Optimised Toolbox for the Design of Rotary Reluctance Motors
I Grace, Rozita Teymourzadeh, S Bright, C V Aravind

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The operation of reluctance machine is highly affected due to the attraction-repulsion principle. The problem has been identified as early over past several decades. Numerous researchers present their work by addressing the issues on the machine design aspects. However it is very tedious and time consuming as the design procedure involves higher analytical derivations and calculations. This paper attempts to present a graphical user interface toolbox to use for the design of reluctance motors. The developed toolbox help the user a simple design procedure for a rotary reluctance motor. The GUI also calculates the analytical values of the aligned, unaligned and intermediate inductance values of the particular design as this gives a comprehensive results on the analytical evaluation of the inductance at various rotor positions. Cyclic Integration Method (CIM) is used for the evaluation of the designed tool box for validation.

Keywords-- Motor; GUI , CIM, Rotary Reluctance; Toolbox

I. INTRODUCTION

The design of motor in general is a complex procedure and hence requires an easy and understandable design method and tool for the designer. Various CAD has being developed for the design of electrical machines. Most have being developed using MATLAB m-file while others have used GUIDE, Simulink and java. Designs have been made mostly for DC machines, AC machines, Induction motors and transformers [4]. Work on CAD design of reluctance motor is gaining popularity as increase in the need to develop new magnetic design of reluctance motor is on the rise [1,2]. Reluctance motors have simplicity in construction, high fault tolerance and makes use of no magnets in its magnetic design. Torque ripple are generated due to the fringing flux that develop just before the overlap position of the stator and rotor teeth. Therefore it is highly important to study the behaviour of the reluctance machine near to the saturation. The study of the inductance slope during the rising edge from unaligned to aligned decides the motoring torque. Variations on the physical dimension of the machine helps to achieve a smoother torque profile with reduced ripples [1,3].

II. DESIGN TOOL

The design of reluctance motor is a complex procedure and hence requires an easy and understandable design method and tool for the designer. This is the reason the GUIDE tool of MATLAB/SIMULINK is used for the design. This tool is picked with preference to m-file because of its user friendly interface compared to m-file been used. The user of m-file has to understand the codes written by the programmer while the user of GUIDE need not worry about the codes used. In designing the GUI, the basic principle involved is taking inputs into the GUI and then an output based on the computational codes fixed into the m-file of the GUI.

Fig. 1: Introductory GUI
The introductory GUI above makes use of a pushbutton that links the user to the rotary SRM design. The first graphic tool is the rotary SRM design guide. The mechanical design parameters for the motor take input such as the bore diameter, length, pole arcs of both the stator and rotor and the capacity values of the required motor under design. These inputs are then used to calculate the other dimensions of the motor. From these, the average torque is evaluated. If the average torque is not equal or greater than the required torque, the user is able to vary the inputs until this is achieved. This in turn helps the user be able to compare various structures of the motor it gives the required torque. Also included in this is the costing analysis for the motor. The developed tool for the machine design for the rotary configuration is as shown in Fig. 2.
The analytical inductance evaluation is used for the inductance profile GUI. The inductance GUI takes input parameters of Number of stator poles \((P_s)\) and rotor poles \((P_r)\), stator pole arc \((\beta_s)\), rotor pole arc \((\beta_r)\), air gap length \((l_g)\), bore diameter \((D)\), stack length \((L)\), shaft diameter \((D_{sh})\), stator back iron thickness \((b_{sy})\), height of stator pole \((h_s)\) and rotor pole \((h_r)\), turns per phase \((T_{ph})\). The second graphic tool has the analytical evaluations of the inductance at various rotor positions. The user is able to see results for the inductance at fully unaligned, aligned and intermediate positions. Graphical representation of the BH curve of the material used, the inductance profile graph, the graph of torque versus rotor position and the flux linkage versus current graph can be analyzed from the result section as shown in Fig. 2.

