An Innovative Hybrid-Excited Multi-Tooth Switched Reluctance Motor for Torque Enhancement

Ehsan Farmahini Farahani, Mohammad Amin Jalali Kondelaji, and Mojtaba Mirsalim, *Senior Member, IEEE*

***Abstract*—Permanent magnets (PMs) have been widely used in different types of electrical machines to improve their performance. This article introduces a novel multi-tooth hybrid-excited switched reluctance motor (MT-HESRM) with PMs placed between the end teeth of the adjacent modules. Thanks to the innovative method of embedding PMs, a unique design is developed. First, the operating principle of the motor is explained, and the magnetic circuit model of the motor is analyzed. The magnetic characteristics in terms of flux density, flux linkage, inductance, and torque are obtained and compared with those of its PM-less counterpart. The mathematical model of the reluctance and PM torques is presented. The reluctance and PM torques are decoupled using the finite-element analysis, and the torque contribution of the PMs is discussed. The steady-state operations of both motors with both current chopping and single-pulse controls are analyzed and compared under different speeds. Finally, both motors are manufactured, the laboratory tests are done, and the experimental results are extracted. Both the simulation and test results elucidate that the MT-HESRM, which has only three small PMs as auxiliary flux sources, has unique features in terms of high output power and torque with a negligible cogging torque.**

***Index Terms*—Hybrid excitation, multi-tooth structure, permanent magnets (PMs), switched reluctance motor (SRM).**

I. Introduction

RECENT advances in strong rare-earth neodymium and samarium cobalt permanent magnets (PMs) have provided opportunities to improve the performance of electrical machines for applications with high-efficiency high-power-density requirements. The PMs can be inserted either in the stator or the rotor to excite the magnetic field. Recently, electrical motors having PMs in the stator have been of high potential due to good heat management and robust rotor structure, since all the excitations are stationary [1], [2]. According to different locating positions of PMs, stator-excited PM motors can be categorized into three types, namely, flux reversal PM motors having PMs surface mounted on stator poles, flux-switching PM (FSPM) motors with PMs sandwiched in stator poles, and doubly salient PM (DSPM) motors, which have PMs inserted in the stator yoke [3]. As another promising candidate, switched reluctance motors (SRMs) have gained popularity for a broad variety of industrial applications, including electric propulsion, renewable energy harvesting, and electric vehicles, to name a few [4], [5]. This type of electric motor offers distinguished advantages in terms of robustness, simple manufacturing process, low cost, high-speed applicability, and reliability [6]. Nevertheless, its drawbacks, especially low power and torque densities, cannot be easily overlooked.

Structurally, both the rotor and the stator have salient poles in SRMs, and the only flux sources are the concentrated windings on the stator poles. Compared to the PM motors, conventional forms of SRMs lack high torque and power densities. Such an issue encourages the employment of auxiliary flux sources (dc windings or PMs) to ameliorate the torque and power densities. To the best of our knowledge, there were a limited number of methods to embed PMs or auxiliary windings in the structure of SRMs in the literature reports. In [7], a hybrid switched reluctance motor (HSRM) is proposed. This structure has PMs in opposition and parallel with the coils and produces an augmented torque because of the field contribution of the PMs. In [8], a new single-phase HSRM with both reluctance and PM interaction torque is introduced, which has an increased torque density along with lower torque ripple compared to a classical single-phase SRM. Lu *et al.* [9] propose a single-phase HSRM with a π-shaped arrangement of ferrite PMs to enhance the torque density. In [10], an SRM with both auxiliary windings and PMs in the stator yoke is designed and constructed. The results show that there is a significant increase in the torque and efficiency. A modular SRM with the A-type stator design is proposed in [11], which has PMs in the stator back iron. It is demonstrated that the torque ripple is reduced. In [12], the authors develop a 6/5-pole modular HSRM with PMs disposed between the two poles of each module. The results indicate that the HSRM has higher torque than the conventional 6/4 and 12/8 SRMs with no cogging torque. In [13]–[15], a 12/8-pole high-torque HSRM is proposed based on the method presented in [12]. It is shown that the HSRM

Manuscript received June 30, 2019; revised September 30, 2019 and December 8, 2019; accepted January 11, 2020. Date of publication January 29, 2020; date of current version October 30, 2020. *(Corresponding author: Ehsan Farmahini Farahani.)*

