PeMSyn – A FREE MATLAB-FEMM BASED EDUCATIONAL TOOL TO ASSIST THE DESIGN AND PERFORMANCE ASSESSMENT OF PERMANENT MAGNET SYNCHRONOUS MACHINES

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Abstract – This paper introduces PeMSyn, a free tool intended to aid the design and simulation processes of permanent magnet synchronous machines. Using PeMSyn, one can effortlessly design a permanent magnet synchronous machine, design its winding distribution and assess the machine performance. The machine performance is evaluated by means of FEA since PeMSyn provides an interaction between Matlab and FEMM. Thus, several machine parameters can be obtained. Another interesting characteristic of PeMSyn is its modularity, which means that each functionality can be run independently and new functionalities and machine topologies can be added either by the user or by means of a new PeMSyn update. Aiming to be simple and user-friendly, PeMSyn was coded in Matlab language in form of a graphical user interface (GUI). Moreover, users can easily translate all labels and variable names to their mother language using a language description file already available in English and Portuguese. The modules, the machine design process, the equations involved and an application are shown in this paper. In order to present guidelines on how to use PeMSyn, an example of machine design is proposed and its performance is assessed.

Keywords – Educational tool, Eletrical machine design, FEA, Graphical user interface, Permanent magnet synchronous machine.

NOMENCLATURE

α^e - angle between phasors.
γ - pole pitch in radians.
μ_0 - permeability of free space.
μ_{rec} - recoil permeability.
ρ - coil pitch.
Φ_P - flux per pole.
ω - rated speed.
ω_{max} - maximum speed.
A_P - polar area for surface mounted magnets.
A_{slt}^{IR} - slot area for inner rotor.
A_{slt}^{OR} - slot area for outer rotor.
B_M - no-load magnet flux density.
B_M^{OP} - on-load magnet flux density.
B_T - maximum tolerable flux density in the iron.
D_r - rotor outer radius.
D_s - stator outer radius.
D_t - maximum wire diameter.
$E_{C_R}^{OR}$ - outer rotor yoke thickness.
E_C - stator yoke thickness.
$E_{C_R}^{IR}$ - inner rotor yoke thickness.
f_{lkg} - leakage factor.
f_{slt} - fill factor.
g - air gap length.
H_c - magnets coercivity.
H_M - no-load magnetic intensity of the magnets.
H_M^{OL} - on-load magnetic intensity of the magnets.
h_s - shoe height.
h_t - width height.
I_{max} - drive current peak.
k_E - back-emf constant.
k_T - torque constant.
L_1 - magnet thickness for the spoke type.
L_M - magnet thickness.
L_{STK} - stack length.
N - total number of turns per phase per pole.
N_c - number of coils.
N_S - number of slots.
N_t - number of turns per coil.
N_{ts} - number of turns per coil for straight teeth.
p - number of pole pairs.
PC - no-load permeance coefficient.
PC^{OL} - on-load permeance coefficient.
R - rotor outer radius.
R_{RY} - inner radius of the magnets.
R_{sh} - shaft radius.
R_{st} - radius over slots.
t - machine periodicity.
T_D - developed torque.
tt - tooth-tip.
V - supply voltage.
WG - wire gauge.
w_o - slot opening.
w_s - total shoe width.
w_t - tooth width.

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I. INTRODUCTION

The employment of electrical machines around the world has been increased significantly. These machines are present from hard drives of computers to big industry applications. Within the different motor types, permanent magnet synchronous machines (PMSM) are gaining prominence for their high power density, low maintenance and inertia [1]. Considering the same output power, the size of a PMSM can be up to 30% and the weight up to 50% less than conventional motors [2]. For their attractive compromise between size and power, PMSM are extensively used in electrical vehicles [3], wind turbines [4] and submarines [1], [2].

The machine design process is made with the aid of finite element analysis (FEA) softwares. QuickField, Altair Flux and FEMM are known examples of FEA tools. The first and second ones are proprietary softwares; the last one is a free and open source software. Altair Flux, for instance, includes electromagnetic simulation toolboxes that are capable of simulating high complex electrical machines topologies. Although any of them can solve electromagnetic problems, during the design and simulation of electrical machines it is necessary to integrate numerical calculation softwares or use specific tools intended to design using their own FEA software.

It is very difficult to contemplate each specific machine design detail in a single software, so it is common for them to be specialized in one kind of machine topology or in executing a single task. Some examples of specific tools are: XFEMM, a cross-platform refactoring of the standart library of FEMM. It can be used along Octave/Matlab or as a standalone programming library. Open Motor is a collection of routines developed to model a generic direct current motor. By adapting its code, it is possible to model brushless direct current motors or switched reluctance motors. SyR-e is an open source software that also interacts with FEMM and Matlab, and it is specialized in designing synchronous reluctance motors. It designs the dimensions of the machine and its windings, optimizes the dimensions parameters to achieve the best torque ratio and its ripple. In addition, it assesses the machine performance by means of calculating the average torque and the behavior of the flux-linkage. On the other hand, Motor Femmulator is a framework intended to draw, simulate and optimize using Genetic Algorithms any motor previously described in Octave language. However, it has never been finished and tested, since its electromagnetic simulation codes are still experimental. In order to study permanent magnet machines, PeMSyn has been developed by the authors of this paper [5].

PeMSyn has been written in Matlab language and works together with FEMM. It has been developed to be a modular software, allowing adaptability and becoming a very attractive solution for a wide variety of machines design when compared to other softwares, such as SyR-e that is very specific. This means that PeMSyn has the potential to design a wide variety of permanent magnet machines, requiring only the addition of a new module to it and, in the future, it will be able to design switched and synchronous reluctance machines. PeMSyn allows a great flexibility for the user when choosing the design parameters that will be used: it is possible to choose the type of slots, the type of rotor, the type of tooth and make seg-

mentation of the poles. In addition, simulations are executed with parallel processing, which allows efficiency in operating time. It is worth mentioning that PeMSyn take into account the armature reaction as well as the saturation effects during the design process and during the performance assessment of the machine's parameters.

