

A computer aided educational tool for design, modeling, and performance analysis of Brushless DC motor in post graduate degree courses

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The design of electrical machines is gaining more popularity in the last years especially in electrical engineering courses. However, commonly-used teaching techniques seem to limit students' understanding and prevent the attainment of the learning objectives. The competence of this subject can be significantly improved when a practical approach based on the use of computer-aided educational tools is followed. Thus, this paper proposes an effective and user-friendly educational tool, which has been developed and successfully implemented in post-graduate courses in order to facilitate the conception of brushless direct current (BLDC) machines design aspect. At first, a step-by-step design procedure is analytically described and then the main tool's characteristics and capabilities are also presented. Finally, its impact assessment has been conducted and the derived results revealed that its application could be extended to the design of various types of electrical motors and generators.

KEYWORDS

BLDC motor, computer aided design, educational tool, engineering courses, finite element method, modeling and simulation

1 | INTRODUCTION

Brushless direct current (BLDC) machines are characterized by high efficiency, great reliability, and high power density, while at the same time the maintenance requirements are less than their counterparts [14]. The above features made them throughout the years quite suitable candidates for several high performance industrial, automotive, medical, and domestic applications [7,27,29]. Until nowadays, plenty of research effort has revealed novel techniques and methodologies for BLDC machine design and analysis [30,31], as a result of the continuously increasing academical and industrial interest. Consequently, the specific subject is gaining popularity, especially in electrical engineering courses, and has become a hot topic in the syllabuses of several under-graduate and post-graduate curriculums.

However, the design procedure of this machine type is not trivial and presents increased complexity [6]. There is a large amount of variables for example, geometrical parameters, and electromagnetic quantities involved that have to be specified, while simultaneously numerous constraints have to be satisfied. The applied constraints refer to the problem specifications and have great impact on the determination of the final machine configuration and performance. Therefore, the theoretical background about classical design methodology, which is provided by scientific literature, seems not to be well received by many engineers and mostly post-graduate students when is not supported by practical experience [24]. Furthermore, the way that both textbooks and classrooms usually treat this subject restricts in many cases the long-term learning of the knowledge and the deep understanding of the principles [5].

On the other hand, various technology motivated strategies have been successfully implemented in the last decades in engineering education in order to improve its quality [2]. Among others, computer-aided educational tools are one of these modern teaching techniques [16], which is very attractive since it has been proven effective complement of lectures and practical sessions [22]. This approach involves: (a) the development of virtual labs [17] or web-based tools [3]; (b) the use of commercial software packages [12]; and (c) the creation of dedicated software for training, as a teaching and demonstration tool [28]. Despite the fact that a large number of commercially available software solutions could be used for simulation, performance analysis, and design of electrical machines at plenty of engineering subjects, the specific perspective seems not to bring always the expected results. The reason for that, is the relatively low “learning to using ratio,” especially for short-term studies (i.e., semester type), and also the high purchasing cost. Moreover, the full development of software by educators themselves, based on the educational needs and objectives, can reinforce even more the students' conceptual knowledge, provide an efficient interaction between students and educators and enhance significantly the learning process [9]. Notwithstanding the aforesaid features, the creation of such software is a quite demanding and time-consuming procedure. Thus, a compromise between these two approaches is usually preferred. In this case, educators take advantage of the capabilities of commercial and/or open-source softwares, while at the same time they incorporate their own prospects, in order to develop a graphical user interface (GUI) with flexible structure and user-friendly environment [26].

In recent literature, many examples of educational tools can be found, which are aimed to improve students' motivation through computer simulation programs and provide them a better visualization of theoretical concepts concerning different aspects of electrical machines, such as design, control, fault diagnosis, etc. For instance, in Ref. [15] an educational tool which permits the magnetostatic analysis of BLDC motors is presented in order to reduce the difficulty of modeling this type of machine when considering non-linear materials and permanent magnets. A relative work has been conducted in Ref. [13], where a simulation program based on circuit equations was developed for the performance analysis of claw-pole permanent magnet stepping motors. Additionally, Gokbulut et al. in Ref. [11] have created an attractive and very promising tool, which enables students: (a) to design neuro-fuzzy systems for the control of induction motors and (b) to understand sufficiently the influence of neuro-fuzzy system parameters variation at motor's performance. An instructive approach for teaching the basics of fuzzy-logic based controller design steps for application in synchronous and BLDC motors has also been proposed in Refs. [8] and [1], respectively. A virtual electrical machine laboratory for the

conduction of various tests (e.g. no-load, full-load, blocked-rotor test) and the fault detection on synchronous [23,25] and induction [10,19] motors can also provide an interactive and cost-effective education and training. Recently, Riba et al. in Ref. [21] presented a computer-aided tool so that to assist students during design process of a switched reluctance motor, therefore making them more familiar with the design of electrical machines topic.

