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Geometry Design of Switched Reluctance Motor to Reduce the Torque Ripple by Finite Element Method and Sensitive Analysis

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This paper presents torque ripple in switched reluctance motor (SRM). The presented method in this paper for torque ripple minimization is based on suitable machine design structure. In this paper, the parameters of one machine are chosen as the reference parameters. Then some of these parameters are chosen for ripple minimization which has no effect on the characteristics of mechanical, power and volume of the reference machine. To get machine torque, the electromagnetic model of each machine with a certain set of parameters is simulated by finite element method (FEM), and then the torque characteristics can be obtained form different machine structure with various machine parameters. Finally, with the parameters sensitivity analysis (PSA), the best parameters can be chosen for the design of machine with minimum torque ripple (TR). The presented design method of SRM in this paper can be accepted as an accurate method based on FEM in the machine design process (MDP) for magnetic circuit instead of the equivalent magnetic circuit (EMC). The FEM which used in the most previous studies was only for machine analysis, but in this paper FEM is used in the MDP as a new method for machine design. So this method of machine design can be replaced with the conventional methods.

Keywords: Finite Element Method, Magnetic Equivalent Circuit, Sensitivity Analysis, Torque Ripple.

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I Introduction

There are two main methods to reduce the torque ripple in Switched Reluctance Motor (SRM). The first one is the machine design structure (MDS) to obtain the better characteristics of the torque, minimum torque ripple and so on. The second one is the best design for motor driver to overcome the limitations of MDS. The aim of this paper is to study only the first method. So, at first, the related papers of MDS have been reviewed for torque ripple reduction.

The first precise study of the existing problems of these kinds of motors was done by Lawrenson and his collaborators in 1980 [1]. They explained in their studies the limitations of rotor and stator poles numbers, poles pitch, phase numbers, arcs length of the rotor and stator, and nominal rating.

The output equation and selection of motor dimensions are presented by Krishnan and his collaborators in 1988 [2]. By Miller, a good collection of problems in the design, methods of control, and effects of different parameters on the performance of SRM are presented in [3] and [4]. So, Ref. [3] is related to the all study up to 1993 and Ref. [4] is related to the design of SRM which these two references caused the design of SRM will be easier. In [5] the sensitivity of rotor and stator pole-pitch/pole-arc in the motor performance are considered. In this study, an analytical method is used based on flow of magnetic flux and two dimensions of FEM. By use of sensitivity analysis the maximum average torque (AT) was selected from different stators, rotor and pole-pitch/pole-arc. In 1992 by Moallem [6], the effects of different rotor faces on the torque are studied. In [7], a new synchronous SRM is presented and analyzed by FEM. The FEM results show that the copper losses in the new machine with comparison of reference machine are reduced to 75 percent with same used copper and same power output condition. In 1991 by Torrey [8], a design procedure for SRM with minimum TR is presented with two methods; the first one is to introduce the problems which may be concerned in the design procedure like applications of torque ripple sensitivity and the second one is the motor design method by the simple control technique which presents the reasonable performance. In [9], a high power SRM motor is designed with specifications of 5 MW, 9000 V, three phases and 6/4. In 1992 by Finch and Faiz [10], all the previous primary design of SRM is considered again. The nonlinear machine model is used in their studies. Also, they examined the effects of main dimension ratio and core losses which were ignored in the previous studies. So, the different criteria are used for optimization and they introduced some comments for limitation of losses. In 1994 the equations of the analytical design to make the performance of SRM are obtained by Radun [11] and [12]. They proposed simplified equations and verified them with high accuracy results of simulation and practical design of an SRM in high power density. In [13], the effects of geometrical dimensions of the output performance of three motors with four phases, different dimensions and different power outputs are considered and compared. Also, the magnetic characteris-

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tics of each the motor are described by two dimensional FEM. In [14], the design of SRM is presented and it is proven that the performance of the system drive is better with increasing of the phase numbers without increasing the number of switches. The problem of commutation in SRM is presented in [15] and [16] while a pair of rotor poles is aligned to a pair of stator poles. In this case the self- inductance is at the maximum value and also in this situation the current commutation in the phases cannot change quickly. Therefore the remained electromagnetic energy which cannot be converted to useful mechanical energy will be caused the mechanical energy loss and reduce the torque in the machine. Therefore, the problem is overcome by designing an auxiliary winding to flow the energy in this winding and produce the useful torque instead of returning it to the power supply and produce the negative torque in the machine. The conditions to obtain the constant power for some special machines are presented in [17]. In their studies different type of 8/6 and 6/4 SRM with various dimensions are considered to see the effects of these variations on steady state condition and dynamic performance.

