Scope for Designing High Torque Switched Reluctance Motor with Low Ripples

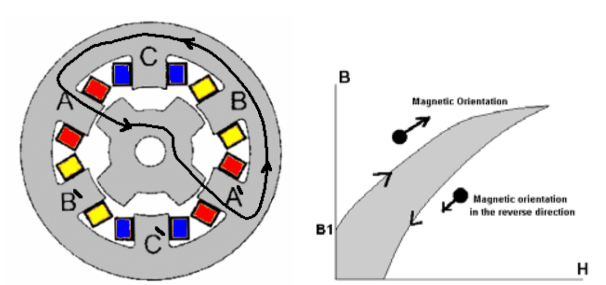
Dr. Eyhab EL-Kharashi
1 El-Sarayat Street, Abdou Basha Square, Abbasia,
11517 Faculty of Engineering,
Electrical Power & Machines Department,
Ain Shams University,
Cairo, Egypt.
EyhabElkharahi@hotmail.com

Abstract

The paper discusses the problem of the ripples in the torque characteristic of the switched reluctance motor which is the main drawback otherwise the SRM possess excellent characteristics for applications in many commercial drives. Lots of researches attempted to solve the problem by changing the design parameters of this type of motors but the average torque decreases. There is limitation on the output torque of the SRM per unit volume; to decrease the ripples the average torque always decreases. From this point of view the paper clarifies the necessity of optimising the SRM for at least two cost functions: low ripples and high average torque. The optimization of the SRM is difficult and inaccurate due to high non-linear characteristic of the SRM; so the paper introduces a direct and simple way to select the parameters of the SRM for these two cost functions. In addition, the paper shows how to adjust the operating parameters to run the SRM to deliver high output torque with low ripples.

1 Introduction

The electric motors used in the drive applications are the induction motors, permanent magnet motors and the switched reluctance motors. The permanent magnet motors have the problem of expensive magnets and the induction motors have the problem of high copper losses in both the rotor and the stator. So the motor designers focus on the SRMs because of their advantages particularly they have high specific output torque (torque/volume). The primary disadvantage of the SRM is the higher torque ripple compared with other conventional motors. The origin of torque pulsations in the SRM is due to the highly nonlinear and discrete nature of torque production mechanism. There are lots of other sources of the ripples such as ripples resulting from using the converters [1-3]. The problem of the torque ripples stand against the use of the SRM in some applications such as servo applications (which needs motor has flat torque characteristic)



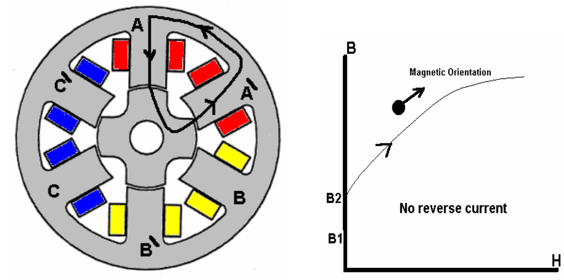


Fig. 1 Three Phases Short Pitch 6/4 SRM

Fig.1 shows cross section of 6/4 short pitch SRM (the coil links one stator tooth only). Although the basic geometry of the SRM looks simple enough, the dimensions and the shape of the rotor and the stator are critical for generating smooth rotation with high torque and power efficiency. Moreover the place of the windings of each phase and its configuration (as shown in the figure there are two different positions for one phase windings) has impact on the output torque (average and ripples). This makes the motor hard to be designed, needs deep understanding of the operation and its performance. The SRMs are non-linear motors and need to work in the highly saturation region [4].

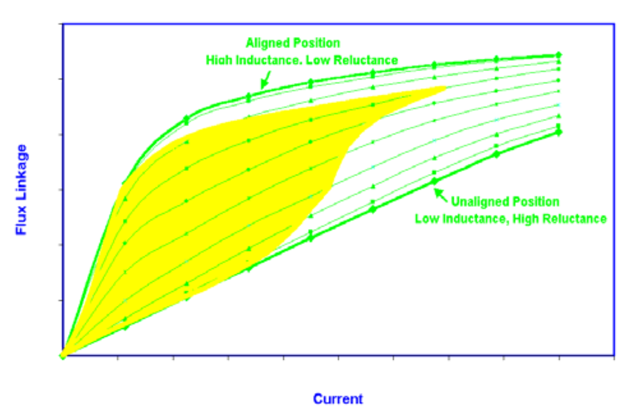


Fig. 2 the Flux-Linkage Trajectory under Voltage Control

The area between the aligned and the unaligned positions shown in Fig. 2 is proportional to the output torque. So to get high output torque the Flux-Linkage trajectory must be deep.

The values of the average torque and the ripples depend on the parameters of the magnetic circuit and its shape. There are two important points for any SRM designer: First, there is limitation on maximum value of the output torque produced by reluctance motor. Second, any attempt to shape the magnetic circuit or to select its parameters for low ripples decreases the average torque [5].

2 The Limitation of the Output Torque the SRM

The torque delivered by an SRM is given instantaneously by the rate of change of co-energy in the machine. In moving from a rotor position, θ, through an angle $\delta\theta$ the co-energy converted to torque is usually represented by the area between the flux-linkage-current curves at angles θ and $\theta + \delta\theta$.
If current is applied at the unaligned position and removed at the aligned position then the mean torque developed is given by the area between the two flux-linkage characteristics at these extreme positions, divided by the angle traversed. Any SRM designer can therefore attempt to increase the output torque of the SRM by increasing this area. It should be noted that the inductance at the aligned position can not be infinity because of many reasons, such as the permeance of the iron, and the inductance at the unaligned position can not be zero because of cross slot leakage flux. So one of the SRM designer's considerations is to increase the area between these two lines as much as possible.

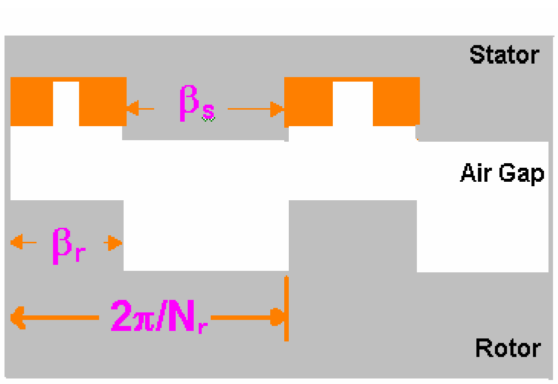


Fig. 3 Simple Linear Case of Doubly Salient Reluctance Motor

Fig. 3 shows a simple rectilinear example of a conventional doubly salient construction. The figure is used here to explain the limitations of the torque in the SRM.

