Emetor – An educational web-based design tool for permanent-magnet synchronous machines

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Abstract- **An educational web-based design tool for permanent-magnet synchronous machines (PMSM) is presented in this article. This tool, named Emetor, has been developed to be used in an undergraduate course on permanent-magnet machines. The technical aspects behind the tool, such as the PMSM's design procedure and the program architecture are presented. The benefits of Emetor in an educational environment are described. Different learning activities are presented to illustrate the potential of Emetor, as well as its suitability for education.**

I. INTRODUCTION

From research topics, permanent-magnet machines have become industrial products within the last decades. Therefore, electrical-machine engineers need to have knowledge on how these machines work and their main characteristics. A basic course in electrical machines can procure this knowledge. However, many of these engineers might have to work on the design of PM machines. Therefore, a dedicated course has been introduced in the international master program in electrical engineering at the Royal Institute of Technology, in order to provide future engineer with this competence.

The goal of this paper is to present a web-based design tool for PMSM used in the undergraduate course for master students entitled Design of PM machines. With this analytical tool, named Emetor [1], it is possible, so far, to design surface-mounted PMSMs with an inner or an outer rotor. The user enters input parameters, such as motor dimensions, materials or winding type, and Emetor calculates different magnetic or electrical properties, e.g. airgap flux-density from the permanent magnets (PMs), back-emf or torque ripple. The design is calculated with the assumption of a linear magnetic circuit.

The pedagogical benefits of using Emetor are numerous. Thanks to the help pages, the students can deepen their knowledge on electrical machines. Furthermore, a student can investigate the influence of different parameters on the performance of the machine and experience the difficulties in analytically designing a PMSM. Finally, discovering and using a new tool is a typical engineering task that allows the students to develop their independency and curiosity.

In this paper, Emetor is presented along with its program architecture, the graphical user interface and the basic models used for the design calculation. Strengths and weaknesses of the tool are emphasized. The pedagogical benefits are then presented and illustrated with examples.