Rather than being accessible only to Portuguese or English speaking users, PeMSyn can be easily translated to any other language. This can be achieved translating a MATLAB script available in its folder. Thus, users may translate field values, variables names and all labels to their own native languages. This linguistic accessibility made it possible for over 230 downloads around the world in more than thirty countries since the release of PeMSyn in 2019-06-14. The choice for coding and building PeMSyn as a Matlab toolbox lies on the fact that Matlab is widely used in numerous universities around the world by students, teachers, professors and researchers.

This paper is organized in two main segments. Section II discusses the machine design process and the equations involved in the design modules considered in PeMSyn. Section III presents an overview of the internal structure of PeMSyn as well as how the armature reaction and saturation effects are taken into account during the design process and performance analysis. Yet, Section IV presents a practical example of machine design and performance assessment using PeMSyn. Section V presents a comparison and validation between the results from PeMSyn, Altair Flux and two real machines. Section VI discusses the PeMSyn usage around the world and futures works to improve the software. Finally, the conclusions are made.

II. PMSM DESIGN

This section presents the guidelines and equations followed by the software design modules. These guidelines are divided into three parts considering the stator, winding and rotor designs. It is valid mentioning that these parts are interrelated. More details regarding PMSM design can be found in [4], [6]–[9].

One must bear in mind that the design of a electrical machines (generators or motors) is an iterative process. This design is accomplished by means of simple equations neglecting the non-linear characteristic of the iron materials. Then, the effects of these non-linearities, such as saturation of the material, caused or not by the armature reaction, can be assessed by means of a finite elements analysis during the simulation process provided by the simulator module. Then, if necessary, the early design must be corrected, new simulations must be carried out until the desired machine performance is achieved.

The first step to design a machine is to determine the supply voltage, rated/maximum speed, output power and rated torque. The supply voltage and maximum speed define the back-emf constant [7], an important machine electrical characteristic. The output power and rated torque define the air gap length [7] and machine volume [4], [6], [8], respectively.

A. Rotor

Most dimensions mentioned in the rotor and stator subsections can be seen in Figure 1 for a better understanding.
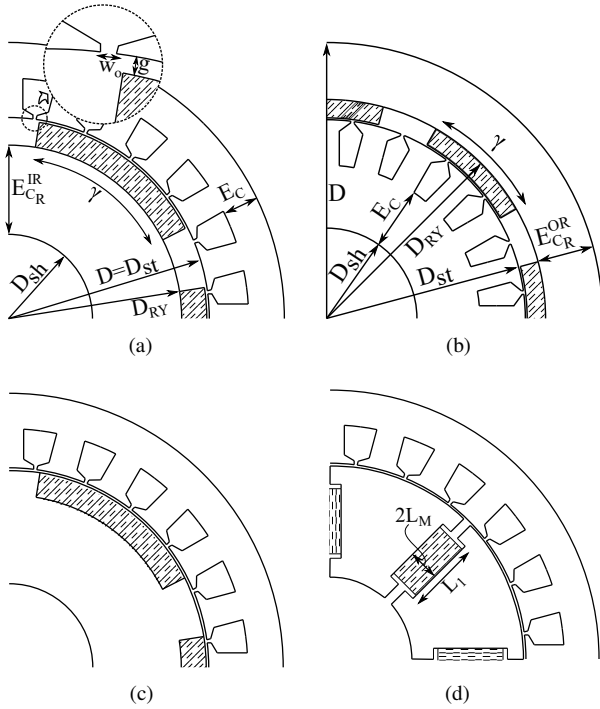
Fig. 1. Machine dimensions and rotor types. (a) Inner rotor (surface mounted). (b) Outer rotor (surface mounted). (c) Inner rotor (inset). (d) Inner rotor (spoke type).

The rotor design starts by choosing the rotor type, i.e., inner or outer rotor. Also, the magnet allocation type must be selected: surface mounted, inset or spoke type. These choices depend on the application, rated/maximum speed and available space [7]. Outer rotors are compact and have high inertia, whereas inner rotors are less compact and have low inertia. Surface mounted magnets are not recommended for high speed applications.

The next step consists in picking the magnet shape, type, grade and a value for the permeance coefficient. SmCo, Nd-FeB or Alnico magnets of many grades are offered by the software, with block or arc shape. The magnet thickness depends on the air gap length, flux leakage factor and permeance coefficient, as (1).

$$L_M = PC \frac{g}{(1 - f_{LKG})}.$$ (1)

To guide the user in making the correct choice for the permeance coefficient and the desired operating point for the permanent magnet, a "PC Module" has been implemented. In this module, the permanent magnet operating point is calculated based on the chosen permeance coefficient and leakage factor informed by the user as described in (2).

$$PC = \frac{B_M}{-\mu_0 \cdot H_M} = L_M \frac{(1 - f_{LKG})}{g}.$$ (2)

The permeance coefficient chosen by the user and based on (2) is considered a starting point and do not takes into account the magnetic load caused by the armature current. As will be described further, after the first design assessment, the user can review the maximum and minimum value for the permanent magnet operating point based on the armature reaction and armature current.