Based on the above, a software educational tool has been developed in the Laboratory of Electrical Machines of the Department of Electrical & Computer Engineering (DECE) at Democritus University of Thrace, Hellas, aiming to guide engineering students in the design procedure of BLDC motors. This tool is currently utilized in a post-graduate (MSc and PhD degree) course namely “*Advanced Topics in Electrical Machines Design*” according to the DECE syllabus. In order to facilitate the design process, a GUI has been created using Matlab software. The GUI enables users (students) to set the main BLDC design parameters, as wells as its specifications, such as output power, efficiency, windings configurations, materials properties, etc. Next, the machine rated performance estimation and the determination of its electromechanical quantities follows, by incorporating the geometrical specifications and the analytical equations into an open-source finite element method analysis software (called FEMM). The aim of this project is to achieve the following (among others) educational goals: (a) to improve students' knowledge on the brushless machines fundamentals; (b) to save time while developing this knowledge; and (c) to contribute to the interpretation of the derived results. According to this approach, great emphasis has been given to the illustration of the results and the development of an effective graphical feedback. Concluding, this study initially describes analytically the steps of BLDC design methodology. Next, the proposed software is thoroughly analyzed and then the assessment results of this tool based on students' responses through the evaluation questionnaires are presented and a relevant discussion is made. Finally, a set of recommendations are provided as a guide for other instructors, who would like to implement the same approach.

2 | PRINCIPLES OF BLDC MOTOR DESIGN AND PERFORMANCE ANALYSIS

A typical BLDC motor involves a balanced three-phase winding, whose coils are wound around stator's teeth and permanent magnets, which are placed on the rotor surface creating a constant magnetic field. When direct current voltage is delivered across a set of the stator coils, the interaction between stator rotating magnetic field and permanent magnets field, results in rotor's revolution and

torque production. A continuous rotational motion with respect to the sequential rotation of stator's magnetic field is achieved by changing properly the windings excitation and thus maintaining the alignment between both fields. Despite the aforementioned common operating principle, this machine type can be classified in various sub-categories depending on: (a) rotor's location (inner or outer) with regard to stator's one; (b) permanent magnets configuration (surface mounted, interior-mounted, buried, V-shaped, etc.); (c) flux direction (axial or radial); and (d) windings excitation type (trapezoidal or sinusoidal). Each structure has its own particular pros and cons. Reader can refer to Refs. [4,18] for further details.

In this study, a radial flux BLDC motor configuration with outer rotor topology, surface-mounted permanent magnets, and trapezoidal excitation has been considered as a case study. Radial flux permanent magnet motors are quite conventional machines and they are widely used at many industrial applications. In these machines, the flux flows radically inside them, while the current flows in the axial direction. The outer rotor topology presents significantly higher power density and lower copper losses than the corresponding inner rotor one. Moreover, it is less heavy and expensive, since it requires less magnet volume for the same amount of output torque. Even higher power density can be achieved when this structure is combined with surface-mounted permanent magnets and full-pitched concentrated windings. At the same time, a trapezoidal back electromotive force (back-emf) can lead to constant torque pulsation and the current signals are easily controlled. Figure 1 shows the cross-section of the examined here BLDC motor, in which detailed geometrical parameters are also presented. For the sake of space these parameters will be explained among others as text follows.

In order to design a motor of this type, a combination of classical design theory and iterative process is required. Figure 2 depicts the generic flowchart followed toward the overall proposed here methodology. At each step of this approach, a large amount of electromechanical quintiles and geometrical parameters is calculated, while at the same time plenty of constraints have to be satisfied. Some of them are imposed by the specific problem characteristics and the desirable motor's performance. The main steps of this procedure are subsequently explained:

2.1 | Step 1— Preliminary requirements

The starting point of the design process involves the determination of some initial specifications such as, the output power (P_{out}), the rated angular speed (ω), the rated torque (T_e), the desired efficiency (η), the number of poles (p), the number of slots (Q_s) and the number of phases. The first

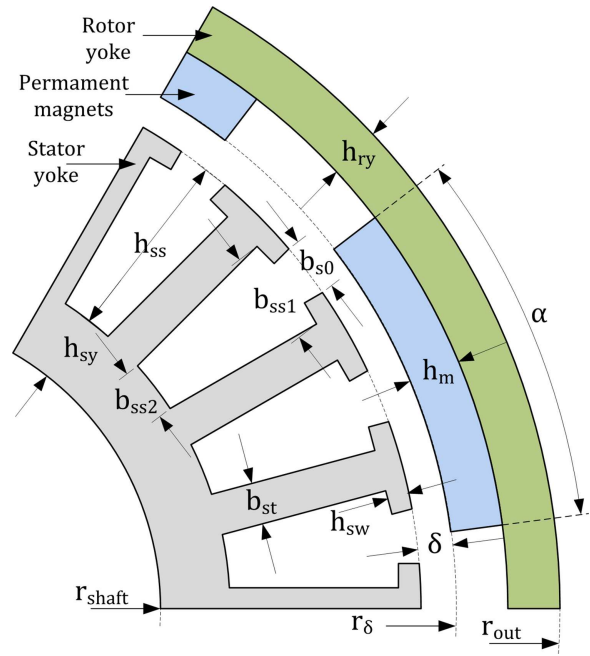


FIGURE 1 BLDC motor's cross section with detailed geometrical parameters

four aforementioned quantities can be easily estimated, while the last three demand the appliance of engineering judgment. Regarding the number of phases, a three-phase stator winding offers a better copper utilization, lower torque ripple and no starting problems compared to a single or two phase winding. Increasing the number of phases to four or five (not a commonly used practice) may bring low benefits in the above features for low and medium voltage BLDC motors. Nevertheless, in such a case both copper winding's and drive-system's switching elements cost will be significantly increased.

