A Virtual Testbed for Instruction and Design of Permanent Magnet Machines

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Abstract: This paper presents the application of the novel concept of virtual learning to the design of a permanent magnet machine. The software is organized in learning modules, each module consisting of : i) explanation layer; ii) exploration layer; iii) (instructional) diagnostic layer. The software combines classical learning tools, such as lecture notes, with computer aided design (CAD) tools. A description of the developed system is presented.

Keywords: Virtual learning, permanent magnet synchronous motor, design.

I. INTRODUCTION

Although the concept of virtual learning was first introduced more than a decade ago, little has been done until recently to implement it, due to the reduced computing power and access to computing facilities for most people. The idea behind virtual learning lies in the possibility of communicating information through high-speed communication system and, when needed, with a local facilitator to supervise a course at a local site. Virtual learning implies many realizations and interpretations, such as computer assisted teaching (on or off-line), video conferencing, etc. This paper seeks to develop modular instructional technologies to create an alternative learning environment to enhance design instruction in general, and a motor design in particular.

A virtual learning system should seek to transfer knowledge from an experienced teacher to the student by using an optimum setting. If this task is accomplished properly, some students may use the system through the World Wide Web, without the use of a local facilitator. The learning systems may also be used as teaching tools by a local teacher-facilitator for more effective instruction of a large number of students.

This paper presents a preliminary result in the development of a virtual learning system for the design of a permanent magnet(PM) machine. The methodology for the development and use of the system and information related to PM machine design are presented.

PE-273-PWRS-0-07-1998 A paper recommended and approved by the IEEE Power Engineering Education Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Power Systems. Manuscript submitted December 23, 1997; made available for printing June 22, 1998.

II. VIRTUAL LEARNING SYSTEM STRUCTURE

The virtual learning system is developed based on modular instructional technology curricula. The learning tool is composed of subsequent modules, each introducing more knowledge to the student. The knowledge content of each module has to be balanced for the optimal transfer of information, preventing the risk of overloading the student. All modules have a similar structure, consisting of:

i) An explanation layer. In the explanation layer, the student is introduced to the information related to the basic fundamental notions. This layer resembles an in-class lecture presentation.

ii) An exploration layer. This layer can be compared to the example problem presented in a class. In the exploration layer the student has to apply the knowledge acquired to a practical example.

iii) An (instructional) diagnostic layer. This layer has two objectives. The first is to develop an interactive learning submodule in a tree structure. At each level, a question is asked and multiple answers are given. The student will select one answer and the interactive learning submodule will indicate whether the correct answer was chosen. The process continues until all topics in the module are covered. Some topics will be addressed in the form of a problem rather than in the multiple choice fashion. The second objective is to time-test the student and to establish whether the student should be allowed to go to the next (deeper) level. This approach corresponds with the exam portion of a classical teaching approach.

The present teaching approach uses simulations (including animation and other graphics, where appropriate) to assist the student in "visualizing" the concepts and to provide the student immediate graphical feedback during the learning process.

A motor design example will best illustrate these concepts. The example presents one of the modules of the virtual learning tool and its three layers.

Explanation layer:

In the present example, the following concepts are presented: a) the relations between the number of poles, phases, layers and slots; b) the back electromotive force (emf), its generation and its influence on the motor/generator operation; and, c) the influence of the number of poles, phases and slots selection on the back emf.

In the design of an AC electric motor, the product of the number of stator slots and layers (number of phases within a slot) should have the following properties: i) the product should be even so that there will be a forward and return path for each coil; ii) the product should be a multiple of the number of phases, so that there will be an even distribution of the phases on the stator; and. iii) the product has to be equal to or larger than the product of the number of poles and phases to satisfy both previous requirements[2].

