In: Electric machines & drives conference (IEMDC), 2013. IEEE International; 2013. p. 1080–7.
[24] Carraro E, Degano M, Morandin M, Bianchi N. PM synchronous machine comparison for light electric vehicles. In: Electric vehicle conference (IEVC), 2014. IEEE International; 2014. p. 1–8.
[25] S.B. Bhat, S.P. Nikam, and B.G. Fernandes, "Design and analysis of ferrite based permanent magnet motor for electric assist bicycle," Electrical machines (ICEM), 2014 International Conference on, 2014, pp. 106–111.
[26] Lee S-J, Kim S-I, Hong J-P, Song B-Y, Park J-W. Characteristic analysis of the water pump motor considering polar anisotropie ferrite bonded magnet. In: Electrical Machines and Systems (ICEMS), 2010 International Conference on; 2010. p. 1242–5.
[27] Gupta RK, Mohan N. A three-phase permanent magnet brushless DC motor for low-power low-speed fan applications - optimizing cost and efficiency. In: Industry applications conference, 2007. 42nd IAS annual meeting. Conference Record of the 2007 IEEE; 2007. p. 846–52.
[28] Pal SK. "Comparative study of the design and manufacturing processes of electrical motors with low and high energy permanent magnets. In: Electrical machines and drives. Sixth International Conference on (Conf. Publ. No. 376); 1993. p. 339–46.
[29] Sekerak P, Hrabovcova V, Pyrhonen J, Kalamen S, Rafajdus P, Onufer M. "Comparison of synchronous motors with different permanent magnet and winding types. IEEE Trans Magn 2013;49:1256–63.
[30] Mihai AM, Benelghali S, Livadaru L, Simion A, Outbib R. FEM analysis upon significance of different permanent magnet types used in a five-phase PM generator for gearless small-scale wind. In: Electrical machines (ICEM), 2012 XXth International conference on; 2012. p. 267–73.
[31] Laurit S, Kallaste A, Vaimann T, Belahcen A. Cost efficiency analysis of slow-speed slotless permanent magnet synchronous generator using different magnetic materials. In: Electric power Quality and Supply reliability conference (PQ), 2014; 2014. p. 221–4.
[32] Lee G-C, Jung T-U. Design comparisons of BLDC motors for electric water pump. In: Vehicle Power and propulsion conference (VPPC), 2012. IEEE; 2012. p. 48–50.
[33] Krizan JA, Sudhoff SD. Theoretical performance boundaries for permanent magnet machines as a function of magnet type. In: Power and energy society general meeting, 2012. IEEE; 2012. p. 1–6.
[34] Jang S-M, Seo H-J, Park Y-S, Park H-I, Choi J-Y. Design and electromagnetic field characteristic analysis of 1.5 kW small scale wind power generator for substitution of Nd-Fe-B to ferrite permanent magnet. IEEE Trans Magn 2012;48:2933–6.
[35] Sekerak P, Hrabovcova V, Onufer M, Kaiamen L, Rafajdus P. Synchronous motors with different PM materials, vol. 2012. *ELEKTRO*; 2012. p. 241–6.
[36] Woo D-K, Lim D-K, Yeo H-K, Ro J-S, Jung H-K. A 2-D finite-element analysis for a permanent magnet synchronous motor taking an overhang effect into consideration. IEEE Trans Magn 2013;49:4894–9.
[37] Kim H-C, Jung T-U. Analysis of rotor overhang effect considering load torque variance in automobile BLDC fan motor. In: Vehicle Power and propulsion conference (VPPC), 2012. IEEE; 2012. p. 68–71.
[38] Petrov I, Pyrhonen J. Performance of low-cost permanent magnet material in PM synchronous machines. IEEE Trans Ind Electron 2013;60:2131–8.
[39] Petrov I, Polikarpova M, Pyrhonen J. Rotor surface ferrite magnet synchronous machine for generator use in a hybrid application — electro-magnetic and thermal analysis. In: Industrial electronics society, IECON 2013 - 39th annual Conference of the IEEE; 2013. p. 3090–5.