In recent decades much research has been done to reduce the adverse effects of torque ripple. For example, changes in stator and rotor pole arcs, optimization of machine parameters as well as optimization of the stator and rotor poles [18]. Some of the mentioned methods have low or high impact on torque ripple of machine, but these influences are not enough to use SRM in many applications such as high speed applications [19]. The rotor shape design for minimum torque ripple using FEM has been presented in reference [20] and also the best rotor geometry to reduce torque ripple was searched and finally the rotor with teeth is recommended. Then the designed SRM has been analyzed with FEM and the results are compared with the conventional form of SRM. The purposed new shape of SRM with teeth can reduce the leakage flux and introduce inductance as a linear curve to reduce torque ripple. The proposed new shape of the rotor is achieved by applying a two-dimensional finite element method. The main reason for torque ripple is the leakage flux due to before overlapping of stator and rotor poles to occur. This flux will be caused the non-linear current and thus the torque ripple. In [22] the optimal values of stator and rotor poles arcs are obtained. In [23] observed that the new mutual magnetic induction motor (fully pitched SRM) has torque ripple higher than the older one.

II Structure Design of SRM for Minimum Torque Ripple

In the last section some important published papers of structural design to reduce torque ripple were studied. Since the number of machine parameters is too much. So, the only effective parameters should be considered in the machine design. For this study a reference machine is considered. Then the desired parameters a reference machine in a specified range will be evaluated and finally the best parameters for the MDS to reduce the torque ripple will be presented.

In this paper, electromagnetic calculations are based on FEM. Since all calculations related to the torque in the sensitivity analysis are based on FEM. Therefore, this method may be introduced as a new method with compare to the others. The parameters of the reference machine are given in Table 1 and the aim is to reduce the torque ripple based on suitable parameters in MDS.

III Switched Reluctance Machine Design Software (SRMDS)

In order to properly design the SRM, special software was designed in the MATLAB by using the toolbox GUIDE. Fig. 1 shows the flowchart for torque calculation of any 6/4 SRM. All dimensional parameters for structure drawing are defined as the inputs in this software. The complete list of the parameters is presented in Table 1. In this program any valid input parameters can be used for machine design. By entering the dimension and electromagnetic parameters as the input data, the program will be started to find the torque in the specified location of rotor and stator. After running the program, the defined dimension and electromagnetic parameters will be transferred to the FEMM4.2 software to analyses the SRM and give the defined results as the outputs. Then, these outputs transfer to the MATLAB software environment for final processing to calculate average torque and torque ripple.

The designed and proposed software for this study is a combination of the mentioned software. First software was designed by GUI from the Matlab toolboxes, second software was designed based on the FEMM4.2 cods, and the third software was written the program by MATLAB commands. The GUI is used to define the parameters of the machine as the inputs. The FEMM4.2 has been used for electromagnetic analyses. The software written by MATLAB commands is used as a main program. In the main program, the input parameters of the designed GUI transfer to the MATLAB main program, then these input data translate to the Matlab commands and after that translate to the FEMM4.2 commands for electromagnetic analysis by calling the FEMM4.2. At the end of the program, the results return to the MATLAB main program for final processing. The method of torque calculation by FEMM4.2 is explained in the appendix. All FEM codes were written by the MATLAB commands so, this software will lead to a unique feature in the design and the analysis of SRM. This advantage has not been observed so far in the design of electrical machines in the published papers. The method which presented in this paper to analyze the machine, can be lead to more accurate design of SRM in compare with conventional methods.

Because of very low computation time , the EMC method is a conventional method to analyze and design an electrical machine instead of FEM. The flux tubes in most of EMC methods for an accurate result are constructed based on a flow of flux in a magnetic circuit which is obtained by FEM. But the results of this simulation are valid only for a machine with constant geometry structure not for a machine with different geometries. So, in the design of machine, the geometric structure of machine should be changed to find the best machine structure. Therefore, the EMC method which was obtained based on a fix machine structure will not be used in the machine

design.
Here may be for the first time, the FEM is used in the repetitive process of electrical machine design with variation of machine parameters to find the best parameters. The flowchart of machine analysis by FEM for any valid machine parameters is shown in Fig-2. For a 4/6 SRM machine, there is 45 degree space between aligned an unaligned position. So, if the rotor wants to finish this space by step of one degree for any each rotor rotation, the FEM software should be called to run for 45 times. In the presented paper, 27 machine models were studied, so the FEM was run 1215 times to analyze the machine in each time.
In this paper the torque was obtained form a machine with stator phase current of 10 A and 100 turns. We know the SRM machine for more efficiency working in the saturation mode. So, for a machine with a special input voltage and rating speed, the current of machine will be greater than the nominal current. Therefore all SRM machines should be controlled by current limiter. Of course the reluctance of machine in unaligned position and near of rotor and stator overlapping is very low and torque in this case has small value. However, the stator current may be has a value near nominal current, but the torque is very low for low reluctance in the mentioned area. Therefore, the selection of nominal current as a constant current in this paper is for determining the required space for stator winding.

