

An educational tool to assist the design process of switched reluctance machines

ABSTRACT

The design of electric machines is a hot topic in the syllabuses of several undergraduate and graduate courses. With the development of hybrid and electrical vehicles, this subject is gaining more popularity, especially in electrical engineering courses. This paper presents a computer-aided educational tool to guide engineering students in the design process of a switched reluctance machine (SRM). A step-by-step design procedure is detailed and a user guide interface (GUI) programmed in the Matlab® environment developed for this purpose is shown. This GUI has been proved a useful tool to help the students to validate the results obtained in their lecture assignments, while aiding to achieve a better understanding of the design process of electric machines. A validation of the educational tool is done by means of finite element method (FEM) simulations.

Keywords Computer-aided design, electrical engineering, sizing equations, switched reluctance motor.

INDEX OF SYMBOLS

A	Area [mm ²]
A_s	Electric loading [A/m]
B	Flux density [T]
b_{sy}, b_{ry}	Width of stator/rotor yoke
β_{sp}, β_{rp}	Stator/rotor polar angle

D	Diameter [mm]
FS	Frame size
Φ	Magnetic flux [Wb]
ψ	Flux linkage [Wb]
g	Air gap length [mm]
h_{sp}, h_{rp}, h_c	Height of stator/rotor pole or coil [mm]
i	Current [A]
J	Current density [A/mm ²]
k_e, k_d	Efficiency, duty cycle
l	Axial length [mm]
L	Inductance [H]
n	Speed [r/min]
N_s, N_r	Number of stator/rotor poles
T	Torque [N·m]
P	Power [W]
q	Number of phases
\mathfrak{R}	Reluctance
T_{ph}	Turns per phase
V	Voltage [V]
ω	Angular speed [rad/s]
$\omega_{sp}, \omega_{rp}, \omega_c$	Width of stator/rotor pole or coil

INTRODUCTION

Hybrid and electric vehicles have several advantages over ICE (internal combustion engine) powered vehicles such as higher efficiency or lower exhaust emissions [1]. Although several types of electric machines exist, SRMs offer appealing features including simple and rugged construction, brushless design, high temperature capability, or fault-tolerant operation among others [2,3]. They are even envisaged for electric vehicle (EV) in-wheel applications [4]. It is also known that SRMs have higher specific torque and efficiency than equivalent induction machines. SRMs have two main drawbacks, i.e. an important and an inherent difficulty in the control due to their inherent non-linear behavior since they operate under saturation conditions, and higher torque ripple than other electric machines. Consequently, SRMs are less applied in industrial environments and therefore much less studied in most electrical engineering courses than other types of electric machines [5]. However, SRMs are good candidates in applications which do not prioritize a very low torque ripple or a fine positioning, such as in electric vehicle

drivetrains [1].

This work is aimed to foster students' interest and motivation in the design of electric machines topic. The learning system presented in this paper involves both machine sizing by means of an iterative system based on analytical equations and the design verification through a computer-aided educational tool. This tool allows the students to validate the design method and calculations proposed in the lecture sessions. Computer-aided educational tools are appealing since they can improve the quality of education, especially in engineering courses. They can also be a good complement of lecture and practical sessions. It is also recognized that these tools can facilitate students learning, since they provide graphical interaction and flexibility, thus some difficult topics become more visual [6,7]. In addition some computer-aided tools allow testing and validating machines and drives in a virtual way, thus minimizing costs and difficulties of experimental tests.

The GUI presented in this paper provides a graphical, friendly and efficient environment that facilitates the design process of SRMs. The GUI allows introducing the main design parameters and restrictions of the SRM to be designed, such as the desired output power, rated speed, rated phase current, number of phases, configuration or materials among others, and calculates the dimensions and the main mechanical, electric and magnetic parameters which describe the behavior of the designed SRM.

It is worth noting that although there are several educational papers dealing with the topic of performance analysis and control of different types of electric machines [5,7,8], the authors of this work have found no educational papers dealing with the topic of designing and sizing SRMs.

COURSE STRUCTURE AND DETAILS

The computer assisted design of the SRM described in this paper is taught in the *Plug-In Hybrid Electric Vehicles: Concept, design and project of Electric propulsion systems*, a 10-weeks elective course of the eighth-semester Degree in Engineering taught at the ETSEIAT school of the Universitat Politècnica de Catalunya (UPC). This course has an estimated students' load of 3 ECTS (European Credit Transfer and Accumulation System). The lectures meet for two one-hour lecture sessions every week, and every two weeks students attend a two-hour practical session in which the computer assisted motor design experiment is taught. The contents of the *Plug-In Hybrid Electric Vehicles: Concept, design and project of Electric propulsion systems* course are as follows:

- Hybrid electric vehicles
- Electric propulsions systems for vehicles
- Electric drive train design
- Design of a control drive system
- Analysis of integration of plug-in hybrid electric vehicles in the distribution grid

THE SIZING PROCEDURE

Electric machines are often initially designed and sized by applying the output equation, which relates the main machine parameters such as length, bore diameter, base speed, electric loading and magnetic flux density to the rated output power [9]. From this equation an estimation of the main dimensions can be obtained, which are the starting point in the design evaluation process.