It is possible to obtain similar characteristics to arc shaped poles when segmenting these poles into several block segments. The number of segments must not be too high, otherwise the segments would have small dimensions, compromising the construction feasibility. Discussions on pole segmentation are made in [10]–[12]. An illustration of the pole segmentation implemented by PeMSyn can be be seen in Figure 2, considering a pole with three segments. It is worth mentioning that only the spoke type motor has no pole segmentation.
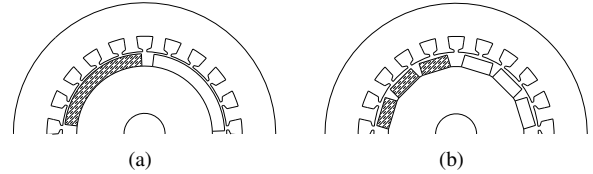

Fig. 2. Comparison between arc shaped and segmented poles. (a) Arc shaped poles. (b) Segmented pole.

The number of poles must now be selected. Many parameters are based on this number, such as the stator/rotor yoke thickness, iron losses and cogging torque. A further discussion on the pole number choice is made in [13].

The polar area for surface mounted magnets is calculated using (3). It depends on the chosen pole pitch, magnet inner radius and stack length values. With the polar area value and magnet flux density, the flux per pole can be calculated by means of (4). The magnet flux density can be obtained by means of the magnet demagnetization curve, offered by the magnet manufacturer, and the chosen permeance coefficient.

$$A_P = (\gamma/p) R_{RY} L_{STK}.$$ (3)

$$\Phi_P = B_M A_P.$$ (4)

The polar area for the spoke-type is considered equal to the one for surface mounted magnets with full pole-pitch. To achieve this, the magnet thickness for the spoke type is obtained by (5). Also, in order to avoid demagnetization, the magnet width is twice the value obtained in (1). Flux barriers and other structural constraints are added automatically by PeMSyn.

$$L_1 = (\pi/2p) R_{RY}.$$ (5)

Finally, the rotor yoke thickness must be calculated. The inner rotor yoke thickness requires no further information from the user, being calculated by (7). For the outer rotor, the user must select its outer radius in order to obtain its yoke thickness through (6). For the inner rotor, it is possible to replace part of this yoke with a lighter non-magnetic material if the required rotor thickness is smaller than the rotor inner radius. This replacement allows a reduction in the rotor weight, inertia and cost. For both cases and for the stator design, a maximum tolerable value for their flux density must be chosen in order to prevent magnetic saturation and reduce the machine volume.

$$E_{C_R}^{OR} = \frac{2\pi B_M (R - L_M)}{4p B_T + 2\pi B_M}.$$ (6)

$$E_{C_R}^{IR} = \frac{\frac{1}{2} B_M A_P}{B_T L_{STK}}.$$ (7)

B. Stator

The stator design starts by picking a number of slots. This number must be a multiple of three in order to accommodate a three-phase winding. If the user chooses a non multiple of three, PeMSyn automatically changes it to one. Also, the winding feasibility must be verified for the chosen combination of slots and pole number. Next, the slot opening must be selected. This value must be sufficient to allow the allocation of the coils. Also, caution is advised when choosing the slot number and opening since these values influence the cogging torque peak [7].

Usually, a small part of the flux produced by the magnets does not reach the stator. Since less flux reaches the stator, the magnet flux density in the iron is lower than expected, thus allowing the stator dimensions to be smaller. This phenomenon is called flux leakage and is taken into account by the leakage factor. The user must choose a value between zero (neglecting leakage) or one (none flux reaches the stator) for this factor.

The first stator dimensions to be obtained are those of the teeth. If the user chose the inner rotor, they must inform the radius over the slots. This radius is automatically calculated for the outer rotor. The teeth dimensions are its width, total shoe width, shoe height, tooth height and tooth-tip. These dimensions are obtained using (8)–(12) respecting the order they were mentioned and can be depicted in Figure 3(a). Also, the teeth types available in PeMSyn, unequal, straight and equal, are shown in Figures 3.b and 3.d, respectively. It is recommended that the ratio between tooth height and shoe height is between two and four [7], being four the standard value considered in PeMSyn.

$$w_t = (1 - f_{lkg}) \frac{(2p)\Phi_P}{N_S B_T L_{STK}}. \tag{8}$$

$$w_s = (2\pi/N_S) R_{st} - w_o. \tag{9}$$

$$h_s = (w_s - w_t)/2. \tag{10}$$

$$h_t = 4h_s. \tag{11}$$
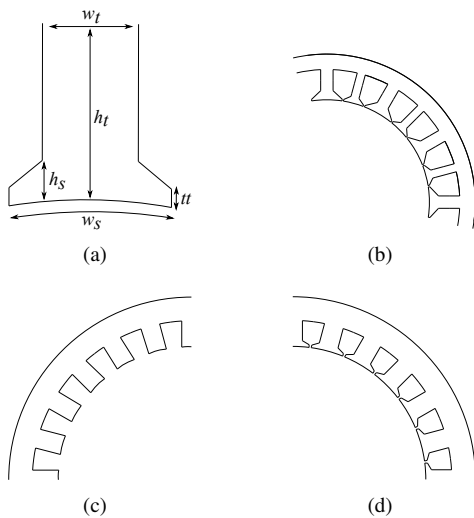
$$tt = w_o/2. \tag{12}$$

Fig. 3. Teeth dimensions and shapes. (a) Teeth dimensions. (b) Unequal teeth. (c) Straight teeth. (d) Equal teeth.

In addition, PeMSyn has three different slot edges geometry available: straight edge, rounded edge and circular bottom edge. These geometries can be seen in Figure 4.
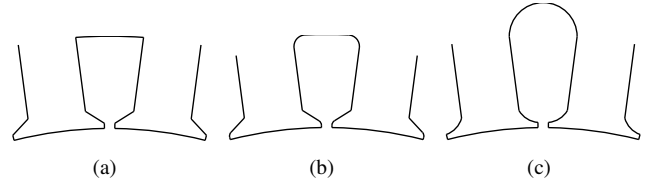

Fig. 4. Geometries available for the borders of the slots. (a) Straight borders. (b) Round borders. (c) Circle borders.