The optimal performance of this method has been validated by comparing the results with the finite element design and analysis tool [3]. The design procedure involves the design of the entire layout of the machine including the physical dimensions such as the diameter, length, rotor size and other standard parameters. The machine specifications of a SRM includes the required power output in horse power \((hp)\), speed \((rpm)\), allowable peak current \((A)\), available dc supply voltage etc., From this value the required torque output can be calculated using the equation:

\[
T_{req} = \frac{P_{hp} \times 7.45.6}{2\pi N \times 60} \text{ N.m} \tag{1}
\]

where,

- \(T_{req}\) - torque required \((\text{N.m})\)
- \(N\) - Speed of the motor \((\text{rev/min})\)

This helps to know the actual torque that is required as provided by the machine specifications. When the average torque calculated is equal to or greater than the required torque, the machine is according to specifications and the user can then use the dimensions for the motor parts to fabricate the motor. The average torque of reluctance motor is derived from the inductance difference between the fully unaligned rotor position and fully aligned rotor position. The equation linking the torque generated, rate of change in inductance and magnitude of current is:

\[
T = \frac{1}{2} \frac{\Delta l \times i_p^2}{\Delta \theta} \tag{2}
\]

where

- \(\Delta l\) = change in inductance,
- \(i_p\) = rated current \((\text{amperes})\),
- \(\Delta \theta\) = change in rotor position

The flowchart used for the machine design procedure in sequential step is shown in Fig. 4.

Design procedures of reluctance machine are documented comprehensively in [1], [2] and this is used as reference for this research work. However the designed values have been verified and validated by introducing an analytical approach method as Cyclic Integration Method (CIM). The cyclic integration method involved the triangulation principle normally employed for the finite element analysis. But in this approach a triangulation on the vector potential is calculated for a small strip of area and later integrated to the whole radial surface. This calculated value is then integrated once again in the circumferential surface of the area enclosed. The optimal performance of this method has been validated by comparing the results with the finite element design and analysis tool [3].
The graphical user interface based on the above design then gives the values of the inductance, magnetic flux density, reluctance for each flux path for fully aligned, unaligned and various intermediate rotor positions. For optimize the performance of the machine designed and to give the user on the motoring slope the total unaligned and aligned inductance is generated by calculations. Form the data the designer can identify and understand the performance comparisons by varying the design values.

To verify that the inductance profile calculations are correct, the cyclic integration method is used to calculate both the unaligned and aligned inductance. The cyclic integration method involves the design of the motor using CAD to determine the angles and limits of the integration and also iterating the magnetic flux density of the stator pole so that the specified magneto motive force (mmf) is derived. However this method of cyclic integration does not take into account the effect of the leakage flux.

\[ \text{MMF} = F = T_{ph} * I_p \quad (3) \]

Once the mmf is calculated the permeance for an entire bounded region is calculated as:

\[ P_{radial} = \int_{ll}^{ul} \mu_0 L dr \frac{d\theta}{r} \quad (4) \]

where  
- \( r \) - radius of the region enclosed  
- \( L \) - stack length of the machine  
- \( ul \) - the upper limit  
- \( ll \) - the lower limit
Then the total reluctance for the selected face is calculated using

$$ R = \int_0^a R_{\text{Radial}} $$  \hspace{1cm} (5)$$

where

$ \theta $ - the angle subtended by the bounded region

After the total reluctance is derived the magnetic flux density of the stator pole is derived using the formula:

$$ B_{sp} = \frac{F}{R \cdot A_{sp}} $$  \hspace{1cm} (6)$$

where $ R $ = Reluctance of the stator pole

$ A_{sp} $ = Area of a stator pole

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**Fig. 6: Analytical magnetic design calculations**

The calculation area for the various position under fully aligned, partially aligned and unaligned conditions are presented in Fig. 7. However the flux lines assumed here is of concentric circles and the limitation on the choice of circle is limited with respect to the high numeric computations involved.

**Fig. 7 Cyclic integration method at various positions**

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**V. PERFORMANCE EVALUATIONS**

Test performance design for the machine is carried out using the developed GUI and an 8/6 reluctance machine design is presented and the inductance values are evaluated using analytical method for checking for the optimisation of the presented toolbox. The GUI inductance profile is test using the inputs in below:

**Fig. 8: Inputs for Inductance Profile**

The results for the fully unaligned and aligned positions are as shown in Fig. 9 below. This shows the inductance for each flux path, the flux density and the reluctance.

**Fig. 9: Results for fully unaligned and aligned positions**
The total unaligned and Unaligned inductance are as shown in FIG. 10.

