

Analysis and Comparison Study of Novel Stator-Segmented Switched Reluctance Motor

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Abstract: This paper presents analysis and comparative study of a novel high-torque three-phase switched reluctance motor (SRM) with magnetically isolated stator segments. In the proposed SRM, each segment has a concentric winding located on the center body of it and two diametrically opposite windings which form the motor phase. There are four salient poles in the stator segment. Two of them share their flux path in the center body of the segment. The rotor has a solid structure including twenty two salient poles. In this unique SRM, stator segments topology, number of the stator segments poles and the rotor poles, and angular distance of the stator segments are selected so that the motor properly operates in both directions. Two-phase design with different pole combination is also possible. During operation, there are short flux paths along two adjacent rotor poles and excited segment poles. Therefore, the proposed SRM has all benefits of the short flux path structures. The principle and fundamentals of the proposed SRM design are detailed in the paper. The motor is analysed using finite element method (FEM) and some comparisons are reasonably carried out with other SRM configurations. Finally, a prototype motor is built and experimental results validate the performance predictions in the proposed motor.

Keywords: Reluctance machines, Switched reluctance motor (SRM), Segmented stator, High-torque design, Finite element method (FEM).

1. Introduction

Switched reluctance motors (SRMs) have been on the focus of many researchers because of their considerable advantages. Simple, brushless and robust structure, low cost, inherent fault tolerance and high efficiency in a wide range of speed are the main advantages of the SRMs [1], [2]. This type of electric motors is a good candidate to be utilized in many applications such as Electric vehicles (EVs), aircraft starter generators and variable speed drive systems [3], [4]. Several researches on the SRM show that its performance may be affected by improvements in drive and control strategy as well as any change in the motor magnetic structure. Unlike some other conventional motors, SRM configuration has been experiencing different topologies in recent years. In some attempts, a little

change in the SRM configurations were done to improve its performance such as obtaining low torque-ripple or high torque density [5]–[8]. In some others, the motor topology is changed significantly. Segmented rotor SRMs and its different structures aiming at high torque introduced in [9], [10]. The segmented rotor SRM also has a short-flux-path structure that may result in low loss machine. Short-flux-path structures may be obtained by segmented stator SRM as well. Two-phase E-core SRMs and its different designs as in [11], [12] show that the short-flux-path segmented stator design may reduce the iron material and losses. In some designs, the SRM topology is completely changed to obtain more torque and efficiency [13], [14]. However, any major modification in SRM structure may affect on motor simplicity and costs.

SRM has a low cost and rigid structure in comparison to the other motor types such as PM motors owing to the absence of any winding or magnetic materials on the rotor. On the other hand, SRM phases are normally driven with unipolar currents and then a variety of low cost power converter can be used. SRM also has comparable torque density among other motors particularly in low speeds. Beside these, SRM new technology may take advantages of some features such as short-flux-paths, flux-reversal-free stator and low copper usage that leads to the high efficiency motor. All these features make it more appropriate for high power application such as EVs [15],

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[16].

It should be mentioned that SRMs suffer from inherent and unavoidable torque ripple that may be improved using some control strategy without any change in the motor magnetic structure [17]. However, high torque density based on the both volume and active material, and also cost-effective designs are the major concerns among SRM topologies.

In this paper study and comparison analysis of a new three-phase SRM configuration is presented. This design has six stator segments and a solid outer rotor structure. The main features of the new SRM design are as following: 1) short-flux-path magnetic structure 2) flux-reversal-free stator 3) balanced radial forces 4) saving in active material and low weight structure 5) more stokes per revolution. Motor power density and efficiency of the proposed motor topology will examine in the latter sections. The paper is organized as follows: Section II describes the proposed motor topology. Section III contains analysis and characteristics of the new SRM design. Comparison studies are explained in section IV and experimental verification are presented in section V. Conclusions are summarized in section VI.

