Double Rotor Synchronous Reluctance Machine: Analysis towards Torque Capability Improvement

M. Al-ani, H. Mahmoud, M. Degano and C. Gerada

***Abstract* -- This paper presents a comparative analysis of double rotor synchronous reluctance machines. Different topologies of the proposed machine have been investigated, such as double rotor with double-sided stator and double rotor with single-sided stator machines. A comparison between these topologies has been conducted to understand the potential of improving the machine capabilities in terms of high average torque/power density, with respect to the conventional synchronous reluctance machine. The benefits of a double rotor topology are described in detail considering different number of stator slots. Furthermore, given the higher structural complexity with respect to a single airgap machine, a mechanical analysis of the inner and outer rotors has been conducted to assess the robustness of the inner and outer rotors iron ribs.**

***Index Terms*—Synchronous reluctance machines, Double rotor machine, Structural analysis, Double airgap machines**

I. INTRODUCTION

DOUBLE rotor machines have been attracting the attention of both industry and academia thanks to their potential higher power density and lower torque ripple capabilities [1-2]. In literature, several works on double rotor machines are presented [3-9]. Several topologies including a double rotor have been investigated, such as induction machine (IM) [3], surface-mounted permanent magnet (SPM) [4-5], flux switching permanent magnet (FSPM) [6-7], and switch reluctance machine (SRM) [8-9]. Additionally, double rotor machines with different rotor structures have been analyzed in [10-11]. All those machines presented are showing higher torque density when compared to their counterpart single rotor machines.

On the other hand, electrical machine topologies without magnets have been collecting the interest of the industry due to the high cost of the permanent magnet materials and because of the uncertainties of their future availability. As a result, synchronous reluctance machine (SynRel) has seen an increased interest and a rapid development because of the absence of permanent magnet materials in their structure [12-14]. The aim of increasing the torque density of the synchronous reluctance machine to compete with the magnet topologies has been the main priority for developers of synchronous reluctance machine [15].

This paper presents an analysis of different double rotor synchronous reluctance (DRSynRel) machines considering a number of winding, slot/pole and flux barrier combinations. The main target is to assess the improved performance, with respect to the conventional single inner rotor SynRel motors. The torque performance for each topology is presented and the potential for enhanced torque density quantitatively defined. In addition, structural analyses have been carried out on both inner and outer rotors to evaluate the robustness of the mechanical structure, considering the maximum operating speed. Finally, a comparison with a conventional single rotor SynRel machine, to highlight both the advantages and disadvantages of the proposed machines, has been conducted.

The work is presented as follows, in section II two stator topologies, single-sided and double-sided, are investigated to define the topology presenting higher torque. Section III is showing a comparison between a conventional single stator machine with two double rotor machines with different stator slot number. The aim of the comparison is to highlight the benefits of the proposed double rotor machine. Finally, section IV presents a structural analysis of the inner and outer rotor of the double rotor machine to validate the mechanical safety of the rotor.

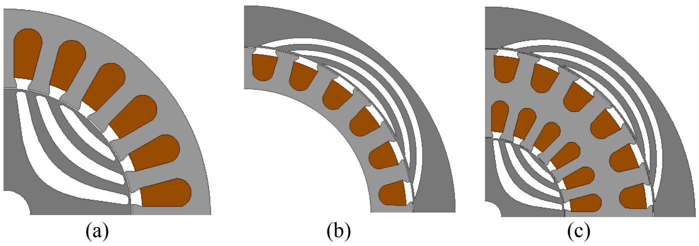

Fig. 1. Cross-sections (a) conventional (b) outer rotor, and (c) double sided stator double rotor synchronous reluctance machines.