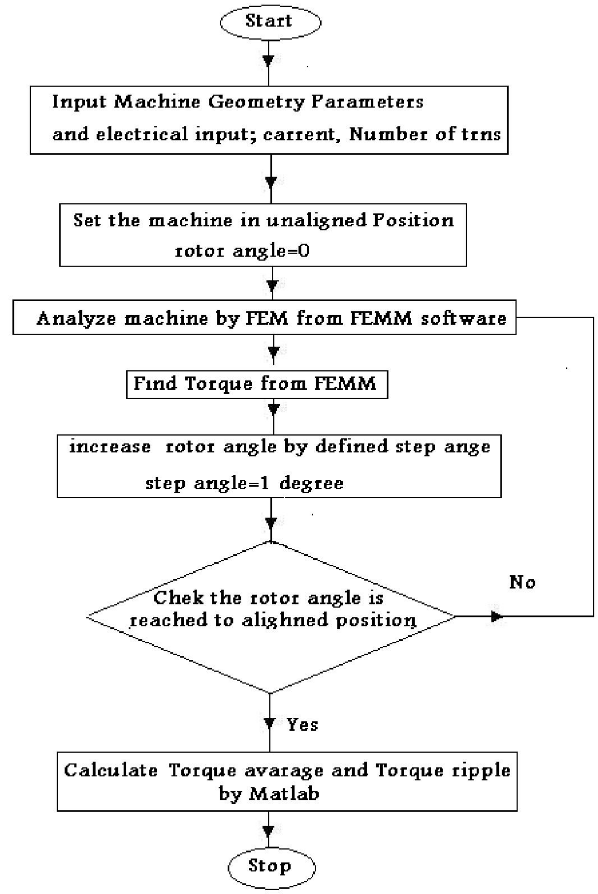


Figure 1: Flowchart for calculation of Torque, Average torque and Torque ripple with input machine parameters based on FEM.

IV SENSITIVITY ANALYSIS ON THE MACHINE PARAMETERS

As mentioned before, the parameters for the reference machine is considered for analysis. The machine parameters are presented in Table 1.
The numbers of reference machine parameters are fifteen. These parameters are given in Table 1 and in this study are defined as the reference machine parameters. Since the purpose of this study is to obtain a lower torque ripple for the reference machine and compare the results with the reference machine. So, respect to reference machine, three points should be considered: first of all, the rating power should be unchanged and secondly, the outer dimensions of the machine should be fixed and thirdly, mechanical specifications of the machine should be same as reference machine.
To achieve the mentioned three conditions, (1) turn ampere and current density should be the constant values for unchanged rating power, (2) height of stator pole, length of stator yoke and stator stack should be unchanged to obtain same frame dimensions as the reference machine and (3) for same mechanical specifications as reference machine, the machine air gap and the diameter of the shaft machines should be unchanged from reference parameters. So, the remained parameters for sensitivity analysis are P (2), P (4), P (5), P (7) and P (9). In Fig. 2 shows some parameters of machine. These parameters are as follow and shown in Fig. 2:

- P (2) = rotor inner radius
- P (4) = rotor inner arc
- P (5) = rotor outer arc
- P (7) = stator inner arc
- P (9) = stator outer arc

A Sensitivity Analysis on the Rotor Inner Radius

According to Table 1, the rotor inner radius is equal to 0.03 meters. To obtain a sensitivity analysis of this parameter on machine torque, the all other parameters in Table 1 are assumed to be constant and the rotor inner radius varied from 0.02 m to .0.049.
The machine analysis with selected parameters is done by FEM for a complete period from the fully aligned position to the fully unaligned position. So, the torque was calculated for the mentioned period. In this case study it was assumed that the fully aligned position occurred in $0°$ and fully unaligned position occurred in $45°$.
The results were obtained for each degree of the rotor rotation with respect to the stator. Fig. 3 shows the machine structures by variations of the desired parameters. Fig. 4 shows the torque curve for one phase and different rotor inner radius from fully aligned position to fully unaligned position. Table 2 shows the value results for variations of the rotor inner radius.
From Fig. 4 and Table 2, it was clearly seen that the best

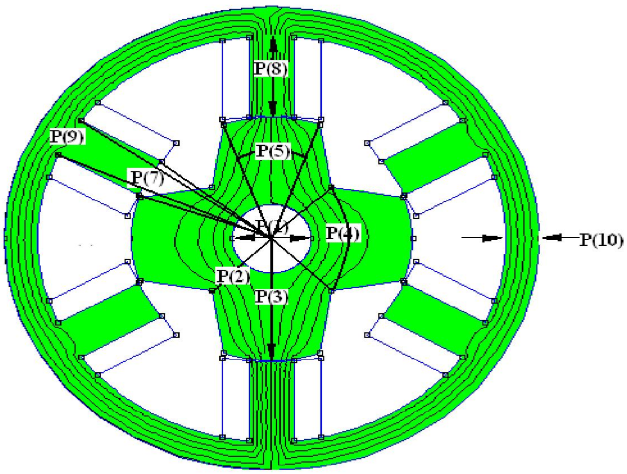


Figure 2: Displays the SRM parameters, P (1) to P (10).