The last stator dimension obtained is its yoke thickness. Equation (13) is used for this. For the outer rotor, if there is sufficient space for the calculated yoke thickness, part of the stator can be replaced by a lighter non-magnetic material, decreasing the machine weight and cost.

$$E_C = \frac{\frac{1}{2}(1 - f_{lkg})B_M A_P}{B_T L_{STK}}. \tag{13}$$

C. Winding

The winding design is made considering the star of slots method [14]–[16]. In this method, the induced voltages of the wires in each slot are represented by phasors. These phasors are divided and assigned to a winding phase. This process results in a balanced and symmetrical winding [14].

The first step is to confirm the winding feasibility for the chosen number of poles and slots. The machine periodicity, obtained by (14), makes this task easy. For a three-phase winding, its construction is feasible if $N_S/3t$ is an integer.

$$t = \gcd(N_S, p). \tag{14}$$

To build the star of slots, a slot must be chosen as reference. Also, the angle between phasors of adjacent slots must be determine using (15). This angle is the angle between two adjacent slots, equal to $2\pi/N_S$, in electrical radians. The phasors are then distributed, see Figure 5.a, starting with the reference slot. Then, they are divided into six sectors of 60°, refer to Figure 5.b, since a three-phase winding is considered. Two sectors, 180° apart from each other, are assigned to each phase, one considered "positive" and the other, "negative" [15].

$$\alpha^e = p(2\pi/N_s). \tag{15}$$

The conductors on the "go" slots of the coils in the positive sector are considered coming out of the page. Those of the coils in the negative sector are oriented into the page. Thus, considering phases a, b and c, to obtain a balanced and symmetrical winding, the sectors must follow the sequence "a+", "c-", "b+", "a-", "c+" and "b-". The "return" slots are found by determining the coil pitch, depicted in Figure 6, which value must not exceed the one obtained with (16). If a single layer winding is desired and feasible, the coil pitch must be an odd number of slots.

$$\rho = \text{int}(N_s/2p). \tag{16}$$

The final steps of the winding design consists in determin-

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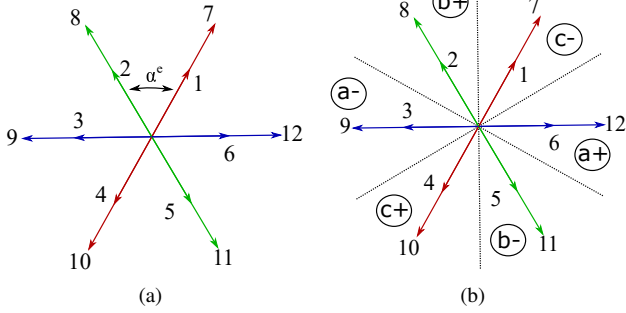
Fig. 5. Star of slots 12 slots and four poles. (a) Distribution of the Phasors. (b) Division into sectors.
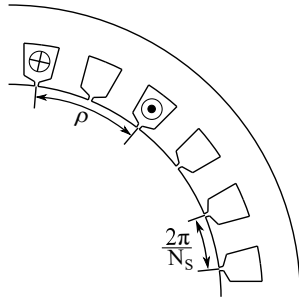

Fig. 6. Schematic of one coil.

ing the number of turns per coil and the wire gauge. To obtain the number of turns, first the back-emf constant must be calculated using (17). Then, equation (18) is utilized. The number of coils are obtained from the star of slots.

$$k_E = 0.9 \left(V / \omega_{max} \right). \tag{17}$$

$$N_t = \text{int} \left(\pi \frac{k_E}{4p(1 - f_{lkg})N_c \Phi_P} \right). \tag{18}$$

If the user desires the straight teeth, a correction must be made in the number of turns. This correction is required since the straight teeth have no shoes, thus reducing the flux-linkage. The correction is automatically made by PeMSyn by means of (19).

$$N_{ts} = \text{int} \left(N_t \, w_s / w_t \right). \tag{19}$$

The first step to obtain the wire gauge consists in calculating the slot area. This area can be obtained through (20) for outer rotor and (21) for inner rotor.

$$A_{slt}^{OR} = \frac{(R_{st} - h_s)^2 - (R_{st} - h_t)^2}{N_S} - w_t(h_t - h_s). \tag{20}$$

$$A_{slt}^{IR} = \frac{(R_{st} + h_t)^2 - (R_{st} + h_s)^2}{N_S} - w_t(h_t - h_s). \tag{21}$$

Finally, the maximum wire diameter possible to be accommodated in the slots is calculated via (22). This calculation takes into account the slot fill factor. This factor is in the range 0.30 to 0.35 for double layer ones and 0.65 to 0.70 for single layer windings [7]. The wire gauge (WG) that has a smaller diameter, but closest to the maximum diameter, is selected.

$$D_t = \sqrt{f_{slt}(A_{slt}/N_t)}. \tag{22}$$

III. PeMSyn - INTERNAL STRUCTURE, ARMATURE REACTION AND SATURATION EFFECTS

As mentioned, PeMSyn is a Matlab-based software, comprising six independent GUIs (Graphical User Interfaces) or "modules". These GUIs were created using the App Designer tool available in Matlab (version 2016b or higher).