II. DIFFERENT TOPOLOGIES OF DOUBLE ROTOR SYNCHRONOUS RELUCTANCE MACHINE

Fig.1 (a) and (b) presents the cross-sections of conventional SynRel machines with inner and outer rotors, respectively. The initial double rotor SynRel machine consists of a summation of the inner and outer rotor machines, which results in a double-sided stator double rotor machine as shown in Fig. 1 (c). The analysis in this section have been carried on using ANSYS FEA electromagnetic package, each rotor is modeled as a different band with the same speed of 5000rpm and both machines have the same current density of 7.1A/mm^2. The net torque is the sum of both inner and outer bands torque. The proposed design offers the advantage of radial toroidal concentrated winding since the inner and outer stators can be treated as separate machines [10], and their correspondent rotor can be aligned according to their winding, as shown Fig. 2. However, the

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need for a thick stator back-iron and two-sided winding consumes large space and constrains the rotors to smaller size. Therefore, this design produces low torque compared to the original single rotor machine. Alternatively, a single-sided stator structure has been proposed, shown in Fig. 3. This structure consists of single parallel stator teeth connected at the inner tooth-tip for mechanical stability. The drawback of this design is the need for the conventional distributed winding of the synchronous reluctance machines, however, this design offers a significant increase in torque by 7 times and reduction in the torque ripple by 50% compared to the double-sided stator, as shown in Table I. This is due to the lack of stator back-iron which allows more space for the stator winding. Fig. 4 presents the radial airgap flux density distribution with the harmonic content of the inner and outer rotor in both machines. From this figure it can be seen that the fundamental component in the single-sided stator machine inner and outer rotor is significantly higher than the double-sided due to the higher current. However, the other harmonics are slightly less in the double-sided stator machine, this result in high torque ripple in the double-sided stator machine as shown in Table I.

TABLE I
COMPARISON BETWEEN DOUBLE ROTOR SYNCHRONOUS RELUCTANCE MACHINES WITH SINGLE-SIDED AND DOUBLE-SIDED STATOR

	Average torque (Nm)	Torque ripple
Signal-sided stator	14.76	31
Double-sided stator	2.17	46

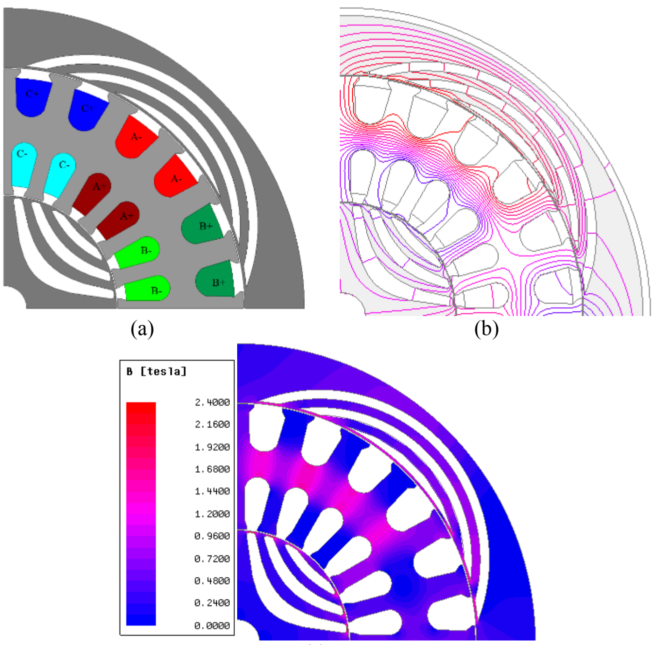


Fig. 2. (a) Cross-section, and (b) equipotential distribution of the radial toroidal concentrated winding configuration of double rotor synchronous reluctance machine with double-sided stator.