The sizing equation of the SRM can be written as,

$$P_{out} = k_e \cdot k_d \cdot \frac{\pi^2}{120} \underbrace{(1 - L_u / L_a)}_{k_L} \cdot (B \cdot A_s) \cdot D^2 \cdot l \cdot n_{SRM,r/\min} \quad (1)$$

k_e being the efficiency, k_d the duty cycle, L_a and L_u being, respectively, the aligned and unaligned inductances, B the stator pole flux density at the aligned position, A_s the electric loading, D the bore or stator inner diameter, l the axial length of the motor and n_{SRM} is the rated or base speed expressed in r/min. Note that (1) supposes constant peak values of phase currents and voltages.

However, to directly size the SRM from (1), some assumptions need to be established, such as the values of k_e , k_d , k_L , B and A_s . The accuracy of the final solution will greatly depend on the degree of uncertainty of these assumptions. Therefore, a more accurate sizing procedure than the direct application of (1) is carried out in this work. Since the SRM is often used as a variable-speed actuator, both the rated output power and the base speed are usually design specifications. Therefore the output torque can be obtained from,

$$T_{out} = \frac{P_{out}}{\omega_{SRM}} = \frac{30}{\pi} \cdot \frac{P_{out}}{n_{SRM,r/min}} \quad (2)$$

Fig. 1 summarizes the procedure applied to design the SRM, which is described in this section.

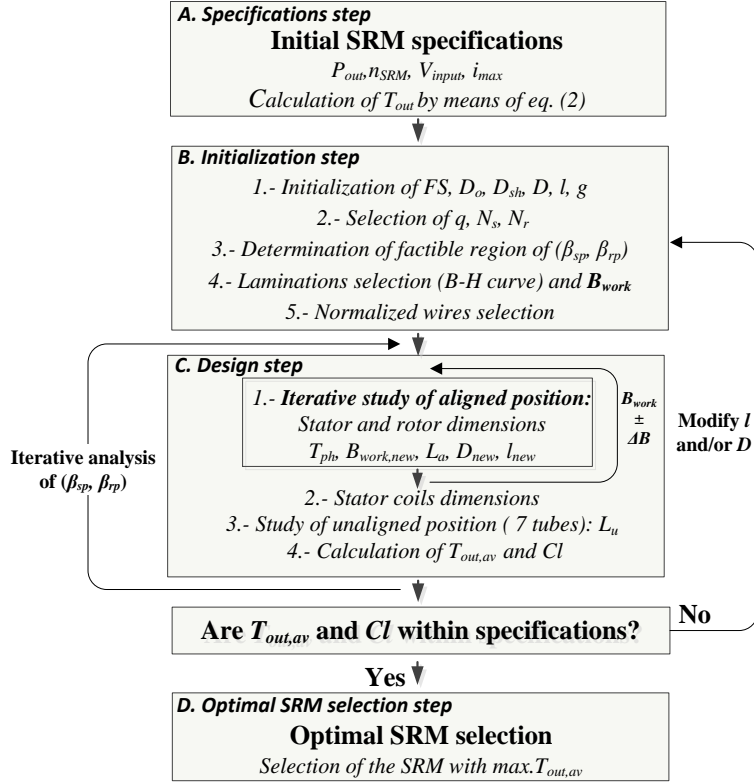


Fig. 1. Steps involved in the design procedure of the SRM.

A. Specifications step

To design a motor for a particular application, some initial specifications are required. SRM design specifications comprise the rated speed, rated output power, allowable flat constant peak value of the phase current, and the available supply voltage. Note that the output torque is fixed from the specified speed and power output, as indicated by (2).

B. Initialization step

In this phase, several initial values of important parameters of the SRM are selected, which are described below.

- 1. Initial values of the frame size, outer stator and shaft diameters and calculation of the laminations length.** The preliminary frame size FS is selected according to Table 1 [10,11].

Table 1. Frame Size Selection for 1500 r/min Motors

Rated speed ω (r/min)	Output power P_{out} (kW)	Frame size FS (mm)
1500	0.12	63
1500	0.18	63
1500	0.25	71
1500	0.37	71
1500	0.55	80
1500	0.75	80
1500	1.10	90
1500	1.50	90
1500	2.20	100
1500	3.00	100
1500	4.00	112
1500	5.50	132
1500	7.50	132
1500	11.0	160
1500	15.0	160
1500	18.5	180
1500	22.0	180
1500	30.0	200
1500	37.0	225
1500	45.0	225
1500	55.0	250
1500	75.0	280
1500	90.0	280

Next, the stator outer diameter is calculated by applying,

$$D_o = (FS - x) \cdot 2 \quad (3)$$

where x is subtracted to account for the machine foot (in the example calculated in Section V

it is assumed $x = 3$ mm). The shaft diameter D_{sh} is selected according to Table 2 [10].

Table 2. Normalized Frame Size and Shaft dimensions [IEC 60034]

Frame size FS (mm)	Frontal width AB (mm)	Outer diameter D_o (mm)	Shaft dimensions (mm)			
			D_{sh}	g_{sh}	f_{sh}	h_{sh}
63	120	120	11	8.5	4	4
71	136	136	14	11.0	5	5
80	154	154	19	15.5	6	6
90	170	174	24	20.0	8	7
100	200	194	28	24.0	8	7
112	230	218	28	24.0	8	7
132	262	258	38	33.0	10	8
160	310	314	42	37.0	12	8
180	341	354	48	42.5	14	9
200	380	394	55	49.0	16	10
225	418	444	60	53.0	18	11
250	473	494	65	58.0	18	11
280	522	554	75	67.5	20	12
315	622	624	80	71.0	22	14

The bore diameter D is initially set equal to the frame size, $D_{ini} \approx FS$, the axial length to $l_{ini} \approx AB$ (see Fig. 2) with the restrictions $0.75 \cdot D_{ini} \leq D \leq 1.25 \cdot D_{ini}$ and $0.5 \cdot l_{ini} \leq l \leq l_{ini}$. It is worth noting that these restrictions can be changed according to the specific SRM application.