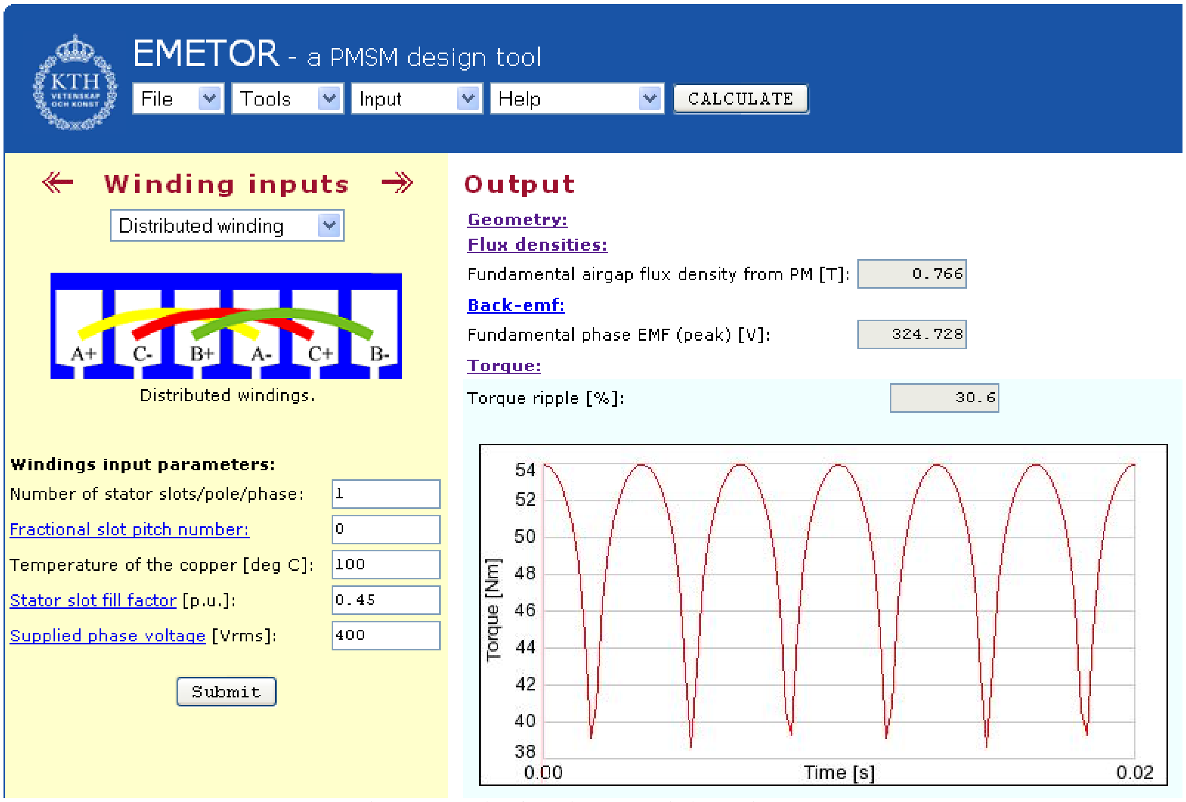
II. DESCRIPTION OF THE TOOL

A. Program architecture of Emetor

Having the tool on the web offers many advantages. First, Emetor is available to anybody with a computer connected to internet. There are no problems of program licence or installation. The students can then access Emetor from any computer. Furthermore, Emetor offers direct links to external web resources and references. The help pages can be adapted according to the students knowledge on electrical machines and to their demands. Finally, the web allows many interesting features. For example, we aim at proposing a forum to the Emetor's users so that they can interact and discuss different topics concerning electrical machines.

Emetor is programmed using html and php (php hypertext preprocessor). Php is used for the numerical calculations. Html and JavaScript are used for the page layout and for the functionalities of the tool, e.g. pop-up windows or links for help pages. Since the tool is online and the calculations are performed on a server, the code and calculations should be optimized to limit the computation time. Therefore, the highest calculated harmonic number and the size of the vectors for the time and angular position have been carefully chosen.

Emetor has been first implemented and tested in Matlab. Programming in php has introduced some limitations in the program. Unlike Matlab that includes an extensive library of functions, only very few functions are available in php. Simple functions should be programmed in php such as checking if an integer is odd or even or calculating the mean value of vector components. The model to calculate the effect of the slotting on the field distribution by using a relative permeance function proposed in [2] is very difficult to implement in php. Indeed, this model requires the solving of a non-linear equation, and therefore, a non-linear solver should be implemented as well in php. The problem is similar for an eventual implementation of a field-weakening calculation module. Calculating the operating point under field-weakening operation, i.e. finding the values of the d- and q-axes current at a given torque and



Windings input parameters:

Number of stator slots/pole/phase: 1

Fractional slot pitch number: 0

Temperature of the copper [deg C]: 100

Stator slot fill factor [p.u.]: 0.45

Supplied phase voltage [Vrms]: 400

Output

Geometry:

Flux densities:

Fundamental airgap flux density from PM [T]: 0.766

Back-emf:

Fundamental phase EMF (peak) [V]: 324.728

Torque:

Torque ripple [%]: 30.6

Fig. 1. Screenshot from the PMSM design tool Emetor.

speed, requires as well solving an equation. Therefore, neither the slotting effect module nor the field-weakening operation calculation module has been included in Emetor.

B. *Design procedure*

Inner or outer rotor PMSMs with surface-mounted PM and distributed or non-overlapping concentrated windings can be designed with Emetor. The design procedure was implemented to limit the number of input parameters. The input parameters are divided in four categories: the topology (inner or outer rotor), materials, windings (see Fig. 1) and design. The material inputs are for example the material density, conductivity of the iron or relative permeability of the PM. From the winding inputs, the winding layout and winding factor are calculated by Emetor. The design inputs are some dimensions of the PMSM, such as the tooth width or the PM thickness and the motor specifications, i.e. rated speed and torque.