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Digital Object Identifier 10.1109/TIE.2020.2969073

A New Exterior-Rotor Multiple Teeth Switched Reluctance Motor With Embedded Permanent Magnets for Torque Enhancement

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In this article, a novel exterior-rotor multiple teeth enhanced-torque switched reluctance motor (SRM) is proposed, which exploits permanent magnets (PMs) inside the end teeth of the neighboring stator poles. First, the topology of the proposed motor, namely PM-SRM, is introduced and its working principle is illustrated. Then, based on the magnetic equivalent circuit (MEC) of the motor, it is proven that the PMs contribute to increase the air-gap flux density and regulate the stator poles flux density. As a result, the output torque of the motor is increased as well. The electromagnetic analyses of the proposed PM-SRM are performed using 3-D finite-element analysis. To validate the improved performance of the proposed PM-SRM, it is compared with its PMless counterpart and a classical 12/10-pole SRM in terms of the output torque and power, losses, and efficiency. It is shown that the proposed motor outperforms the two compared motors in terms of the output power and torque, and efficiency. Finally, a prototype of the motor is fabricated and tested to evaluate the predicted results. Both simulation and experimental results demonstrate the high torque and power production capability of the proposed PM-SRM.

Index Terms—**Exterior rotor, multiple teeth structures, permanent magnet (PM), switched reluctance motor (SRM).**

I. Introduction

Switched reluctance motors (SRMs) outperform permanent-magnet (PM) machines in terms of cost, reliability, and robustness. However, they exhibit lower torque density than PM machines. Embedding PMs or dc windings in the structure of SRMs, which intensifies the air-gap flux density, can help to surmount this shortcoming. This simple, yet effective method leads to a new type of motors called PM-SRMs. PM-SRMs are structurally similar to flux-switching PM motors (FSPMs). In FSPMs, the PMs are embraced with sinusoidal-fed windings [1]–[3], while the PM-SRMs have PMs in a diversity of methods, in which the windings are excited with a switched dc voltage.

Several structures of PM-SRMs, in which the PMs are placed between the two poles of each C-shape module, are presented in the literature. The results of these studies show that all of the proposed motors produce much higher torque in comparison with their classical counterparts [4]–[6]. Kondelaji and Mirsalim [7] proposed a new double-stator SRM with PMs between the pole tips of the outer modules. It is shown that the proposed SRM offers higher torque than the classical SRMs. In [8], the PMs are embedded in the stator back iron, which leads to a noticeable increase in the output torque. In [9] and [10], a new PM-SRM with an E-core structure was proposed, in which the PMs are deployed inside the common poles of the stator. The results show that the output torque of the motor is higher than that of the conventional SRM with the same size. In [11], the PMs are parked between two adjacent poles of a divided teeth stator, which results in a significant enhancement in the output torque. Furthermore, in [12], the PMs and the auxiliary windings are employed together to enhance the torque density of the motor.

According to the proposed motors in the literature, it can be found that more research is required to propose new structures, which produce much higher torque utilizing lower PM volume. This article introduces a new 48/50-tooth exterior-rotor multiple teeth PM-SRM, in which the PMs are embedded between the end teeth of the neighboring stator poles. This efficacious structure leads to a dramatic increase in the output torque and power. The motor topology and its working principle are clarified based on the simplified magnetic equivalent circuit (MEC). The static and dynamic performances of the proposed motor are illustrated and the results are compared with those of its PMless counterpart and a classical 12/10 SRM. Finally, a prototype of the proposed motor is manufactured, and the test results are presented followed by a brief conclusion.

II. Structure Analysis

A. Motor Topology

Fig. 1 depicts the configuration of the proposed exterior-rotor PM-SRM with multiple teeth structures. The motor is composed of three phases, each of which has four concentrated windings. Each stator pole consists of four small teeth and the rotor comprises 50 teeth, so the motor has a 48/50-tooth configuration. Six PMs are embedded inside the gap between the end teeth of the neighboring stator poles, all of which have the same magnetization direction. Table I lists the main dimensions and parameters of the proposed PM-SRM, PMless SRM, and a classical external rotor 12/10-pole SRM.