The air gap length is also selected in this stage according to previous SRM design experience, which suggests g values for small machines of 0.18 - 0.25 mm and for integral horsepower machines of 0.3 - 0.5 mm. SRMs require small air gaps to achieve a high inductance ratio L_a/L_u , which allows maximizing power and torque densities. However, small air gaps tend to induce high surface loss due to the air gap flux harmonics, which can be significantly reduced by using high-quality rotor laminations.

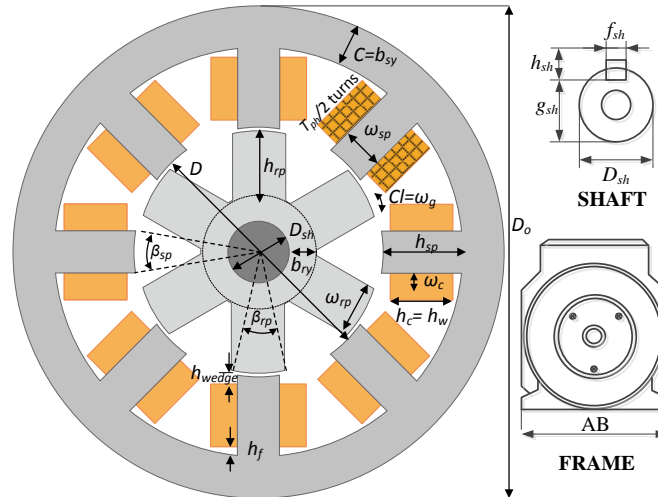


Fig. 2. Basic geometry of a 8/6 SRM.

- 2. Phases and poles number selection.** The designer usually fixes both the number of stator and rotor poles, N_s and N_r , respectively. Although there are many possible combinations, some of them are preferred, highlighting the 6/4 ($q = 3$ phases) and 8/6 ($q = 4$ phases) combinations. The 6/4 machine offers geometric simplicity and the use of a small number of power switches, whereas the 8/6 structure exhibits lower torque ripple at the expense of requiring a converter with more switches and higher losses because of the higher switching frequency.

3. **Selection of the stator and rotor pole angles.** In this paper a process to select the best pair of stator and rotor polar angles, β_{sp} and β_{rp} respectively, is applied since they greatly influence the final behavior of the SRM. The (β_{sp}, β_{rp}) pair producing the greater torque is selected. To this end three conditions are imposed:

- a. *First condition.* The stator pole angle β_{sp} is usually set smaller than the rotor pole angle β_{rp} , i.e. $\beta_{sp} < \beta_{rp}$.
- b. *Second condition.* The effective torque region is larger than the stroke angle $\varepsilon = 360^\circ / (N_s \cdot q)$ but smaller than the stator pole angle β_{sp} . Note that $q = N_s / 2$ is the number of stator phases. Therefore, to ensure starting capability at any initial position, it must be accomplished $\beta_{sp} > \varepsilon$. For a 8/6 SRM it results in $\varepsilon = 15^\circ$.
- c. *Third condition.* The inductance profile of each stator phase repeats every $360^\circ / N_r$. Within the zone in which the stator and rotor pole arcs are not overlapped, the phase inductance remains at its minimum unaligned value L_u . To avoid any overlap between the stator and rotor poles in the unaligned position, the angle between the corners of two adjacent rotor poles must be greater than the stator pole arc. This condition is attained when $360^\circ / N_r - \beta_{rp} > \beta_{sp}$.

The three conditions can be represented in a graph to describe a feasible triangle, as shown in Fig. 3. The feasible pairs of pole angles (β_{sp}, β_{rp}) must lie within this triangle.

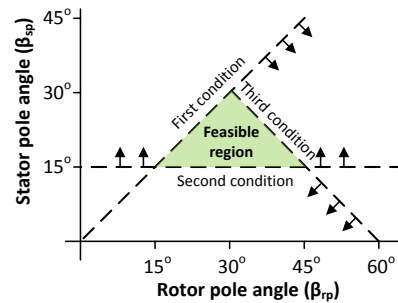


Fig. 3. Feasible triangle region for a 8/6 SRM.

The feasible region restricts the possible combinations of stator and rotor pole angles but does not provide the better solution. It is possible to search for the combination (β_{sp}, β_{rp}) that produces the maximum torque following the procedure described in section III.C [12], which is obtained from the full design of the SRM. Therefore, successive iterations must be performed to obtain the optimum value of the (β_{sp}, β_{rp}) pole angles.

4. **Laminations material selection.** The stator and rotor laminations material and thickness must be selected. During the design phase it is assumed that the stator pole operates at the point B_{work} of the $B-H$ magnetization curve, as shown in Fig. 4. This point is used to limit the maximum flux density in any part of the SRM. It is known that the points with maximum magnetic flux density are located in the stator poles, so the stator poles are designed to operate at a magnetic flux density B_{work} below the saturation point. From this value, the rest of the machine can be designed.