2. Motor Description

This section describes the structure and basic operating principle of the novel segmented stator SRM. The proposed motor has three phases and it has an outer-rotor structure. Other configurations of the proposed SRM topology, for example two-phase segmented stator SRM with different number of poles, are also possible and will have the same operating principles. The three-phase segmented stator SRM is shown in Fig. 1.

The number of segments is twice of the motor phase. In such a SRM, there are diametrically symmetric fluxes in each opposite segment which result in balanced radial forces. The proposed structure has three phases and each segment has a concentric winding located on the center body of the segment and two diametrically opposite windings which form the motor phase. In Fig. 1(a), the Phase A is energized and it is in fully aligned position. If the Phase B is energized after the Phase A as in Fig. 1(b), the rotor will rotate counterclockwise. Otherwise, if the Phase C energized after the Phase A as in Fig. 1(c), the rotor will rotate clockwise. Numerical analysis and particularly finite element (FE) analysis is a good way to evaluate magnetic circuits in any design. Fig. 2 shows the flux lines in aligned and unaligned positions for adjusted excitation current in one phase.

The SRMs normally work in the saturation area. The magnetic flux density reaches about 1.9 T for the segmented stator SRM in Fig. 2(b). For unaligned position as in Fig. 2(a), the phase has much smaller flux densities in which the maximum value is about 0.4 T. It should be mentioned that the magnetic flux density difference and

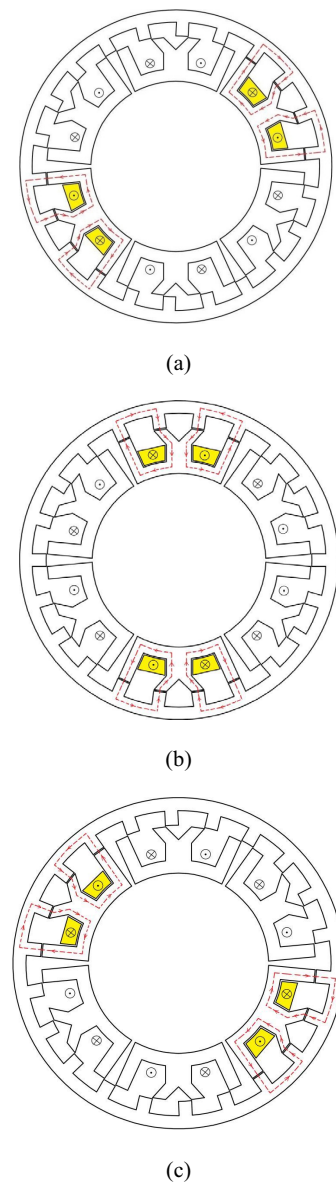


Fig. 1. Three-phase segmented stator SRM with phase flux paths when (a) Phase A, (b) Phase B and (c) Phase C are energized

hence phase flux difference between aligned and unaligned positions can directly affect the energy conversion capacity. To initially evaluate the motor efficiency, it is necessary to consider the motor losses. Core losses are important in motor magnetic design and it consists of both eddy current and hysteresis losses. In the proposed motor, laminations are used to decrease eddy current losses as in many others. On the other side, hysteresis losses depend on flux density, flux variations and steel volume containing magnetic flux.

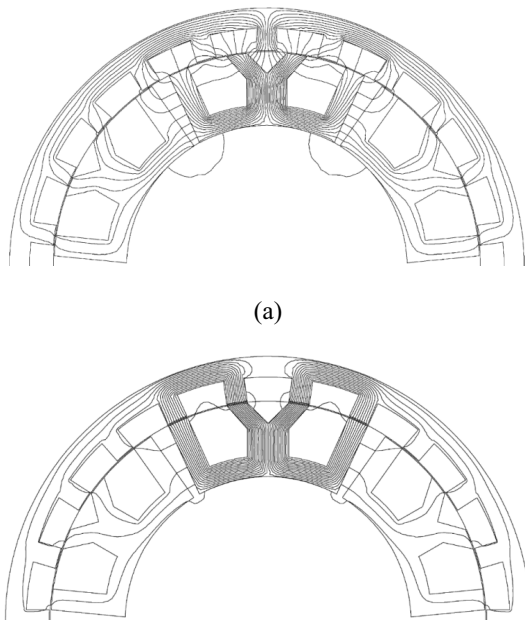


Fig. 2. Flux lines of the proposed segmented stator SRM in the (a) unaligned and (b) aligned positions.