A flowchart representing the PeMSyn algorithm can be found in Figure 7. For sake of clarity, the treatment of exceptions was not shown.
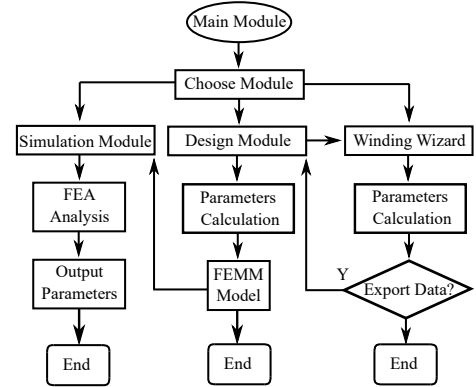

Fig. 7. Basic PeMSyn algorithm flowchart.

The link between Matlab and FEMM is made via the design and simulation modules. The first one requires some input data from the user (the winding wizard module can be initiated to assist in the winding design process), then calculates all the parameters described in Section II and, finally, creates a model in FEMM. The later allows the results obtained via the FEA made by FEMM, for the created model or another one, to be directly treated and assessed in the Matlab workspace.

In order to take into account the saturation and armature reaction effects during the design and assessment of the PMSM, the simulation module implements the On-load Back-EMF Maxwell Stress Tensor along with the Frozen Permeability Method as proposed and described in [17] for proper assessment of the machine on-load back-EMF. This way, the no-load and on-load back-emf waveforms and harmonic content can be compared, guiding the decision of the user on changing some machine design parameters. Last but not least, all machine's output parameters (flux-linkage, inductance and cogging torque) are assessed considering the armature reaction and saturation effects (on-load condition) and are compared to their no-load counterparts.

The simulation module has an inherent parallel processing available to speed up the simulation process, thus reducing the time to evaluate the machine performance. To manage the processor chipset load, the user can choose the number of local cores that will work. This number vary from 1 (no parallel processing) to the maximum number of cores found by means of the Matlab function *"maxNumCompThreads"*.

As mentioned in section II, the "PC Module" that can be opened during the design process to guide the user in choosing the proper permanent magnet operating point. This module assesses the on-load permanent magnet operating point considering the worst case of saturation and demagnetization of the permanent magnet taking into account the total number

of turns per phase per pole (N) and the rated peak current. To perform this assessment, this module needs to be opened again after the user finishes the design, since the total number of turns per phase per pole is calculated based on the winding distribution, the number of turns per coil and pole number.

The assessment of the on-load permanent magnet operating point is performed by the "PC Module" by means of (23), (24) and (25) which are derived from the magnetic circuit model.

$$B_M^{OL} = B_r + \left[\frac{\mu_{rec}\mu_0}{\mu_{rec}g + (1 - f_{LKG})L_M} \right] (\mu_{rec}gH_c \mp NI_{max}/2). \tag{23}$$

$$H_M^{OL} = \frac{\mu_{rec}gH_c \mp NI_{max}/2}{\mu_{rec}g + (1 - f_{LKG})L_M}. \tag{24}$$

$$PC^{OL} = \mu_{rec} \frac{H_cL_M(1 - f_{LKG}) \pm NI_{max}/2}{\mu_{rec}gH_c \mp NI_{max}/2}. \tag{25}$$

Note that if I_{max} is zero in (25), this equation becomes equal to (2).

Therefore, an approximation of the actual range for B_M, H_M and PC considering the armature reaction, saturation and demagnetization effects for the on-load condition is also calculated.

IV. EXAMPLE OF PMSM MACHINE DESIGN AND PERFORMANCE ASSESSMENT USING PeMSyn

The present section is a PeMSyn walk-through via an example of machine design and its performance assessment.

A. Machine Design

The example of machine design consists in designing the machine which parameters are listed in Table I. The 1018 steel is used in both the stator and rotor, the magnets are NdFeB 32 MGOe and the shaft is made of 316 stainless steel. An inner rotor with surface mounted magnets is considered, with straight slot edges.

TABLE I
Basic Machine Parameters

Parameter	Value	Parameter	Value
$2p$	4	w_o (mm)	2
γ	150°	D_{sh} (mm)	20
N_S	24	V (V)	380
T_D (Nm)	4.68	ω (rpm)	1500
g (mm)	1	ω_{max} (rpm)	2000
D_{st} (mm)	96	PC	6
L_{STK} (mm)	102	B_M (T)	0.9879
B_T (T)	1.5	f_{lkg}	0.05
f_{slt}	0.35		

To start the project the main module must be initialized. Then, the user must choose the design module accordingly to the chosen rotor type. For this example, the Inner Rotor: SM-PMSM (Surface Mounted Permanent Magnet Synchronous Machine) module must be opened. See Figures 8 and 9. Once the design module is opened, the information listed in Table I must be filled in. The "Help" button must be pressed (see Figure 10) if the user wants some assistance to determine the value of PC and B_M or to evaluate the effects of the armature reaction on these parameters.

The number of turns per coil and wire gauge fields must

be left with their default values ("0" and "-", respectively) for automatic computation. Otherwise, the user must fill in their desired values.

The finite elements mesh density generated by FEMM may be altered through the mesh size panel. Two options are available: the user must enter a fixed value for this mesh density or check the auto box, in which case FEMM will decide the mesh density value.