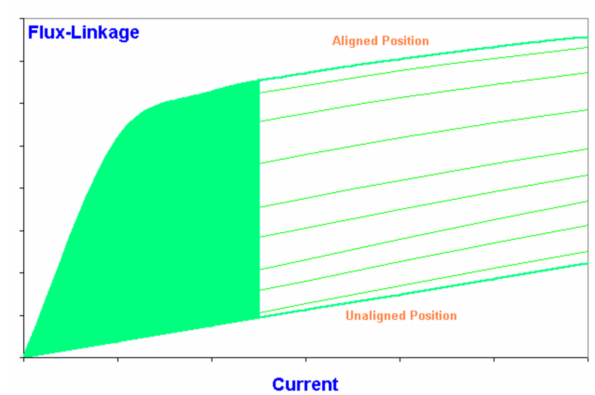


Fig. 4 the Non Linear Characteristic of the Switched Reluctance Motor (The Flux-Linkage Trajectory under Current Control)

Fig. 3 shows typical flux-linkage/current curves for a range of positions and also a typical flux-linkage locus traversed under current control. To increase the output torque of the SRM the area contained by the locus must be increased. Clearly, either the flux-linkage at the aligned position must rise or that at the unaligned position must fall.
To maximise the aligned inductance L_{max} one stator tooth must be aligned with one rotor tooth. To minimise the unaligned inductance L_{min} it is essential that there is no overlap between rotor and stator poles. Therefore, a design constraint exists [6] wherein the relationship $\beta_r+\beta_s \le 2\pi/N_r$ must be satisfied where N_r is the number of rotor poles, β_s is the stator tooth width and β_r is the rotor tooth width. Under the above constraint L_{min} is limited by the leakage fields. The cross-sectional area of the flux path in the aligned position is maximised when $\beta_s=\beta_r=\pi/N_r$. The aligned inductance, L_{max}, is then limited by the permeance of the main flux path. At low values of excitation this is dominated by the air gap length, whilst at high excitation levels it is dominated by magnetic saturation of the laminations [6].

Fig. 4 shows the non-linear characteristic of the SRM and the area shown inside it the flux linkage trajectory. The characteristic is fixed for the motor but the area shown inside it depends on the operating conditions of the motor. The area between the aligned and unaligned positions is proportional to the output torque of this motor. So to get much output torque the operating conditions must make the flux linkage trajectory fill much area between the aligned and the unaligned positions. Or by another words the operating conditions must make the flux linkage trajectory be deeply in the saturation region to get much torque. So any mathematical model for this motor will be difficult and inaccurate because of the saturation is included that needs some approximations. In addition, the switched reluctance motors are doubly salient and usually have many slots that are hard to be modeled by mathematical model. The adaptive two dimensions finite element 2D FE is used here to get precise prediction of the torque and the performance of this type of motors [7-8] and it is based on mesh modification and error estimation algorithms.

2.2 The Shape of the Magnetic Circuit and the Torque Ripples

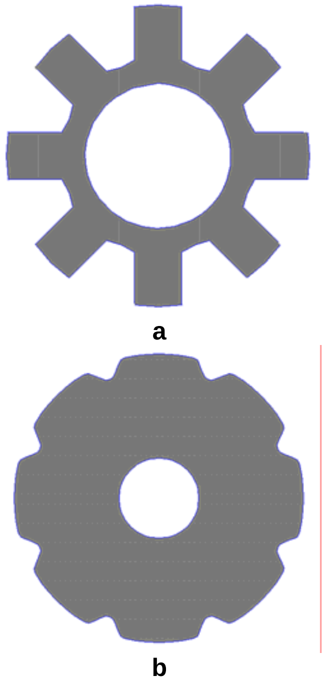


Fig. 5 Two Rotors for Different SRMs

Fig. 5 shows two rotors of the SRM. The SRM which has the upper rotor gives both high average torque and high torque ripple. High average torque because the change in the reluctance is big (the gap between the maximum inductance and the minimum inductance is big); and high ripples because the dips in the torque characteristic are big. The lower rotor is graded over the entire pole pitch so that smooth air gap variation, i.e. smooth reluctance variation, that decreases the torque ripple very much. But this SRM, which has the lower rotor, delivers low average torque because the gap between the maximum and minimum inductances is small [9].

3 Using 2D Adaptive Finite Element Method for Modeling the SRM

The magnetic flux in the SRM is determined by computing the magnetic vector potential, A, using the non-linear Poisson's equation

$$\frac{\partial}{\partial x}(\upsilon\frac{\partial A}{\partial x})+\frac{\partial}{\partial y}(\upsilon\frac{\partial A}{\partial y})=-J$$

Where υ is the magnetic relativity (which is function of both the position and the magnetic flux density) and J is the current density.

3.1 Finite element Process

12/8 SRM is considered to explain the procedures of using the adaptive finite element for modeling the SRM. The stator core back half the stator tooth (the standard design).

Step1 Initial Mesh Generation

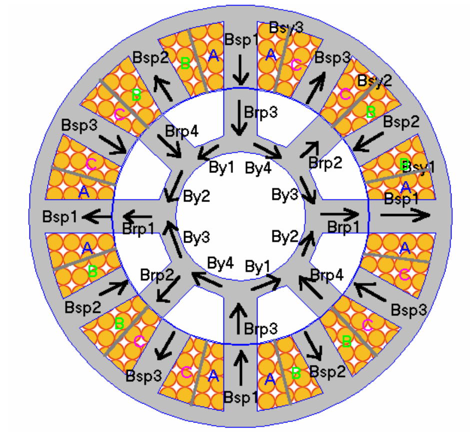


Fig. 6 the SRM which is due to be Modelled by the Adaptive Finite Element

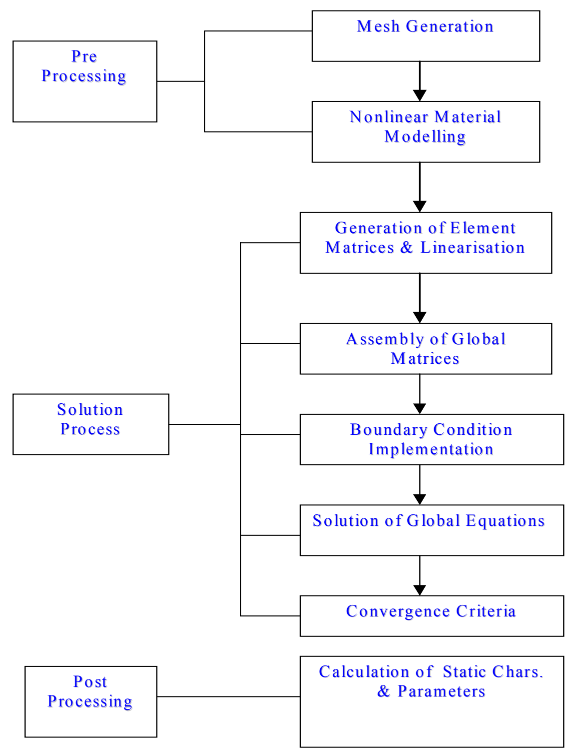


Fig. 7 Finite Element Flow Chart Process

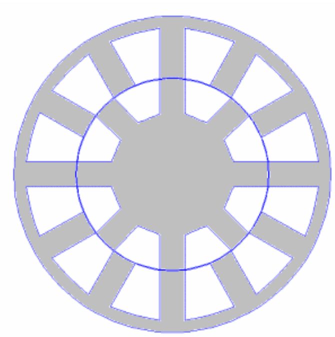


Fig. 8 the Magnetic Circuit of the 12/8 Short Pitch SRM which will be Converted to Coarse Meshes in its Simulation by the Finite Element

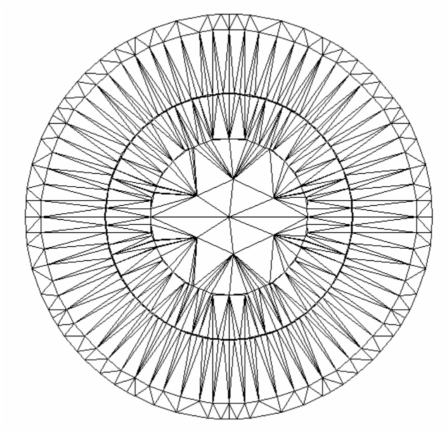


Fig. 9 Initial Mesh

Fig. 9 shows the first step in the finite element process is to generate a set of 'objects' to define the geometry. These objects are defined by co-ordinate pairs, taken in counter clockwise order, defining successive vertices of polygonal figure defining the component. In this case, there are five objects: the stator, the air gap, the two conductors, and the rotor. This way of representing the SRM means that curved surfaces are represented as a series of straight lines; therefore, an adequate number of points need to be used, particularly in the important air gap area and it is preferable to be equal space. This object definition is then used to create an initial mesh [10].