In the proposed SRM, some rotor and stator segment sections with their names are depicted in Fig. 3. As shown, in order to decrease flux leakage between the stator segments, the corner part of the segments can be slightly modified. Additionally, (see Fig. 1) the phase windings on the segments are wound such that the flux direction in any two adjacent poles of the nearby segments is the same. The ideal flux variations neglecting leakage between segments and also considering no mutual excitation are shown in Fig. 4 for different steel sections. There are no flux reversals in the stator segments whose volume is 52% of the whole steel volume. The highest number of variations including flux reversals happens in the rotor poles in which flux varies 12 times in half a revolution. However, the rotor pole volume is about 19.5% of the whole

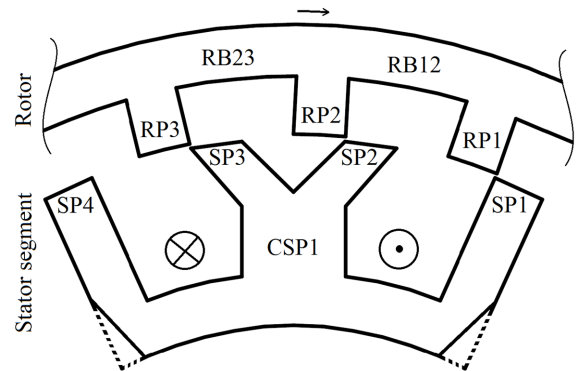


Fig. 3. Flux regions and stator segment modification.

steel volume and it is less than stator segments volume with no flux reversals. The rotor back-iron section has half of the number of variations in the rotor pole. On the other side, this section has less non-zero-flux periods in an electrical cycle (18.18%). Some results of the flux variation during motor operation are summarized in Table I. The relation between design parameters is presented in the following equations.

$$N_s = 2N_p \quad (1)$$

$$N_r = (2/3)(N_p)(3N_p + D_s + 1) \quad (2)$$

N_s stands for number of stator segments and N_r for the rotor poles. N_p is the motor phases and D_s is displacement factor between stator segments. It should be mentioned that displacement between segments must be proportional to the pole arc angle for proper operation.

3. Torque Analysis of the Stator-Segmented SRM

This section presents torque analysis of the proposed segmented stator SRM comparing with conventional design. In order to get insight into the proposed SRM, two

Table I. Flux distribution analysis results.

Steel section	Steel usage	Non-zero Flux intervals	Flux variations in half rev.	Flux reversals
Stator segment	52%	33%	11	No
Rotor pole	19.5%	30%	12	YES
Rotor Back-iron	28.5%	18.18%	6	YES

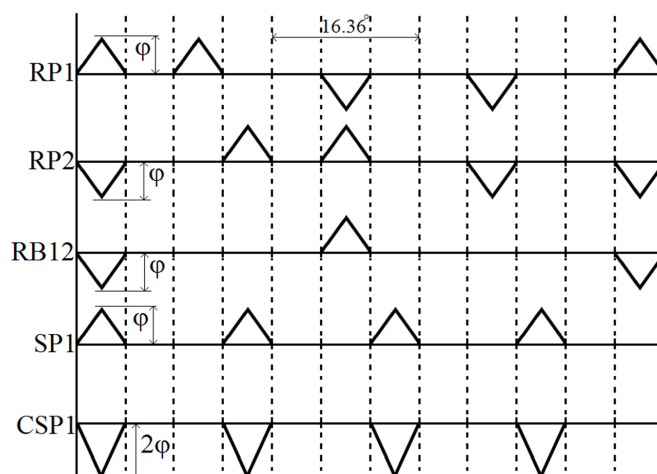


Fig. 4. Flux distribution waveforms in the proposed segmented stator SRM.