PeMSyn also offers a winding design module, considering the star of slots method for this design, as mentioned. Refer to Figure 11. This module may be accessed via the main module or through any design module via the "Wizard" button. For the later case, the designed winding data may be exported to the design module through the "Export" button. To design the winding, some information must be filled in and the "Design" button must be pressed. Schematics for the winding and the star of slots are available on the module once the design is finished and both can be saved.
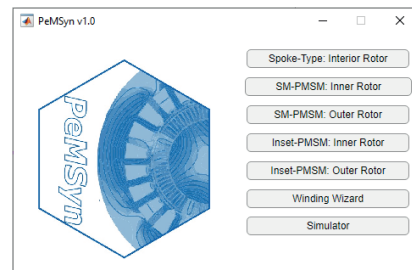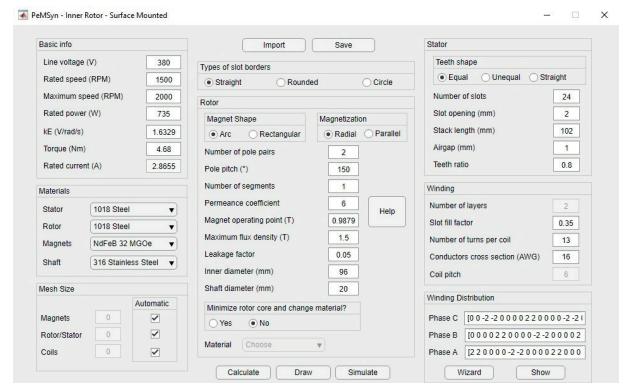

Fig. 8. Main Module

Fig. 9. Inner Rotor SM-PMSM Design Module

At this point, all the data needed for the machine design is filled in the design module. The next step is to press the "Calculate" button, followed by the "Draw" one. The remainder parameters are automatically computed by PeMSyn, the machine CAD is drawn and the material are assigned to their respective places/regions. A section of the FEMM model created is shown in Figure 12 and the design results in Table II. This model, design results and input data can be saved by pressing the "Save" button.

PeMSyn automatically adds some conditions to the created model in order to mitigate numerical errors derived from the first order elements used by FEMM.

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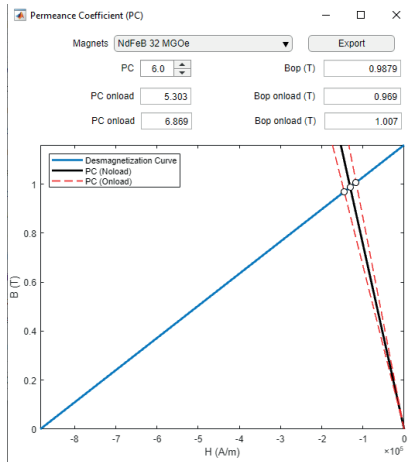Eletrôn. Potên., Fortaleza, v. 25, n. 2, p. 163-172, abr./jun. 2020
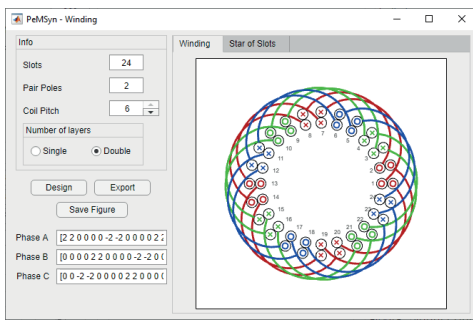
Fig. 10. PC module (no- and on-load).

Fig. 11. Winding Design Module

B. Performance Assessment

A module to simulate the created model is also built in PeMSyn. This module can be accessed through the main module or by pressing the "Simulate" button within any design module. The simulation module is shown in Figure 13. Some information is required from the user along with the simulation type (no-load, on-load or both), the drive current waveform (sinusoidal or square) and the number of parallel processes if available. For the on-load simulation, the drive peak current must be calculated through (26).

$$I_{max} = \frac{T_D}{k_T} = \frac{T_D}{k_E}. \tag{26}$$

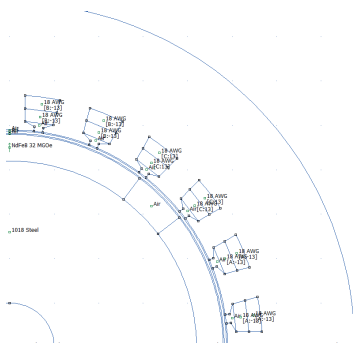This module can simulate any PMSM model created in FEMM if some conditions are satisfied. This conditions are:

Fig. 12. Model Created in FEMM

TABLE II
Design Values

Parameter	Value	Parameter	Value
w_t (mm)	6.96	E_C (mm)	20.89
w_s (mm)	10.83	$E_{C_R}^{IR}$ (mm)	21.99
tt (mm)	1.00	L_M (mm)	6.00
h_s (mm)	1.93	WG (AWG)	18
h_t (mm)	7.73	N_t	13

stator must be in group one, windings in group two, rotor in group three and there must be three circuits named "A", "B" and "C". Also, the poles must be aligned with phase "A" (the flux linkage in this phase must be maximum).

When the simulation finishes, the data results and graphics are automatically saved in the same directory of the simulated model. It is also possible to visualize these results navigating through the tabs available in the module. The PM flux-linkage, back-emf and cogging torque are obtained for both the no-load and on-load simulations, allowing to observe the effects of the armature reaction. The result of the on-load simulation is the developed electromagnetic torque, torque curve capability. The back-emf waveforms (no-load and on-load) for the example considered can be seen in Figure 14. The difference between the no-load and on-load waveforms are related to the saturation effects and armature reaction that have been assessed using the method proposed in [17].
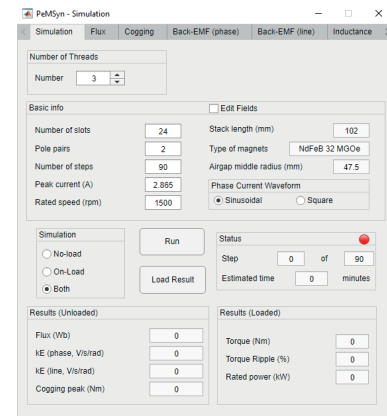

Fig. 13. Simulation Module

TABLE III
Simulation Results

Parameter	Value
Current Peak (A)	2.87
Average Torque (Nm)	4.63
Torque Ripple (%)	19.23
Power (kW)	0.73
Cogging Peak (Nm)	0.703
Back-EMF Constant (V-rad/s)	0.975