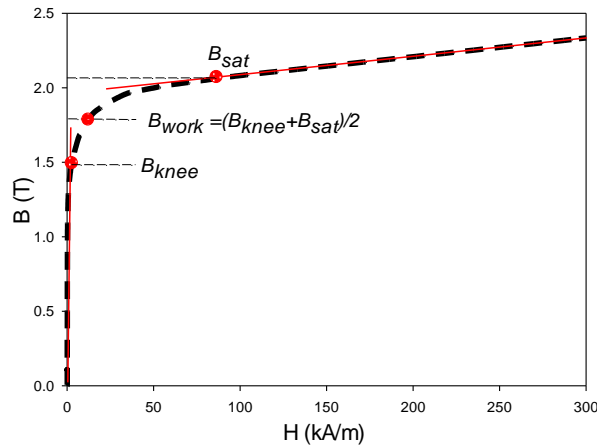


Fig. 4. B-H curve example for M235-35A steel laminations

5. **Normalized wires selection.** The cross-section of the conductors is calculated from the number of phases q , the peak phase current i_{max} (which has been initially settled) and the current density J (typical values for air cooled motors are within 4-8 A/mm²) as [9]:

$$A_{conductor}(mm^2) = \frac{i_{max}}{J(A/mm^2) \cdot \sqrt{q}} \quad (4)$$

The section of the normalized conductors is obtained by selecting from Table 3 the section closer but greater than the value obtained from (4).

TABLE 3. Normalized conductors Dimensions (American Wire Gauge)

AWG	D_w (mm)	A_c (mm ²)	R_s (Ohms/km)
1	7.348	42.400	0.407
2	6.544	33.600	0.513
3	5.827	26.700	0.647
4	5.189	21.200	0.815
5	4.621	16.800	1.028
6	4.115	13.300	1.296
7	3.665	10.500	1.634
8	3.264	8.370	2.061
9	2.906	6.630	2.599
10	2.588	5.260	3.277
11	2.305	4.170	4.132
12	2.053	3.310	5.211
13	1.828	2.620	6.571
14	1.628	2.080	8.286
15	1.450	1.650	10.450
16	1.291	1.310	13.170
17	1.150	1.040	16.610
18	1.024	0.823	20.950
19	0.912	0.653	26.420
20	0.812	0.518	33.310
21	0.723	0.410	42.000
22	0.644	0.326	52.960
23	0.573	0.258	66.790
24	0.511	0.205	84.220
25	0.455	0.162	106.200
26	0.405	0.129	133.900
27	0.361	0.102	168.900
28	0.321	0.081	212.900
29	0.286	0.064	268.500
30	0.255	0.051	338.600

C. Design step

In this stage, an iterative process is performed to determine the main SRM dimensions. It is based on the analysis of the aligned and unaligned positions since (1) states that SRMs' performance is greatly influenced by k_L (at the rated phase current k_L usually falls within the

range $0.65 < k_L < 0.75$) which depends on the ratio between the aligned and unaligned inductances. Therefore, the sizing process of the SRM requires an accurate calculation of both inductances. To this end, in this section the values of both L_u and L_a inductances are calculated by means of reluctance models, although it is known that this method provides an inherent error, especially due to the calculation of the unaligned inductance [9].

1. Iterative study of the aligned position. The aligned position is reached when the symmetry axes of the stator and rotor poles coincide. The analytical calculation of the flux linkages for the aligned position neglects the leakage flux. Initially, a prospective flux density B_{work} in the stator poles is assumed. From it, the flux densities of different sections of the SRM are calculated by applying flux continuity conditions, assuming that the areas of the cross sections (air gap, stator and rotor poles and yokes) are known.

Now the **stator dimensions** can be calculated on the basis of maximum magnetic flux density in the stator. A good practice consists in limiting the flux density of the stator yoke around half the value in the stator poles, that is, $B_{s,y} = 0.5 \cdot B_{work}$ [9]. The width ω_{sp} of the stator poles is selected to accommodate the pole flux density, so

$$\omega_{sp} = D \cdot \beta_{sp} / 2 \quad (5)$$

Since the flux density in the stator core is limited to one-half of the flux density in the stator poles, the stator yoke width results in,

$$b_{sy} \approx \omega_{sp} \quad (6)$$

Next, the height of the stator poles is calculated from Fig. 2 as,

$$h_{sp} = \frac{D_0 - 2b_{sy} - D}{2} \quad (7)$$

Now, the **rotor dimensions** are selected. In [9] it is suggested to limit the flux density of the rotor yoke around 80% of that in the stator poles, thus $B_{ry} = 0.8 \cdot B_{max}$. Based on the flux

density condition above, the rotor yoke width results in,

$$b_{ry} = \omega_{sp} / 1.6 \quad (8)$$

Finally, from the geometry shown in Fig. 1, the rotor pole height is calculated as,

$$h_{rp} = \frac{D - 2 \cdot g - D_{sh} - 2 \cdot b_{ry}}{2} \quad (9)$$

Once the stator and rotor dimensions are known, the flux densities in the different parts of the SRM can be calculated, so the relative magnetic permeability μ_r in each section of the SRM is obtained from the $B-H$ curve of the steel laminations. Next, from the flux path lengths and the magnetic field densities in the different parts of the SRMs, the magnetomotive forces (MMFs) are obtained by applying the equivalent magnetic circuit corresponding to the aligned position, which is shown in Fig. 5.