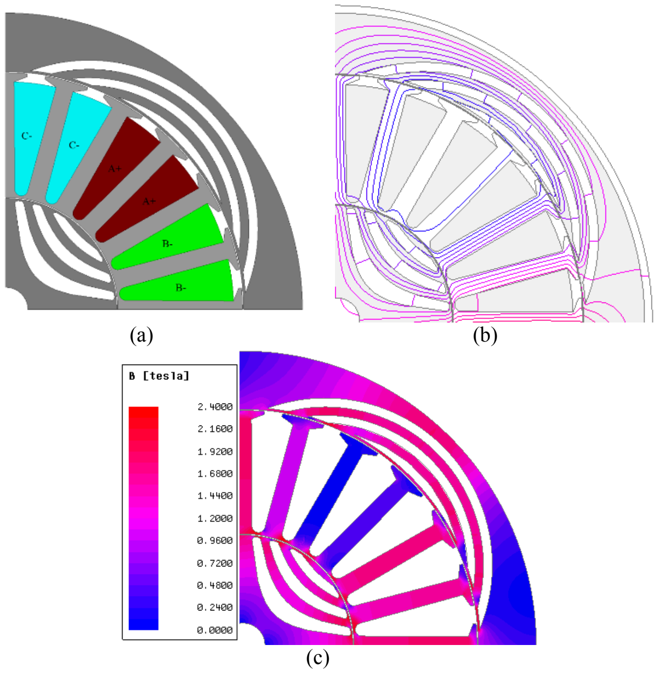
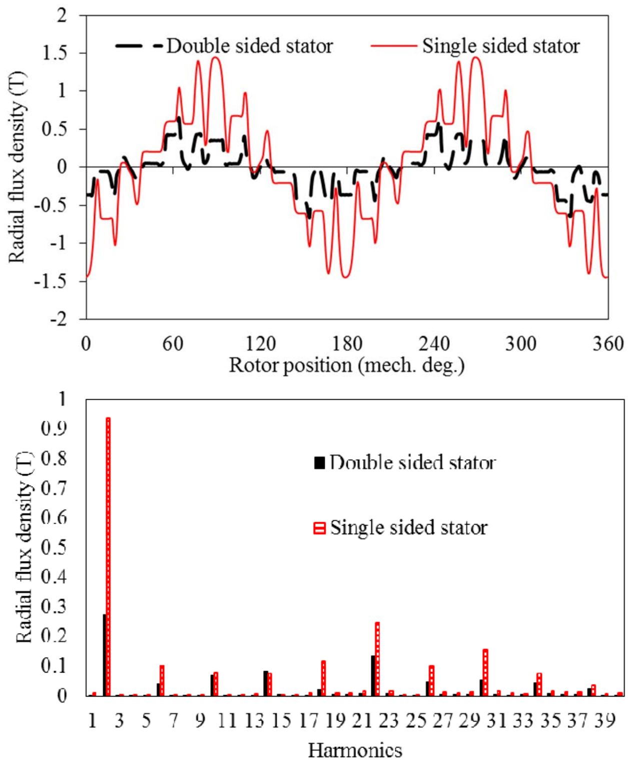


Fig. 3. (a) Cross-section, and (b) equipotential distribution of the distributed winding double rotor synchronous reluctance machine with single-sided stator.



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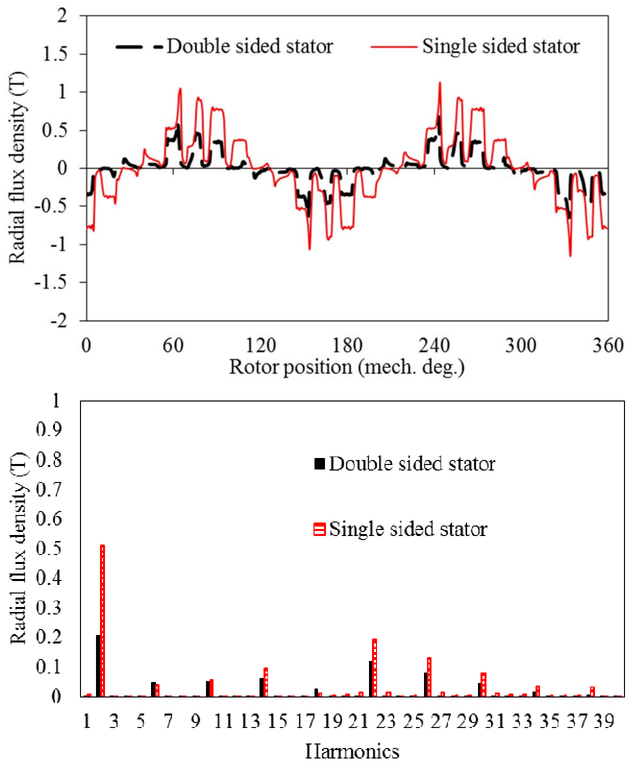