A guideline can also be given for the selection of poles-slots combination, since these variables are critical and have great importance for the overall motor's performance. A proper choice can result in the elimination of higher order harmonics' presence in the airgap flux density distribution and the reduction of iron losses and torque ripple. Furthermore, designers should also take into account the followings: (a) increasing the poles number, there will be less need for rotor and stator back iron since the total flux will be spread over more poles and as a consequence more space will be available for copper windings; (b) the electrical frequency increases as the poles number rises affecting vastly the iron losses and lowering motor's efficiency; (c) a small number of slots contributes effectively to cost reduction but a very small number increases the surface of the slots and the total copper's volume; and (d) with a large number of slots the leakage reactance is reduced and therefore the problems associated with the field harmonics and the magnetic noise.

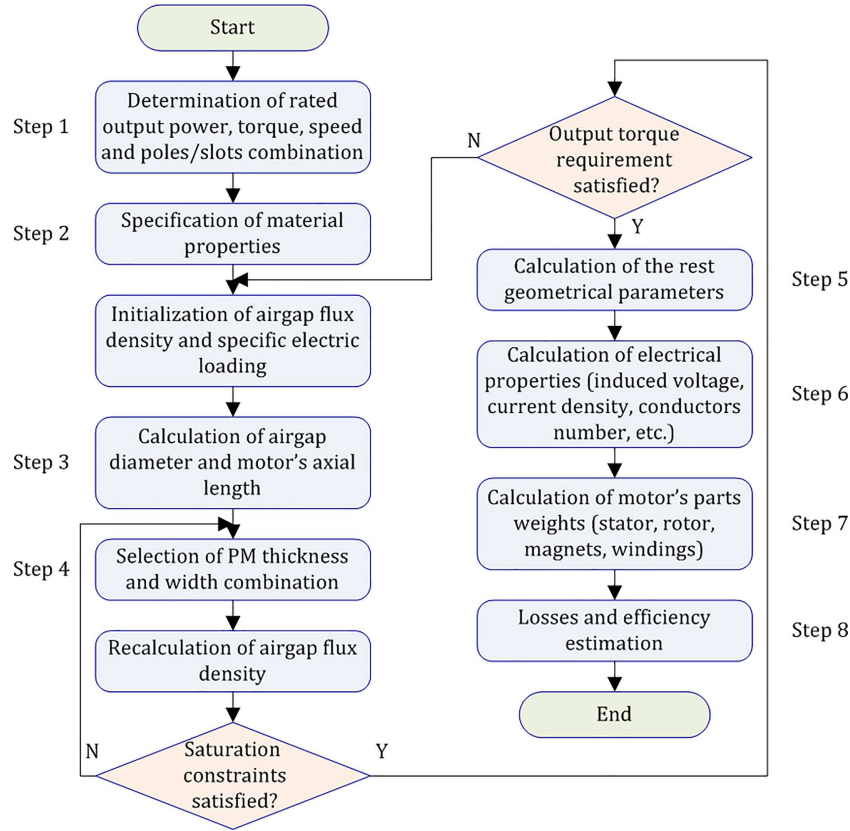


FIGURE 2 BLDC motor design and performance analysis procedure algorithm developed

2.2 | Step 2—Material properties specification

After the initialization of the above parameters, the materials selection and their properties determination are following. High quality ferromagnetic materials, such as silicon or low carbon steel, could be an efficient choice for stator and rotor core. While choosing a steel, the core losses for a given electrical frequency should also be considered as they directly influence motor's efficiency. The selection of permanent magnets is made according with the application characteristics. Generally, it is preferable for the magnets to present: (a) wide operating temperature range; (b) high corrosion resistance; (c) low radiation sensitivity; and (d) high efficiency to cost ratio. For all these reasons, neodymium rare earth magnets are usually chosen for low cost applications.

2.3 | Step 3—Determination of motor's dimensions

The starting point for the estimation of motor's basic dimensions (i.e., airgap diameter and axial length) is the torque requirement. The product of these two parameters can be obtained from Equation 1 by modifying properly the classical sizing equation for the case of trapezoidal excitation.

$$D_\delta^2 L = \frac{T_e \sqrt{6}}{\pi B_g q} \quad (1)$$

where T_e is the rated output torque in Nm, B_g is the flat top value of flux density in the airgap in T, q is the specific electrical loading in A/m, D_δ is motor's airgap diameter in mm and can be considered as $D_\delta = 2r_\delta$ (r_δ is the airgap radius in mm) and L is motor's axial length also in mm. B_g is a crucial parameter for the magnetic circuit of the machine. Its value depends on motor's structure and permanent magnets height and width, while at the same is limited by the saturation points of materials used for stator and rotor core. Typical values for this quantity lie between 0.6 and 1.1 T. The specific electric loading is related with copper losses, the maximum acceptable current density, the heat dissipation and the cooling strategy (air, oil, or liquid cooling). Reader can refer to Ref. [20] for further information, in which indicative values of this parameter are provided for various output power to speed ratios.