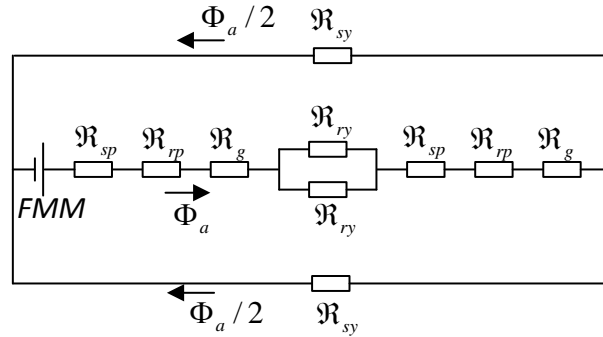


Fig. 5. Aligned position equivalent magnetic circuit for the 8/6 SRM.

The equivalent reluctance of the equivalent magnetic circuit corresponding to the aligned position shown in Fig. 5 is,

$$\mathfrak{R}_{tot,a} = 2 \cdot (\mathfrak{R}_{sp} + \mathfrak{R}_{rp} + \mathfrak{R}_g) + (\mathfrak{R}_{sy} + \mathfrak{R}_{ry}) / 2 \quad (10)$$

The reluctances are calculated by applying $\mathfrak{R} = l / (\mu_o \cdot \mu_r \cdot A)$, so the length of the magnetic paths, the cross sectional areas and the relative permittivities of each path must be known, which are listed in Table 4.

Table 4. Magnetic Path Lengths, Cross Sections And Flux Densities

Part	Length	Cross section	Flux density
Stator pole	$l_{sp} = h_{sp} + b_{sy} / 2$	$A_{sp} = \beta_{sp} \cdot (D / 2) \cdot l \cdot f_s$	$B_{sp} = B_{work}$
Stator yoke	$l_{sy} = \pi \cdot (D_o - b_{sy}) / 2$	$A_{sy} = b_{sy} \cdot l \cdot f_s$	$B_{sy} = B_{sp} / 2$
Rotor pole	$l_{rp} = h_{rp} + (D / 2 - D_{sh} / 2 - h_{rp} - g) / 2$	$A_{rp} = \beta_{rp} \cdot (D / 2) \cdot l \cdot f_s$	$B_{rp} = B_{sp} \cdot A_{sp} / A_{rp}$
Rotor yoke	$l_{ry} = \pi \cdot (D / 2 - h_{rp} - g + D_{sh} / 2) / 2$	$A_{ry} = (D / 2 - h_{rp} - g) \cdot l \cdot f_s$	$B_{ry} = 0.8 \cdot B_{sp}$
Gap	$l_g = g$	$A_g = (A_{sp} + A_{rp}) / 2 \cdot f_s$	$B_g = B_{sp} \cdot A_{sp} / A_g$

f_s is the laminations stacking factor

Neglecting the leakage paths, the magnetic flux flowing from stator to rotor when considering the aligned position is obtained as,

$$\Phi_a = B_{sp} \cdot A_{sp} \quad (11)$$

And the total magnetomotive force is obtained as,

$$FMM = \Phi_a \cdot \mathfrak{R}_{tot,a} = B_{sp} \cdot A_{sp} \cdot \mathfrak{R}_{tot,a} \quad (12)$$

From (12) the number of turns per phase is obtained, which must be an even number,

$$T_{ph} = \text{int}_{\text{even}} (FMM / i_{\max}) \quad (13)$$

Next, the magnetomotive force is recalculated from the number of turns as,

$$FMM^* = T_{ph} \cdot i_{\max} \quad (14)$$

Finally, the FMM obtained from (14) is compared with the one calculated from (12) and if the error is greater than a certain tolerance value ε , an iteration process is applied to adjust the initial prospective value of the flux density B_{work} until the error is below the tolerance value,

$$\begin{aligned} \text{If } FMM^* < FMM - \varepsilon \text{ then } B_{work,new} &= B_{work} + 0.1(\text{T}) \\ \text{If } FMM^* > FMM + \varepsilon \text{ then } B_{work,new} &= B_{work} - 0.1(\text{T}) \end{aligned} \quad (15)$$

Finally, the aligned inductance is calculated as,

$$L_a = T_{ph} \cdot \Phi_a / i_{\max} \quad (16)$$

2. **Stator coils dimensions.** The stator coil area is the product of the coil width ω_c by the coil height h_c and by a coil fill factor K_u , which can also be expressed as the product of the conductors cross section area a_c by half of the number of turns T_{ph} per phase,

$$K_u \cdot h_c \cdot \omega_c = a_c \cdot \frac{T_{ph}}{2} \quad (17)$$

The maximum value of ω_c is obtained from the geometry in Fig. 2 as,

$$\omega_c = \frac{1}{2} \left[\frac{\pi \cdot D}{N_s} - \left(\beta_s \cdot \frac{D}{2} + Cl \right) \right] \quad (18)$$

Cl being the clearance between consecutive coils.