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Fig. 4. (a) Inner rotor, and (b) outer rotor radial airgap flux density distribution and harmonics of the single and double-sided stator machines.

III. Comparison with Conventional Single Rotor Synchronous Reluctance Machine

A comparison between a conventional single rotor and double rotor single-sided stator SynRel machines has been conducted in the previous section. In the following part, two double rotor SynRel machines with 36 and 24 stator slots with identical inner and outer rotors are analyzed. Table II lists the main design parameters of the three compared machines. All the machines have the same outer diameter, axial length, material and current density. The same airgap length used in the single rotor machine is used for both inner and outer airgaps in the double rotor machine. The single rotor machine has an outer rib thickness of 0.4mm whereas the double rotor machines inner rotor rib thickness is 0.5mm and the outer is 0.8mm. Fig. 5 presents the cross-section of the three compared topologies. Furthermore, the ratio of steel to air K_{air} in the conventional single rotor machine is 0.46. Therefore, similar ratio of 0.44 is used in the double rotor machine for the total of both rotors, i.e. the ratio of the total steel to air in the inner and outer rotors is 0.44.

The radial airgap flux density and their harmonic content of the three machines are shown in Fig. 6. Fig. 7 presents the torque waveforms of the two double rotor machines. The torque can be found by [16]:

$$T_e = -\frac{D}{2}\int_0^{2\pi} B_g(\theta_r)K_s(\theta_r)\frac{DL_{stk}}{2}\,d\theta_r \qquad (1)$$

Where D is the airgap diameter, B_g is the airgap flux density, K_s is the electrical loading, L_{sk} is the axial length, and θ_r is the coordinate angle (mechanical degree).

Therefore, the fundamental component for the inner and outer rotor results in similar average torque. Similarly, the other harmonic components lead to higher torque ripple in the outer rotor. The net torque of the double rotor machine is the summation of the inner and outer rotor torque and therefore, low torque ripple in the net torque is found. This is since the peak torque ripple of the inner and outer rotors exists in different direction at the same instant as seen in Fig. 7. Table III compares the average torque and torque ripple of the three compared machines. It can be seen the double rotor machine with 24 stator slots has 38% higher torque and same torque ripple compared to the single rotor machine, whereas the double rotor machine with 36 stator slots has 20% higher torque and 7% less ripple.