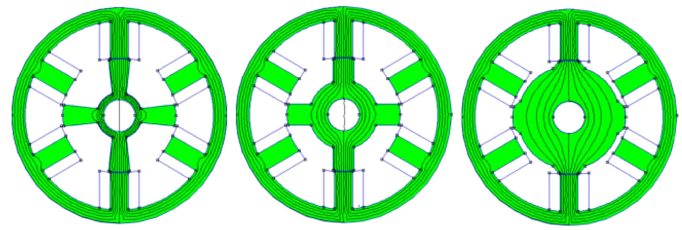

(a) 0.2 m (b) 0.3 m (c) 0.45 m

Figure 3: Machine structures with different rotor inner radius.

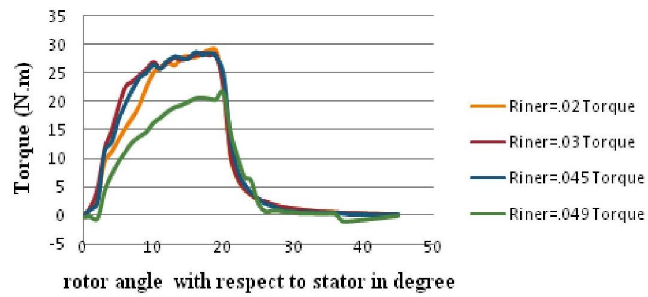


Figure 4: The torque results from sensitivity analysis on the rotor inner radius with different values.

torque pick, average torque, and torque ripple is obtained by $P(2) = 0.03$ or Model-2 for machine parameters. But Fig. 3 shows that the used iron in rotor for the larger radius is greater than the small one. Because of increasing the rotor yoke length by increasing the rotor inner radius, the iron losses may be less than the small rotor inner radius. However, the iron loss calculation is not the scope of this study for all case studies.

Table 1: Reference Machine Parameters.

Parameter	Definition of parameter	Value
$P(1)$	Rotor shaft radius	0.014
$P(2)$	Rotor inner radius	0.03
$P(3)$	Rotor outer radius	0.049
$P(4)$	Rotor inner arc	36.52
$P(5)$	Rotor outer arc	22
$P(6)$	Number of rotor poles	4
$P(7)$	Stator inner arc	18
$P(8)$	Length of stator pole	0.032
$P(9)$	Stator outer arc	10.98
$P(10)$	Length of yoke	0.012
$P(11)$	Number of stator poles	6
$P(12)$	Air gap	0.0005
$P(13)$	Stack length	0.2
$P(14)$	Current	100
$P(15)$	Phase winding turns	10

Table 2: Result Values for Variations of the Rotor Inner Radius.

Model	Rotor inner radius (m)	T_{av} (N)	T_{max} (N)	T_{ripple}
1	$P(2) = 0.02$	9.75	28.98	0.66
2	$P(2) = 0.03$	10.59	28.59	0.63
3	$P(2) = 0.04$	10.39	28.63	0.64
4	$P(2) = 0.05$	7.15	21.73	0.67

B Sensitivity analysis on the rotor inner arc

According to Table 1 the rotor inner arc is equal to 36.52 degrees. To obtain a sensitivity analysis of this parameter on the machine torque, the all other parameters in Table 1 are assumed to be constant and the rotor inner arc varied from 25 to 90 degrees.

The machine analysis with selected parameters is done by finite element method for a complete period from full aligned position to full unaligned position.

Fig. 5 shows the machine structures by variations of the desired parameters. Fig. 6 shows the torque curve for one phase and different rotor inner arcs from fully aligned position to fully unaligned position.

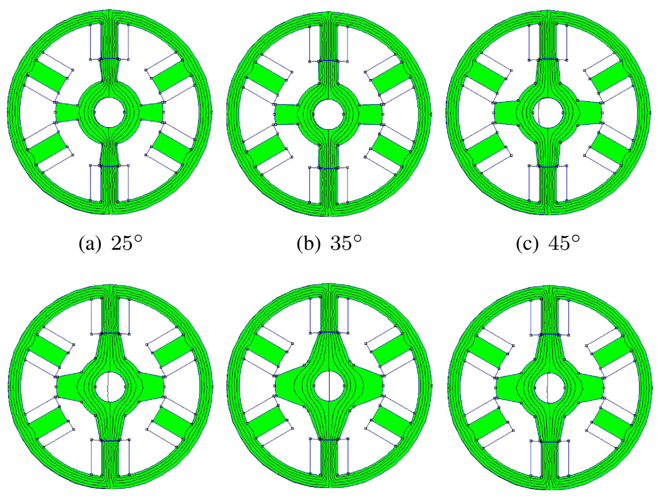
From Fig. 6 and Table 3, it was clearly seen that the torque pick, average torque and torque ripple are not significant sensitive by increasing the rotor inner arc. But Fig. 5 shows that the iron used in rotor for larger rotor inner arc is greater than the small one. So in this case the iron loss may be less than the small rotor inner arc. Because, the reluctance in the rotor poles is less than the large rotor inner arc.

C Sensitivity analysis on the rotor outer arc

According to Table 1, the rotor outer arc is equal to 22 degrees. To obtain a sensitivity analysis of this parameter on the machine torque, the all other parameters in Table 1 are assumed to be constant and the rotor outer arc varied from 22 to 60 degrees.