Therefore, preliminary assumptions have to be established for both of the above variables. After that, the determination of D_δ and L follows. The selection of their values can be easily made in some cases. For example, if the motor is intended to be used as a part of an electric or hybrid vehicle's direct-drive traction system, motor's outer diameter

(r_{out}) is limited by the size of the rim. However, if any constraints are imposed, the selection is based on the designer's experience. Some guideline for this aspect can also be provided. For this purpose, an aspect ratio t_p/L is defined in order to help engineers to make the proper choice. In the above ratio, t_p is the pole pitch ratio and can be calculated by applying Equation 2,

$$\tau_p = \frac{\pi D_\delta}{p} \quad (2)$$

Indicatively, the aspect ratio takes values between 0.5 and 0.9 for 2-poles motors and between 0.7 and 1.5 for 4-poles motors. By choosing the proper value, the length of the end-windings will become smaller, motor's inertia will be sufficient and the back-emf can be significantly enhanced for the same amount of airgap flux density.

2.4 | Step 4—Magnetic properties estimation

In this step, several geometrical characteristics which are related with the motor's magnetic circuit have to be specified. Among them, permanent magnets height (h_m) and pole arc to pole pitch ratio (α) are of great importance, as they essentially affect the magnitude of the fundamental harmonic of the airgap flux density and finally motor's performance. The pole arc to pole pitch ratio defines the magnet width that is, how much the magnet covers the total pole pitch and takes values between 0 and 1, where 1 means that the magnet covers the total pole area. Moreover, the value of magnet's height must be carefully chosen, since the final motor's structure should be acceptable from technical, economical, and manufacturing point of view. Simultaneously, a set of imposed saturation constraints for different motors parts have to be satisfied. For this purpose, an iterative process is proposed to be implemented. This procedure starts with the initialization of some parameters such as, h_m , α and slot top width (b_{ss1}). Then for given r_δ and L (they have been estimated previously) the calculation of the amplitude of fundamental airgap flux density (B_m) is conducted applying the following equation:

$$B_m = \frac{B_r k_{leak}}{1 + \frac{\mu_r \delta k_c}{h_m}} \quad (3)$$

where B_r is the remanent flux density of the magnet, k_{leak} is the leakage factor which represents the percentage of the flux lines that pass through the airgap, δ is the airgap length, k_c is Carter's coefficient and μ_r is the relative magnet permeability. The airgap length is another crucial design input that has to be selected by designer. Generally, permanent magnet machines permit low values for airgap length, such as 0.5 or 1 mm. The leakage factor is given in Equation 4, in which constant c is

considered equal to 3.0 for an outer rotor topology. In order to calculate Carter's coefficient slot opening width (b_{s0}) has to be chosen first. In this study, this parameter has been set equal to 2.5 mm. Then, the specific coefficient can be derived from Equation 5. In this equation, τ_s is the slot pitch and is defined in Equation 6, where k_{open} is slot opening width to slot top width ratio and is given is Equation 7.

$$k_{leak} = \frac{100 - (7p/60 - c)}{100} \quad (4)$$

$$k_c = \tau_s \left(\tau_s - \frac{(k_{open} b_{ss1})^2}{k_{open} b_{ss1} + 5\delta} \right)^{-1} \quad (5)$$

$$\tau_s = \frac{\pi D_\delta}{Q_s} \quad (6)$$

$$k_{open} = \frac{b_{ss0}}{b_{ss1}} \quad (7)$$

Next, for given B_m the produced magnetic flux of each pole (φ_{pole}) can be calculated by applying Equation 8, where A_{pole} is the pole's area and can be obtained from Equation 9. Assuming that the magnetic flux is equally spread to both stator and rotor core, the magnetic flux at stator (φ_{sy}) and rotor (φ_{ry}) yoke is derived from Equation 10. Combining Equations 11–15, which define stator slot height (h_{ss}), stator yoke height (h_{sy}), rotor yoke height (h_{ry}), flux density at stator yoke (B_{sy}), and flux density at rotor yoke (B_{ry}) respectively, a system with five equations and five unknown variables is created. This system has to be incorporated in the iterative process. At each step of this procedure the variables h_m , α , and b_{ss1} take new values. The process terminates when the saturation constraints for stator and rotor yoke, which are imposed by material properties and selected by designer, are no longer satisfied. If this happens, the algorithms returns at the starting point of this step and the values of the three aforementioned parameters are properly modified. At this step, except from the constraints which are related to the magnetic circuit of the motor, designer could also incorporate various constraints and requirements, such as the maximum acceptable permanent magnets weight, current density, torque ripple, cogging torque, etc. For the sake of space, these quantities and the relative constraints are not presented here. Reader can refer to Ref. [31] for additional information. Before continuing with the next step, the process involves a last check with regard to the achievement of the required output torque. If this goal has been met, the procedure continues to the forthcoming step (i.e., Step 5). On the contrary, the algorithm returns to Step 3 and then the values of the basic parameters involved in the specific step (i.e., motor's airgap diameter and axial length) are revised.