B. Analysis of the Working Principle With MEC Model

Fig. 2 illustrates the flux flow patterns of the proposed PM-SRM. Under zero excitation current, the flux of the PMs

Manuscript received July 1, 2019; revised September 29, 2019; accepted November 10, 2019. Date of current version January 20, 2020. Corresponding author: E. Farmahini Farahani (e-mail: ehsanfarahani@aut.ac.ir).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TMAG.2019.2955884

IET Electric Power Applications

Research Article

Comprehensive study on divided-teeth and permanent magnet assisted outer-rotor switched reluctance motors

ISSN 1751-8660
Received on 16th March 2020
Revised 18th May 2020
Accepted on 5th August 2020
E-First on 17th September 2020
doi: 10.1049/iet-epa.2020.0189
www.ietdl.org

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Abstract: A comprehensive study on divided-teeth permanent-magnet assisted outer-rotor switched reluctance motors (SRMs) is carried out. Foremost, it looks into the impact of the number of teeth per stator pole. The average and maximum torque profiles of the compared structures are obtained using finite-element simulations. It is shown that as the number of teeth increases, higher torque is obtained. Then, six small PMs are inserted inside the teeth of neighbouring modules to form new hybrid reluctance motors (HRMs). The four permanent-magnet assisted SRMs are compared in terms of the average and maximum torques using finite-element simulations. Based on the comparison results, the 48/50 HRM is selected as the best candidate among all compared SRMs and HRMs. The magnetic flux density distributions, static torque, and flux linkage characteristics of the proposed HRM are obtained. Moreover, the cogging torque profile of the motor is obtained, which approximates to zero. Next, the steady-state performances of the proposed HRM are obtained under low- and high-operating speeds. Finally, a prototype of the machine is constructed and the test results are obtained and compared with those of the simulations, which show that there is a good agreement between these results.

1 Introduction

Nowadays, e-bikes are one of the most used vehicles for urban transportation, especially in crowded cities, where the shortage of parking areas and heavy traffic are the central problems. Using an e-bike is most common for short daily trips. Electrical motors are one of the main facilities of the e-bikes, which determine the power, torque, and speed of the bicycle. Furthermore, electrical motors have a major contribution in determining the price of e-bikes. Recently, switched reluctance motors (SRMs) have become one of the suitable candidates for this application due to their inherent advantages such as high reliability and robustness, low cost, high-speed capability, and simple manufacturing process. Nevertheless, the torque and power densities of these motors are not as high as the permanent magnet (PM) motors [1–4]. Lately, many types of research studies are carried out for the goal of increasing the output torque of SRMs and in this regard, several methods are introduced.

The first effective method is applying a modular structure, which results in an increment in the output torque of the motor. The main merit of a modular structure is the shorter flux path than the conventional structure. The shortened flux path leads to lower magnetomotive force drop and lower core losses. In [5], a modular stator 8/6 SRM is proposed, in which the stator is composed of eight C-type cores. The results show that the proposed motor offers better characteristics in terms of torque and efficiency in comparison with the conventional 8/6 SRM. In [6, 7], a novel 6/4 SRM with six modular E-type cores is proposed. Two different winding arrangements with single- and double-coil configurations are proposed and compared. It is illustrated that the proposed motor surpasses the classical 6/4 SRM in terms of torque and power densities and torque ripple. In [8, 9], a novel modular stator 16/14 SRM is introduced, in which the stator is created of eight separated C-type cores. The main advantage of this structure is its high torque density. Labak and Kar [10] proposed a new five-phase pancake shaped axial flux SRM with 15 independent C-type cores. It is evident from the results that the proposed motor produces higher torque due to its modular structure. In [11], a segmented rotor SRM is proposed, which has 12 stator poles and 26 segmented rotor poles. It is illustrated that the proposed motor produces higher torque than its conventional counterpart. In [12], a new 12/14 dual-stator SRM is proposed, which applies modular stator and segmented rotor. The results show that the proposed SRM can produce higher torque and lower torque ripple than its classical counterparts.