V. COMPARISON AND VALIDATION WITH REAL MACHINES

In order to validate and assess the performance and effectiveness of PeMSyn, two real permanent magnet machines have been taken into account and have been reproduced by
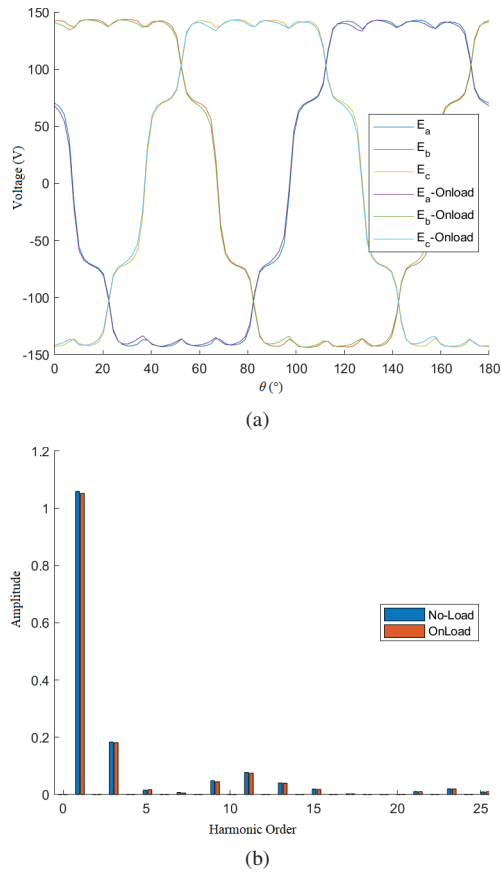
Fig. 14. Simulation results. (a) No-load and on-load Back-EMF. (b) No-load and on-load Back-EMF harmonic content.

means of PeMSyn, using eqs. (1), (3), (4), (7) to (10), (12) to (15), (17), (18), (20) and (21), considering their basic characteristics/dimensions available in [18] and [19]. For sake of clarity, these two machines have not been designed following the same design equations which justify the differences that can be found in the following paragraphs.

These machines are inner rotors but one is spoke-type and the other one is a surface mounted magnets. The spoke-type machine is described in [18] and is referred here as Ref1, whereas the surface mounted as Ref2 and is described in [19].

All models used for this comparison, both the reference ones and the ones replicated with PeMSyn, can be seen in Figure 15. The ones created using PeMSyn are presented in 15.b and Figure 15.d and the original ones in Figure 15.a and Figure 15.c. For sake of comparison, the Ref2 motor has also been re-designed and simulated using Altair Flux.

The dimensions of these machines are listed in Table IV, where Ref1# is the replication of Ref1 with PeMSyn, Ref2# is the one of Ref2 and Ref2F is the replication of Ref2 with Altair Flux.

It is possible to notice from Figure 15 and Table IV that although the rotor outer diameter is unaltered when replicating the real machines using PeMSyn, the stator dimensions are reduced. The reduction in the stator dimensions is due to the fact that PeMSyn follows the guidelines proposed in [7] with some improvements considering the armature reaction and leakage factor. These guidelines result in smaller teeth, as can be depicted in Figure 15, thus in a more compact machine. In addi-
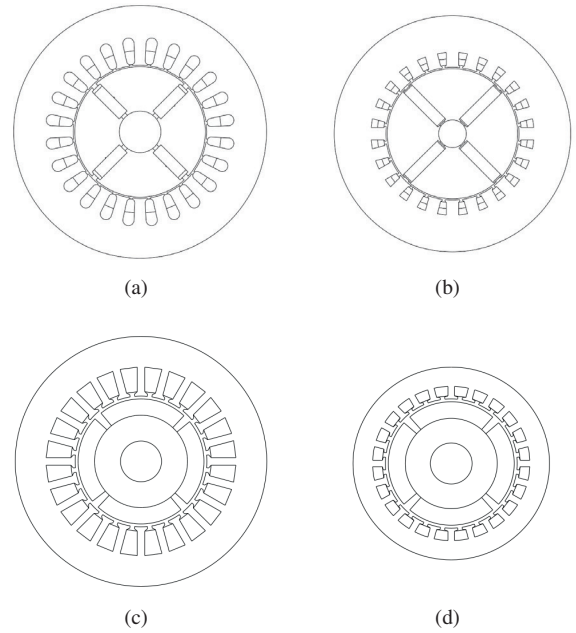

Fig. 15. Reference and PeMSyn models. (a) Ref1 (spoke type). (b) Ref1# (spoke type). (c) Ref2 (surface mounted). (d) Ref2# (surface mounted).

tion, a difference in the value of L_M is also presented.

TABLE IV
Simulation Results

Parameter	Ref1#	Ref1	Ref2#	Ref2	Ref2F
w_t (mm)	8.90	8.16	3.06	3.52	3.40
w_s (mm)	10.57	10.36	5.90	5.90	5.88
tt (mm)	1.00	0.81	1.04	1.00	1.00
h_t (mm)	10.57	19.47	5.90	13.40	13.91
h_s (mm)	1.50	3.32	1.42	1.95	1.61
L_1 (mm)	33.74	25.4	-	-	-
L_M (mm)	4.04	4.05	7.68	7.60	7.60
E_C (mm)	22.91	26.71	14.35	9.18	22.69
D_s (mm)	170.56	182.00	91.16	116.60	134.40
D_r (mm)	94.00	94.00	58.30	58.30	58.14
WG (AWG)	18	20	29	20	20
N_t	13	19	109	105	105

The models shown in Figure 15 have been simulated using the Simulation module available in PeMSyn. The Ref2F has been modeled, designed and simulated in Altair Flux. The performance parameters for all machines are presented and compared in Table V. Furthermore, Figures 16.a and 16.b show the torque waveforms of these machines. For the Case 1 (spoke-type machines), the PeMSyn model presented an average torque 8.43% lower than the reference machine, but with a torque ripple 6.77% smaller. For Case 2 (surface mounted machines), PeMSyn model showed an average torque 2.23% higher and torque ripple 0.35% higher than the reference machine. Case 3 (Comparison between PeMSyn and Altair Flux) Altair Flux model showed an average torque 1.90% smaller and ripple 22.52% higher than the reference machine. So, comparing the performance of the machines designed using PeMSyn and Altair Flux, it is possible to notice that PeMSyn's machine has higher average torque higher although the overall performance is close to Altair Flux's machine.