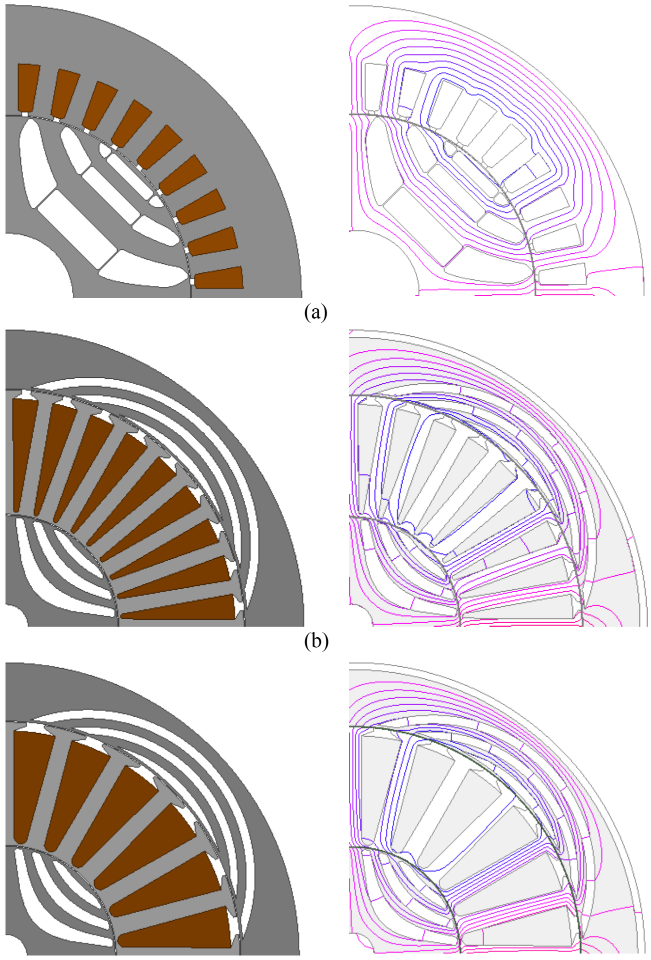
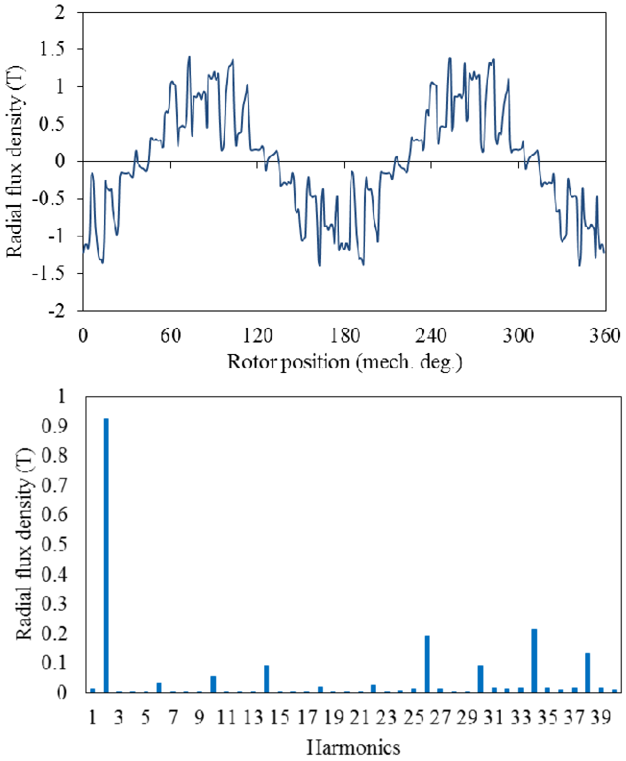


Fig. 5. Cross-section and equipotential distribution of (a) conventional single rotor (b) double rotor with 36 slots, and (c) double rotor with 24 slots.

TABLE II
Main Design Parameter of the Three Compared Machines

	SR	DR 36	DR 24
Stator outer diameter (mm)	200	200	200
Inner rotor outer diameter (mm)	124.3	75	75
Outer rotor inner diameter (mm)	-	160	160
Axial length (mm)	40	40	40
Airgap length (mm)	0.35	0.35	0.35
Inner rotor bridge thickness (mm)	0.4	0.5	0.5
Outer rotor bridge thickness (mm)	-	0.8	0.8
Current density (A/mm^2)	7.1	7.1	7.1
Rated speed (rpm)	5000	5000	5000

*SR is single rotor machine, DR 36 is double rotor machine with 36 slots and DR 24 is double rotor with 24 slots.