From these inputs, different output characteristics are calculated. As shown in Fig. 2, the open-circuit airgap field is calculated from the given dimensions and materials properties. The phase current is then obtained from the given torque, the calculated open-ciruit airgap flux density and other inputs, so that the designed PMSM delivers the specified torque at the given speed. Other calculated outputs are the back-emf waveform, active weight, inductances, losses and torque ripple (not including cogging) (see Fig. 1).

It is assumed that the iron does not saturate. This means that the problem is linear. The slots of the machine are trapezoidal with flat bottoms and the teeth are straight i.e. the tooth width is constant all along the tooth.

C. *Models*

The models are adapted for both overlapping and non-overlapping windings. Analytical models for the design of PMSMs can be found in the literature. In [2]-[5], Zhu proposes models to calculate the open-circuit field and armature field for surface-mounted PMSMs. It accounts for both overlapping and non-overlapping windings. In [6], Proca shows how the models from Zhu can be included in a procedure to design surface-mounted PMSMs. In [7], EL-Refaie presents also a design procedure based on Zhu's models but with models specific to PMSMs with non-overlapping concentrated windings. His procedure includes also resistance, inductance, and losses calculations of such machines. Emetor is based as well on Zhu's model. Because of the difficulties of php programming described earlier, the slot effects on the field distribution are,

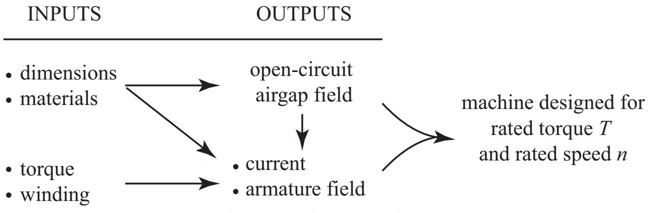


Fig. 2. Design procedure.

however, not taken into account.

They are few particularities in designing PMSMs with non-overlapping concentrated windings, which are described in the followings.

Some PMSMs with non-overlapping concentrated windings, so-called modular PM machines, have a stator mmf distribution with fewer poles than in the rotor. This is illustrated in Fig. 3 for a 28-pole/24-slot modular PMSM. The stator mmf harmonic component interacting in the mean torque production is not the fundamental, but a higher harmonic component of order equal to the number of pole pairs $p/2$. It is then called “main harmonic” component in [8] or “synchronous frequency component” in [7]. The order of the synchronous frequency component for the 28-pole/24-slot machine is then 28/2=14 (see first line under the spectra in Fig. 3). Another possible description of the winding is to define the main harmonic component as the fundamental, considering electrical angle instead of mechanical angle as previously done. This description considering electrical angle has been used in e.g. [9]. The relation between the two sets of harmonic orders is shown under the spectra of Fig. 3 for the 28-pole/24-slot machine. This implies that all the harmonics of mechanical order lower than $p/2$ are now sub-harmonics i.e. with electrical orders of fractional values lower than 1. It can be shown that the sub-harmonic components in the mmf (and all other orders than $kp/2$, k being an integer) do not play any role in the analytical calculations of the back-emf and the mean value of the torque. It is then convenient to have the “synchronous-component” winding factor equal to the component of order 1, disregarding the harmonics of fractional orders. The models of the machines with distributed windings with the winding factor and back-emf calculations can then be used for the PMSM with concentrated windings. Interestingly, if all the harmonics of fractional values are taken away from the true mmf, the reduced mmf is corresponding to the mmf of a PMSM with distributed windings. This is illustrated for the 28-pole/24-slot PMSM in Fig. 4. Therefore, when calculating the armature field distribution, all the harmonics should be considered in order to find a distribution as in Fig. 3 instead of a distribution as in Fig. 4.