[40] Kim H, You Y-M, Kwon B. Rotor shape optimization of interior permanent magnet BLDC motor according to magnetization direction. IEEE Trans Magn 2013;49:2193–6.
[41] Im Y-H, Hwang S-I, Jang S-M, Choi J-Y, Choi J-H. Analysis of torque pulsation considering interior permanent magnet rotor rib shape using response surface methodology. IEEE Trans Magn 2012;48:979–82.
[42] Chaudhari BK, Fernandes BG, Pillai SK. A new hybrid rotor geometry for permanent magnet synchronous motor. In: Power electronic Drives and energy Systems for industrial growth, 1998. Proceedings. 1998 international Conference on, vol. 1; 1998. p. 260–3. vol. 1.
[43] Chaudhari BN, Fernandes BG. Permanent magnet synchronous motor for general purpose energy efficient drive. In: Power engineering society winter meeting, 2000, vol. 1. IEEE; 2000. p. 213–8. vol. 1.
[44] Sun T, Kwon SO, Lee J-J, Hong J-P. Investigation and comparison of system efficiency on the PMSM considering Nd-Fe-B magnet and Ferrite magnet. In: Telecommunications energy conference, 2009. INTELEC 2009. 31st International; 2009. p. 1–6.
[45] Fang L, Lee BH, Lee JJ, Kim HJ, Hong J-P. Study on high-efficiency characteristics of interior permanent magnet synchronous motor with different magnet material. In: Electrical Machines and Systems, 2009. ICEMS 2009.

International conference on; 2009. p. 1–4.
[46] Richter E, Neumann T. Line start permanent magnet motors with different materials. IEEE Trans Magn 1984;20:1762–4.
[47] Vartanian R, Toliyat HA, Akin B, Poley R. Power factor improvement of synchronous reluctance motors (SynRM) using permanent magnets for drive size reduction. In: Applied power electronics conference and exposition (APEC), 2012. Twenty-Seventh Annual IEEE; 2012. p. 628–33.
[48] Shen JX, Cai S, Shao H, Hao H. Evaluation of low-cost high-performance synchronous motors for ventilation application. In: 2015 International Conference on Sustainable mobility applications. Renewables and Technology (SMART); 2015. p. 1–6.
[49] Wang Y, Ionel DM, Jiang M, Stretz SJ. Establishing the relative merits of synchronous reluctance and PM assisted technology through systematic design optimization. IEEE Trans Ind Appl 2016:1.
[50] Armando E, Guglielmi P, Pastorelli M, Pellegrino G, Vagati A. Performance of IPM-PMASR motors with ferrite injection for home appliance washing machine. In: Industry applications society annual meeting, 2008. IAS '08. IEEE; 2008. p. 1–6.
[51] Prieto D, Dague B, Dessante P, Vidal P, Vannier J. Effect of magnets on average torque and power factor of Synchronous Reluctance Motors. In: Electrical machines (ICEM), 2012 XXth International conference on; 2012. p. 213–9.
[52] Barcaro M, Bianchi N. Interior PM machines using ferrite to replace rare-earth surface PM machines. In: industry applications, IEEE Transactions on; 2013. p. 1.
[53] Carraro E, Degano M, Morandin M, Bianchi N. Formula SAE electric competition: electrical motor design. In: Electric machines & drives conference (IEMDC), 2013. IEEE International; 2013. p. 1142–8.
[54] Musuroi S, Sorandaru C, Greconici M, Olarescu VN, Weinman M. Low-cost ferrite permanent magnet assisted synchronous reluctance rotor an alternative solution for rare earth permanent magnet synchronous motors. In: Industrial electronics society, IECON 2013 - 39th annual Conference of the IEEE; 2013. p. 2966–70.