Applying PMs in the stator structure of SRMs is the second efficacious method for torque enhancement. In [13, 14], the authors have proposed a novel 12/16 E-core SRM with embedded PMs inside the common poles of the stator. It can be found from the results that the proposed motor produces higher torque than the conventional 8/6 SRM. In [15], a novel 6/10 PM-assisted SRM (PMSRM) is presented, in which PMs are inserted between adjacent stator poles of a divided teeth SRM. It is shown that the PMs lead to a significant increase in the flux density of the air-gap and consequently the average torque of the motor is increased. Andrada *et al*. [16] introduced a novel 6/5 PMSRM, which employs three PMs embedded between the poles of each phase. It is shown that the proposed motors have higher average torque than their conventional counterparts. A novel 12/8 PMSRM is presented in [17], in which PMs are employed between the two poles of each phase. It is illustrated that the proposed motor has better torque characteristics than its PM-less counterpart thanks to the air-gap flux density increment created by the embedded PMs. Additionally, in [18], Ding *et al*. have proposed another PMSRM with the same stator as in [17] but with a different number of rotor poles. The results show that the proposed 12/10 PMSRM outperforms the conventional SRM in terms of the average torque. In [19], a novel A-type PMSRM with implanted PMS inside the stator yoke is proposed. It is shown that this structure offers higher torque than the conventional structure.

Recent studies show that applying the outer rotor instead of the inner rotor will increase the output torque of the motor. In [20], a four-phase 16/20 outer-rotor SRM is proposed and optimised. It is shown that the proposed motor produces a high average torque for an in-wheel drive vehicle. A novel 6/10 external-rotor SRM is presented in [21] for the e-bike application. The results approved the suitability of the proposed structure for this application. Furthermore, another external-rotor SRM for electric vehicles with 18/12 configuration is proposed in [22].

Teethed-Pole Switched Reluctance Motors Assisted with Permanent Magnets: Analysis and Evaluation

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***Abstract*—In this paper, a new multi-tooth switched reluctance motor (MT-SRM) is proposed and then based on the original topology, three novel multi-tooth hybrid reluctance motors (MT-HRMs) are introduced to improve the torque characteristics of the SRM. The proposed structures are an MT-HRM with permanent magnets (PMs) between the side teeth of the adjacent modules, an MT-HRM with PMs in the yoke, and finally an MT-HRM with dual-PM configuration. The operating principles of the MT-HRMs are illustrated and the flux adjusting effect and outstanding torque production ability of the PMs are demonstrated through the theoretical and simulation results. The flux distributions and static torque and flux linkage profiles of the motors are obtained and compared. The four proposed motors are compared in terms of the steady-state current and torque waveforms. All the simulation results indicate that the PM-assisted structures can achieve higher torque and power than their PMless counterpart with deploying only three/six small PMs. The four motors are prototyped and the experimental results are carried out. Both the experimental and simulation results prove the effectiveness of the proposed MT-HRMs.**

***Index Terms*—High torque density, hybrid reluctance motor, multi-tooth structure, permanent magnets.**

I. Introduction

As a viable candidate for a diverse assortment of industrial applications, switched reluctance motor (SRM) performs satisfactorily in harsh environments owing to its incomparable rigidity and robustness [1]–[4]. Although this type of electric motor meets most of the requirements for industrial applications, it exhibits lower torque compared to the permanent magnet (PM) motors, which blocks its widespread utilization.

The literature reports on various techniques to enhance the torque characteristics of SRMs. One effective way to enhance the torque performance of SRMs is to optimize the structure of the motor. Different methods have been proposed in the literature to optimize the structure of SRMs. In [5], a 6/4 SRM is optimized using the orthogonal table method. The results show that the torque of the motor is increased compared to the initial design. The Taguchi method is used in [6] in order to optimize the structure of an 8/6 SRM. The results indicate that the torque of the motor is improved to a considerable extent. In [7], a multi-objective optimization is proposed using the particle swarm method which leads to an optimized structure that has an enhanced torque compared to the original design. Furthermore, in [8], the structure of an outer rotor SRM is optimized employing the Pareto-based multi-objective differential evolution algorithm, the results of which illustrated that the optimized motor has improved torque.