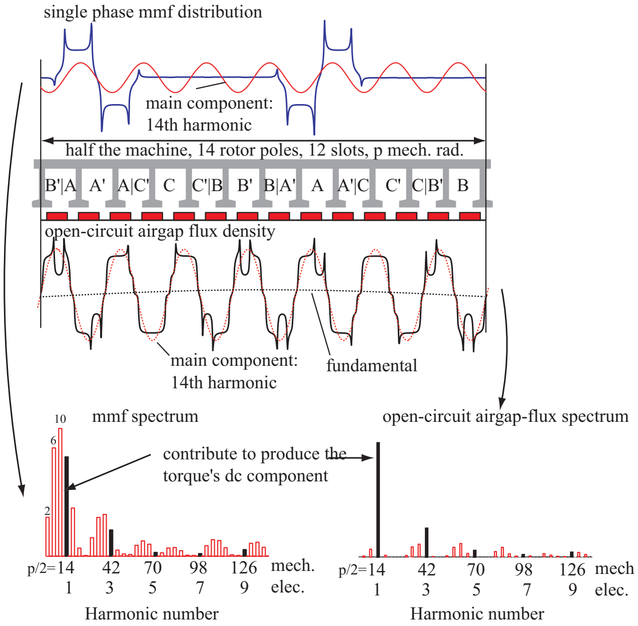


Fig. 3. Mmf distribution and open-circuit airgap flux density and their spectrum for a 28-pole/24-slot PM motor with concentrated windings.

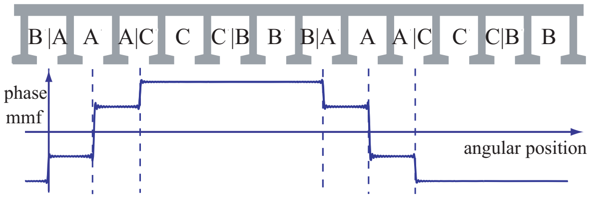


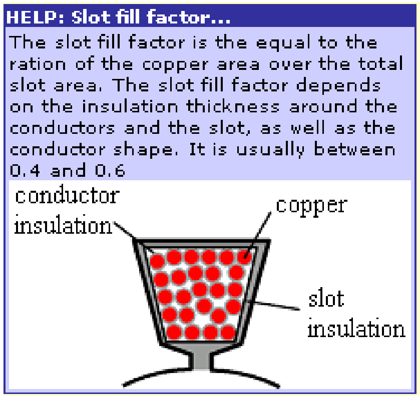
Fig. 4. Single phase mmf distribution for a 28-pole/24-slot PM motor when only considering the harmonics of integral (or $kp/2$) orders.

The phase resistance is calculated differently for the two types of windings due to the shorter end-windings with concentrated windings. Finally, the inductance is calculated from the armature field by taking all the harmonics into account. The main component gives the magnetizing inductance but the harmonic components contribute to the leakage inductance that is not negligible for machines with concentrated windings.

III. PEDAGOGICAL BENEFITS

As future electrical machine engineers, students are likely to use design programs. Whether it is a commercial software or an in-house developed tool, its utilization requires not only a general knowledge about PM machines, but also the ability to critically analyze obtained results and understand the influence of the assumptions or model limitations. Therefore, using a design tool during undergraduate education gives an opportunity to start developing the required skills in a less stressful environment than a company.

If the students are missing some knowledge on electrical machines, they can first refer to the different online helps that Emetor provides. Fig. 5 shows an example of a help pop-up window that appears when dragging the mouse over “slot fill factor”. The online information will progressively be


HELP: Slot fill factor...

The slot fill factor is the equal to the ration of the copper area over the total slot area. The slot fill factor depends on the insulation thickness around the conductors and the slot, as well as the conductor shape. It is usually between 0.4 and 0.6

Fig. 5. Example of help pop-up window.

completed depending on the student needs.

To get familiar with the tool, to use it properly, as well as to strengthen their knowledge, tutorial activities may be planned. Emetor may then be used for a project in which the goal is to design a PM machine for an industrial application.

A. Tutorials

At the beginning of the course, the students have hardly ever seen a PM machine other than as a cross-section in a book. Therefore, they have no experience to refer to when it is time to analyze the values obtained for different machine dimensions or characteristics. Acquiring this experience takes time. However, relevant tutorials may supply first sets of reference values. They allow as well discovering the different aspects and possibilities of the program.

Some examples of possible tutorial activities are presented here, using a 28-pole outer-rotor surface-mounted PM (SMPM) motor with non-overlapping concentrated windings, as an example. This motor was thoroughly investigated both theoretical and experimentally in a doctoral project [10].

