Overview of inner rotor radial permanent magnet machines for electric vehicles

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Abstract. Nowadays, there is fast growing interest in electric vehicles from automakers, governments and customers due to increasing concern of our environment. This paper presents an overview of various inner rotor radial permanent magnet electric machines for application to electric vehicles (EVs). First of all, the classification and brief introduction of radial permanent magnet machines are presented. The key features of the machines, including the advantages and disadvantages of the machines are summarized. Furthermore, the latest development of the machines is also reviewed. Then, the structure of viable electric machines that have been applied to electric vehicles, including radial permanent magnet synchronous machines (PMSM), switched reluctance (SRM), interior permanent magnet (IPM) and flux switching machines (FSM) types are being reviewed.

1. Introduction
Nowadays, dominance of permanent magnet machines become more due to its cost affordability of high energy permanent magnets. These machines offer many exclusive topographies. Due to the fact that field excitation losses are eliminated, subsequently reduces the rotor loss reduction makes them more efficient. Hence increases the motor efficiency improved greatly and higher power density is achieved. Besides that, small thickness of magnets results small magnet dimensions [1,2].

Even though, in 1830s PM excitation system was been introduced to electrical machines, but it was unfavorable to employ on machines due to low quality of hard magnet materials. Later, PM excitation system have regained interest of researcher with the discovery of Alnico in 1931, barium ferrite in 1950s and particularly rare-earth neodymium-iron-boron (NdFeB) material in 1983. The accessibility of high energy PM materials (especially rare earth PMs) are the main source of power for utilization of novel topologies of PM machines, thus AFPM machines defibrillated. With the availability of more affordable PM materials, radial permanent magnet and AFPM machines may play a more important role in the near future [3,4].

The structure of a PM machine gives superiorities for the control of their speed and position. Indeed, the armature field can be accurately controlled, and it tends to be constantly synchronized with the rotor. Therefore, it winds up advantageous to execute exact position control and speed on PM machines. A few structure sorts of synchronous PM machines are conceivable. Certainly, these verities are associated with magnets and their arrangements at the rotor. The rare earth Neodymium-iron-boron (NdFeB) magnets, which have the largest flux densities among the PMs can provide the best magnetic
force performance compared to those made by conventional magnets [5-7]. Depending on the magnet topology in rotor, PM machines can be classified in terms of the magnetization patterns such as radial flux, axial flux, radial-axial and circumferential flux machines [8,9]. While the PMs are arranged in the inner cylinder on the rotor unit in the radial flux machines, so that the torque is produced from magnetic flux that is perpendicular to the rotor shaft, the magnets are arranged on a disk, so that the magnetic flux flowing parallel to the shaft produces the torque in the axial flux machine [10-14].

Most of the PM motors are of radial-flux type commonly. It is due to the fabrication is upfront and conventional, using slotted stators with standard round radial laminations, and the electrical loading can be maximized because of the use of the slots [15]. Permanent magnet is used as an excitation source in motors as well as generators. However permanent magnet machines have many magnetization patterns such as radial, axial and combined radial and axial flux permanent magnet machines. In this paper, the influence of different magnetization patterns in the performance of three-phase permanent magnet machines has been investigated.

This paper focuses on the PM machines with radial magnetization pattern. Furthermore, PM machines are classified based on structure such as inner rotor, outer rotor, dual rotor and dual stator. Figure 1 illustrates the classification of the main types of electric machines [16-20].

![Figure 1. The classification of PMSM](image)

2. Inner Radial permanent magnet machines
The first radial flux machines were discovered in 1837 and since then used most extensively. In radial configuration the magnetic flux flows perpendicular to the direction of the rotor rotation, that either can be external or internal. It’s used widespread because of the constructive features, especially stator lamination topology is less expensive [21]. Radial magnetization pattern is used in motors as well as generators.

2.1. Structure Review of Inner Permanent Magnet Synchronous machines (PMSM)
Radial magnetization pattern can used applied to the permanent magnet motors, motors are in different size and shapes for the different applications. In this section different kind of PM motors will be reviewed.
In order to attain control on radial force of multisector permanent magnet (MSPM) machine a spatial distribution of the winding set within the stator [22]. A substitute force control method for MSPM machines is presented as shown in Figure 2. An alternate radial force and torque control is utilized to a multisector PM motor consisting in conventional 18 slots-six poles in a winding configuration of surface mounted PMSM. The control of x-y forces and torque over each sector independently permits through distribution of three windings. The modelling and characterization of the MSPM machine is developed in combination with the force/torque control technique.