[55] Hayakawa K, Sanada M, Morimoto S, Inoue Y. Evaluation of IPMSMs with concentrated windings using powder magnets for high torque. In: Power Electronics and drive Systems (PEDS), 2013 IEEE 10th International conference on; 2013. p. 735–40.
[56] Matsumoto Y, Miki I, Morinaga K. Study on IPMSM with ferrite magnets driven at high speeds. In: Electrical Machines and Systems (ICEMS), 2013 International Conference on; 2013. p. 1064–7.
[57] Obata M, Morimoto S, Sanada M, Inoue Y. Performance of PMASynRM with ferrite magnets for EV/HEV applications considering productivity. IEEE Trans Ind Appl 2014;50:2427–35.
[58] Sanada M, Morimoto S, Inoue Y. Development of high-power PMASynRM using ferrite magnets for reducing rare-earth material use. In: Power electronics conference (IPEC-Hiroshima 2014 - ECCE-ASIA), 2014. International; 2014. p. 3519–24.
[59] Paradkar M, Boecker J. Design of a high performance ferrite magnet-assisted synchronous reluctance motor for an electric vehicle. In: IECON 2012 - 38th annual Conference on IEEE industrial electronics society; 2012. p. 4099–103.
[60] Jeong Y-H, Kim K, Kim Y-J, Park B-S, Jung S-Y. Design characteristics of PMa-SynRM and performance comparison with IPMSM based on numerical analysis. In: Electrical machines (ICEM), 2012 XXth International Conference on; 2012. p. 164–70.
[61] Cai H, Guan B, Xu L. Low-cost ferrite PM-assisted synchronous reluctance machine for electric vehicles. IEEE Trans Ind Electron 2014;61:5741–8.
[62] Bianchi N. Synchronous reluctance and interior permanent magnet motors. In: Electrical Machines Design Control and Diagnosis (WEMDCD), 2013 IEEE Workshop on; 2013. p. 75–84.
[63] Obata M, Morimoto S, Sanada M, Inoue Y. Performance evaluation of high power and low torque ripple structure of rare-earth free PMASynRM with ferrite magnet. In: Power Electronics and drive Systems (PEDS), 2013 IEEE 10th International conference on; 2013. p. 714–9.
[64] Zhao W, Chen D, Lipo T, Kwon B. "Performance improvement of ferrite-assisted synchronous reluctance machines using asymmetrical rotor configurations. IEEE Trans Magn 2015:1.
[65] Tokuda T, Sanada M, Morimoto S. Influence of rotor structure on performance of permanent magnet assisted synchronous reluctance motor. In: Electrical Machines and Systems, 2009. ICEMS 2009. International conference on; 2009. p. 1–6.
[66] Takishima D, Miki I, Nakamura M. Study of torque performance for IPMSM with ferrite magnet. In: Power electronics, electrical drives, Automation and motion (SPEEDAM), 2012 International Symposium on; 2012. p. 83–6.
[67] Sanada M, Inoue Y, Morimoto S. Rotor structure for reducing demagnetization of magnet in a PMASynRM with ferrite permanent magnet and its characteristics. In: Energy Conversion Congress and Exposition (ECCE). IEEE; 2011. p. 4189–94. 2011.
[68] Vagati A, Boazzo B, Guglielmi P, Pellegrino G. Design of ferrite assisted synchronous reluctance machines robust towards demagnetization. In: industry applications, IEEE Transactions on; 2013. p. 1.
[69] Isfanuti A-S, Baba M, Tutelea L, Moldovan A, Boldea I. Surface NdFeB versus Ferrite IPM motor drive for low power (100W to 2000W) applications: FEM embedded optimal design with full step torque response validation in sensorless vector control. In: Industrial electronics society, IECON 2013 - 39th annual Conference of the IEEE; 2013. p. 3177–82.
[70] Eriksson S, Bernhoff H. Rotor design for PM generators reflecting the unstable neodymium price. In: Electrical machines (ICEM), 2012 XXth International Conference on; 2012. p. 1419–23.