Getting started with Emetor

To begin with, students may be given all the information about an existing motor, and asked to create the motor model in Emetor. Feeding the data requires understanding the name and signification of each parameter, and the help pop-up windows limit the possible misinterpretations about the definitions of the different parameters. Looking at the cross-section of the motor drawn in the geometry output module gives a first experience on the relative thickness of the different parts of the magnetic circuit (see Fig.6). It is also important that the users/students start using as quickly as possible the save and load functions. These functions are important as the generated files allow retrieving designs done at different sessions. They may also be used to import or export data with other software packages like Matlab and Excel.

Short tasks may allow the students to strengthen their knowledge on electrical machine. For example, they can be asked to draw the armature reaction flux density of the modeled motor and calculate its amplitude by using Ampere's law. They can then compare their results with the waveform calculated by Emetor, as in Fig. 7 for the 28-pole motor. This comparison allows emphasizing one of the limitations of Emetor. The small ripple that can be seen in Fig. 7 is due to the restricted number of considered harmonics chosen to limit the calculation time.

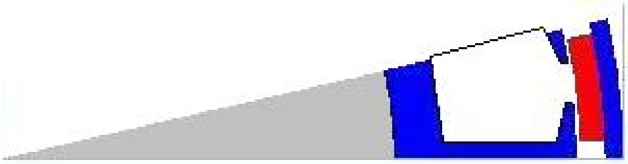


Fig. 6. Cross-section of a 28-pole SMPM prototype in Emetor.

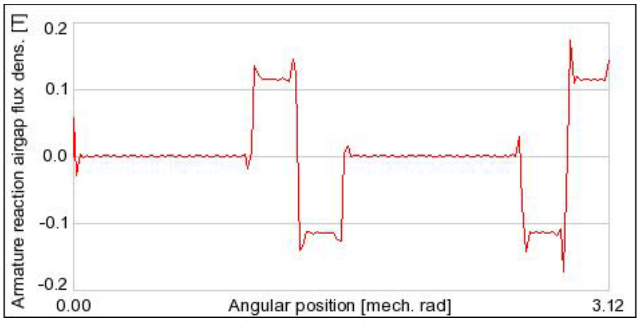


Fig. 7. Armature reaction flux density of the 28-pole SMPM prototype calculated in Emetor.

Building a library of existing machines for various applications (different power range, speed range, cooling systems, PM materials, etc…) is planned, introducing in a near future the possibility for the students to compare design key numbers for various applications. All Emetor users are warmly encouraged to submit their applications and tutorial ideas to the developing team, to help building up the library of models.

Towards complex design tasks with Emetor

Once a minimum of experience in critical analysis of design results has been gathered together with software skills, short design tasks could be proposed in form of tutorials as well. Any design parameter variation and investigation of the influence on output characteristics is interesting for a design beginner.

Emetor does not allow like in Matlab or in Excel to do intensive parametric study. However, varying one parameter at a time in steps (e.g. the airgap thickness taking 3 different values, 0.8 pu, 1 pu and 1.2 pu) and comparing the output characteristics (e.g. maximum airgap PM flux density, current loading, Joule loss, etc…) gives a solid basic knowledge before dealing with more complex variations. This allows also illustrating how Emetor's design procedure described in Fig. 2 works. An example is shown in Table I for the 28-pole prototype motor. As can be seen, the fundamental airgap PM flux density varies with the airgap length. Emetor increases or decreases the current so that the nominal torque can be achieved. Furthermore, at that stage, it can be illustrated that some parameters have more influence than others.

An example of more complex variation could be to vary the airgap thickness but to compensate with the magnet height to keep the maximum airgap PM flux density constant at the same time, letting the students decide which output parameters are now relevant to compare.

These are only a few examples of what could be done with Emetor in terms of tutorials, aiming at developing the students' machine design skills progressively. More examples will be developed, based on student feedback gathered each year and

TABLE I
PARAMETRIC STUDY ON THE 28-POLE SMPM PROTOTYPE

Airgap length [p.u.]	0.8	1	1.2
Fundamental airgap PM flux density [p.u.]	1.027	1	0.973
Phase current [p.u.]	0.98	1	1.018
Torque [p.u.]	1	1	1

from the discussion within the users' forum.