different conventional SRM structures are selected for comparison. In these three SRMs, some assumptions are considered to make the comparison more reasonable. (a) Conventional 6/4 SRM is initially selected as a common design. The segmented stator SRM has several rotor poles with small phase conduction intervals. Therefore, a 6/22 design of conventional structure are also considered to complete the comparison. (b) For all three SRMs, the external diameter and the stack length are the same. Therefore, the motor volumes are equal. Additionally, these SRMs are designed using the same steel and air-gap

lengths. (c) Each SRM has three phases with two windings per phase. In the conventional structures, these two windings are located on the two opposite stator poles. In the proposed SRM, these windings are located on the two opposite stator segments. (d) In the conventional structures, the stator and rotor back-iron lengths are half the pole width because they carry half of the pole flux. In the segmented stator SRM, the rotor and stator segment back-iron lengths and pole width are equal because they carry the same flux. Additionally, in the center body of the stator segment two poles share their flux path. Therefore, the

Table II. Dimensions of three different SRM designs.

Design parameter	Conventional 6/4 SRM	Conventional 6/22 SRM	Proposed 6 (segment)/22 SRM
Motor outer diameter (mm)	172	172	172
Motor active length (mm)	35	35	35
Number of motor phases	3	3	3
Number of windings per phase	2	2	2
Air gap length (mm)	0.6	0.6	0.6
Number of phase winding turn	120	120	120
Slot fill factor	0.4	0.4	0.4
Steel material	M270-35a	M270-35a	M270-35a
Air gap diameter (mm)	61.6	75	71
Rotor and stator (or segments) pole arc (deg)	20	60/11	60/11
Rotor pole height (mm)	12	7	7.54
Stator pole (or segment) height (mm)	13.2	6.7	24.3
Rotor back-iron length (mm)	10.7	3.58	6.76
Stator (or segment) back-iron length (mm)	10.7	3.58	6.76
Iron mass (kg)	2.99	1.28	2.56
Copper mass (kg)	1.23	0.96	0.97
Total mass (active material) (kg)	4.22	2.24	3.53

width of the stator center body is twice of the pole width.

The most important dimensions and characteristics of the three SRM designs are presented in Table II. The procedures of torque analysis are explained using some different steps. At the first step, phase torques of these three SRMs versus rotor positions are calculated according to different currents. Additionally, these SRMs have an equal number of winding turn. Therefore, the torques will be also based on some fixed magnetomotive force (MMF) values. However, as can be seen in Table II, these SRMs enjoy different masses of active materials. Therefore, in the second step, torque densities are analysed for different excitations to make the comparisons more reasonable.

Phase torque densities for three SRMs are depicted in Fig. 5. As can be seen, the torque density of the segmented stator SRM is the highest in comparison to the other two SRMs. The torque density of the conventional 6/4 SRM is comparable with that of 6/22 SRM. However, it uses 61.3% more active material. Considering active materials, the stator segmented SRM also exhibits the highest torque and 6/4 SRM has more torque in comparison to the 6/22 SRM. It should be mentioned that for the given excitation currents, rotor pole of the stator segmented SRM experiences flux density of 0.99T to 1.9T in aligned position. The flux densities in rotor pole for conventional 6/4 SRM are 1.18T to 1.89T and for 6/22 SRM are 1.17T to 1.79T, all in aligned position.