[71] Spooner E, Williamson AC, Catto G. Modular design of permanent-magnet generators for wind turbines. IEE Proc Elec Power Appl 1996;143:388–95.
[72] Galioto SJ, Reddy PB, El-Refaie AM, Alexander JP. Effect of magnet types on performance of high-speed spoke interior-permanent-magnet machines designed for traction applications. IEEE Trans Ind Appl 2015;51:2148–60.
[73] Demmelmayr F, Weiss B, Troyer M, Schroedl M. Comparison of PM-machines with ferrite and NdFeB magnets in terms of machine performance and sensorless start-up control. In: Industrial technology (ICIT), 2013. IEEE International Conference on; 2013. p. 272–7.
[74] Chen Q, Liu G, Zhao W, Shao M, Liu Z. Design and analysis of the new high-reliability motors with hybrid permanent magnet material. IEEE Trans Magn 2014;50:1–10.
[75] Kim K-C, Lee J. The dynamic analysis of a spoke-type permanent magnet generator with large overhang. IEEE Trans Magn 2005;41:3805–7.
[76] Kakihara W, Takemoto M, Ogasawara S. Rotor structure in 50 kW spoke-type interior permanent magnet synchronous motor with ferrite permanent magnets for automotive applications. In: energy conversion Congress and exposition (ECCE). IEEE; 2013. p. 606–13. 2013.
[77] Atallah K, Wang J. A rotor with axially and circumferentially magnetized permanent magnets. IEEE Trans Magn 2012;48:3230–3.
[78] Matsuhashi D, Matsuo K, Okitsu T, Ashikaga T, Mizuno T. Comparison study of various motors for EVs and the potentiality of a ferrite magnet motor. In: Power electronics conference (IPEC-Hiroshima 2014 - ECCE-ASIA), 2014 International; 2014. p. 1886–91.
[79] Ohira S, Hasegawa N, Miki I, Matsuhashi D, Okitsu T. Torque characteristics of IPMSM with spoke and axial type magnets. In: Power electronics, electrical drives, Automation and motion (SPEEDAM), 2012 International Symposium on; 2012. p. 818–21.
[80] Seo I-M, Kim H-K, Hur J. Design and analysis of modified spoke type BLDC motor using a ferrite permanent-magnet. In: Electrical Machines and Systems (ICEMS), 2014 17th International Conference on; 2014. p. 1701–5.
[81] Kim H-W, Kim K-T, Jo Y-S, Hur J. Optimization methods of torque density for developing the neodymium free SPOKE-type BLDC motor. IEEE Trans Magn 2013;49:2173–6.
[82] Kim H-W, Kim K-T, Kim B-W, Hur J, Jo Y-S. Design of new spoke type brushless DC motor for neodymium permanent magnet free. In: Vehicle Power and propulsion conference (VPPC), 2012. IEEE; 2012. p. 133–7.
[83] Rahman MM, Kim K-T, Hur J. Design and optimization of neodymium-free SPOKE-type motor with segmented wing-shaped PM. IEEE Trans Magn 2014;50:865–8.
[84] Rahman MM, Kim K-T, Hur J. Design and analysis of neodymium free SPOKE-type motor with segmented wing shape permanent-magnet for concentrating flux density. In: Energy Conversion Congress and exposition (ECCE), 2013. IEEE; 2013. p. 4991–7.
[85] Kondo K, Kusase S, Maekawa T, Hanada K. A new PM-assisted synchronous reluctance motor with three-dimensional trench air gap. IEEE Trans Ind Appl 2014;50:2485–92.
[86] Kim S-I, Cho J, Park S, Park T, Lim S. Characteristics comparison of a conventional and modified spoke-type ferrite magnet motor for traction drives of low-speed electric vehicles. IEEE Trans Ind Appl 2013;49:2516–23.