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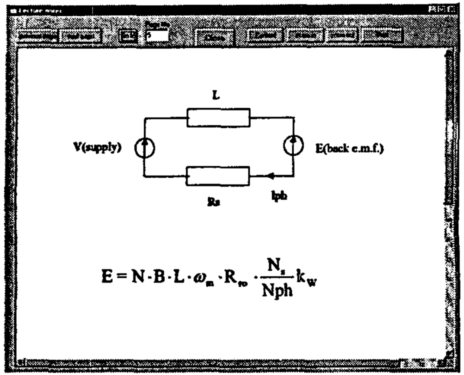
The back emf is the voltage induced in the stator coils by the variable flux generated by the movement of the permanent magnets[2]. Fig. 1 shows a simplified equivalent circuit of the motor per phase.



$$E = N \cdot B \cdot L \cdot \omega_m \cdot R_{ro} \cdot \frac{N_s}{Nph} k_w$$

Fig. 1 Equivalent motor circuit per phase

The figure is a caption of the program's explanation layer. The back emf determines the operation condition of the machine. If the back emf is larger than the supply voltage, then the machine will function as a generator. If the back emf is smaller than the supply voltage, then a motor operation will be encountered. The equation in Figure 1 is the back emf formula, assuming steady state conditions and a sinusoidal distribution of the magnetic field over the motor airgap. N is the number of turns per coil, B_g is the air gap flux density (rms), L is the length of the stack, ω_m is the angular speed, R_{ro} is the rotor radius, Ns is the number of slots, Nph is the number of phases and k_w is the winding factor. While most of the factors in the equation will be explained in consequent modules, it is important to note that the back emf is influenced by the choice of the number of slots.

Considering that the motor is designed for a certain rated speed and that the other factors have been established, the mere selection of the number of slots can make the machine a motor or a generator at rated speed. The back emf equation assumes a sinusoidal shape for the back emf. In reality, the emf shape can range from an approximately squared (or trapezoidal) shape to the sinusoidal shape, depending on the number of slots, the magnet shape and the winding distribution in the slots. The latter two factors will be explained in a consequent module. This module introduces only the influence of the selection of the number of slots on the back emf shape and its harmonic content. As a rule, a large number of slots will result in a sinusoidal emf shape, whereas a small number is likely to determine a square shape for the back emf. Fig. 2 shows a caption from the program with the comparison of back emf shapes when using 18 and 72 slots for a three-phase machine with six poles.

Exploration layer:

In this section, the knowledge acquired in the explanation layer will be applied to a practical design example. Assume that you are to design a rotor-stator topology for a 5 Hp, 120 volt, three phase, six pole motor. You are to find the optimal number that would simultaneously reduce back emf harmonics and still offer motor operation conditions. Using the simulator provided with the learning tool, you can simulate the motor and visualize the effect of different number of slots over the back emf amplitude and its harmonic content.

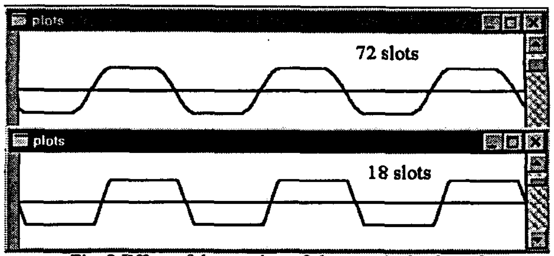


Fig. 2 Effect of the number of slots on the back emf

Fig. 3 presents a caption of the harmonic distribution of the back emf for two of the choices, 18 slots and 72 slots. Two new concepts are also introduced, the distribution factor and pitch factor. The product of the two factors gives the winding factor, k_w, which was introduced in the back emf formula, but not explained at this stage.