Step2 Boundary Conditions, Sources, and Material Data

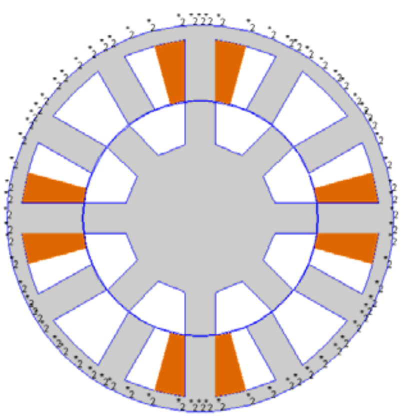


Fig. 10 Boundary Condition

The geometry and layout of the SRM is known from the design stage, and consequently, the information required to define iron saturation curves, conductor positions, and boundary conditions is all on hand. The task is to map this information onto initial finite element mesh [10].

Step3 Adaptive Solution

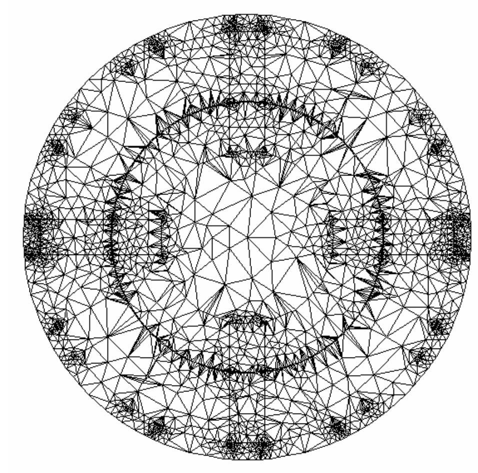


Fig. 11 the Mesh after Adaptation

The initial mesh is very coarse, and the use of this mesh produces gross error. The automatic method used here is based on the ability to estimate the error present in trial solutions. Given this ability, it is then possible to add nodes where the error is highest. As nodes are added, it is necessary to reform the elemental connections to give as near optimal a mesh as possible [10].

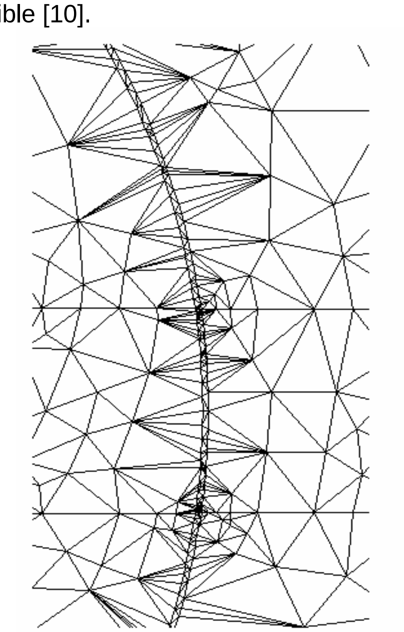


Fig. 12 the Meshes after Adaptation near the Air Gap

Fig. 11 shows the mesh after adaptation for the motor shown in Fig. 12 and it is clear the meshes fit all the parts and especially the small parts that can not be modelled mathematically such as the air gap [10].

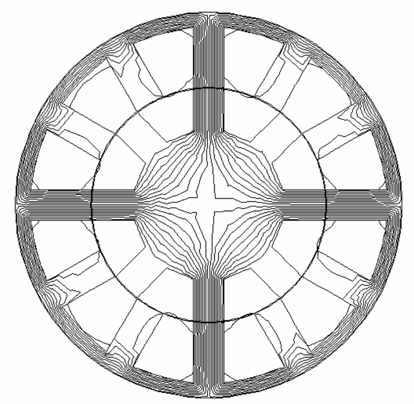


Fig. 13 the Magnetic Flux Plot at the Aligned Position when One Phase of 12/8 Short Pitch SRM is Active

Fig. 13 shows the equipotential plot. These equipotential plots represent the flux distribution in the motor. The flux distribution pattern its self gives the nature of saturation that occurs in different parts of the motor. As an example if some of flux plot lines do not go to the rotor but go to another pole or go to the core back that means the pole is heavily saturated [10].

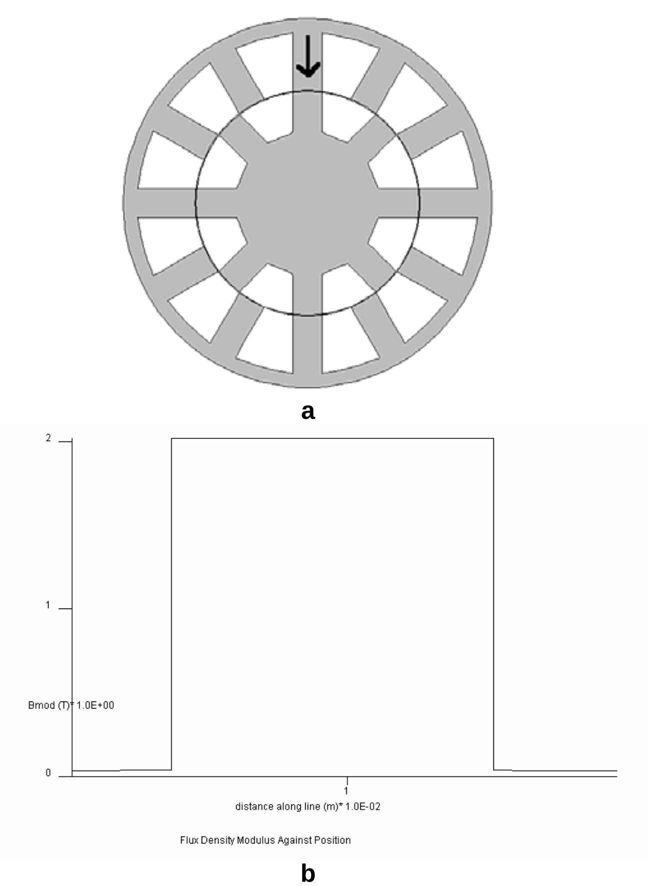


Fig. 14 the Flux Density in the Position Shown

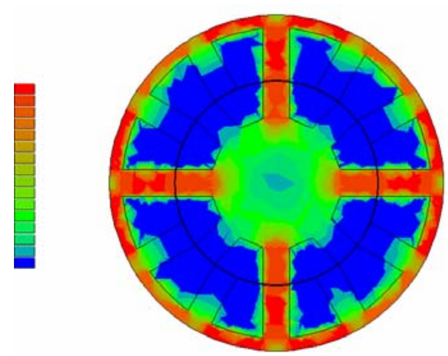


Fig. 15 Finite Element Gives Indication about the Flux Density Distribution in the SRM when One Phase of 12/8 Short Pitch is Active