Fig. 7 shows the machine structures by variations of rotor outer arcs. Fig. 8 shows the torque curve for one phase and different rotor outer arcs from full aligned position to full unaligned position by FEM analysis.

From Fig. 8 and Table 4 it was clearly seen that the torque



(a) 25° (b) 35° (c) 45°

(d) 55° (e) 80° (f) 90°

Figure 5: Machine structures with different rotor inner radius.

pick, average torque and torque ripple are not very sensitive with variation of rotor outer arc from 22 to 50 degrees by increasing the rotor inner arc. The best result in this case is obtained by $P(5) = 30$ or Model-18 of machine parameters. But Fig. 5 shows that the used iron in rotor for larger rotor inner arc is greater than the small one. So, the iron loss will be less than the small rotor inner arc. Because, the reluctance in the rotor poles is less than the larger rotor inner arc.

D Sensitivity analysis on the rotor inner and outer arcs

According to Table 1 the rotor inner arc is equal to 36.52 degrees. At this stage, from the results of previous sections, the rotor inner arc has been chosen equal to $90°$. Then, sensitivity analysis of the rotor outer arc carried out like previous sections. Fig. 9 shows the machine structures by variations of rotor outer arcs when the rotor inner arcs is $90°$. Fig. 10 shows the torque curves by FEM analysis for one phase and different rotor outer arcs when the rotor inner arc is $90°$ and rotor was rotated from full aligned position to full unaligned position.

Table 3: Result Values for Variations of the Rotor Inner Arc.

Model	Rotor inner arc (degree)	T_{av} (N)	T_{max} (N)	T_{ripple}
5	$P(4) = 25$	10.35	28.47	0.64
6	$P(4) = 30$	10.31	28.06	0.63
7	$P(4) = 35$	10.62	28.8	0.63
8	$P(4) = 36.5$	10.59	28.59	0.63
9	$P(4) = 40$	10.55	29.12	0.64
10	$P(4) = 45$	10.56	28.76	0.63
11	$P(4) = 50$	10.67	28.86	0.63
12	$P(4) = 55$	10.82	29.81	0.64
13	$P(4) = 60$	10.76	28.86	0.63
14	$P(4) = 70$	10.97	29.45	0.63
15	$P(4) = 80$	10.88	28.95	0.62
16	$P(4) = 90$	10.79	29.14	0.63

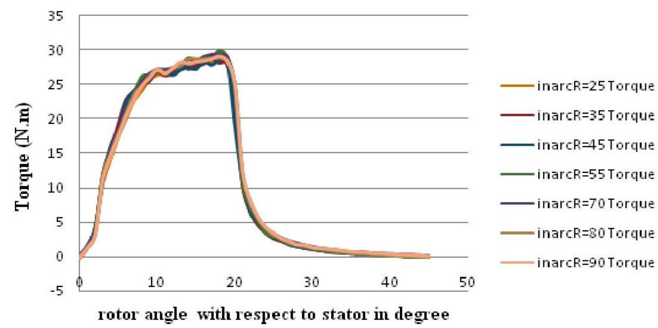


Figure 6: Torque results from sensitivity analysis on the rotor inner arc with different values.

From Fig. 10 and Table 5, it was clearly seen that the torque pick, average torque and torque ripple are not significant sensitive by increasing the rotor inner arc with fix rotor outer of $90°$. But Fig. 6 shows that the used iron in rotor for larger rotor inner arc is greater than the small one. So in this case the iron loss may be less than the small rotor inner arc. Because, the reluctance in the rotor poles is less than the larger rotor inner arc. The results of Model-23 may be better than the others because of higher torques.

E Sensitivity analysis on the rotor inner and outer arcs, and stator inner and outer arcs simultaneously

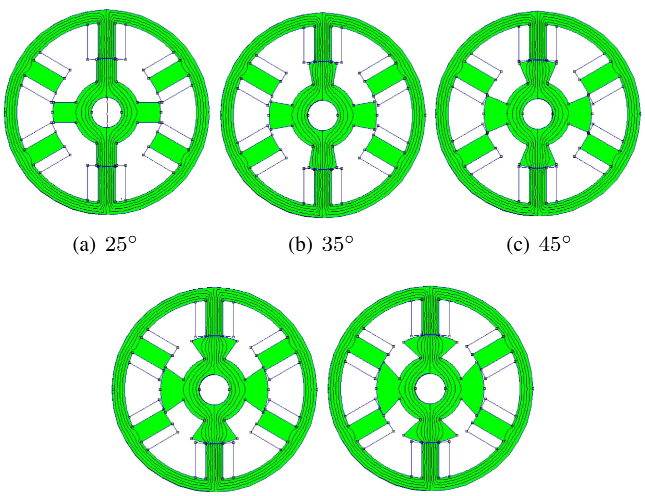
At this stage, the results of previous sections have been chosen for the rotor inner arc $90°$ and rotor outer arc $40°$. Then the sensitivity analysis on the stator inner and outer arcs carried out

Table 4: Result Values for Variations of the Rotor Inner Arc.