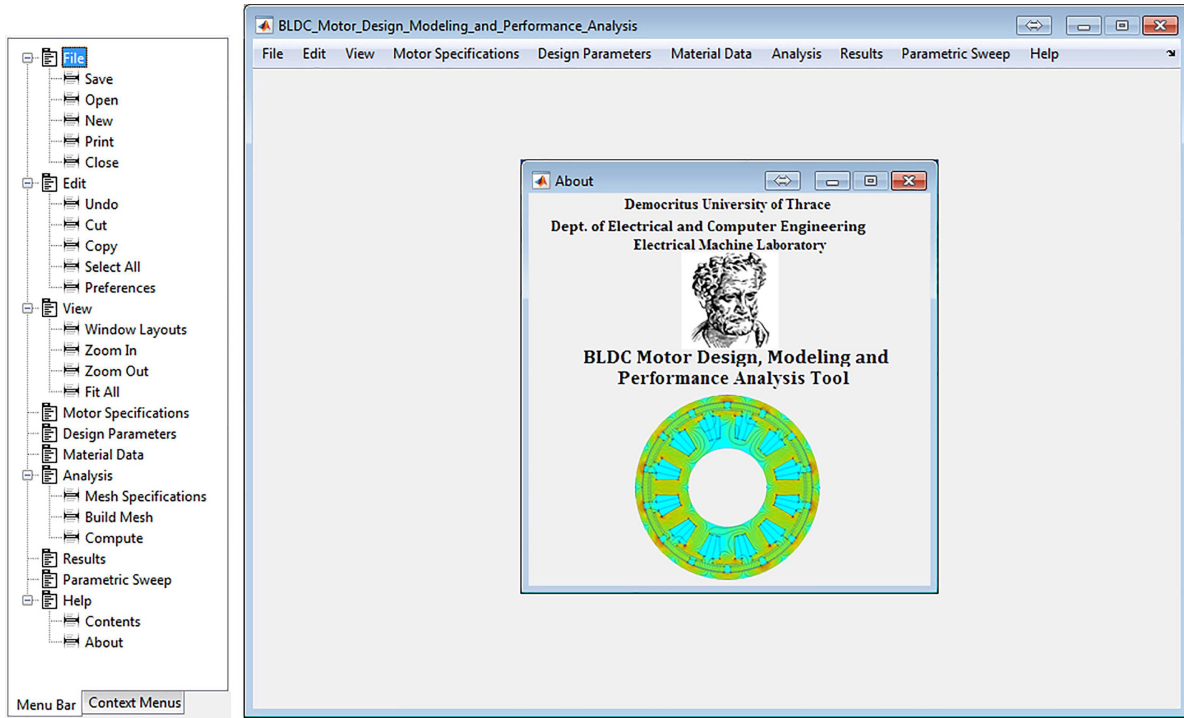


FIGURE 3 General view of the main window of the BLDC designer GUI application along with an exploded view of the menus

$$\varphi_{\text{pole}} = B_m A_{\text{pole}} \quad (8)$$

$$A_{\text{pole}} = \frac{\pi D_{\delta} L}{p} \quad (9)$$

$$\varphi_{\text{sy}} = \varphi_{\text{ry}} = \frac{\varphi_{\text{pole}}}{2} \quad (10)$$

$$h_{\text{ss}} = (r_{\delta} - \delta - r_{\text{shaft}}) - \frac{\pi B_m}{p B_{\text{sy}}} \quad (11)$$

$$h_{\text{sy}} = r_{\delta} - \delta - r_{\text{shaft}} - h_{\text{ss}} \quad (12)$$

$$h_{\text{ry}} = \frac{B_m \pi r_{\delta}}{B_{\text{ry}} p} \quad (13)$$

$$B_{\text{sy}} = \frac{\varphi_{\text{sy}}}{h_{\text{sy}} L} \quad (14)$$

$$B_{\text{ry}} = \frac{\varphi_{\text{ry}}}{h_{\text{ry}} L} \quad (15)$$

slow teeth width (b_{st}) and slot base width (b_{ss2}) can be expressed as shown successively in Equations 16–20, where h_{sw} is the stator tooth tip height and in our case this quantity has been set equal to 1.5 mm.

$$A_{\text{slot}} = \frac{1}{2} (b_{\text{ss1}} + b_{\text{ss2}}) (h_{\text{ss}} - h_{\text{sw}}) \quad (16)$$

$$r_{\text{out}} = r_{\delta} + \delta + h_m + h_{\text{ry}} \quad (17)$$

$$r_{\text{shaft}} = r_{\delta} - \delta - h_{\text{ss}} - h_{\text{sy}} \quad (18)$$

$$b_{\text{st}} = \frac{2\pi(r_{\delta} - \delta - h_{\text{sw}})}{Q_s} - b_{\text{ss1}} \quad (19)$$

$$b_{\text{ss2}} = \frac{2\pi(r_{\delta} - \delta - h_{\text{ss}})}{Q_s} - b_{\text{st}} \quad (20)$$