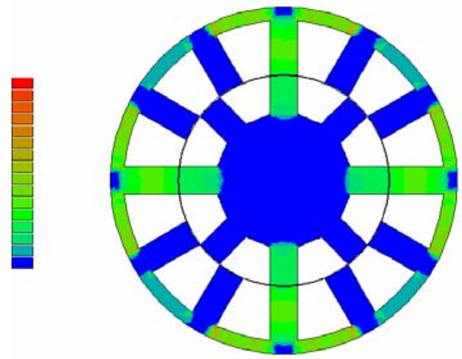


Fig. 16 Finite Element Gives Indication about the Saturation when One Phase of 12/8 Short Pitch is Active

The previous procedures show how the adaptive finite element is used to model the SRM. The design had a core back width of one half the tooth width, as it was considered that such a design should give the maximum magnetic capability. However, such a narrow core back depth would not generally be chosen for drive applications because the mechanical stiffness of the core is very low. This results in high levels of acoustic noise, which is a generally known disadvantage of SRMs. For this reason the core back depth of the design used in the next part is increased to 85% of the tooth width to model the SRM and to see the shape of the torque. The increased core back depth reduces the slot area; hence the winding volume and MMF capability are also reduced [11]. Dimensions of the machine which will be modelled are given in Table 1.

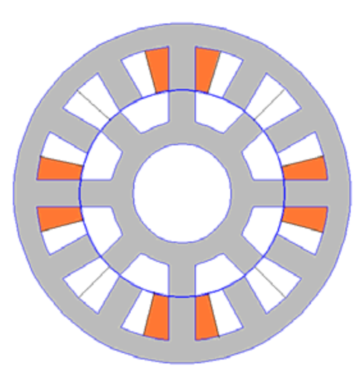


Fig. 17 12/8 SRM (wide core-backs)

Stator Outside Diameter	150 mm
Shaft Diameter	43.64 mm
Rotor Diameter	90.8 mm
Air Gap Length	0.3 mm
Stator Core-Back	10 mm
Rotor Core Back	10 mm
Stator Tooth Width	11.76 mm
Rotor Tooth Width	11.76 mm

Table 1: Dimensions of Wide Core-Back 12/8 SRM

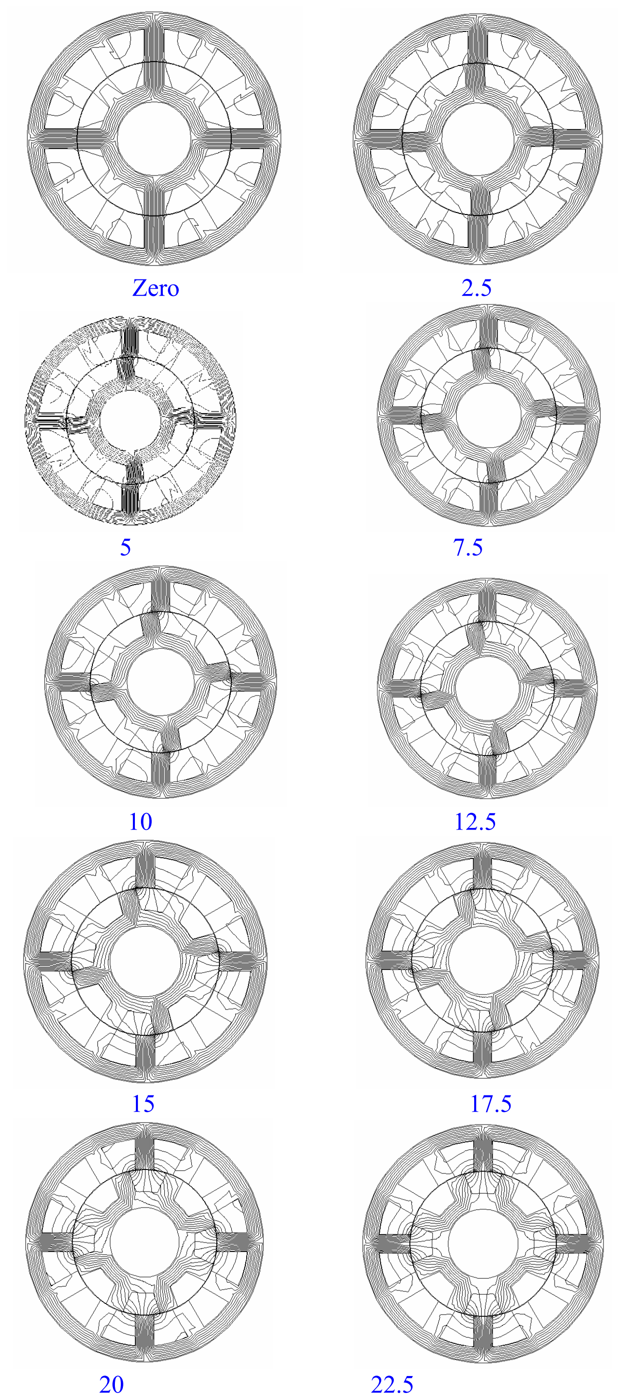


Fig. 18 12/8 SRM Models for a Range of Rotor Positions

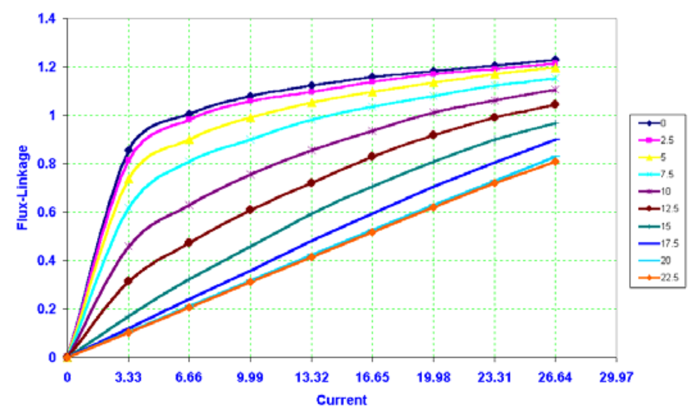


Fig. 19 Flux-Linkage Characteristic versus the Current for the Wide Core-Backs SRM

Fig. 19 shows the Flux-Linkage characteristic resulting from the above models. The vertical axis represents the flux-linkage per phase, whilst the horizontal axis represents the current per slot [11]. Each slot is assumed to contain 150 conductors.

The static torque characteristics for this machine can be derived from the Flux-Linkage characteristic of Fig. 19 by determining the instantaneous variation of co-energy and differentiating this with respect to the position.