After completing a set of carefully chosen tutorials, the students should then be ready to use Emetor for an individual project, in which the goal is to design a PM machine for an industrial application.

B. *Project*

Emetor has actually been developed with the idea that students may use it to carry out design tasks for an industrial application within the project part of the course. The course is 7 weeks long, and the students take two courses in parallel.

In 2007, the course had two industrial applications, split in such a way that each student had a different set of specifications. The project work conducted by one of the student is presented here to illustrate what can be done with Emetor. The student actually used the Matlab version of Emetor, as the web-based version was part of the course development for 2008. However, the web-based version was used to produce the results presented here. The specifications are presented in Table II. It was decided that one student would design a four pole motor and another one would design an eight-pole motor.

To be able to use Emetor, an initial set of dimensions needs to be calculated. Sizing equations (simplified models) and design procedure were first presented during lecturing time, together with a numerical example. The student made the key assumptions presented in Table III based on his knowledge after one week of the course. The cross-section of the obtained initial design is shown in Fig. 8a, illustrating that the assumption A3 is not suitable for an eight pole motor. More characteristics of the initial design are given in the first column of Table IV.

TABLE II
SPECIFICATIONS FOR DESIGNED PMSM

Specification	Value	Specification	Value
Motor type	SMPM	Topology rotor	inner
Magnet remanence flux density [T]	1.08	Cooling system	Water (40°C) in outer mantel
Number of phases	3		
Shaft power [kW]	22	Weigth max. [kg]	10
Nominal speed [rpm]	3000	Length max. [mm]	$L = 150$
Nominal torque [Nm]	65	Outer diameter max. [mm]	$D_0 = 350$
Efficiency min.	0.95	Number of slots per pole per phase	1
Temperature of the winding [°C]	100	Number of poles	8

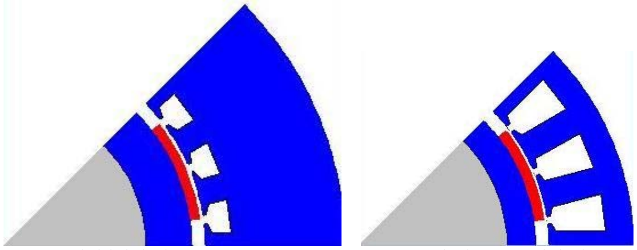
TABLE III
ASSUMPTIONS USED TO OBTAIN INITIAL DESIGN

Nr	Assumption	Comments
A1	$\Delta T = 60°C$	Temperature diff. copper-water
A2	$h_{eq} = 50$ W/m^2/°C	Equivalent heat exchange coefficient copper-water [12, 13] (see Fig. 9)
A3	D_0/D=1.8	Ratio outer diameter / airgap diameter
A4	J = 10 A/mm2	Current density
A5	0.9 T	Fundamental PM airgap flux density
A6	$L = D$	Axial length of stator laminations
A7	1 mm	Airgap thickness

Using Emetor to run a parametric study, an improved design was obtained (see Fig. 8b, second column of Table IV). The student then used finite-element (FE) simulations (weeks 3-4) to check the main performance of his improved motor. He could see that the expected torque was 6% lower than expected because the stator teeth get saturated. A high torque ripple of 51% was also obtained as the number of pole per phase is only equal to 1. The FE-calculated iron losses were 8% higher than calculated with Emetor (week 5), suggesting that the models in Emetor work fine in this case.

The next task conducted by the student (weeks 6-7) was to develop a more advanced thermal model for the stator using [11,12]. The model is shown in Fig.9a. Moving all the losses together with the end-windings losses (worst case), a new value for the equivalent heat exchange coefficient copper-water h_{eq} was found, equal to 237 W/m^2/°C, nearly 5 times the assumed initial value (A2 in Table III). This allowed the student to reduce the active length of his motor from 100 to 72 mm, reducing the weight of active material by 25% (see third column in Table IV).