Another efficacious method is to employ segmented-rotor/stator structures [2], [9]. Employing divided teeth structures is another efficacious method for torque enhancement of SRMs. In [10], the authors proposed a new external-rotor E-core SRM with divided teeth. The results proved that the designed topology exhibits higher torque density than the classical SRMs. Reference [11] proposed a new DC-excited multi-tooth SRM. The results showed that the proposed machine has better torque performance and the acceptable noise effect. In [12], a new enhanced torque in-wheel SRM was proposed with divided teeth structure for EV applications. The results of this study proved that multi-tooth structures can enhance the output torque to a significant extent. A new multi-tooth outer rotor PM-SRM is proposed in [13], which has PMs between the teeth of the neighboring poles. The proposed motor exhibits high average torque compared to single-tooth SRM. Another key method for torque density enhancement of SRMs is to apply auxiliary flux sources; DC windings or PMs. Employing both of the auxiliary flux sources has been proven to be an efficacious technique to enhance the torque characteristics of SRMs to a considerable extent. But, the latter has become more attractive to the researchers since the former exhibits copper losses and increases the overall heat generation. The idea of applying PMs in the SRMs has combined the advantages of the classical SRMs and PM motors and introduced an improved type of reluctance motors, known as hybrid reluctance motors (HRMs). In [14], the authors proposed a new single-phase HRM, which uses both the reluctance and PM interaction torque. It was shown that the proposed HRM had higher torque density compared to the conventional single-phase SRM. In [15], another single-phase HRM with π-shaped arrangement of ferrite PMs was designed and constructed to improve the torque density. In [16], a new HR motor with employing both auxiliary windings and PMs inside the stator yoke was proposed with the aim of enhancing the torque characteristics. Reference [17] introduced a new high-torque HRM with A-type stator design, which had PMs in the stator back-iron. In [18], Andrada et al developed a modular HRM with three independent electromagnets and three PMs, each of which was located between the two poles of one electromagnet. The results indicated that the HRM produced higher torque than the conventional SRMs. In [19], an improved 12/8-pole modular-stator high-torque HRM was proposed inspired by the work of Andrada [18]. Additionally, this idea was generalized by the same authors to a 12/10-pole HRM [20]. The results of these researches signified

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Performance Analysis of a New Switched Reluctance Motor With Two Sets of Embedded Permanent Magnets

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***Abstract*—This article proposes an enhanced-torque switched reluctance motor with two sets of permanent magnets (PM-SRM) embedded inside the stator yoke and the end teeth of the neighboring modules. The PMs contribute to intensify the air-gap flux density and reduce the magnetic saturation in the stator poles. As a result, the output torque can be enhanced to a significant extent. The working principle of the proposed PM-SRM is clarified using its magnetic circuit model (MCM). The characteristics of the PM-SRM are obtained and compared with classical 12/8 and 6/5 SRMs and hybrid reluctance motors (HRMs) in terms of static and average torque and average torque per PMs volume. The steady-state performance of the PM-SRM in terms of current and torque waveforms is carried out, and the PM-SRM is compared with considered SRMs and HRMs in terms of output torque, power, and efficiency. All the comparisons demonstrate the out-performance of the proposed PM-SRM over other SRMs and HRMs. To validate the simulation results, a prototype of the PM-SRM is manufactured and the experimental results are obtained. Both the simulation and experimental results are indicative of the fact that the proposed PM-SRM can gain high torque and high PM utilization factor, simultaneously.**

***Index Terms*—High torque density, magnetic circuit model, permanent magnets, switched reluctance motor.**

I. Introduction

ELECTRICAL motors are one of the key devices in many industrial fields. In the recent decade, switched reluctance motors (SRMs) have been one of the outstanding candidates for numerous industrial applications owing to their advantageous features such as robustness, fault tolerance, low manufacturing cost, and high reliability [1]–[4]. In SRMs, both the rotor and stator have salient poles, and there are neither windings nor permanent magnets (PMs) on the rotor and the only flux sources are concentrated coils wrapped around the stator poles. Therefore, the main heat loss source is on the stator, which simplifies the cooling process. Nonetheless, it suffers from some inherent drawbacks such as low torque and power densities.