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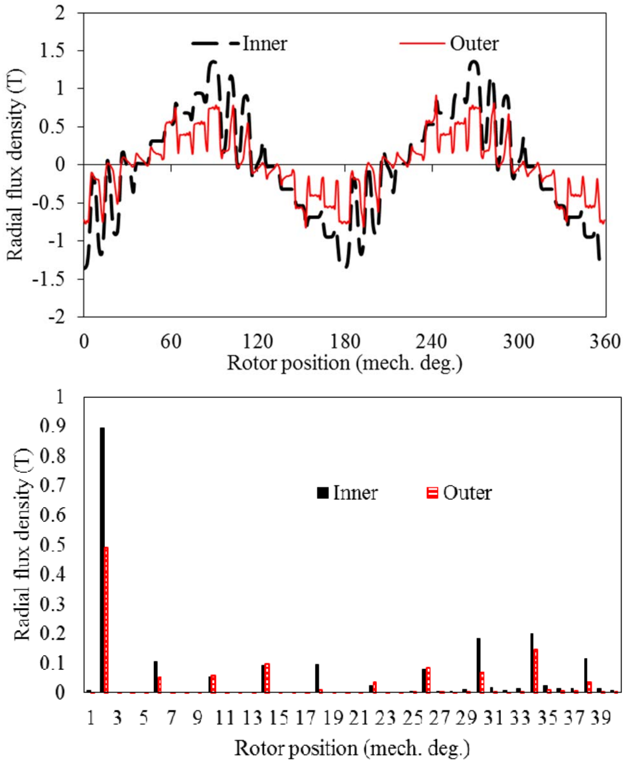

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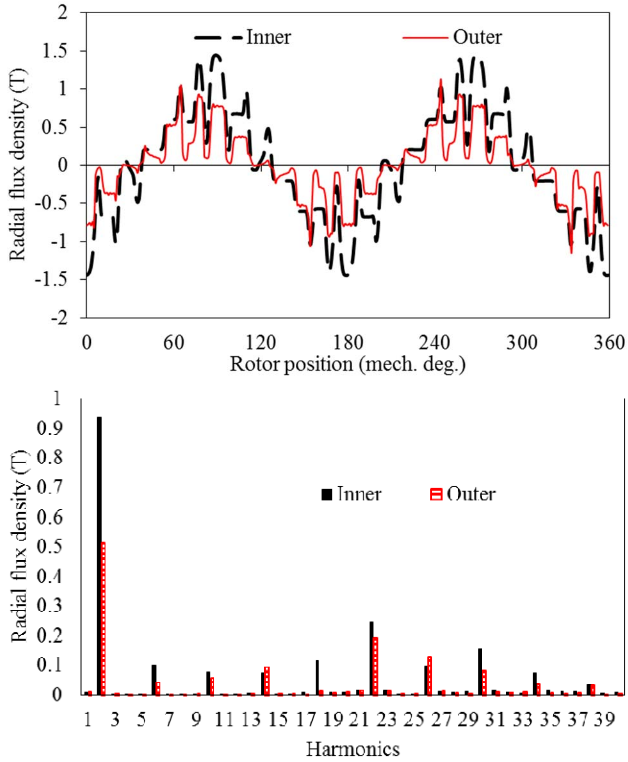

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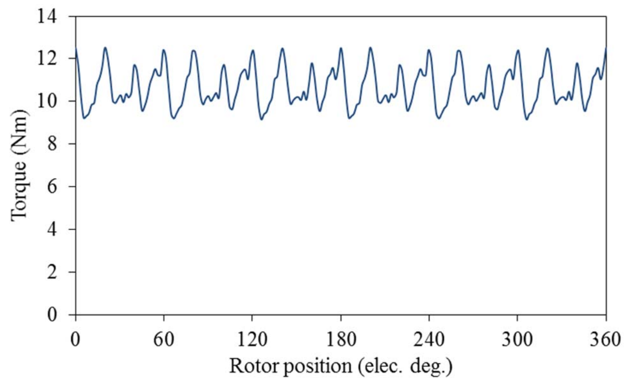
Fig. 6. (a) Conventional single rotor (b) Double rotor with 36 slot, and (c) Double rotor with 24 slot radial airgap flux density distribution and harmonics.