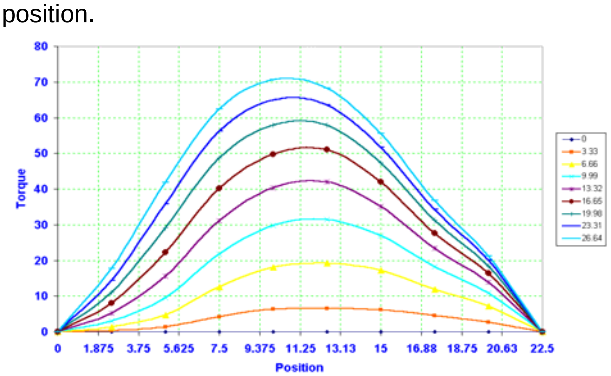
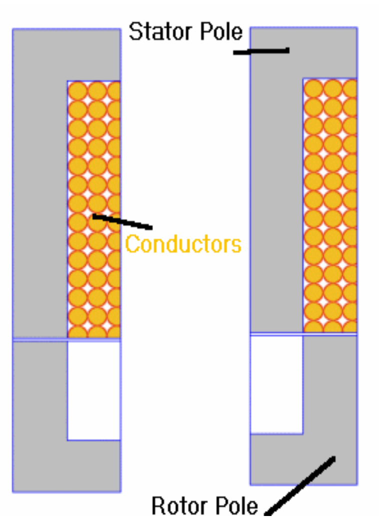


Fig. 20 Predicted Static Torque Characteristic for the 12/8 SRM

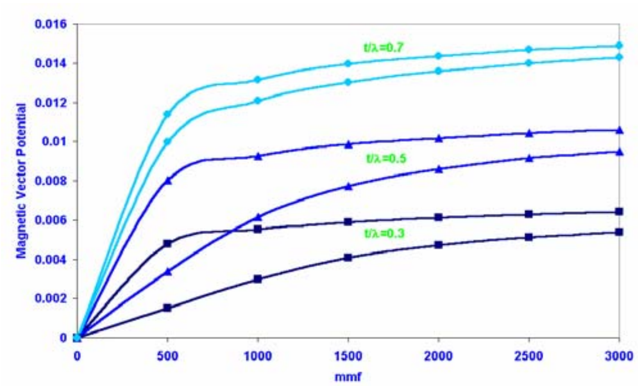
Fig. 20 shows the static torque characteristic of the 12/8 SRM, this SRM has high average torque and high ripples torque. It was designed according to the standard ways of designing the SRM; the ratio tooth width/pole arc=0.33, and the rotor outside diameter 0.6 the stator outside diameter; but wide core backs [11].

4 Using the Adaptive 2D Finite Element to Clarify the Impact of Selecting the Parameters of the Magnetic Circuit on the Average Torque and the Ripples

A simple rectilinear model is considered to show that there is impact of changing the parameters on the torque (average and ripples) [12].



a b



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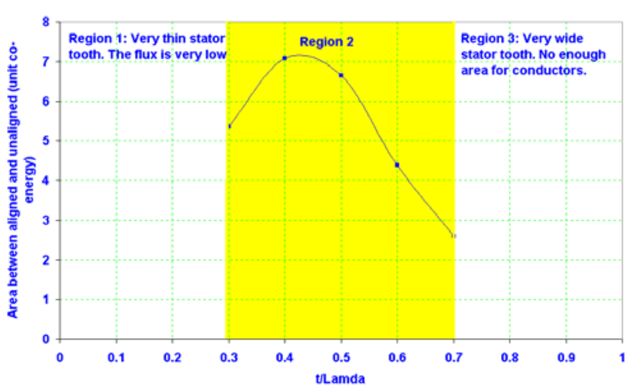

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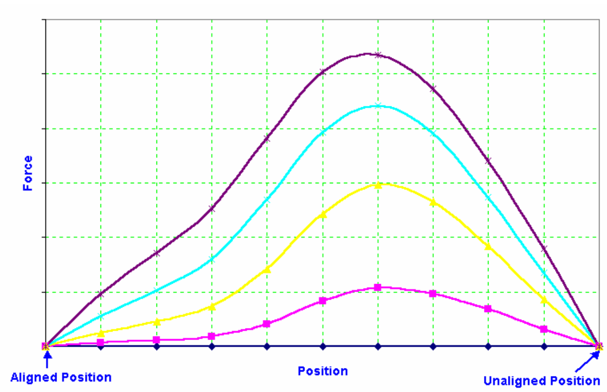

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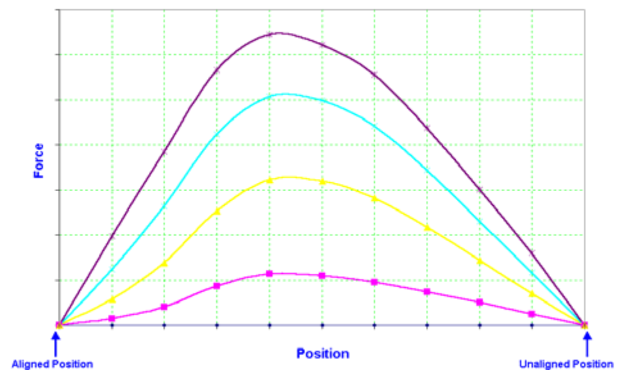


f

(t tooth width, λ pole arc)
a One pole stator aligned with one pole rotor.
b One pole stator unaligned with one pole rotor.
c The effect of changing t/λ on the torque (the area between the aligned and unaligned positions is proportional to the torque.
e,f two different torque characteristic for two different values of t/λ to indicate the effect of changing t/λ on the ripples (the top of the torque is peaky)

Fig. 21 Simple Case to Highlight the Need of the Overall Optimisation

Fig. 21 shows simple rectilinear case, one stator pole and one rotor pole, the rotor pole is moved from the aligned position to the unaligned position and the area between the aligned position and the unaligned position is under investigation for different values of t/λ. The figure shows the aligned and the unaligned positions of these two cases. Not only the area between the aligned and the unaligned positions changed but also the shape and the value of these positions also changed that has influence on the ripples. From this point of view the parameters of the SRM must be selected for high average torque and low ripples [12]. Fig. 21 (e and f) show two different shapes of torque for two different values of t/λ and it is clear the ripples from one to other.

5 Optimisation of the Reluctance Motors Generally

The reluctance motors are high nonlinear motors. Using the mathematical model to simulate this type of motors then making global optimisation for the motor entirely is complicated and difficult. In addition, the mechanical issue should be considered otherwise the SRM may be optimized entirely but mechanically unbalanced.

6 Step by step method for the Selectionon of the Parameters of the SRM

This paper introduces the step by step technique as the best way to select the parameters of the SRM for high average torque and low ripples.

a- The step by step method for selecting the parameters of the SRM depends on drawing 3-diamensions graphs, in each step the X-axis is the ratio of the stator tooth width to the pole arc, the Y-axis is the ratio of the rotor tooth width to the pole arc and the Z-axis is the cost function. The number of the 3-dimensions graphs equal the number of the goals required to be achieved [12].

b- To select the best parameters of the SRM for high average torque and low ripples; two three dimensions graphs should be drawn for two cost functions: the average torque and the torque ripples. From these two graphs the best values for the tooth width of the stator and the tooth width of the rotor will be known. Initially the core back width of the stator half the stator tooth width and the core back of the rotor half the rotor tooth width; the rotor outside diameter = 0.6 the stator outside diameter [12].