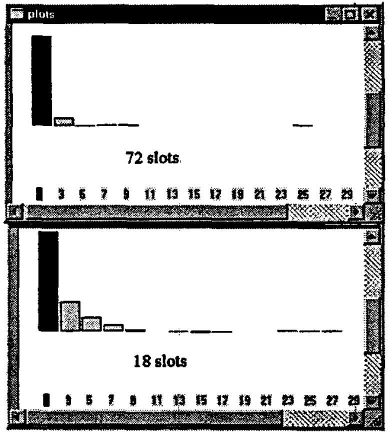


Fig. 3 Harmonic distribution for two slot choices

There is a phase shift between the emf generated in each coil, and the total emf is reduced by a factor called the distribution factor, kd. An approximation based on sinusoidal back emf distributions is :

$$k_d = \frac{\sin\left(\frac{Nspp * \theta_{se}}{2}\right)}{Nspp * \sin\left(\frac{\theta_{se}}{2}\right)} \tag{1}$$

where θ_{se} is the slot pitch in electrical radians, and Nspp is the number of slots per poles per phase. Also, because the coil pitch is smaller than the pole pitch, the net coil area exposed to the flux is reduced, as shown in Fig. 4.

Therefore, the induced voltage is also reduced. The pitch factor, kp, is defined to account for this reduction:

$$k_p = \frac{\text{integer part of Nspp}}{\text{Nspp}} \tag{2}$$

Diagnostic layer

The diagnostic layer is composed of several questions to test the student's understanding of the presented concepts. Fig. 5 presents a typical diagnostic structure for the explanation and exploration layers previously presented. The first few questions relate to the relationship between the number of slots and the number of phases, poles and layers, and are exemplified on a

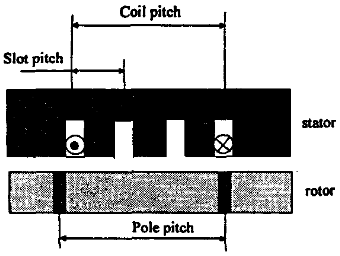


Fig. 4 Coil, slot and pole pitch

motor with three phases and four poles. The gray boxes represent bad answers. The correct answer for the first question is 12, since the minimum number of slots for a single layer configuration is the product between the number of phases and poles. For the second question, if two layers were used, the minimum number of slots to be used is half the number for a single layer. For the third question, if you were to use more slots than the minimum (to decrease the harmonic content of the back emf) the rules presented in the explanation layer apply. Since they are not a multiple of the number of phases, 14 and 20 are not valid numbers; the correct answer is 72, since it is a multiple of the number of phases and of the number of poles and is larger than the product of the two numbers. Correct answers would also have been 18, 24, 30, 36, 42, etc. The correct answer to the fourth question is that 24 slots are more likely to reduce the back emf harmonics than six slots.

The second part of the diagnostic test is related to the relation between the number of slots and the back emf, and is more of a design problem than a multiple-choice test. You have to go through several iterations to choose the optimal number of slots for a given design. A simulator will calculate the back emf value and its harmonics content.

A sequence of possible iterations is also drawn, corresponding to the logical sequence in the design. An example of the back emf amplitude and harmonic content for 18 and 72 slots was shown in Figures 2 and 3. For this stage of the design, you are only concerned that the amplitude of the back emf is smaller than the supply voltage, and that the value of the harmonic content is smaller than the required value. Several other parameters, such as the diameter of the rotor, the type of magnets used for the poles, the number of turns per slot, etc need to be known to do this calculation. The parameters used for this analysis are given in Appendix A. The program also provides this information for completeness, but the use of these variables in motor design will be explained in later modules.

If these tests are passed, the student is allowed to move to the next (deeper) level. This will include concepts regarding harmonic reduction using fractional slot-pitch, winding design, mmf waveforms, etc. Some of these concepts were already used in the exploration layer, but only summarily described at that stage. The next level is also composed as a module with explanation, exploration and diagnostic layers.

The learning module is further expanded until all the relevant concepts are introduced. All learning modules will be developed using an object-oriented structure that will allow the seamless addition of new blocks and menus.

III. OBJECT-ORIENTED PROGRAMMING

Object-oriented programming (OOP) is a concept that was introduced more than a decade ago. Since then, most of the existing software has been written in OOP[1].