In article [23], the general expression of the frequency and corresponding mode number of radial force harmonics is formulated. The lowest mode number of radial force harmonics is obtained. The respective radial forces of three motors, with slot/pole 24/8, 12/8, and 12/10, the cross section and structure parameters of which are shown in Figure 3 and Figure 4. In the next step, a weak-coupling electromagnetic-structure FEM is introduced. The electromagnetic vibration induced by electromagnetic force is predicted.

Nowadays, in high power electric vehicles such as trucks and mountain sport vehicles modular permanent magnet synchronous machines (PMSMs) have used extensively. Meanwhile high torque density, high reliability, low noise and vibrations are the advantages over conventional PMFM.
[24], the 16P/24S modular motor has been studied, the performance of the modular three phase permanent magnet synchronous machine based on radial force and vibration under two phase open circuit faults as shown in Figure 5. First, the formula for the armature magnetomotive force are derived in a normal and faulty conditions. Therefore, the analysis of air-gap magnetic field and radial force density are observed theoretically. Second, finite element simulation of four-unit modular machine has been verified the theoretical analysis. from the results it is analysed that asymmetrical fault conveys larger and richer low frequency harmonics. Particularly $2f$, $4f$, and $6f$, and thus results in more vibration that validated the experiments of similar sized modular motor.

2.2. Structure Review of Inner Permanent Magnet Switch Reluctance machines (SRM)

In [25], it is studies that the switched reluctance motor (SRM) has an outstanding performance in appropriate circumstances due to the intrinsic fault tolerance, robustness and strength of sustaining the intense temperature variations. Additionally, the individuality features of SRM being as a bearing less motor because of magnetic attraction force between the rotor and stator poles is in the radial direction. In order to overcome coupling issue between torque and suspending force control in the conventional bearing less SRM a novel bearing less SRM biased permanent magnet is introduced as shown in Figure 6.

The arrangement of two thin permanent magnets have been placed in each stator pole in such a way that permanent magnets are magnetized in line with each stator pole winding polarity as shown in Figure 7. The four corresponding permanent magnets should match coils with respect to flux direction
during the phase excitation. Thus, the flux cancellation occurs partially in other phases as shaded in the figure (position “A”) between the energized winding and permanent magnet of phase B owing to share of stator back iron as a flux path in two-phase 4/2 SRM. Likewise, 4/2 SRM, conventional SRM gives flux a big bottleneck in raising power density by employing permanent magnet into the magnetic structure [26].

In accordance with 4/2 SRM, the two permanent magnets of two phase 8/10 SRM in every stator excitation pole and four loops in Figure 8 are signified with flux paths while two phases flux path excited separately. It is clear that permanent magnet suppressed in the stator poles of phase A, to generate magnetic field in line direction of the coils of identical phase, however, unlike in 4/2 SRM the other flux paths parted from the other phase. Therefore, the additional permanent magnets inside stator excitation pole boosts the power density of the proposed structure due to the independent production of the flux between the phases. Subsequently no flux cancellation at all [26].

The cross-sectional view of the two-phase E-core SRM as shown in Figure 9. There are two E-shaped stators cores in which phase coils are wound on small pole concentrically at the end and no winding in between the two large common poles. By amending the stator pole pitch numerous rotor poles can be feasible. In order to generate the positive torque at each rotor position, the rotor pole surfaces are made asymmetrically shaped. Thus, it generates a non-uniform airgap between stator and rotor poles [27,28].

2.3. Structure Review of Interior Permanent Magnet machines (IPM)

![Figure 10. 12-pole IPM machine [29]](image)

![Figure 11. Cross sectional view of a motor. (a) line-start IPM. (b) RF-hysteresis IPM [30]](image)

![Figure 12. Conventional IPM [31]](image)

![Figure 13. IPM motor](image)
In [29] the author examined the mechanical design issues of conventionally (also referred to as transverse or radially) laminated IPM rotors as shown in Figure 10. Only the centrifugal force is considered as this is likely the dominant source of mechanical stress in high speed designs. Each of several key rotor design features are examined in turn with respect to their influence on the rotor stress state and electromagnetic performance. Because of the high torque, smaller size, higher efficiency and power factor of the self-start interior permanent magnet (IPM) motor is probably replaceable of the conventional induction motor. In Figure 11, a novel self-starts radial flux hysteresis 1-HP three phase 4 Pole IPM motor is introduced by uniting the benefits of hysteresis and permanent magnet motors. For the applications of high-speed sensor makes the RF-hysteresis IPM motor an appropriate applicant because of the availability of self-starting and active stabilization. Though, torque ripples and total harmonic distortion are not been considered to minimization. Finite element analysis tool has been executed to design and analysis the performance of 3 phase 4 pole 1 HP RF hysteresis IPM motor. From the analysis it is observed that IPM motor has better self-starting and synchronization competences compared to same rated cage-equipped and CF-hysteresis IPM motors. Designed RF-hysteresis IPM motor is also compared with 1- HP circumferential flux type hysteresis and caged equipped IPM motors. After found on analysis and simulation, RF hysteresis IPM motor demonstrates a high self-starting capability [30].