The torque is directly proportion to the co-energy [12]:

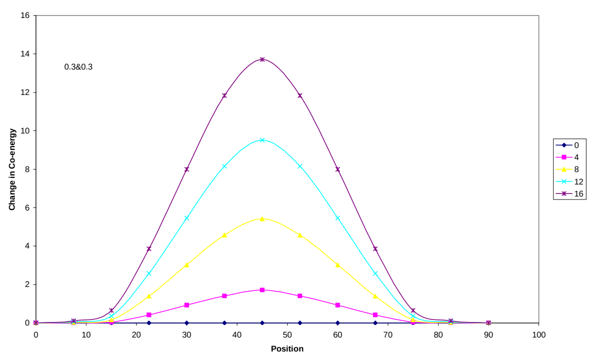
$$T = \frac{\partial \, \text{Coenergy}}{\partial \, \theta}$$

7 Effect of Air Gap on the Average Torque in SRM

In SRM the air-gap geometry plays a vital role on their performance. The radial length of the air-gap is made as small as mechanically possible to increase the saturation so that the developed torque is maximum.

8 Selecting the Parameters of 6/4 SRM for high Average Torque and Low Ripples

A 6/4 SRM is considered for selecting the best parameters for high average and low ripples.



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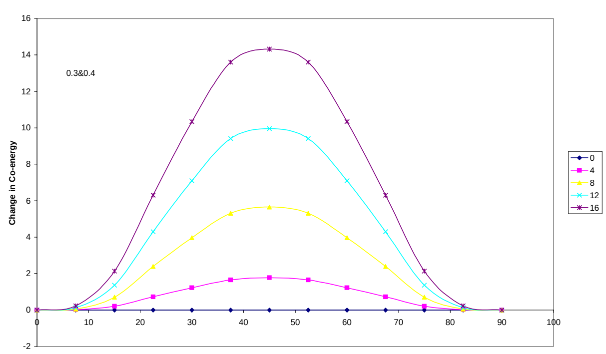
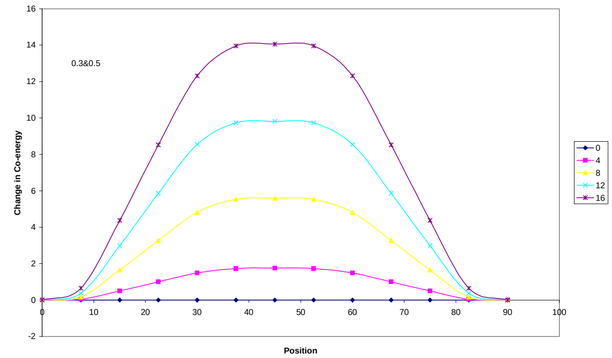


Case 0.3 & 0.4



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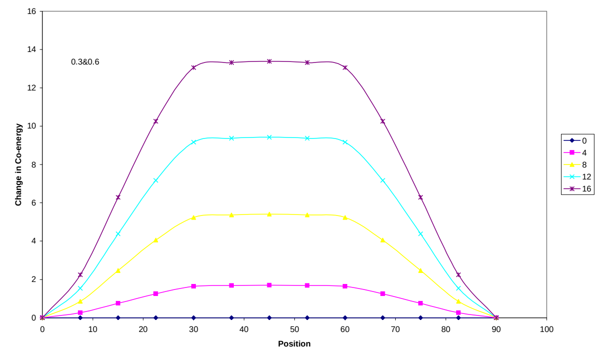

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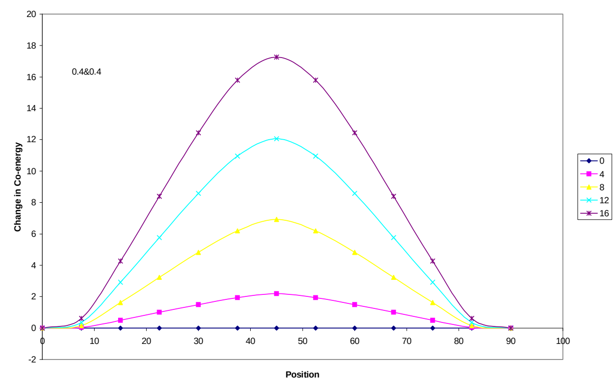

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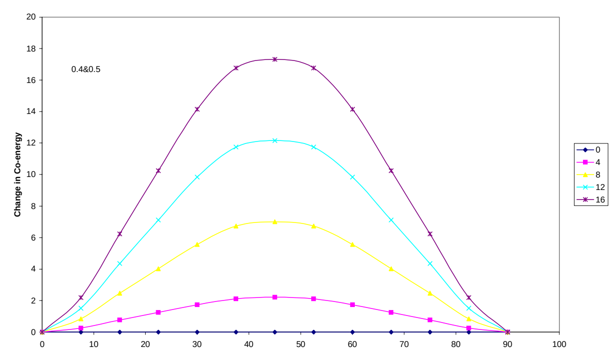

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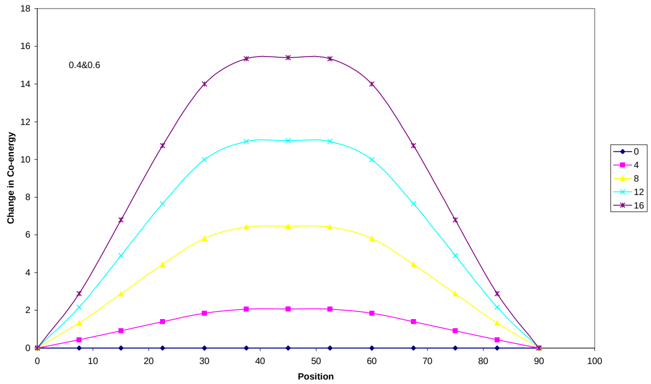

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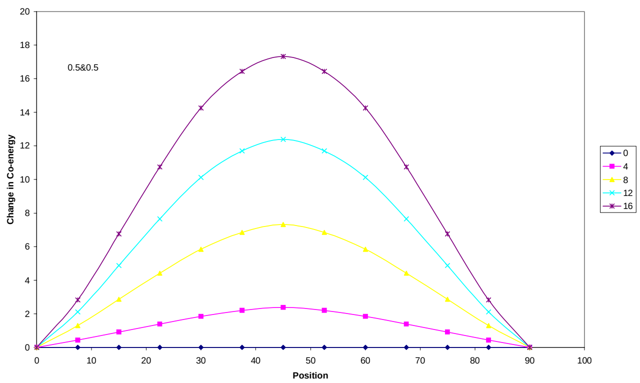