Model	Rotor inner arc (degree)	T_{av} (N)	T_{max} (N)	T_{ripple}
5	$P(4) = 25$	10.35	28.47	0.64
6	$P(4) = 30$	10.31	28.06	0.63
7	$P(4) = 35$	10.62	28.8	0.63
8	$P(4) = 36.5$	10.59	28.59	0.63
9	$P(4) = 40$	10.55	29.12	0.64
10	$P(4) = 45$	10.56	28.76	0.63
11	$P(4) = 50$	10.67	28.86	0.63
12	$P(4) = 55$	10.82	29.81	0.64
13	$P(4) = 60$	10.76	28.86	0.63
14	$P(4) = 70$	10.97	29.45	0.63
15	$P(4) = 80$	10.88	28.95	0.62
16	$P(4) = 90$	10.79	29.14	0.63

Table 5: Values of Rotor Inner Arc=90° ($P(4) = 90$) and Outer Arcs.

Model	Outer arcs	T_{av} (N)	T_{max} (N)	T_{ripple}
22	$P(5) = 22$	10.77	29.14	0.63
23	$P(5) = 30$	10.88	29.9	0.64
24	$P(5) = 40$	10.86	29.18	0.63



(a) 25° (b) 35° (c) 45°

(d) 55° (e) 80°

Figure 7: Machine structures with different rotor inner radius.

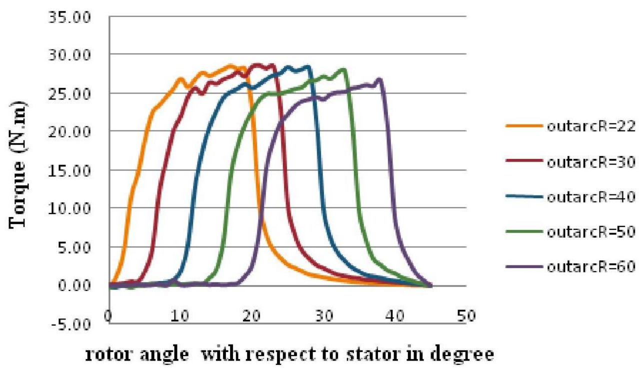
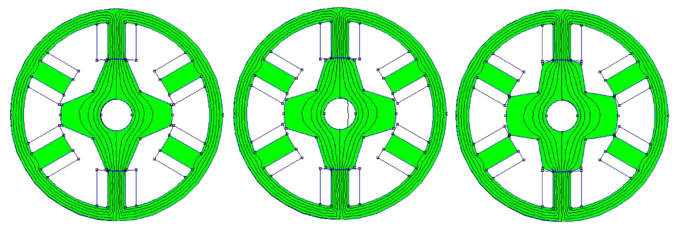


Figure 8: Torque results from sensitivity analysis on the rotor inner arc with different values.



(a) 22° (b) 30° (c) 40°

Figure 9: Machine structures for rotor inner arc 90° and different rotor outer arcs.

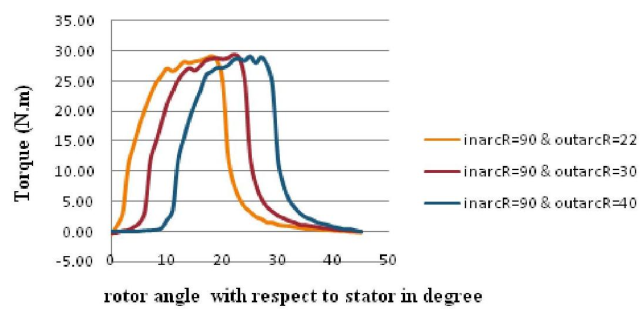


Figure 10: Torque results from sensitivity analysis with rotor inner arc 90° and different values of the rotor outer arcs.

like previous sections.

Fig. 11 shows the machine structures by variations of stator inner and outer arcs when the rotor inner arc is 90° and rotor outer arcs is 40°. Fig. 11 shows the torque curves by FEM analysis for one phase and different stator inner and outer arcs when the rotor inner arcs is 90° and rotor outer arcs is 40° and rotor was rotated from full aligned position to full unaligned position.

From Fig. 12 and Table 6 it was clearly seen that the torque pick, average torque and torque ripple are the best for Model-27 or machine with these parameters: 90° rotor inner arc, 40° rotor outer arc, 40° stator inner arcs and 30o stator outer arcs. Also, Fig. 11 shows that the Model-27 used more iron in the rotor and the stator. In this case the iron loss may be less than the other Models of machine.

V Results of Sensitivity Analysis

The all sensitivity analysis results which were shown before in Tables 1-6 are gathered in Table-7. From variations of the reference machine parameters in 29 machines with different parameters of reference machine have been obtained. Each machine with a certain set of parameters was defined by a code number. The code number of reference machine is defined by Model-2. In all tables the torque ripple can be calculated from Eq. 1.