2.5 | Step 5—Calculation of rest geometrical parameters

Some more geometrical characteristics such as, total slot area (A_{slot}), motor's outer radius (r_{out}), motor shaft radius (r_{shaft}),

2.6 | Step 6—Electrical properties determination

After sizing the motor, the features of stator winding have to be specified. At first, copper wire's current density (J_{Cu}) can be calculated by applying Equation 21, in which s_{ff} is the stator slot fill factor. Commonly used values for this parameter is 0.6 and 0.65. Next, the designer must assume a value for the produced back-emf (E_{ph}). In a BLDC motor with trapezoidal excitation the maximum developed back-emf can not exceed

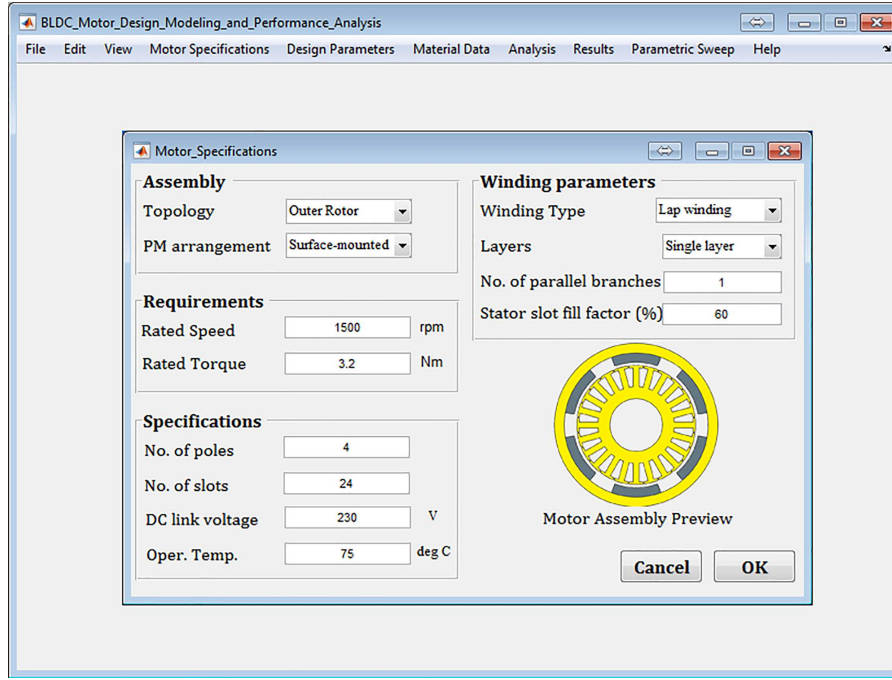


FIGURE 4 “Motor Specifications” window—initialization of motor's parameters

the minimum available dc-link voltage. Consequently, the maximum value of back-emf must be chosen with regard to drive system parameters. Then, the number of turns per phase (N_{ph}) is given by Equation 22, where ω is the electrical angular speed. Finally, rms phase current (I_{rms}), conductor's area (A_{Cu}), phase resistance (R_{ph}), dc-link current (I_{DC}), and dc-link voltage (V_{DC}) can be obtained from Equations 23–27, respectively. In Equation 25 σ_{Cu} denotes copper's resistivity and l_{Cu} denotes conductor's length.

$$J_{Cu} = \frac{2\pi q(r_\delta - \delta)}{s_{ff} A_{slot}} \quad (21)$$

$$N_{ph} = \frac{E_{ph}}{2B_m L(r_\delta - \delta)\omega} \quad (22)$$

$$I_{rms} = \frac{2q\pi(r_\delta - \delta)}{6N_{ph}} \quad (23)$$

$$A_{Cu} = \frac{I_{rms}}{J_{Cu}} \quad (24)$$

$$R_{ph} = \frac{\sigma_{Cu} N_{ph}}{A_{Cu}} \left[\left(\frac{2\pi(r_\delta - \delta) - h_{ss}}{p} + 2L \right) + 0.014 \right] \quad (25)$$

$$I_{DC} = \sqrt{\frac{3}{2}} I_{rms} \quad (26)$$

$$V_{DC} = 2I_{rms} R_{ph} + E_{ph} \quad (27)$$

2.7 | Step 7—Calculation of motor's parts masses

This step involves the calculation of total motor's mass (M_{tot}). The mass of a BLDC motor is comprised of the mass of stator yoke (M_{sy}), stator teeth (M_{st}), rotor yoke (M_{ry}), stator winding (M_{Cu}), and permanent magnets (M_{pm}). The above quantities can be calculated by applying Equations 28–33, where d_{sy} is stator core density, d_{ry} is rotor core density, d_{Cu} is copper winding density and d_{pm} is permanent magnet density.