Torque density analysis is a good way to understand the motor torque capability based on its active materials. On the other hand, it is also important to know how much copper losses are considered for given torque. Therefore, at the next step, the torque densities are calculated based on given copper losses. Fig. 6 shows the torque densities for different copper losses in three SRM designs. As can be seen, the segmented stator SRM exhibits the highest torque densities in different copper losses among other SRMs. It should be mentioned that for the given copper losses, rotor pole of the segmented stator SRM experiences flux density of 1.52T to 1.86T in aligned position. The flux density in the rotor pole for conventional 6/4 SRM is 1.62T to 1.84T and for 6/22 SRM is 1.48T to 1.76T all in aligned position.

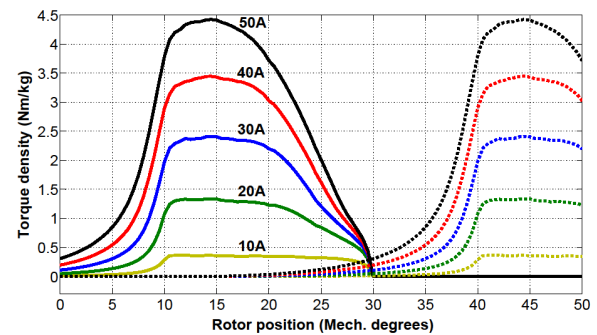
The motors have the same outer volume but employ different active material mass. From the comparisons, the average torque and torque density of the segmented stator SRM is higher than the others. At the copper losses of 30W, the proposed SRM produces 58.6% higher torque than the 6/4 SRM and 17% higher than 6/22 SRM. The comparison between two conventional topologies (6/4 and 6/22) shows that the increase of number of the rotor poles has not a direct relation with the torque capacity. In other words, energy conversion and hence torque production is mainly affected by the main SRM topology. It should also be mentioned that the segmented stator SRM and 6/22 SRM exhibit the same number of strokes per rev-

olution which is 5.5 times higher than that of conventional 6/4 SRM.

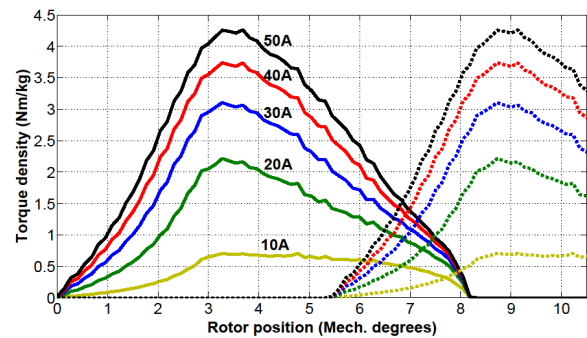
4. Design parameters and experimental verification

In this section, at first, the effect of motor design variables such as rotor and stator segment pole arcs, rotor pole and stator segment height and air-gap length, number of turns and stack length are considered.

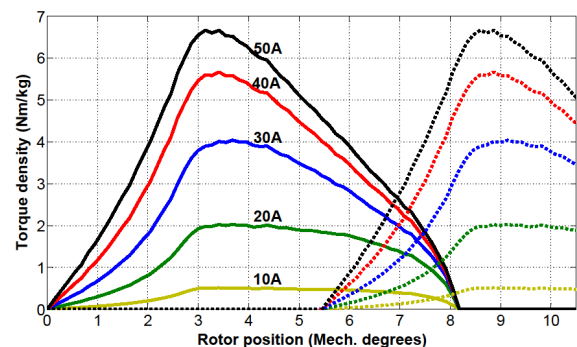
(a) Rotor and segment pole arc: The state of overlap-



(a)

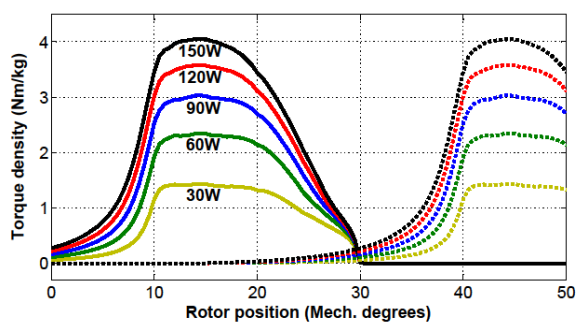


(b)