Unlike "classical" top-down or structured programming, where data and execution code are separate entities, object-oriented programming offers the advantage of embedding the two into program units called objects. This offers greater flexibility in programming and usage; the programmer can add code at any time, with little effort, and without having to rewrite the program. In many practical situations, there is no need to compile the entire program, just the part that has been added. Also, modifying code becomes easier since the user does not have to worry about the entire program, only about the particular class (the generic representation of an object) being changed. Related to OOP is the graphical user interface (GUI), another concept that allowed ease of use and made the computer more "user friendly." Although the use of GUIs brought an increase in both memory usage and a decrease in computation speed in the early stages of their existence, with the development of faster computers with larger memory, this disadvantage has been overcome.

Furthermore, the introduction of GUIs has increased the efficiency of work from the user's side, by allowing faster communication, data input or output, printing, etc., and by making the computer more "attractive" for even non-traditional users. Instead of punching strange combinations of keys, and having to be very familiar with the program structure, the GUIs offered the easiness of WYSWYG (what you see is what you get), a concept that allows the user to simply click on the graphical symbol on the screen (buttons, menus, check boxes, etc.) to perform the same operation. Furthermore, in most cases, there is no need to read manuals, since most information is displayed in an intuitive fashion.

IV. PM MACHINE DESIGN AS A VIRTUAL LEARNING TOOL

This section presents the application of previous notions about teaching by means of a computer program to the design of a PM machine. The program can be used either as a teaching tool or as a design tool. Although the program follows the layer-by-layer structure (explanation, exploration and learning diagnostic), this section will concentrate more on the design method than on the teaching approach. Many of the design steps and program details are intentionally skipped to keep the paper at an appropriate length.

IV.1. Starting point - the program console

The program contains a main window console that is permanently displayed on the screen. A caption of the console window is shown in Fig. 6. A text window is displayed in the main console; the text contains information pertinent to every design step, from both the program and from the design procedure point-of view.

Two << and >> buttons allow the user to go back and forth through the design. The design step number and its name are displayed in two text boxes as well. If the user is familiar with some of the design aspects and passes the learning diagnostics tests, he or she may "jump" over them by typing the