[87] Kim S-I, Park S, Park T, Cho J, Kim W, Lim S. Investigation and experimental verification of a novel spoke-type ferrite-magnet motor for electric-vehicle traction drive applications. IEEE Trans Ind Electron 2014;61:5763–70.
[88] Xia B, fei w, Luk PCK, Wu D. Design of a multi-layer interior ferrite permanent magnet synchronous machine for traction applications. In: Power electronics, Machines and drives (PEMD 2014), 7th IET International conference on; 2014. p. 1–6.
[89] Fei W, Liang W, Luk PC-K. Influence of magnet layer number on electromagnetic performance of ferrite interior permanent magnet synchronous machine. In: Electrical Machines and Systems (ICEMS), 2014 17th International Conference on; 2014. p. 1–7.
[90] Dorrell DG, Hsieh M-F, Knight AM. Alternative rotor designs for high performance brushless permanent magnet machines for hybrid electric vehicles. IEEE Trans Magn 2012;48:835–8.
[91] Lee B, Kang G-H, Hur J, You D-W. Design of spoke type BLDC motors with high power density for traction applications. In: Industry applications conference, 2004. 39th IAS annual meeting. Conference record of the 2004 IEEE, vol. 2; 2004. p. 1068–74. vol. 2.
[92] Kang G-H, Hur J, Sung H-G, Hong J-P. Optimal design of spoke type BLDC motor considering irreversible demagnetization of permanent magnet. In: Electrical Machines and systems, 2003. ICEMS 2003, vol. 1. Sixth International Conference on; 2003. p. 234–7. vol. 1.
[93] Yamada A, Miki I. Novel rotor structure of permanent magnet synchronous motor with rare earth and ferrite magnets. In: Power electronics, electrical drives, Automation and motion (SPEEDAM), 2014 International Symposium on; 2014. p. 1–5.
[94] Yamada A, Miki I. New permanent magnet synchronous motor with reduced rare earth magnets. In: Electrical Machines and Systems (ICEMS), 2014 17th International Conference on; 2014. p. 391–6.
[95] Gazdac AM, Martis CS, Mabwe AM, Biro K. Analysis of material influence on the performance of the dual-rotor permanent magnet induction machine. In: Optimization of Electrical and electronic equipment (OPTIM), 2012 13th

International Conference on; 2012. p. 453–9.
[96] Qu R, Lipo TA. Dual-rotor, radial-flux, toroidally wound, permanent-magnet machines. IEEE Trans Ind Appl 2003;39:1665–73.
[97] Leonardi F, Matsuo T, Li Y, Lipo TA, McCleer P. Design considerations and test results for a doubly salient PM motor with flux control. In: Industry applications conference, 1996. Thirty-first IAS annual meeting, IAS '96., conference record of the 1996 IEEE, vol. 1; 1996. p. 458–63. vol. 1.
[98] Hua W, Zhang G, Cheng M. Flux-regulation theories and principles of hybrid-excited flux-switching machines. IEEE Trans Ind Electron 2015;62:5359–69.
[99] Kurihara K, Kubota T, Shimazaki M, Nakamura T. EMF and efficiency measurements of a novel self-excited reluctance generator. In: Electric machines & drives conference (IEMDC), 2011 IEEE International; 2011. p. 1195–200.
[100] Afinowi IAA, Zhu ZQ, Guan Y, Mipo JC, Farah P. Performance analysis of switched-flux machines with hybrid NdFeB and ferrite magnets. In: Electrical Machines and Systems (ICEMS), 2014 17th International Conference on; 2014. p. 3110–6.
[101] Hoang E, Gabsi M, Lecrivain M, Multon B. Influence of magnetic losses on maximum power limits of synchronous permanent magnet drives in flux-weakening mode. In: Industry applications conference, 2000. Conference record of the 2000 IEEE, vol. 1; 2000. p. 299–303. vol. 1.
[102] Zhang J, Cheng M, Feng X. Design and comparison of wind power permanent magnet generator with doubly salient structure and full pitched windings. In: Electric utility Deregulation and Restructuring and power technologies (DRPT), 2011 4th International Conference on; 2011. p. 1329–34.