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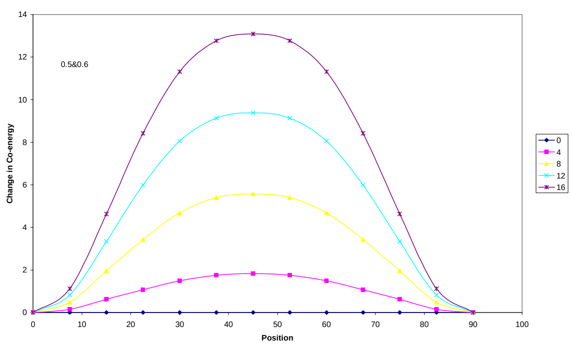
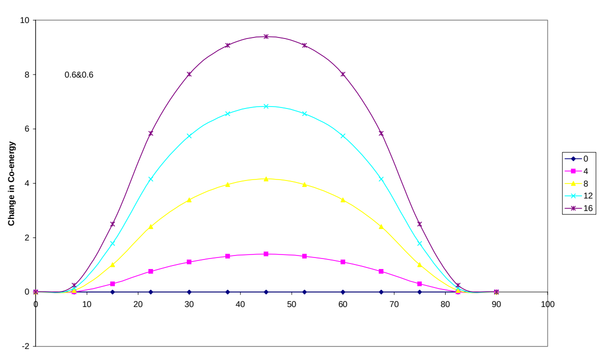


Case 0.5 &0.6



Case 0.6 &0.6

Fig. 22 Co-energy Change for Different Values for Pole Width over Pole arc in both the Rotor and the Stator

Straight line in the co-energy shape means constant in the torque characteristic because the differentiation of the straight line is constant.

Here the selection of the parameters for two targets: First, for maximum average torque, second for low ripple torque. The torque is proportional to the co-energy so the area under the curve of the co-energy is proportional to the average torque and the length of the straight line is proportional to the flat part in the torque characteristic [12].

Tooth width / Pole arc	0.3	0.4	0.5	0.6
0.3	45.696	47.72	46.86676	34.98204
0.4	47.72	57.56464	57.7084	51.34808
0.5	46.86676	57.7048	57.75548	21.81152
0.6	34.98204	51.34808	21.81152	15.661

Table 2 the Area between the Aligned Position and Unaligned Position in Unit Area

From table 2 the case of t/λ (0.4 & 0.5) and (0.5 & 0.5) are two cases give the highest average torque. Assume two coils each coil has 200 turns.

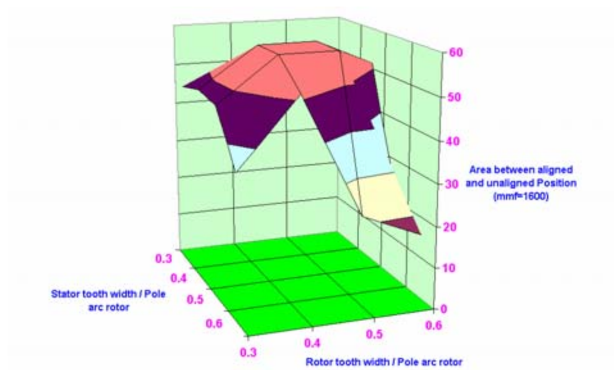


Fig. 23 Effect of Changing the Pole Arc on the Average Torque

Tooth Width / Pole Arc	0.3	0.4	0.5	0.6
0.3	22.5	22.5	22.5	22.5
0.4	22.5	30	30	22.5
0.5	22.5	30	22.5	22.5
0.6	22.5	22.5	22.5	7.5

Table 3 the Length of the Straight Lines in the Co-Energy Change in Degrees

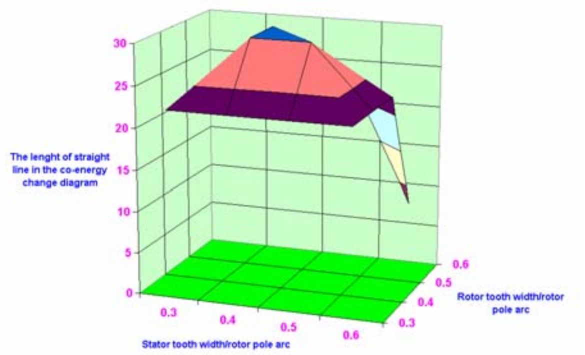


Fig. 24 the Length of the Straight Line in the Shape of the Co-energy Change versus the Value of the Teeth Widths to the pole arc

Fig. 23 shows that when the ratio of t/λ equal 0.4 & 0.4 and 0.4 & 0.5 the area between the aligned position and the unaligned position is maximum. And from Fig. 24 the length of the straight line in the co-energy change is the highest at the same ratios. So from these two cases the best ratios for the tooth width to the pole arc are 0.4 & 0.4 and 0.4 & 0.5. But 0.4 &0.5 is preferable to avoid the negative torque. These ratios for this 6/4 SRM particularly but for any other SRM not valid; each SRM its parameters must be selected by the same way [12].

9 Increasing the Stator Core Back to Decrease the Torque Ripple More

The SRM which has t_r/λ = t_s/λ has low ripples and significant output but no flat top [13-15]. To get flat top the stator core back has to be increased to decrease the saturation [13-15].

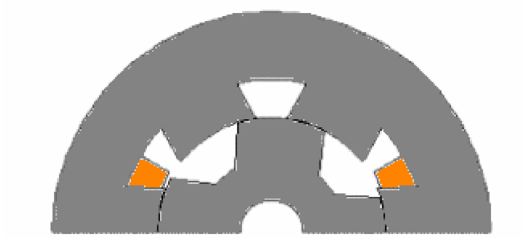


Fig. 25 SRM has t/λ=0.5 & 0.5 Wide Stator Core Back

Fig. 25 shows an example of SRM has equal teeth in the rotor and stator. The core back of the stator is very wide.
The dimensions of the machine:
Stator: Bore diameter 91.4mm, outside diameter 175mm, height of the slot 15mm and width of the tooth 35.7mm.
Rotor: Air gap length 0.3mm, shaft diameter 25mm, height of slot 16.5mm, width of tooth 35.7mm.

And outside axial length 150 mm.

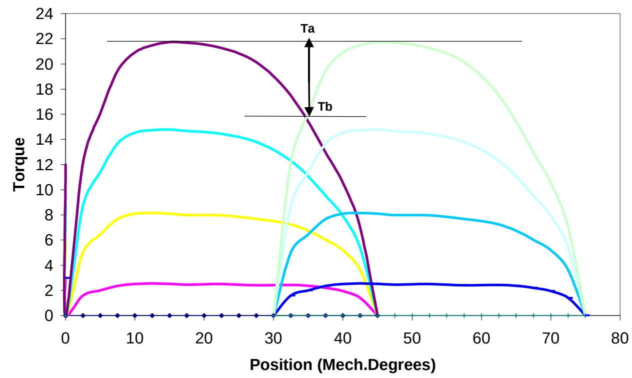


Fig. 26 the Shape of Static Torque in Case t/λ 0.5 & 0.5

Fig. 26 shows that increasing the core back depth to be equal to the tooth width approximately decrease the ripple in the torque characteristic [13-15].