From (17) and (18) it results,

$$h_c = \frac{a_c \cdot T_{ph}}{K_u} \left[\frac{\pi \cdot D}{N_s} - \left(\beta_s \cdot \frac{D}{2} + Cl \right) \right]^{-1} \quad (19)$$

Next, since the coil must be placed between two consecutive stator poles and some extra space is required to ensemble the coils, the stator pole height h_{sp} is obtained from the coil height h_c by applying a security factor,

$$h_{sp} = 1.2 \cdot h_c \quad (20)$$

3. Study of the fully unaligned position. Calculation of L_u .

From (1) and (2) it is clear that to obtain the output power and torque power of the machine, both the aligned and fully unaligned inductances are required. In the unaligned position the center of the interpolar rotor gap coincides with the midpoint of the stator pole. In this case the leakage flux cannot be omitted, so the leakage paths must be calculated analytically. For this purpose seven flux paths are analyzed [9] to calculate the unaligned inductance (see Fig. 6). For the i -th flux path the length $l_{element,i}$, cross section $A_{element,i}$, magnetic field density $B_{element,i}$, magnetic flux $\Phi_{element,i}$ and reluctance $\mathfrak{R}_{element,i}$ of each element, as well as the total

MMF_i across each path must be calculated by applying $MMF_i = \sum_{elements} \Phi_{element,i} \cdot \mathfrak{R}_{element,i}$. Then, the unaligned inductance contribution due to the i -th path is calculated as $L_{u,i} = T_{ph} \cdot \Phi_{element,i} / i_{max}$. Finally, the total unaligned inductance is calculated as the sum of all contributions,

$$L_u = \sum_{i=1..7} L_{u,i} \quad (21)$$

Further details of the calculation process are found in [9,13].

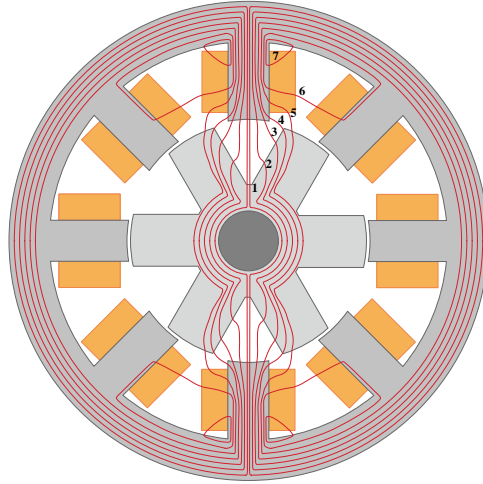


Fig. 6. Flux paths considered to calculate the unaligned inductance.

4. **Calculation of the output torque and the coils clearance.** By assuming that during a stroke the current remains almost constant, the SRM torque can be calculated from the electromechanical energy conversion as [14],

$$T_{out} = \frac{\partial W_{mec}}{\partial \theta} \approx \left[\frac{\partial W}{\partial \theta} \right]_{i=const} \quad (22)$$

Where θ is the angular displacement and W is calculated from the magnetization curves as indicated in Fig. 7. Therefore, the flux linkages against the current characteristic must be calculated for both the aligned and unaligned positions, assuming that the current is almost constant between the unaligned and aligned positions. The torque per stroke of the SRM is obtained from the area between the aligned and unaligned positions, which may be calculated

by applying the trapezoidal integration rule. This calculation discretizes the current into n points ($\Delta i = i_{\max} / n$) and calculates the corresponding flux linkages for both the aligned and unaligned positions.

The mechanical work per stroke done is obtained by calculating the area enclosed between the aligned and unaligned flux linkage versus current curves depicted in Fig. 7 as [9,13],

$$W = W_a - W_u = [(\Psi_1 + \Psi_2 + \dots + \Psi_{n-1}) \cdot \Delta i + \Psi_n \cdot \Delta i / 2] - \Psi_u \cdot i_{\max} / 2 \quad (23)$$

Since the number of strokes or current pulses in a complete revolution is $S = N_s \cdot N_r / 2$, the average torque is obtained by applying,

$$T_{out,av} = \frac{S \cdot W}{2 \cdot \pi} = \frac{N_s \cdot N_r \cdot W}{4 \cdot \pi} \quad (24)$$

If $T_{out,av}$ doesn't match with the initial specifications, i.e. $0.95 \cdot T_{out} \leq T_{out,av} \leq 1.05 \cdot T_{out}$ it is necessary to modify the stack length accordingly and to recalculate the SRM (see Fig. 1).

The clearance between adjacent coils is also calculated in this step. If the resulting clearance Cl is lower than a minimum specified value, the bore diameter D must be modified to allow space enough for assembling and disassembling the coils in the stator, so the SRM must be recalculated (see Fig. 1).

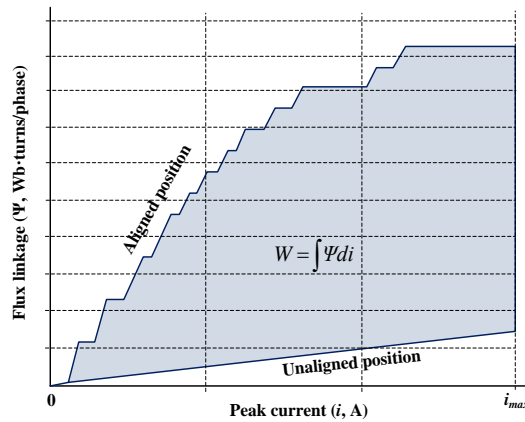


Fig. 7. Aligned and unaligned magnetization curves of the SRM, from which the average torque is calculated.