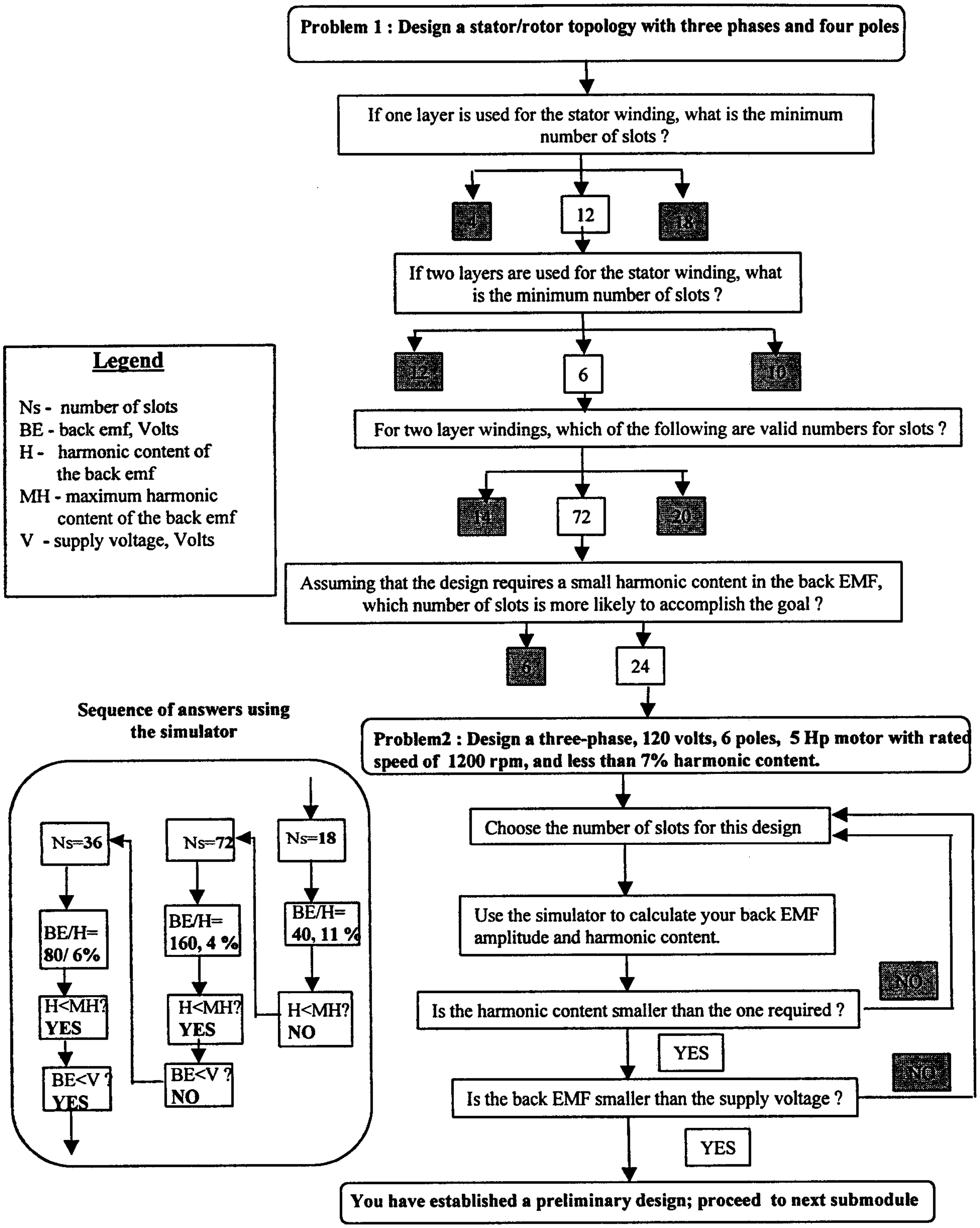
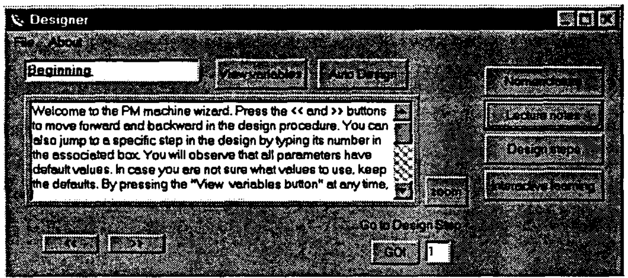


Fig. 5 Diagnostic layer example



Welcome to the PM machine wizard. Press the << and >> buttons to move forward and backward in the design procedure. You can also jump to a specific step in the design by typing its number in the associated box. You will observe that all parameters have default values. In case you are not sure what values to use, keep the defaults. By pressing the "View variables button" at any time,

Fig. 6 Main console window

corresponding design step number in the text box and pressing the "Go!" button. By pressing the "View variables" button at any time, the user is able to see the list of all variables in the design, as specified in that design step. Using the File menu, the design can be saved at any time. The "Autodesign" button helps to predetermine the best design values with respect to efficiency, with a minimal set of requirements. The "Nomenclature" button shows a nomenclature of all symbols used in the design. The "Lecture notes" button brings up a set of lecture notes that formed the basis of the design. A caption of the "Lecture notes" window is shown in Fig. 1. The "Interactive learning" button triggers the layer-by-layer structure. The window has typical text buttons that allow the user to quickly browse through the notes. It is also possible to print parts of or the entire lecture document.

IV.2 Design steps

The design steps are separate objects that are introduced sequentially in the design. The following paragraphs will describe the most important design steps and their implementation.