Manuscript received July 6, 2019; revised October 16, 2019; accepted December 28, 2019. Date of publication January 9, 2020; date of current version May 20, 2020. Paper no. TEC-00726-2019. *(Corresponding author: Ehsan Farmahini Farahani.)*

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Digital Object Identifier 10.1109/TEC.2020.2965180

Recently, different methods have been presented in the literature to improve the torque performance of SRMs. These methods include applying modular-stator structures [5]–[8], segmented rotor [9]–[11], and dual-stator/rotor configurations [12]–[14]. Another effective method for torque enhancement of SRMs is employing auxiliary flux sources (DC windings or PMs) on the stator, which enhances the torque density of SRMs. These types of SRMs not only have the advantages of the conventional SRMs, but also have high torque density and much lower cogging torque than the PM motors.

Different methods of embedding PMs in the structure of SRMs are presented in the literature. One method is to assist the PMs as auxiliary poles. This method is mostly used in single-phase SRMs, where auxiliary poles are required for self-starting capability. It also enhances the output torque and is cost-effective. However, it results in a high cogging torque. In [15], a new single-phase hybrid reluctance motor (HRM) is proposed, which exploits both the reluctance torque and the PM interaction torque. It is demonstrated that the proposed motor has higher torque density than the conventional single-phase SRM. However, the cogging torque is high. In [16], another single-phase HRM, topologically identical to the HRM in [15], with π-shape PM arrangement is suggested to improve the torque capability of the motor. However, it has a high cogging torque.

Another method is to employ both PMs and auxiliary windings. Although this method enhances the output torque, it increases the copper losses of the motor. In [17], an SRM with both auxiliary windings and PMs on the stator yoke is proposed. The results demonstrated that there is an increment in the output torque. However, the existence of the PMs leads to insufficient winding area, which restricts the torque density.

Another type of PM-SRMs is presented in recent studies, which exploits the PMs between the two poles of each phase. In this method, the PMs contribute to enhance the air-gap flux density, which results in higher torque. However, the available winding space is limited by the PMs. In [18], the authors proposed a novel modular 6/5 HRM with embedded PMs between the two poles of each phase and parallel to the phase winding. It was shown that the proposed motor has higher torque density compared to the classical SRM. In [19], a 12/8-pole modular-stator HRM is presented, where each module is structurally the same as [18]. The results indicated that the proposed motor has much higher torque and power densities in comparison with the conventional SRM. In [20], the authors designed a

Divided Teeth Switched Reluctance Motor with Different Tooth Combinations

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***Abstract*—In this article, three novel divided-teeth switched reluctance motors (SRMs) with 24/26, 36/38, and 48/50 tooth combinations are proposed. First, the topologies of the proposed SRMs are introduced. Next, the three divided teeth SRMs along with a conventional 12/10-pole SRM are simulated using a 2-dimensional finite element method (FEM) and the results are obtained and compared concerning distributions of magnetic flux density, flux linkage, static torque, and maximum and average torque. The results indicate that as the number of teeth augments, the output torque of the motor enhances. Hence, the 48/50-tooth SRM produces the largest average torque among all proposed motors, which may be selected as an appropriate choice for high-torque applications. Finally, the steady-state results of the 48/50 motor are obtained using a chopping current control (CCC) to illustrate the normal working of the machine.**

***Index Terms*—Divided teeth, finite element analysis, high torque, switched reluctance motor.**

I. Introduction

Switched reluctance motors (SRMs) are applied in a variety of the industry applications such as electric vehicles due to their notable advantages including low price, robustness, high-speed usage and reliability. However, SRMs suffer from some drawbacks including reduced power and torque densities in comparison with permanent magnet (PM) motors [1]–[5].

Recently, several methods are proposed to increase the average torque of SR motors. One efficient method is applying permanent magnets in the stator geometry of the SRMs. In [6], [7], the PMs are embedded in the common poles of an E-Core 12/16 SRM, which causes a high boost in the output torque of the proposed motor. In [8], [9], the PMs are placed between the two neighboring poles of the one module. The simulation results elucidate that the suggested motors produce much larger average torque than the conventional SRMs. In [10], the authors proposed an A-type SR motor, in which the permanent magnets are applied in the stator yoke and the simulation results show that the proposed motor has better torque characteristics in contrast to its conventional counterpart. The authors in [11] propose a new PM-SRM equipped with two layers of permanent magnets, which has enhanced torque and output power.