D. Optimal SRM selection step

The selection of the optimal SRM is based on the solution achieving maximum torque. For all combinations (β_{sp}, β_{rp}) explored during the design phase, the one achieving the maximum average torque is selected.

THE MATLAB GUI DEVELOPED

This section describes the Matlab® graphical user interface (GUI) developed to assist the students in designing the SRM and validating the results attained in the assignments of the lecture sessions. The main window of the GUI consists of three main blocks, as illustrated in Fig. 8.

The first block consists of a set of buttons allowing the user to run a new SRM calculation, plot a drawing of the SRM or start a new design. In the second block the user sets the initial design specifications, including P_{out} , n_{SRM} , N_s/N_r , g , laminations material, $B_{work,ini}$, i_{max} , J_{max} and the geometric restrictions of the coils. The third block displays the output values provided by the program, which include the final dimensions of the SRM and diverse performance parameters as well as a graphical window which allows the user selecting among the B-H curve, the magnetization curves of the designed SRM, and the set of (β_{sp}, β_{rp}) solutions explored during the iterative design process.

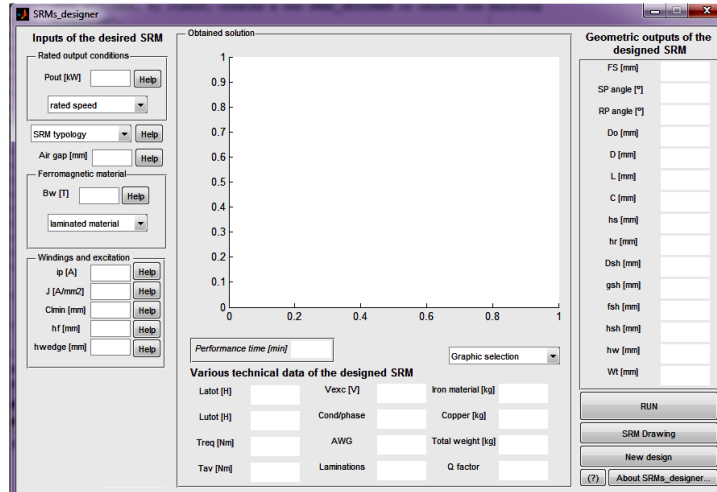


Fig. 8. General aspect of the main window of the SRM Designer GUI application.

Fig. 9 displays the three main sections of the GUI.

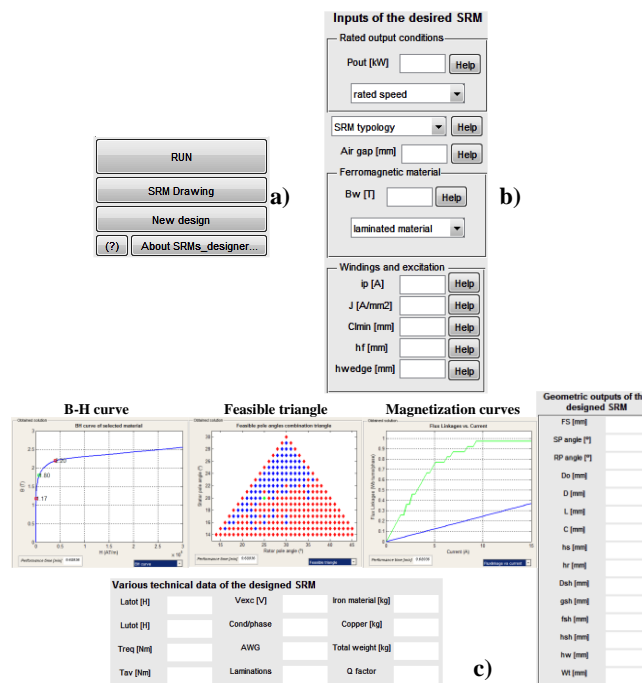


Fig. 9. a) Run, drawing and other buttons b) Initial specifications block of the GUI. c) Outputs section and graphical information provided by the GUI.

RESULTS AND FEM VALIDATION

In this section a SRM is designed from the design specifications established by the user such as

the rated speed, flat value of current and output power among others. The results for a given SRM attained by the GUI, which is based on the analytical design method described in Section III are presented and afterwards validated through FEM simulations.

Table 5 shows the main design parameters sought of the SRM. These parameters are introduced in the inputs block of the GUI in order to size the SRM.

Table 5. Main SRM specifications

Quantity	Value
Output power, P_{out}	5000 W
Rated speed, n_{SRM}	1500 r/min
Topology	8/6
Number of phases, q	4
Stator poles flux density, B_{work}	1.8 T
Current, flat value, i_{max}	15 A
Air gap length, g	0.4 mm
Steel laminations	M235-35A

Table 6 summarizes some of the parameters outputted by the GUI.