Figure 12 shows the conventional interior permanent magnet (IPM) motor, which adopts distributed winding. It can be seen the rotor contains thick and wide arc-shaped PMs with radial polarization to produce large torque. However, the large PMs will lead to the relatively smaller L_d. Meanwhile, the iron q-axis path contributes to the large L_q. Thus, L_q is greater than L_d, which is a typical characteristic of conventional IPM motor [31].

The key point of the IPM design is the minimization of the d-axis inductance. To this aim, a multiple barrier rotor structure was chosen, as shown in Figure 13 (right). Moreover, to reduce torque ripple and high-speed losses the combination 24/20 of stator and rotor slots per pole pair was conveniently chosen. The PM flux was designed according to (9): thus the overload curve is not exactly flat in this case, as previously discussed.

2.4. Structure Review of Flux Switching Permanent Magnet machines (FSM)

![Figure 14. PMFSM configuration [32]](image)

![Figure 15. Single-phase 4S/8P PMFSM [32]](image)
Over the past decade, flux switching machines (FSMs) have gained a lot of focus of researchers and cross over the brushless machines for deliberation of same application. In FSM, all the excitation sources, even magnets producing sources are on stator which gives more advantages in assembly, cooling and preservation of magnets. However, many different combinations of primary excitation in the stator has been discovered. Just as armature winding, PMs and hybrid combination of windings and PMs.

In [32], the new design of 12S-8P flux switching using segmental rotor with PM as primary excitation is introduced as shown in Figure 14. The design and experimental three-phase synchronous PMFSM with segmental rotor have been employed by the author. No load and load characterized for analyzing the performance of motor. From the simulation and experimental results, it is observed that the segmented rotor motor with PM excitation can accomplish approximately twice of torque of same sized segmented rotor motor with a DC field excitation.

In [33], single-phase PMFSM is 4S/8P, designed for high torque density applications shown in Figure 15 is documented. The motor consists of concentrated winding with low PM volume inserted between stator teeth. The motor has advantages of low cost, high flux linkage and low winding loss. However, disadvantages of the motor are high cogging torque, high induced back-emf and large slot area as torque of the motor is dependent on high electrical loading.

In a conventional doubly salient pole PMFSM, the slot area of the stator is reduced by placing both the armature conductor and the PM on it and the PM is sandwiched between stator teeth as shown in Figure 16. If the PM volume is large, it may always increase the eddy current loss, hence the necessity to reduce PM usage by employing stator segmentation designs such as C-core, E-core and multi-tooth and multi-PMs as discussed in [33,34]. In the three-phase 12S/10P PMFSM, both the armature coil and many PMs are located on the stator. Normally, they will reduce the area of slot, but employing C-core stator laminated module with the PM sandwiched between the stator helps to increase the slot area while the PM volume is reduced as designed in [35] and shown in Figure 17. In this arrangement, less stator material and PM volume have been used for a high output torque.

3. Conclusion

In this paper a comprehensive review highlighting design structure of inner radial permanent magnet machines, its advantages and drawbacks of each topology as well as recent trends in incorporating PMs in the motor design to boost the overall performance of motor. From the review its concluded that all the motors are useful to use for electric vehicles. Since flux switching machines have all active parts on stator core, which makes them a better candidate because of high torque and less losses compared to others.
4. References

[1] Borisavljevic A 2012 *Limits, modelling and design of high-speed permanent magnet machines* (Springer Science & Business Media)

[2] Aydin M, Huang S and Lipo T A 2004 *Conf. Record of Speedam(USA)* pp 61-71

[3] Gieras J F, Wang R J and Kamper M J 2008 *Axial flux permanent magnet brushless machines* (Springer: Dordrecht).