Preliminary parameters (motor equation)

Most of the design of the permanent magnet motor (and, in general, of any electric motor) is done by electric, magnetic and power calculations. The general procedure is to start with certain dimensions and configurations, iterating those until the best performance is obtained. Therefore, there is the need for the initial values to begin the iterative procedure. Any design starts by specifying the rated power and rated speed. Based on this information, the rated torque is calculated. The initial geometrical values for the design will be given by the following empirical equation:

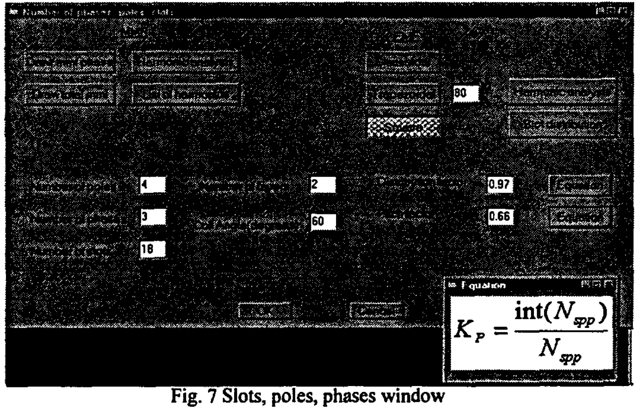
$$T = k \cdot D^2 \cdot L$$

where T is the torque in Nm, D is the rotor diameter, L is the stack length and k is an empirical constant between 5000 and 20000. Although the relation does not offer the values of D and L, they can be calculated if one of them is known (sometimes, the design requirement specifies certain restrictions in length or diameter). If they are not known, a proportion value between L and D can be considered: D=L/3. The values obtained from the previous equation will not necessarily be the final values of the design, since they can be changed until the best design is obtained.

Number of poles, phases, slots

The choice in the number of poles, phases and slots has very few limitations, and is more the choice of the designer. The program offers the possibility of trying different configurations and testing their significant dimensions. Fig. 7 shows a caption from this design step. All the text boxes in the window are accessible to the user. If an incompatible number is introduced (for example, an odd number of poles) warnings are issued.

The choice of number of poles, phases and slots determines the distribution of both the magnetomotive force (mmf) along the airgap, and also the distribution of the back emf per phase. For the latter, since the shape of the magnetic field distribution for the PM poles is not known (it depends merely on the shape of the magnets), the user can choose between a sinusoidal, square or trapezoidal distribution, by far the most common distributions. The program allows the user to visualize the two waveforms and to analyze them using harmonic analysis, as shown in Fig. 2 and 3. It is also possible to analyze the phase distribution in the slots, one of the issues difficult to understand analytically.



$$K_P = \frac{\mathrm{int}(N_{spp})}{N_{spp}}$$

Fig. 7 Slots, poles, phases window

Materials choices (data bases)

Many types of PM materials are available today. The most popular are the alnico, ferrite (ceramic), rare-earth samarium-cobalt and neodymium-iron-boron. A data base is constructed for them, as well as for the other materials used in the design. The user may choose between the existing magnets in the data base, or enter his or her own. Similarly, a material selection exists for the core materials.

Magnet dimensions

The surface mounted magnets with radial magnetization are used in this design. Further developments will include other types of magnet mounting or magnetization. Fig. 8 shows a caption from the design step where magnet dimensions are specified.