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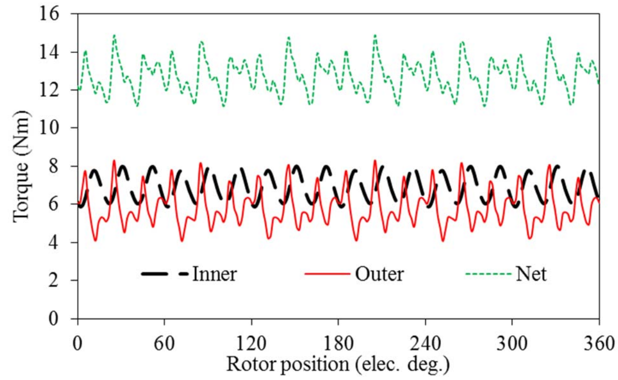

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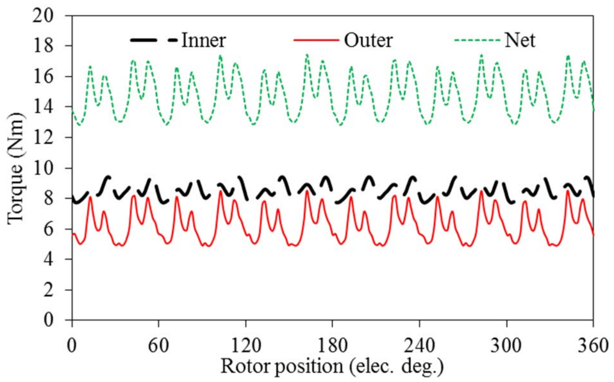

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Fig. 7. Torque waveforms of (a) Conventional single rotor (b) Double rotor with 36 slots, and (c) Double rotor with 24 slots.

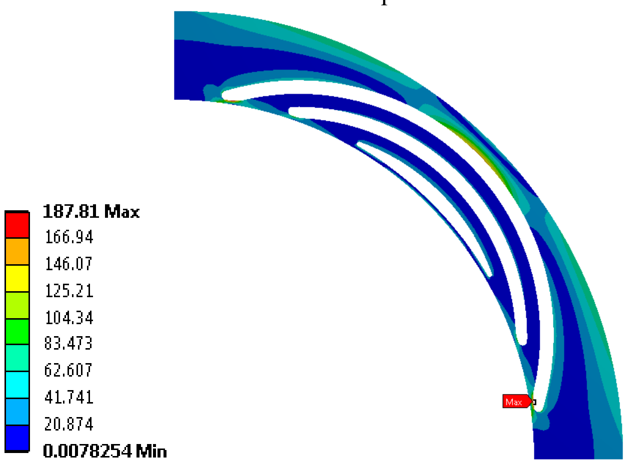
TABLE III
COMPARISON BETWEEN DOUBLE ROTOR AND SINGLE ROTOR SYNCHRONOUS RELUCTANCE MACHINES.

	Average torque (Nm)	Torque ripple
Single rotor	10.69	31
Double rotor 36	12.73	29
Double rotor 24	14.76	31

IV. MECHANICAL STRESS ANALYSIS

Due to the presents of the flux barrier bridges in the synchronous reluctance rotors, the mechanical stress generated in these bridges due to the high speed rotation need to be examined. The stress distribution in the inner and outer rotor of the double rotor machine is shown in Fig. 8. The analysis has been conducted using ANSYS FEA structural package, the load condition is rotational speed of 5000rpm.

The inner rotor has a maximum stress of 106 MPa which is significantly lower than the yield strength of the used material which is 350 MPa. While, the outer rotor exhibits higher maximum stress of 187 MPa, this stress still lower than that of the yield and therefore this ensure a safe operation. Furthermore, the deformation in the inner rotor is negligible, whereas the outer rotor has relatively large deformation. Therefore, the thickness of the bridges in both inner and outer rotors can be reduced further within the allowable limit of the manufacturing process. This would results in a further increase in the torque.