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TABLE V
Simulation Results

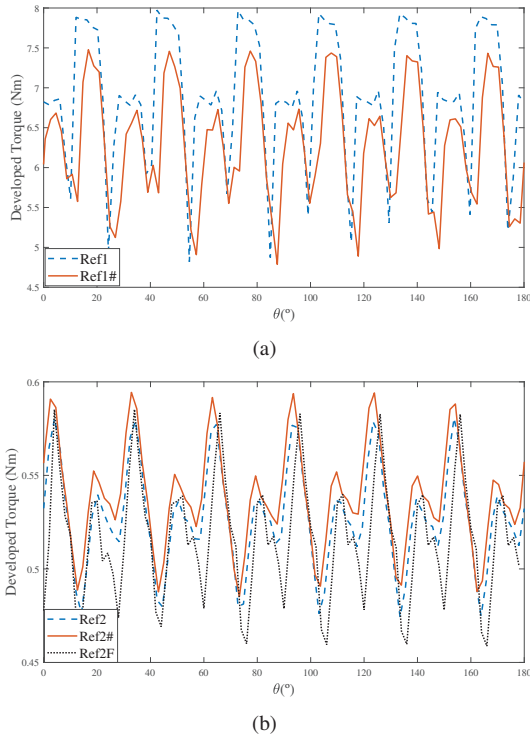| Parameter	Ref1#	Ref1	Ref2#	Ref2	Ref2F
Flux Linkage (Wb)	1.08	1.16	0.440	0.434	0.428
k_E (V-rad/s)	1.76	1.91	0.691	0.682	0.675
Cogging peak (Nm)	1.63	1.87	0.065	0.064	0.048
Average Torque (Nm)	6.30	6.88	0.539	0.527	0.517
Torque Ripple (%)	42.69	45.79	20.24	20.17	24.51
Rated power (W)	1385.7	1514.0	200.3	196.1	191.9

(a)

(b)

Fig. 16. Developed torque comparison. (a) Case 1 (spoke-type). (b) Case 2 (surface mounted)..

One can verify that, based on this Section V, PeMSyn is a valuable free tool for PM machine design and performance assessment with good accuracy.

VI. PeMSyn IN THE WORLD AND FUTURE WORKS

PeMSyn was released for download on SourceForge platform on 2019-06-14 without the armature and saturation effects assessment and without the Spoke-type machine design implemented. It was introduced in the form of a conference paper in December of 2019 in COBEP [5]. As shown on Figure 17 PeMSyn has been downloaded in many countries around the world.

Thanks to the users feedback, all reported bugs have been fixed. Furthermore, some improvements in the latest release have been suggested by the users.

PeMSyn has been recently updated and, as discussed in the paper, the armature reaction, the saturation effects have been implemented as well as the validation of the design procedure and performance assessment have been carried out. Last but not least, parallel processing has also been implemented to speed up the simulation. A new design module was added in 2020-02-28, the spoke type, and the user may now choose
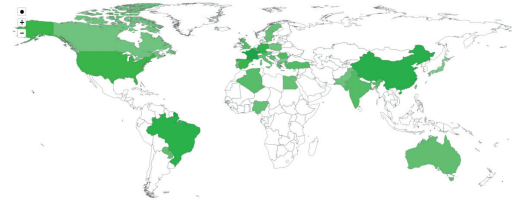
Fig. 17. PeMSyn in the World in `https://sourceforge.net/projects/pemsyn/files/stats/map`, access in 2020-05-22.

between different types of geometries for the slots edges. For future works it is expected to add options of V- and U-type topologies, the possibility of using anti-periodic boundaries in the design modules in order to reduce the simulation time. Improvements in the simulation module are also being prepared. All these and more will be available in future updates.

VII. CONCLUSIONS

As shown and discussed, PeMSyn integrates functionalities such as: winding design, Finite Element Analysis, thanks to the interaction between Matlab and FEMM, possibility of including additional machine topologies, automation of drawing and sizing of a machine requiring only its input parameters. These functionalities are presented as modules, allowing to access each of them independently. Thanks to the modularity of PeMSyn, it is easy to add new features.

The example in this paper proved that PeMSyn is simple and user-friendly, but also a powerful tool. Therefore, it is an interesting choice for the design and performance assessment of PM machines.

Furthermore, PeMSyn has been validated based on two real machines with different machines topologies.

As shown, PeMSyn has already reached different parts of the world, demonstrating to be an accessible and borderless tool. Considering these facts, PeMSyn is a remarkable tool to design, simulate and understand the behaviour of any machine. PeMSyn is suitable for researchers, undergraduate and graduate students of electrical engineering involved with electrical machines. PeMSyn can be used during electrical machines classes to improve the learning curve and help the students understanding the behaviour of different types of machines. Graduate students and researchers can do quick designs and quick performance analysis of permanent magnet synchronous machines they are investigating.

VIII. ACKNOWLEDGEMENTS

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