The project was concluded by presenting orally the contents of the final report, describing the process, the results and their



a- initial design b- improved design

Fig. 8. Cross sections drawn by Emetor

TABLE IV
EVOLUTION OF THE SMPM MOTOR DIMENSIONS DURING THE DESIGN

Dimension/Parameter	Initial	Improved	Final
Core length L [mm]	159	100	72
Outer stator diameter D_0 [mm]	287	232	232
Rotor diameter D	159	150	150
Stator slot width [mm]	11.1	10.5	10.5
Stator slot height [mm]	11.2	24	24
Heat exchange coefficient h_{eq} [W/m^2/°C]	42 [a]	70 [a]	238 [b]
Current loading [kA/m]	19.9	35.3	49.1
Current density [A/mm^2]	6.53	4.33	6
Total copper losses [W]	346	306	514
Total iron losses [W]	218	329	237
Active weight [kg]	62.6	22.9	17.3

[a] considering copper losses only.

[b] considering sum of copper and iron losses.

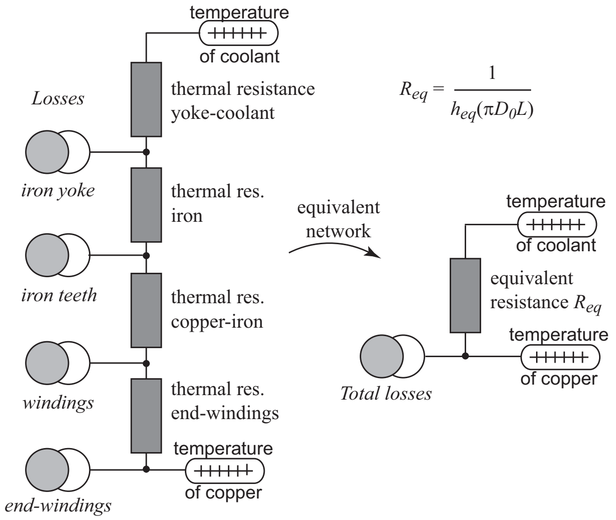


Fig. 9. Improved thermal models

analysis, as well as opposing on another student's report.

IV. FUTURE POSSIBLE DEVELOPMENTS

The potential of further development of Emetor is considerable. First, the models such as the iron losses could be improved. New models could be added as for example to calculate the cogging torque, or mechanical losses. A thermal model could also be included in Emetor. The design procedure could be modified or completed in order to give the user more flexibility in its design. For example, the designer could design the machine for a specified rated current and speed and check the obtained torque.

Furthermore, other topologies of PM machines could be considered. The easiest to implement from the present models is the inset PM machine. Inset PM machines have surface-mounted PMs with iron interpoles that give a salient structure. The open-circuit airgap flux density could be calculated from [13]. d- and q-axis inductances should also be calculated in order to estimate the reluctance torque. Implementing other topologies with buried PM is more difficult. Additional inputs are first required to describe the position of the PMs in the rotor. Besides, PMSMs with buried PMs have highly saturated iron bridges that hold the PMs in the rotor.

Some effort should also be devoted to the improvement of the user interface. Designing an optimal user interface is challenging, due to the complexity of Emetor and the high number of inputs and outputs. The feedback from the users will help to continue improve this interface. As mentioned earlier, the help pages and pop-ups could be completed and a forum would allow the students to discuss diverse issues on electrical machines.

V. CONCLUSION

An educational tool to design PMSM machines called Emetor has been presented. It allows investigating PMSM motors with inner or outer rotor and distributed or concentrated (double-layer) windings.

Emetor is web-based so it is free of access through internet. Users should be aware that the analytical models assume a linear magnetic circuit (no saturation).

By using the program in appropriate learning activities, students have the possibility to improve their skills on electrical machines and work on typical design tasks. Some examples of tutorials and the results obtained during a project have been presented.

Further developments of the program will be driven by educational purposes, using student feedback as well as inputs from the user forum.

ACKNOWLEDGMENT

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