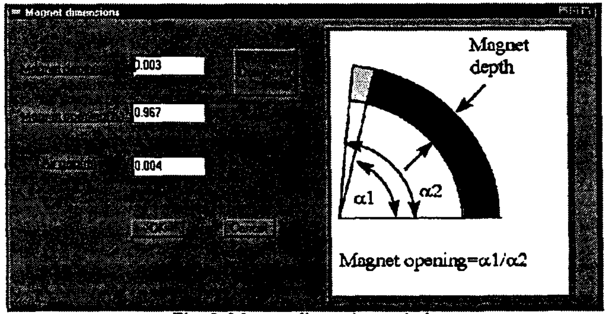
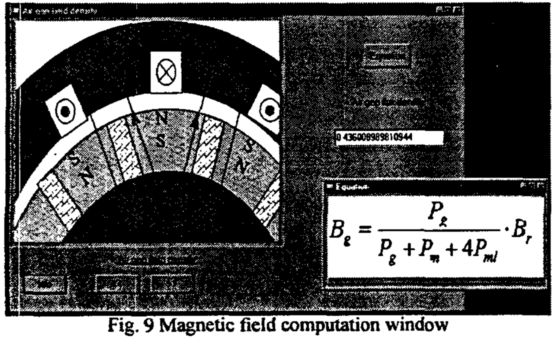


Fig. 8 Magnet dimensions window

Magnetic circuit

There are several design steps that contribute to magnetic circuit analysis. The purpose of these steps is the calculation of the magnetic field density in the air gap. The analysis starts with the equivalent magnetic circuit of a pair of poles, as shown in the caption in Fig. 9.



0.436008989810944

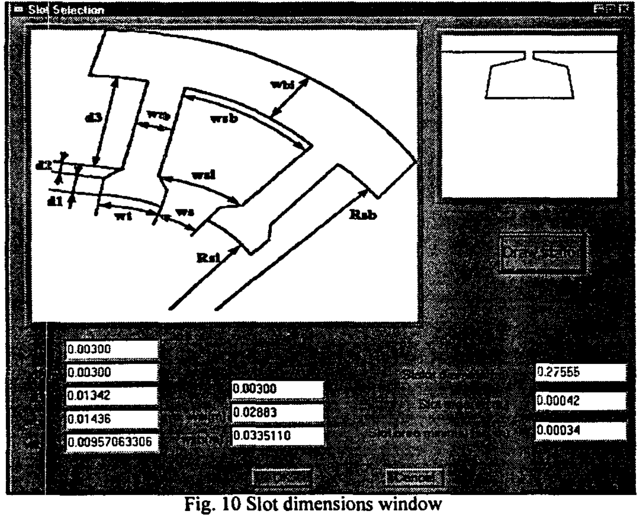
$$B_g = \frac{P_g}{P_g + P_m + 4P_{ml}} \cdot B_r$$

Fig. 9 Magnetic field computation window

The window also shows a typical configuration of the design steps that calculate motor parameters or values. An equation button pops-up an equation window if necessary. The "Info" button displays information regarding the design step, and there is also a picture related to the step. A series of approximations is needed to calculate the elements of the circuit, such as the permanent magnet leakage permeance, the air gap permeance, and the permanent magnet leakage.

Further sizing

Once the air gap flux density is known, based on the rated torque formula, the rated slot current can be calculated. Based on the slot current and the maximum admissible current density, the slot area can be calculated. Also, from the solution of the magnetic circuit, minimal dimensions can be established for the teeth width and stator bore, so that they will not saturate. Fig. 10 shows a caption from the slot dimensions step.



0.00300
0.00300
0.01342
0.01436
0.00957063306
0.00300
0.02883
0.0335110
0.27555
0.00042
0.00034

Fig. 10 Slot dimensions window

The user establishes the other dimensions of the slot, and different geometries can be generated, ranging from the rectangular slot ($w_s=w_{sb}$) to the typical shoe configuration (w_s as small as one conductor width). A picture of the new slot geometry is displayed. An entire stator section can be displayed with the corresponding button.

At each change in dimensions, the saturation of the teeth and iron bore and maximum current density of the slot windings are checked, and if they are larger than the admissible values, a warning window appears.

Back emf and number of turns

At this point, the only parameter to be chosen is the number of turns per slot. The number of turns affects several motor parameters, such as inductances, resistances, and back emf. Since, from this point, all the parameters of the motor can be calculated, the program initializes the value of the number of turns as the integer that will determine the closest value to the rated torque required; the user can then change it. If the number is too large, the motor behaves as a generator at the given operating point. Therefore, a warning message is displayed if this happens. Warnings are also generated if the saturation value for the iron is surpassed, if the calculated current may demagnetize the magnets, or if the current density is larger than the admissible value. Since most PM motors are controlled by power converters, the user can check the performance of the motor at different supply voltages by changing the value in the associated box.