[103] Kuroda Y, Morita M, Hazeyama M, Azuma M, Inoue M. Improvement of a claw pole motor using additional ferrite magnets for hybrid electric vehicles. In: Electrical machines (ICEM), 2010 XIX International conference on; 2010. p. 1–3.
[104] Azuma M, Morita M, Hazeyama M, Kuroda Y, Daikoku A, Inoue M. Fundamental characteristics of a claw pole motor using additional ferrite magnets for HEV. In: Electric vehicle conference (IEVC), 2012 IEEE International; 2012. p. 1–4.
[105] Binns KJ, Low T-S. Performance and application of multistacked imbricated permanent magnet generators. IEE Proc B Elec Power Appl 1983;130:407–14.
[106] Brockerhoff P, Burkhardt Y, Ehlgen T, Lucas P. Electrical drivetrain without rare earth magnets and integrated inverter with inherent redundancy. In: Electric drives production conference (EDPC), 2013 3rd International; 2013. p. 1–7.
[107] Wang Z, Masaki R, Morinaga S, Enomoto Y, Itabashi H, Ito M, Tanigawa S. Development of an axial gap motor with amorphous metal cores. IEEE Trans Ind Appl 2011;47:1293–9.
[108] Zhao W, Lipo TA, Kwon B. Design and analysis of a novel dual stator axial flux spoke-type ferrite permanent magnet machine. In: Industrial electronics society, IECON 2013 - 39th annual Conference of the IEEE; 2013. p. 2714–9.
[109] Chiba K, Chino S, Takemoto M, Ogasawara S. Fundamental analysis for a ferrite permanent magnet axial gap motor with coreless rotor structure. In: Electrical Machines and Systems (ICEMS), 2012 15th International Conference on; 2012. p. 1–6.
[110] Sone K, Takemoto M, Ogasawara S, Takezaki K, Hino W. Consideration of 10kW in-wheel type axial-gap motor using ferrite permanent magnets. In: Power electronics conference (IPEC-Hiroshima 2014 - ECCE-ASIA), 2014 International; 2014. p. 3525–31.
[111] Sone K, Ogasawara S, Takezaki K, Hino W. Operation characteristics of ferrite permanent magnet in-wheel axial-gap motor with coreless rotor structure for electric city commuters. Mc. of 10kW in-wheel type axial-gap motor using ferrite permanent magnets Takemoto. In: Energy Conversion congress and exposition (ECCE), 2013. IEEE; 2013. p. 3186–93.
[112] Miura T, Chino S, Takemoto M, Ogasawara S, Chiba A, Hoshi N. A ferrite permanent magnet axial gap motor with segmented rotor structure for the next generation hybrid vehicle. In: Electrical machines (ICEM), 2010 XIX International Conference on; 2010. p. 1–6.
[113] Chino S, Ogasawara S, Miura T, Chiba A, Takemoto M, Hoshi N. Fundamental characteristics of a ferrite permanent magnet axial gap motor with segmented rotor structure for the hybrid electric vehicle. In: Energy Conversion Congress and exposition (ECCE), 2011. IEEE; 2011. p. 2805–11.
[114] Hosoya R, Shimada H, Shimomura S. Design of a ferrite magnet vernier machine for an in-wheel machine. In: Energy Conversion Congress and exposition (ECCE), 2011. IEEE; 2011. p. 2790–7.
[115] Sato K, Hosoya R, Shimomura S. Improved ferrite magnet vernier machine for an in-wheel machine. In: Power and energy (PECon), 2012 IEEE International conference on; 2012. p. 414–9.
[116] Vartanian R, Deshpande Y, Toliyat HA. Performance analysis of a ferrite based fractional horsepower permanent magnet assisted SynRM for fan and pump applications. In: Electric machines & drives conference (IEMDC), 2013. IEEE International; 2013. p. 1405–10.