$$M_{sy} = \pi[(r_\delta - \delta - h_{ss})^2 - r_{shaft}^2] L d_{sy} \quad (28)$$

$$M_{st} = Q_s b_{st} h_{ss} L d_{sy} \quad (29)$$

$$M_{ry} = \pi[r_{out}^2 - (r_{out} - h_{ry})^2] L d_{ry} \quad (30)$$

$$M_{Cu} = \frac{3}{2} N_{ph} A_{Cu} \left[\left(\frac{2\pi(r_\delta - \delta) - h_{ss}}{p} + 2L \right) + 0.014 \right] d_{Cu} \quad (31)$$

$$M_{pm} = \pi[(r_{out} - h_{ry})^2 - r_\delta^2] \alpha L d_{pm} \quad (32)$$

$$M_{tot} = M_{sy} + M_{st} + M_{ry} + M_{Cu} + M_{pm} \quad (33)$$

2.8 | Step 8—Performance analysis

The losses in the machine windings are pure resistive and can be expressed as shown in Equation 34. The iron losses consist

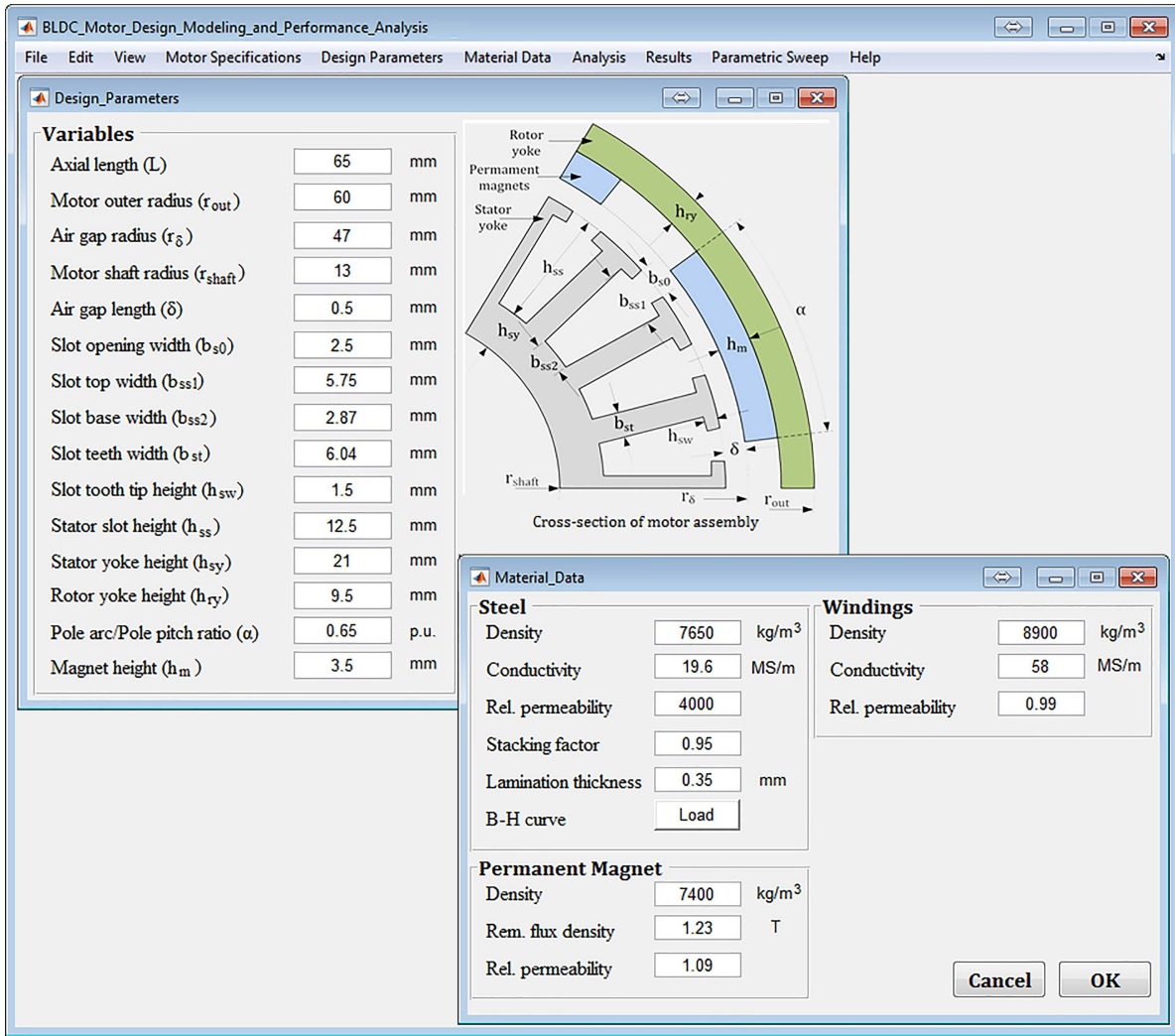


FIGURE 5 Design parameters and materials properties specification windows

of hysteresis and eddy current losses. Assuming a trapezoidal excitation and consequently a trapezoidal flux density variation, the hysteresis losses (P_{hyst}) and eddy current losses (P_{eddy}) per mass unit can be derived from Equations 35 and 36.