[4] Mesquita M M G 2012 *Winding losses calculation for a 10 MW ironless-stator axial flux permanent magnet generator for offshore wind power plant* (Technical University of Lisbon: Master’s Thesis)

[5] Collocott S J, Dunlop J B, Gwan P B, Kalan B A, Lovatt H C, Wu W and Watterson P 2004 *China Magnet Symposium (China)* pp 1-17

[6] Jahns T 2017 *IEEE Electrification Magazine* 5 6-18

[7] Qiao Z, Pan S, Xiong J, Cheng L, Lin P and Luo J 2017 *J. Elect. Materials* 46 660-7

[8] Cavagnino A, Lazzari M, Profumo F and Tenconi A 2002 *IEEE Trans. Ind. Applications* 38 1517-24

[9] Arslan S and kurt E 2017 *European Conference on Renewable Energy Systems (Bosnia-Herzegovina)* pp 1- 9.

[10] Zhao C and Zhu H 2017 *IEEE Trans. Ind. Electron.* 64 6127-36

[11] Faiz J, Valipour Z, Shokri-Kojouri M and Khan M A 2016 *2nd Int. Conf on Intelligent Energy and Power Systems (USA)* pp 1-7

[12] Park H J, Woo D K, Jung S Y and Jung H K 2016 *IEEE Int. Conf. on Electrical Machines and Systems (Chiba, Japan)* pp 1-4.

[13] Virtič P, Vražič M and Papa G *IEEE Trans. Energy Convers.* 31 150-158

[14] Hemeida A, Taha M, Abdallah A A E, Vansompel H, Dupré L and Sergeant P 2017 *IEEE Trans. Energy Convers.* 32 111-121

[15] Dorrell D G, Hsieh M F, Popescu M, Evans L, Staton D A and Grout V 2011 *IEEE Trans. Ind. Electron.* 58 3741-57

[16] Tang Y, Paulides J J H, Motoasca T E and Lomonova E A 2012 *IEEE Trans. Magn.* 48 3583-86

[17] Pollock C, Pollock H, Barron R, Coles J R, Moule D, Court A and Sutton R 2006 *IEEE Trans. Ind. Applications* 42 1177-84

[18] Zhou Y J and Zha Z Q 2014 *IEEE Trans. Ind. Applications* 50 3335-45

[19] Zhou Y J and Zha Z Q 2013 *IEEE Energy Conversion Congress and Exposition (Colorado, USA)* pp 904-911.

[20] Chau K T, Chan C C and Liu C 2008 *IEEE Trans. Ind. Electron.* 55 2246-57

[21] Lee D H, Pham T H and Ahn J W 2012 *IEEE Trans. Ind. Electron.* 60 3637-43

[22] Valente G, Papini L, Formentini A, Gerada, C and Zanchetta P 2017 *IEEE Trans. Ind. Electron.* 65 5395-5405

[23] Yang H and Chen Y 2013 *IEEE Trans. Energy Convers.* 29 38-45

[24] Song Z, Yu Y, Chai F and Tang Y 2018 *IEEE Trans. Magn.* 54 1-5.

[25] Wang H, Liu J, Bao J and Xue B 2014 *IEEE Trans. Ind. Applications* 61 6947-55

[26] Lee C and Krishnan R 2009 *IEEE Trans. Ind. Applications* 45 1804-14

[27] Krishnan R Lobo N S *Apparatus and method that prevent flux reversal in the stator backmaterial of a two-phase SRM.* U.S. Patent 7 015 615, March 21, 2006

[28] Oh S G and Krishnan R 2007 *IEEE Trans. Ind. Applications* 43 1247-57

[29] Lovelace E C, Jahns T M, Keim T A and Lang J H 2004 *IEEE Trans. Ind. Applications* 40 806-812

[30] Rabbi S F, Zhou P and Rahman M A 2017 *IEEE Trans. Magn.* 53 1-4

[31] Yang S, Zhu X, Xiang Z, Fan D, Wu W and Yin J 2017 *AIP Advances* 7 1-6

[32] Zulu A, Mecrow B C and Armstrong M 2012 *IEEE Trans. Ind. Applications* 48 2259-67.
[33] Jusoh L I, Erwan S, Kumar R, Bahrim F S and Omar M F 2017 *Int. J. Appl. Eng. Res.* **12** 1377-82

[34] Andre N, Sami H, Mohamed G, Mathieu M and Didier L 2017 *Int. Conf. on Electric Machines and Drives (Miami USA)* pp 1-8

[35] Zhu Z Q and Chen J T 2010 *IEEE Trans. Magn.* **46** 1447-53

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