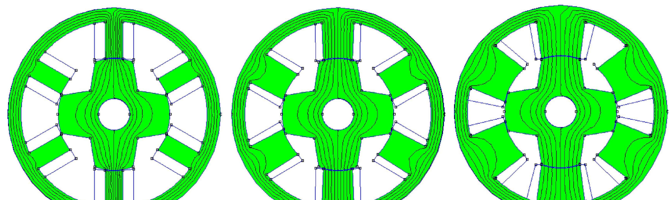
$$T_{ipple} = \frac{T_{\max} - T_{\min}}{T_{av}} \tag{1}$$

The results can be summarized as follows:

- The minimum TR and maximum AT for variations of the rotor inner radius from $P(2) = 0.02$ to $P(2) = 0.049$ will be occurred at $P(2) = 0.03$, this machine in Table 2 is called Model-2.
- The minimum TR and maximum AT for variations of the rotor inner arcs from $P(4) = 25^\circ$ to $P(4) = 90^\circ$ will be occurred at $P(4) = 80^\circ$, this machine in Table 2 is called Model-15.
- Variations of the rotor outer arcs from $P(5) = 22^\circ$ to

Table 6: Values of Rotor Inner Arc=90° ($P(4) = 90^\circ$) and Outer Arcs=40° ($P(4) = 40^\circ$) with Different Stator Inner and Outer Arcs.

Model	Stator Inner and Outer arcs	T_{av} (N)	T_{max} (N)	T_{ripple}
25	$P(7) = 18$ $P(9) = 11$	10.86	29.18	0.62
26	$P(7) = 30$ $P(9) = 20$	16.61	29.97	0.44
27	$P(7) = 40$ $P(9) = 30$	20.16	32.48	0.37



(a) $18°, 11°$ (b) $30°, 20°$ (c) $40°, 30°$

Figure 11: Machine structures for rotor inner arc $90°$ and different rotor outer arcs.

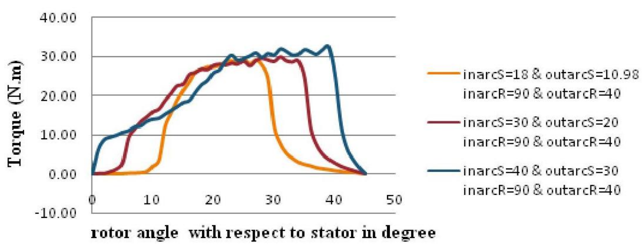


Figure 12: Torque results from sensitivity analysis with rotor inner arc $90°$ and rotor outer arc $40°$, and different stator inner and outer arcs values.

$P(5) = 60°$ for machines with Model-17 to Model-21 has same torque ripple and at $P(5) = 60°$ has maximum AT for a machine with Model-21.

- Variations of the rotor outer arcs from $P(5) = 22°$ to $P(5) = 40°$ for machines with Model-22 to Model-24 has minimum TR and equal torque when $P(4) = 90°$ and has maximum AT for machine with Model-23.
- Variations of the stator inner and outer arcs with considering rotor inner arc is $P(4) = 90°$ and rotor outer arcs is $P(5) = 40°$ shows that machine with Model-27 has minimum TR and maximum AT.
- Final results for minimum TR and maximum AT show that machine with Model-27 is the best machine, and the results of torque vs to rotor angle is shown in Fig. 13. Also, the structure of this machine with reference machine is shown in Fig. 14.

VI CONCLUSION

In this paper a switched reluctance machine was designed from sensitivity analysis on dimensional machine parameters of a reference machine. The aim of this study was modified the reference machine to achieve the minimum TR and maximum AT. The results show that the designed machine through sensitivity analysis was better than reference machine. In this study for first time, the design of an electrical machine was presented based on FEM in an iterative manner. So far, in the design of electrical machine, the researchers have been used the EMC for fast computation time in an iterative manner. Some researchers have used FEM only for analysis the final designed machine and others have used it to improve the EMC. In the published papers , we have not seen the design of electrical machine based on FEM

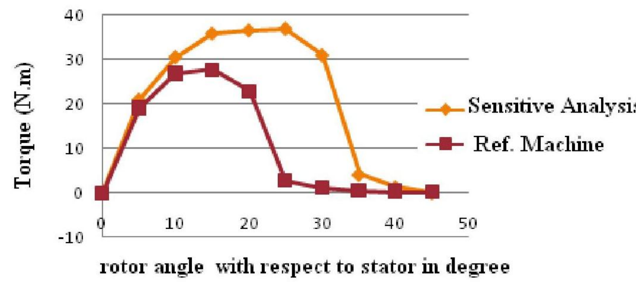
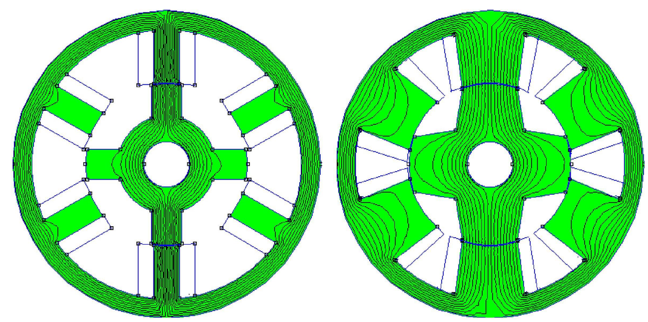


Figure 13: Results of sensitivity analysis on torque in compare to reference machine.