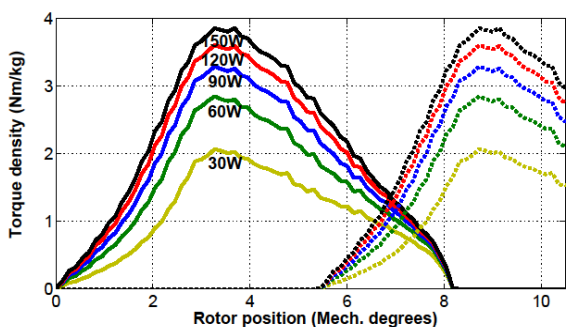


(c)

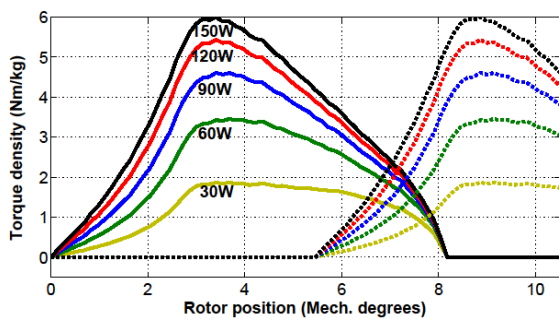
Fig. 5. Torque density of (a) conv. 6/4 SRM, (b) conv. 6/22 SRM and (c) segmented stator 6(seg.)/22 SRM for given currents.



(a)



(b)

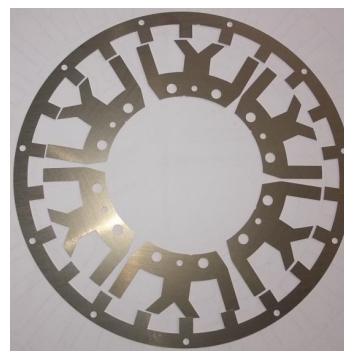


(c)

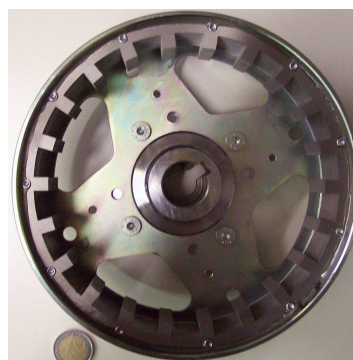
Fig. 6. Torque density of (a) conv. 6/4 SRM, (b) conv. 6/22 SRM and (c) segmented stator 6(seg.)/22 SRM for given copper losses

ping between inductance profiles of the motor phases are mainly affected by pole arcs. On the other side, the self-starting ability of SRM depends on the inductance profile overlapping state. To ensure self-starting in the proposed SRM, the minimum value of the arc angle for both rotor pole and the stator segment is $120/22$. Any increase in both angles can also affect the torque ripple. The increase of one of them improves commutation between phases during operation. It should also be mentioned that it is better to increase the rotor pole angle because any increase in stator segment pole angle results in smaller winding slot area.

(b) Height of the rotor pole and segment: Considering



(a)



(b)



(c)

Fig. 7. Prototype of the proposed segmented stator SRM. (a) Rotor and segment laminations, (b) rotor, (c) stator.

a fixed motor outer diameter, any increase of the rotor pole height results in decrease of both stator segment height and air-gap diameter. Change of the rotor pole height does not mainly affect the motor torque by itself but its impact on the stator segment height or air-gap diameter can affect the torque. Additionally, winding slot area is proportional to the segment height. However, stator segments must be mechanically fixed and this limits the segment height.