Equivalent circuit

The equivalent circuit of the motor is similar to the one used for a brush-type DC motor. Several steps are necessary to calculate the elements of the equivalent circuit, and, to maintain simplicity and paper length, will not be shown. Each step follows the step type shown in Fig. 9, with drawings, "Info" button, "Equation" button and text box for the parameter value. Once the elements of the circuit are calculated, the value of the slot current is computed. In most cases, this value is different than the initial assumption for the slot current. Therefore, performance parameters, such as torque, losses, efficiency, etc. have to be reevaluated. As shown earlier, warnings are issued in case the admissible values are surpassed.

Losses and thermal analysis

There are three main sources of losses in the PM motor: the mechanical losses, produced by friction between the moving parts of the motor; the copper losses, caused by the currents passing the winding resistance; the core losses, produced both by the nonlinear behavior of the ferromagnetic materials of the stator and rotor core (e.g. hysteresis) and by the eddy currents induced in the core. Since the mechanical losses require knowledge of the moving parts (bearings) and are usually much smaller than the other losses they will be neglected in this design procedure. The winding losses are calculated using the resistances from the previous design step (the equivalent circuit). The core losses are approximated as a function of the volume of the stator steel and the per volume loss given by the manufacturer for the core material. The material data base contains values of the per volume loss as a function of the maximum flux density and frequency of the input current. Due to the high complexity of the stator and rotor, an accurate thermal analysis should use Finite Element Analysis (FEA). However, an approximate temperature distribution can be calculated. Fig. 11 presents the equivalent thermal circuit for the motor.

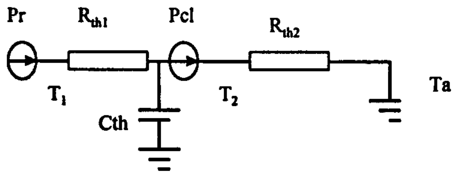


Fig. 11. Equivalent thermal circuit

The two heat sources are the winding loss (P_r) and the core loss (P_{cl}). The heat is transferred through radiation and convection from the windings to the stator through the thermal resistance of the winding iron interface (R_{th1}) . The heat is transferred to the air outside the stator (at ambient temperature, T_a) by the stator through radiation (R_{th2}). Some of the thermal energy is also accumulated in the thermal capacitance of the stator (C_{th}). The values of the thermal circuit components are calculated using the radiation and convection coefficients for iron, copper and air in the material data base. After solving the thermal circuit the temperature distribution is compared to the maximum admissible values. Warning messages are issued if appropriate.

Performance

The user can check the steady-state performance parameters at the rated operating condition. Also, several graphs can be generated for other operating points. Up to this point, the design has been based on steady-state calculations and empirical equations. For more accurate results FEA is necessary. The program provides a simple way to generate the geometry file for FEA in the current design.

V. CONCLUSIONS

A virtual learning tool was developed for the design of a permanent magnet machine. The tool combines classical learning methods, such as lecture notes, with computer aided design (CAD) methods. The software combines several programming concepts such as OOP and GUI. It is the intention of the authors to further develop this program to include other types of machines (induction, reluctance, etc.) and drive systems.

Appendix A Additional information for example problem: Magnet type: Nd-B-Fe, Magnet depth: 1 cm, Magnet opening: 96 %, Number of turns per slot: 7, Rotor length: 32 cm, Rotor diameter: 15 cm, Air gap: 2 mm, Slot opening: 4 mm

VI ACKNOWLEDGMENT

This work is supported in part by National Science Foundation Grant No. 732884 and the Delphi Automotive System.

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VIII. BIOGRAPHIES

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