(a) Reference machine (b) Machine desidned by sensitivity analysis

Figure 14: Machine structures.

in an iterative design process. It is clear that with variation of machine parameters, the EMC cannot give an accurate model for all variations. So, in this paper a new method for electrical machine design was introduced. The aim of this study was to reach the minimum TR and maximum AT for a given machine. In this study the design procedure was applied only on some important dimensional parameters. The sensitivity analysis of selected parameters applied to find the torque with new parameters by FEM in one stroke. The variations of the parameters caused to produce 27 models of machine which were different from reference machine. The final results of these 27 models of machine are tabulated for torque ripple and average torque which are considered as the aims of this study.

VII APPENDIX

This section discusses some of the different methods of deducing forces and torques using FEMM4.2.

A Lorentz Force/Torque

If one is attempting to compute the force on a collection of currents in a region containing only materials with a unit relative permeability, the volume integral of Lorentz torque is always the method to use. Lorentz force results tend to be very accurate. However, again, they are only applicable for the forces on conductors of with unit permeability.

Table 7: Sensitivity Analysis on Torque and Ripple.

Model	machine parameter	T_{av}	T_{max}	T_{ripple}
1	$P(2) = 0.02$	9.75	28.98	0.66
2	$P(2) = 0.03$	10.59	28.59	0.63
3	$P(2) = 0.04$	10.39	28.63	0.64
4	$P(2) = 0.05$	7.15	21.73	0.67
5	$P(4) = 25$	10.35	28.47	0.64
6	$P(4) = 30$	10.31	28.06	0.63
7	$P(4) = 35$	10.62	28.8	0.63
8	$P(4) = 36.5$	10.59	28.59	0.63
9	$P(4) = 40$	10.55	29.12	0.64
10	$P(4) = 45$	10.56	28.76	0.63
11	$P(4) = 50$	10.67	28.86	0.63
12	$P(4) = 55$	10.82	29.81	0.64
13	$P(4) = 60$	10.76	28.86	0.63
14	$P(4) = 70$	10.97	29.45	0.63
15	$P(4) = 80$	10.88	28.95	0.62
16	$P(4) = 90$	10.79	29.14	0.63
17	$P(5) = 22$	10.59	28.59	0.63
18	$P(5) = 30$	10.68	28.69	0.63
19	$P(5) = 40$	10.58	28.47	0.63
20	$P(5) = 50$	10.31	27.89	0.63
21	$P(5) = 60$	9.97	26.78	0.63
22	$P(5) = 22$ $P(4) = 9$	10.77	29.14	0.63
23	$P(5) = 30$ $P(4) = 90$	10.88	29.9	0.64
24	$P(5) = 40$ $P(4) = 90$	10.86	29.18	0.63
25	$P(7) = 18$ $P(9) = 11$ $P(5) = 40$ $P(4) = 90$	10.86	29.18	0.628
26	$P(7) = 30$ $P(9) = 20$ $P(5) = 40$ $P(4) = 90$	16.61	29.97	0.446
27	$P(7) = 40$ $P(9) = 30$ $P(5) = 40$ $P(4) = 90$	20.16	32.48	0.379

B Weighted Stress Tensor Volume Integral

This volume integral greatly simplifies the computation of forces and torques, as compared to evaluating forces via the stress tensor line integral of differentiation of coenergy. Merely select the blocks upon which force or torque is to be computed and evaluate the integral. No particular art is required in getting good force or torque results (as opposed to the Stress tensor line integral). Although the results tend to be more accurate with finer meshing around the region upon which the force or torque is to be computed. One limitation of the Weighted Stress Tensor integral is that the regions upon which the force is being computed must be entirely surrounded by air and/or abutting a boundary. In cases which the desired region abuts a non-air region, force results may be deduced from differentiation of coenergy.

C Maxwell Stress Tensor Line Integral

The indiscriminate use Maxwells Stress Tensor can result in bad predictions forces and torques. The goal of this section is to explain how to set up problems and properly choose integration paths. So, good estimations of force and torque might be obtained via stress tensor methods. Generally, you should not use the Stress Tensor line integral to compute forces and torques if it can be avoided (i.e. use the volume integral version instead). Maxwells stress tensor prescribes a force per unit area produced by the magnetic field on a surface. The differential force produced is:

$$dF = \frac{1}{2}\left(H(B \cdot n) + B(H \cdot n) - (H \cdot B)n\right) \tag{A-1}$$

where n denotes the direction normal to the surface at the point of interest. The net force on an object is obtained by creating a surface totally enclosing the object of interest and integrating the magnetic stress over that surface.

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