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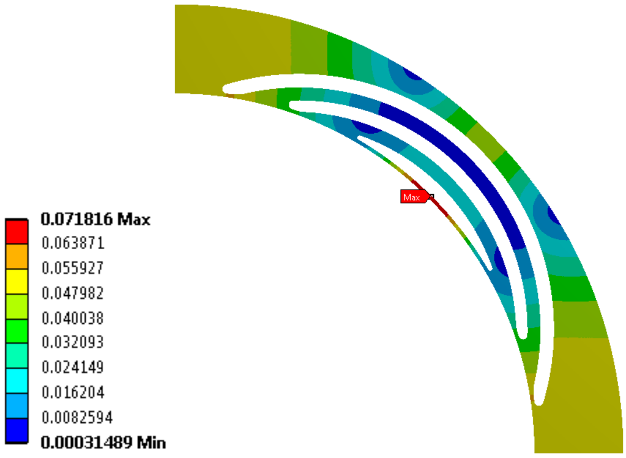

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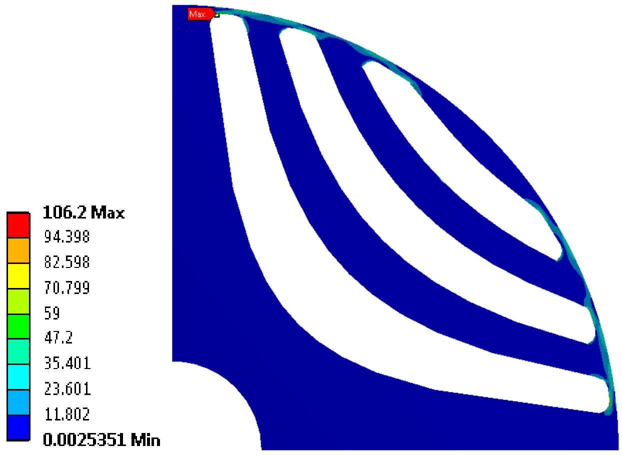

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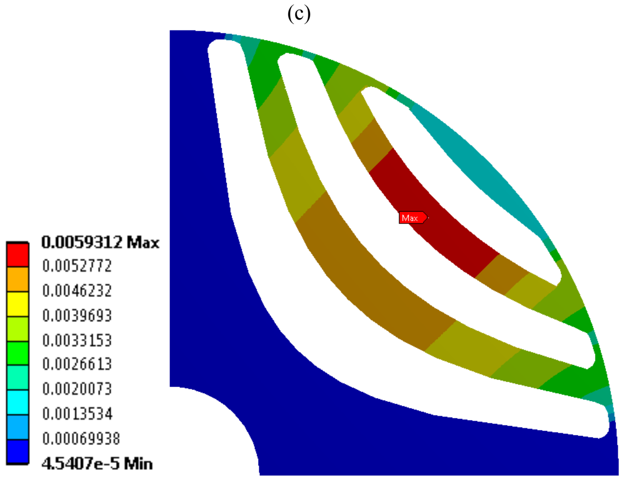

(d)

Fig. 8. Mechanical stress and deformation distribution in inner rotor (a) and (b) and outer rotor (c) and (d) of the double rotor machine.

V. CONCLUSION

Double rotor synchronous reluctance machines have been analyzed and investigated in this paper. Two stator topologies have been studied, double sided with concentrated winding and single sided with distributed winding. It is found that single sided stator has higher torque compared to single sided due to the large space consumed by the stator due to the need of two stator back-irons. A comparison between a conventional single rotor and two double rotor machines with 24 and 36 stator slots has been conducted.

From the comparison, the double rotor machines can produce higher torque and less torque ripple, when compared with the single rotor machine. Finally, mechanical analysis of the inner and outer rotor has been carried out. It is found that both rotors operate safely at the desired speed. In conclusion, the preliminary design of the double rotor machine shown a good torque and low torque ripple. A further work including electromagnetic and mechanical optimization of different double rotor synchronous reluctance machines with different stator slot/rotor pole with different number of flux barriers will be conducted and reported in the future.

VI. References

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