Table 6. Geometry of the optimized SRM

Quantity	Value obtained
Stator polar angle, β_s	25°
Rotor polar angle, β_r	20°
Frame size, FS	112
Outer diameter, D_o	218 mm
Bore diameter, D	109.6 mm
Shaft diameter, D_{sh}	28.0 mm
Stack length, l	132.3 mm
Stator pole height, h_{sp}	35.9 mm
Rotor pole height, h_{rp}	29.0 mm
Stator yoke width, $C=b_{sy}$	18.3 mm
Rotor yoke width, b_{ry}	11.4 mm
Air gap length, g	0.4 mm
Number of turns per phase, T_{ph}	212/2

Next, a validation of the SRM design procedure detailed in Section III is performed by means of FEM simulations, which is a widely used method for electromagnetic design and validation. The FEMM 4.2 package software was used [15] for this purpose. Figs. 10 show the mesh and the

magnetic flux density distribution for the aligned and fully unaligned positions obtained by applying the FEM model of the SRM dealt with. The mesh is composed of 8168 triangular elements and a total of 4126 nodes.

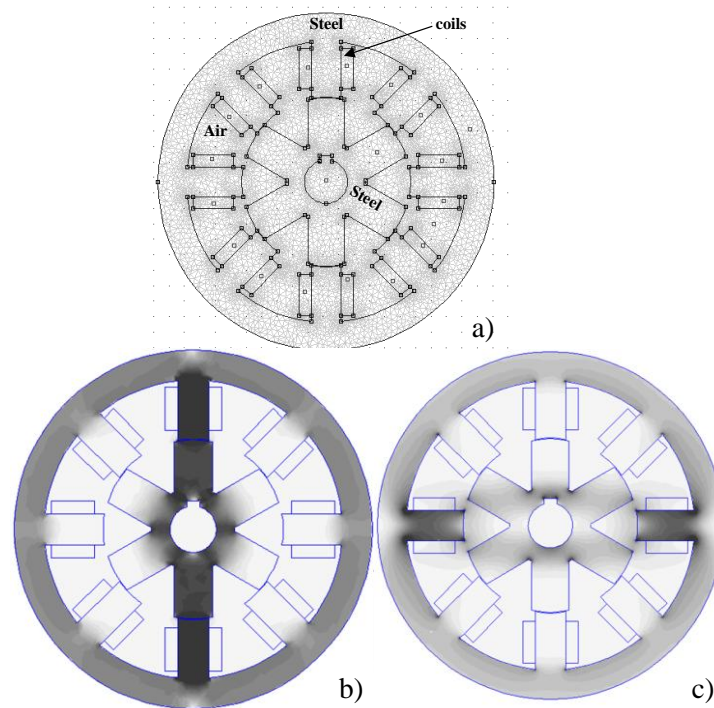


Fig. 10. a) Mesh of the analyzed SRM. FEM results of the flux density distribution. a) Aligned position flux density. b) Completely unaligned position flux density.

Table 7 compares the results obtained by means of both the Matlab® GUI and FEMM software. According to these results, the solution calculated through the analytical process presented in this paper agrees reasonably well with the results provided by the FEM model, thus being a validation of this design procedure.

Table 7. Results Summary

Quantity	Design algorithm	FEM	Error
Stator pole average flux density, B_w	1.8 T	2.0 T	11.1%
Aligned inductance, L_a	68.2 mH	70.5 mH	3.4%
Aligned inductance, L_u	24.6 mH	19.8 mH	19.5%
Flux linkage aligned position, ψ_a	0.99 Wb	1.06 Wb	7.1%
Flux linkage unaligned position, ψ_u	0.37 Wb	0.30 Wb	3.3%

ASSESSMENT OF THE EDUCATIONAL TOOL

This educational tool was developed at the Electrical Engineering Department of the UPC. It was intended to provide students a fast and visual system to validate the design of SRMs with the aim of stimulating the students' interest in the design of electrical machines. It was taught to 46 students of the *Plug-In Hybrid Electric Vehicles. Concept, design and project of Electric propulsion systems* course in the second semester of the 2013-2014 academic year. To assess the impact of the computer-aided educational tool in their learning performance, the students were asked to fill a questionnaire. Students had to grade the six-question form according to the five-level Likert item, where 1 means *strongly disagree* and 5 means *strongly agree*. The six questions and the students' responses are reported in Table 8.

Table 8. Students' responses to the questionnaire.

Question	1	2	3	4	5	Average
The computer aided session is well related to the topics that I am studying in the lectures	0	1	7	22	16	4.15
The computer aided session has helped me to understand the course topics	0	0	6	25	15	4.20
The SRM design GUI is user friendly and intuitive	0	0	4	24	18	4.30
I would recommend this simulation experiment to be used in forthcoming editions of the course	0	0	5	22	19	4.30
I would like to go beyond the computer experiment and do research on my own	0	0	9	23	14	4.11
This methodology lets provide me with skills I expect to use in future	0	1	8	23	14	4.09
Global average						4.19

As shown in Table 8, the average grade was 4.15 in the 1-5 scale. Therefore it can be concluded that this two-hour computer-aided session helps students in consolidating their previous knowledge while stimulating their interest in the design of electric machines.

CONCLUSION

This paper has presented a computer-aided educational tool to assist the design process of a SRM. The main objective of this tool is to help electrical engineering students during the design process of a SRM, therefore fostering students' motivation in the area of design of electrical machines. The paper has covered the technical aspects of the design steps, a sizing example of a SRM by using the educational tool presented here, and the results validation by means of FEM simulations. Finally, an assessment of the students' satisfaction about the usefulness and impact on learning performance related to the use of this tool has been presented. The preliminary results of the assessment summarized in Section VI related to students' satisfaction with the educational aspects of the educational tool suggest that it is a helpful tool for improving students' motivation and learning effectiveness in the design of electric machines.

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