Another key method is using modular structures to increase the output torque of SRMs. Reference [12] proposed two 6/4 modular-stator SRMs, which offer larger average torque in comparison to the traditional SR motor. Additionally, in [13], a 6/5 SRM with C-shape core is proposed, that produces larger average torque than its counterparts. In [4], Szabo proposed a novel modular stator SRM that has eight independent cores. The provided simulation results demonstrated that the suggested motors offers more satisfactory torque performance as a result of its modular structure.

Employing double stator structure is another way to increase the output torque of SR motors as well. In [14], a novel double-stator SRM is presented, which produces larger average torque than the single-stator SRM. In [15], a new double stator 12/8 SRM is investigated and it is proven that the suggested motor delivers larger torque than its counterpart. The proposed motor in [16] is composed of tow inner and outer rotors. The results depict that the introduced topology has better torque characteristics than its single-rotor counterpart. Applying divided teeth structure is another technique to enhance the average torque of SRMs. In [17], a new outer-rotor E-core SR motor is proposed in which the common poles have dual-tooth structure and the results demonstrate that the suggested structure offers larger torque than the classical 12/8 SR motor. In [18], the authors proposed a new divided teeth SRM, in which each pole contains four teeth to enhance the average torque of the introduced structure. A 6/16 SRM is investigated in [19] in which each stator pole is divided into two teeth. It is displayed that the suggested motor offers larger static torque than the classic 6/8 and 6/10 SRMs. Moreover, in [20], a PM-assisted divided teeth 6/10 SRM is proposed and prototyped. It is shown that there is a noticeable increment in term of average torque in comparison to the conventional SRMs.

In this paper three novel divided teeth 24/26, 36/38, and 48/50 SRMs are proposed. The proposed motors are simulated using 2-D finite element method (FEM). To verify the outperformance of the suggested structures, the three proposed motors are compared with each other and a conventional 12/10 SR motor with an equal size and the results are obtained concerning magnetic flux density distribution, flux linkage, and static torque. The steady state results of the proposed 48/50 SRM are represented . Finally some conclusions are provided.

978-1-7281-5849-5/20/$31.00 ©2020 IEEE

A Comprehensive Analysis of an Axial Flux Switched Reluctance Motor with Different Number of Rotor Poles

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***Abstract*—In this paper, two 12/10 and 12/14 axial flux switched reluctance motors (AFSRMs) with the same stator and different number of rotor poles are proposed and compared with each other in terms of flux linkage, flux density distributions, and performance parameters such as static and dynamic torques. To make simulation results more effective, both structures are studied with the same physical parameters. The two proposed structures are simulated using 3D finite element analysis (FEA). The results show that the proposed 12/10 AFSRM outperforms the 12/14 AFSRM in term of average torque. For a better comparison, the steady state characteristics of both motors are obtained using current chopping control (CCC) mode and the results show that the proposed 12/10 AFSRM outperforms its 12/14 counterpart.**

***Index Terms*—switched reluctance motor, axial flux, high torque, finite element analysis**

I. Introduction

SRMs have turned into a worthy candidate for a lot of industrial applications like electric vehicles, aircraft starter/generators, and renewable energy harvesting due to the recent improvements of power electronics, new control techniques, and high-performance and low-cost controllers [1]–[6]. In SRMs, the concentric windings are mounted on the stator poles and there are neither windings nor PMs on the structure of thr rotor, which leads to several advantages like low manufacturing and maintenance costs, robustness, inherent fault tolerance, and high-speed capability. However, they suffer from some disadvantages in comparison to other type of machines, including high torque ripple and acoustic noise and low torque and power density [7], [8]. Much of the recent researches are concentrated to enhance the output torque of radial flux type SRMs and only a few works have been done in the field of axial flux machines [9]–[11]. In [9] a segmented rotor axial flux SRM is proposed for EV applications. The presented machine includes higher number of rotor segments than the stator slots which results in a significant increase in the torque density, winding overhang length reduction, better mechanical rigidity, and higher fault tolerant capability. The effect of the stator and rotor poles arcs in the output torque of a 12/8 pole axial flux SRM is investigated in [12], which has led to an optimized machine with reduced torque ripple.