$$\% \text{ Ripple} = \frac{T_a - T_b}{T_a} = \frac{22-16}{22} = 27.27\%$$

9 Adjusting the Overlap Region for Smooth Torque

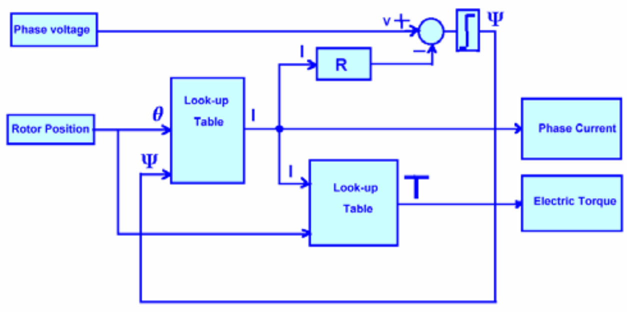
The basic rules governing SRM design to ensure there is overlap between the torque production regions of each phase. For this 6/4 SRM there is one phase for every two stator poles $(q = N_s/2)$, the extent of this overlap is dependent upon N_s, N_r, β_s and β_r [16]. The majority of the torque ripple occurs in this overlap region as the responsibility for torque production is handed from one phase to another. The extent of the overlap sets a limit on the amount of control that the motor can be expected to exert over torque ripple. The general expression of calculating the overlap region in reluctance drives:
Overlap = $\min(\beta_s,\beta_r)-2\pi/N_sN_r$ (1)
This expression shows that the amount of overlap increases with N_s and N_r. Overlap is also proportional to β_s and β_r [16].
For this motor
$N_s = 6$ and $N_r = 4$
Tooth width in both the rotor and stator =35.7
Stator bore diameter =91.4

$$\beta_s = \frac{360*35.7}{91.4*\pi} = 44.758 \text{ degrees}$$

and the rotor diameter 90.8

$$\beta_r = \frac{360*35.7}{90.8*\pi} = 45 \text{ degrees}$$

Substituting in equ. (1)
Overlap = 44.758 –12=32.758 degrees.



Block Diagram of the Simulation of Matlab toolbox of SRM

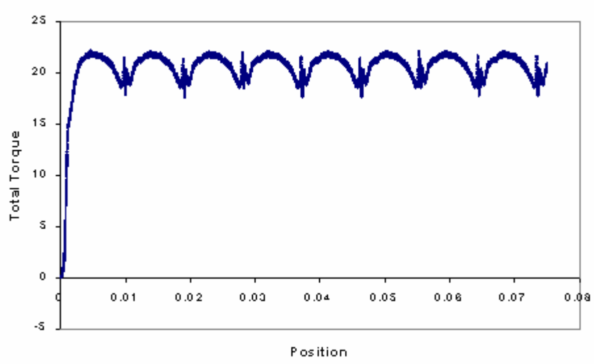


Fig. 27 the Performance at 550 rpm for the SRM Shown in Fig. 25

Fig. 27 shows low ripples in the torque characteristic when equ. 1 is used to estimate the switching angle. The percentage of torque ripple at 550 rpm is very low [17-19].

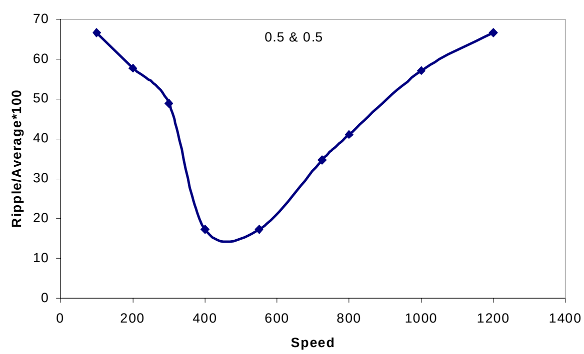


Fig. 28 the Percentage of Torque Ripple/ Average Torque versus the Speed

Fig. 28 shows that the ripple torque will be minimum when the SRM runs between 350 rpm and 550 rpm and the on/off angles kept const [17-19].

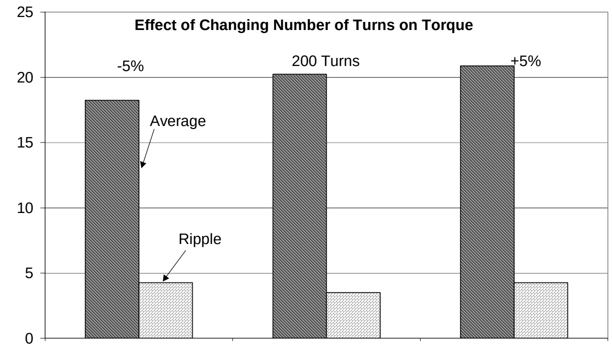


Fig. 29 Effect of Changing the Number of Turns on the Torque Characteristic

Fig. 29 shows the effect of small change in the number of turns on the average torque and the torque ripple. The machine has 200 turns each coil 100. The figure indicates when the number of turns increased 5% the average torque increased but the ripple also increased (Ripple/Average)*100=(4.25/20.875)*100=20.35%
and when the number of turns decreased 5%
(Ripple/Average)*100=(4.25/18.25)*100=23.28%
but at 200 Turns:
(Ripple/Average)*100=(3.5/20.25)*100=17.2839%
So 200 turns give minimum ripple and good average [17-19].

10 Testing the Selected Parameters for another Number of Poles

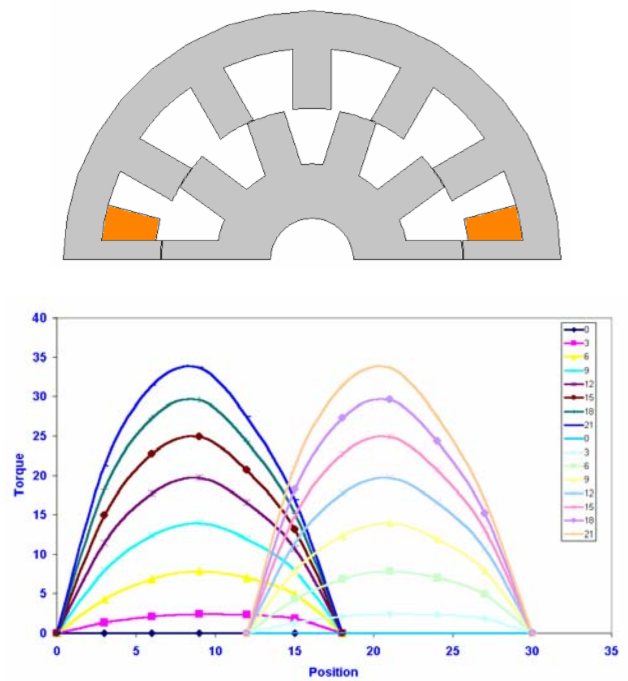


Fig. 30 Best Values of the Stator and Rotor Teeth widths to the Pole arc for 6/4 SRM not the Best for Other Numbers of Poles

Fig. 30 shows the same ratios of the teeth widths to the pole arcs are used for the same SRM but different number of poles. The ripples is high not like the previous number of poles. From this point of view it is necessary to select the parameters for each design and there is not general formula for parameters for high average and low ripples [20].

11 Conclusion

The paper clarifies the point of the limitation of the reluctance torque per unit volume and how it stands against shaping the magnetic circuit and selecting its parameters to minimize the ripples, by another If the SRM designer attempt to select the parameters of the SRM to minimize the ripples he has to scarify some of the average torque. From this point of view the paper presents simple way of selecting the parameters of the SRM for high average torque and low ripples. Then the paper highlighted some design points to get more flatter torque by widening the core back and selecting the on/off angles. The paper indicted an important aspect that the best parameters for one SRM not valid for the same SRM which has different design or different number of poles.

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