![Fig. 10: Total unaligned and aligned Position](image)

To verify the values the cyclic integration method based on the CAD design for the same parameters of the designed machine is performance.

![Fig. 11: Flux maps at fully unaligned Position](image)

The unaligned inductance of a reluctance motor takes place from zero degrees (0°) or \((180/P_r)\) angle of rotor pole from stator pole and \(((180/P_s) - (\beta_s + \beta_r))\). With reference to the example; the rotor positions at fully unaligned position fall within 30° and 10° from rotor poles to stator poles. This gives two distinct regions for the unaligned inductance which are calculated and the average taken as the inductance of the SRM machine at fully unaligned position. The limits of integration are 15.37 and 0 for part a and 17.52 and 7.89 for part b. The inductance values derived from these are:

- Unaligned Inductance for part a = 16.6mH
- Unaligned Inductance for part b = 4.7mH
- Total Unaligned Inductance = \((\text{part a} + \text{part b})/2\)
  = 10.7mH

![Fig. 12: Flux map for aligned inductance](image)

The result of the aligned inductance from the cyclic integration method is = 64mH.

The comparison between analytical (GUI) and the cyclic integration method is as shown in the table below:

<table>
<thead>
<tr>
<th></th>
<th>GUI (mH)</th>
<th>Analytical (mH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aligned inductance</td>
<td>66.7652</td>
<td>64</td>
</tr>
<tr>
<td>Unaligned inductance</td>
<td>11.4217</td>
<td>10.7</td>
</tr>
</tbody>
</table>

Percentage difference between the values for unaligned inductance is 6.31% while that for aligned is 4.14%. The difference in values comes as a result of assumptions in the calculations. For example, the cyclic integration method does not take into account the leakage flux and the integration path is based on assumption. The fully unaligned position for this motor takes place between 0° and 10° rotor pole position to stator pole position. To get a more accurate result, more regions can be selected and their inductance derived. The final inductance then takes the sum of all regions and average value can be derived by the numbers of regions taken. In general, from the error calculations, the percentage difference is seen to be minimal and the GUI results verified to be accurate. Since the inductance have being calculated and verified, the torque of the machine can now be computed. The average torque is derived based on uniform current in the rising edge of the inductance profile. The average torque is calculated by:

\[ T_{av} = \frac{\delta w_m P_r P_s}{4\pi} \]  

where

- \(T_{av}\) -average torque
- \(\delta w_m\) -total work done
- \(P_r\) -number of rotor poles
- \(P_s\) -number of stator poles

The total work done is calculated by subtracting the work done in the unaligned position from that of in the aligned positions. The work done is calculated by multiplying the flux linkage and the corresponding current.

![Average Torque (Nm) 25.1199](image)

**Fig.13: Torque result**

VI. **Optimisation of Machine Design Using the Developed Tool**

Two different variations are presented with for the same base values and the results are presented. The machine specifications are as shown in Fig. 11. To show different design, two test condition input are used Input A and Input B as shown in Fig. 15 & Fig 17 respectively. Based on the output Fig. 16 & Fig 18 for the two input conditions A and B respectively, the optimal design is considered for fabrication.
The design output of the motor gives the required torque, back iron thickness, rotor and stator height, pole width, turns per phase, MMF, peak current, aligned and unaligned inductance of the motor and finally the average torque. If the average torque generated does not give the required output, the user is required to change some inputs parameters such as the stator and rotor pole arc. This helps move the average torque closer to the required torque. When this is achieved, the motor can then be said to have been designed. The above results compare the design for two separate inputs. As seen from results the average torque calculated is less than the required torque in
In this case, the input parameters where then varied, changing the pole arcs. From results B, it is seen that the average torque is greater than the required torque. This shows that the design of the SRM parameters is accurate at this stage. The design of the motor using CAD is as shown in Fig.19.

A generalised tool box for optimisation of the design of rotary reluctance motor is presented. An 8/6 model with two different design parameters is presented to identify the optimisation procedure from the toolbox developed. The design is broken down into three main paths: the inductance calculations, the analysis of the motor and the design based on the motor parameters [1,2]. The flux linkage and stator current are generated using the coding as a result of the inductance derived from the inductance profile. This would help the designer to optimise the model for good machine design.

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