(c) Winding turns and stack length: The phase inductance is proportional to the square of the winding turns and any increase of the turns results in low nominal phase current. For given DC link voltage, a low number of wind-

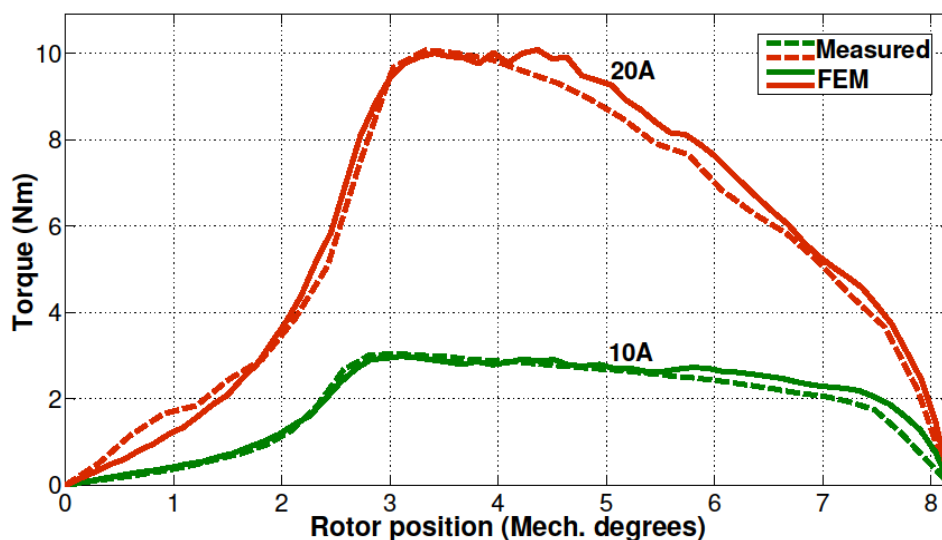


Fig. 8. Static torque profiles of FEM result and experimentally measured results.

ing turns and hence low inductance results in fast phase current response and improves commutation during high speed operation. The phase inductance is also proportional to the motor stack length. In a specific output power, it is preferred for the proposed motor to have higher diameter instead of having higher stack length. In this case, the motor exhibits low inductance, higher winding slot area and also higher pole arc angles.

It should be mentioned that the design initial parameters for the analysis are selected so that the motor diameter and active length are constant. The other parameters for each SRM design are selected according to approximately 1.7T set-point for flux density in the flux path.

A prototype was built so as to verify the design and working operations of the segmented stator SRM. The geometric parameters are provided in Table II. Fig. 7(a) shows the laminations of the rotor and the stator segments. The outer rotor with 22 salient poles is shown in Figure. 7(b). Fig. 7(c) depicts stator structure including segments and their windings. As shown, the stator segments are inserted into the aluminium fixture.

The measured static torque profile and FEM obtained torque profile for 10 and 20 A are shown in Figure. 8. The simulated and experimental results are in reasonable agreement. The maximum average torque error is less than 7%.

5. Conclusions

In this paper, initial analysis and comparative study of a new segmented stator SRM is introduced. The motor has unique structure and unlike conventional SRM, it has short flux path because of magnetically isolated stator segments. Initial analysis was performed using FEM and

the results were compared with the most conventional 6/4 SRM. The proposed segmented stator SRM has more rotor poles in comparison to the conventional 6/4 SRM. Therefore, another conventional-type SRM with the same number of rotor poles is also considered to make the comparison more reasonable. The results show that the proposed SRM has at least 25% higher torque in comparison to the conventional ones. The segmented stator SRM has no flux reversals in the stator segments which contain more than 50% of the motor core. The segmented stator SRM produces more strokes per revolution and has a good performance in low speeds. The new motor has balanced radial forces as well. The static torques experimentally measured and correlated with the FEM results. The results confirm that this motor is a good candidate for low-cost and high-torque applications.

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