In [13], a pancake shaped axial flux SRM is introduced and simulated for the EV applications. In this paper a new modified phase winding is proposed to reach a better efficiency and ruggedness and the results show the superiority of the proposed structure. In [14], a novel 12/15 radial field C-core SRM is proposed and the design procedure of the proposed motor is presented. It is shown that the proposed structure benefits from the advantages of both axial and radial field SRMs, which offers high output torque at low excitation currents. A novel axial flux SRM is proposed in [15]. The proposed structure is optimized using grain oriented electrical steel in order to improve the torque characteristics of the motor by taking advantages of the material's excellent magnetic properties in the rolling direction. This machine could be used in a lot of applications, which require high torque, such as in-wheel drive vehicles.

In this paper, two 3-phase AFSRM are presented. The stator of the both motors are the same but for evaluating the impact of the number of rotor poles in the output torque of the motor, two rotors with 10 and 12 poles are presented. A 3D finite element analysis(FEA) is applied to simulate the proposed motors. The static characteristics of the two motors are displayed and the flux density distribution, flux linkage, and torque of the two presented motors are compared. For a better comparison the average and maximum static torque values are compared

978-1-7281-5849-5/20/$31.00 ©2020 IEEE

A Preliminary Study on Flux-Boosted Enhanced-Torque Switched Reluctance Motors: Teethed-Pole and PM-Inserted Structures

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***Abstract*—This article proposes an innovative teethed-pole flux-boosted switched reluctance motor (SRM) with permanent magnets (PMs) inserted inside the stator back-iron and neighboring teeth. Both the yoke and the tooth magnets enhance the air-gap flux density significantly. However, the former lowers the saturation level in the stator back-iron and the latter decreases it inside the poles of stator. The proposed SR motor is defined and its basics of operation are delineated. To illustrate the efficacy of the PMs on the operation of the proposed SRM, simulations are carried out in terms of the distributions of flux density, flux linkage, and output torque adopting a two-dimensional finite element method (FEM). The results illustrate that the introduced dual-PM structure delivers higher torque than its PMless, tooth-PM, and yoke-PM counterparts. Furthermore, the reluctance and PM torques are segregated to reveal that the tooth PMs make more contribution in torque production than the yoke PMs.**

***Index Terms*—High torque, permanent magnet, switched reluctance motor, teethed-pole.**

I. Introduction

Electric vehicles (EVs) industry is growing rapidly due to the recent developments in power electronics, batteries, and electric motors. Among various types of electric motors, permanent magnet synchronous motors (PMSMs) exhibit unrivaled characteristics including low torque ripple, high torque density, and high efficiency [1, 2]. However, critical concerns regarding the cost of rare-earth PM material entail considerable efforts to diminish the PMs consumption in electric motors without sacrificing the performance. In this point of view, PMSMs are not suitable candidates for EV industry. Furthermore, having PMs on the rotor, restricts the speed range of these motors.

As a newly introduced promising candidate for vehicular technology, switched reluctance motors (SRMs) bring several advantages such as zero- or low-magnet structure and high-speed capability, which outweigh their two main drawbacks; low torque density and high torque ripple [3, 4, 5, 6, 7]. However, these drawbacks can be either reduced or removed by adopting new control techniques and employing new geometrical modifications.

The literature abounds with several key techniques to promote the operational features of SRMs. One prominent method is to assist Neodymium PMs as flux intensifiers in the stator [8, 9, 10, 11, 12, 13, 14, 15]. The PMs are supposed to intensify the air-gaps flux density without imposing any saturation on the steel lamination. To realize this potential, several reformed topologies are introduced in the literature.

Andrada et al. propose a C-core SR motor with permanent magnets mounted between the slot openings of the cores [8]. It is clarified that this structure can enhance the output torque. However, the winding space is sacrificed to such an extent that the torque production capability is capped. Inspired by the work of Andrada, improved structures of SRMs with different pole configurations are proposed in [9, 10, 16]. The results conclude that in comparison with the classical structures, the adopted method is capable of enhancing the output torque to a significant extent. Moreover, a new dual-stator SRM with high-torque capability is proposed in [11, 5], which applied the same method of [8].

In [12, 13], common-pole E-core SRMs are proposed with PMs inside the unwound poles. The output torque is increased, while the robustness is considerably suppressed. A novel boosted-torque SR motor with divided teeth topology is investigated in [14], which uses permanent magnets inside the neighboring poles of the modules. The flux adjusting ability of the PMs along with their flux intensifying role are analyzed. The results of this study elucidate the outperformance of the

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