$$P_{cu} = 2I_{DC}^2 R_{ph} \quad (34)$$

$$P_{hyst} = k_h f B^\beta \quad (35)$$

$$P_{eddy} = k_e f^2 B^2 \quad (36)$$

where k_h is the hysteresis coefficient and k_e is the eddy current coefficient for steel, f is the electrical frequency, B is the peak magnetic flux density reached in the core and β is the Steinmetz constant for steel and varies between 1.5 and 2.5 depending on the core material. The hysteresis losses depend on the peak value of magnetic flux density, the frequency of the flux density variation and the area of the

hysteresis loop. The eddy currents are circulating currents that are induced in the iron core by the magnetic field around the turns of the coil. For a given core, this type of loss is proportional to the frequency, the maximum flux density and the conductivity of the core. Typical values ranges for the hysteresis and eddy current coefficient are 40–55 and 0.04–0.07, respectively for silicon steel laminations. Frictional losses (P_{fric}) have also to be estimated. This type of losses is attributed to the friction between motor's outer diameter (D_{out}), which can be considered as $D_{out} = 2r_{out}$ and the bearing. They depend on many factors, such as the bearing type, the rotor's outer diameter, rotor's angular speed, and friction coefficient between the rotor's core and the bearings. During motor's starting performance, these losses are negligible and they increase as the speed rises. In general, frictional losses are proportional to the rotor's angular speed. An analytical formula for the frictional losses calculation is given in Equation 37, where k is a constant which takes values between 1.0 and 3.0, M_{ry} is the rotor yoke mass and ω is the

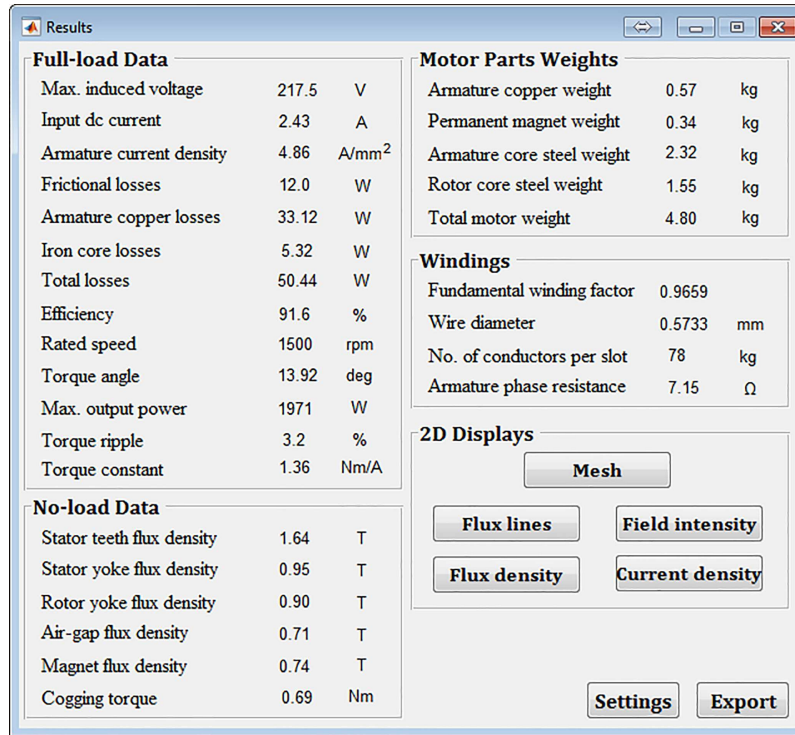


FIGURE 6 General view of proposed tool's post-processing window

rotor's angular speed. Finally, BLDC motor's efficiency can be written as shown is Equation 38.

$$P_{\text{fric}} = 10^{-3} k M_{\text{ry}} \omega \quad (37)$$

$$\eta = \frac{T_e \omega}{T_e \omega + P_{\text{Cu}} + P_{\text{eddy}} + P_{\text{hyst}} + P_{\text{fric}}} \quad (38)$$

3 | DESCRIPTION OF PROPOSED EDUCATIONAL TOOL

This section describes thoroughly the proposed here educational software tool and highlights its capabilities. The tool's architecture is based on the following concept: At first, through a quite friendly graphical interface (GUI), which has been developed using Matlab software, the user (student) specifies the problem's input data, that is, the desirable BLDC motor's characteristics and the geometrical parameters. Next, by implementing a simple but effective algorithm, which incorporates all the analytical equations that govern the previously described design procedure, the machine sizing and the construction of its equivalent circuit are conducted. The geometrical specifications of the final motor topology are then implemented in an open source finite element method analysis software (namely FEMM), which is called by the main tool. FEMM package software permits the performance of 2D

simulations in order to estimate several electromechanical quantities and motor's behavior at full and no-load operation. Finally, the derived results as well as the motor's configuration are graphically illustrated by the main tool (i.e., using Matlab) for a better perception of the examined problem. For this purpose, various results display capabilities, which can be modified by a dynamic way, are provided to the user. This feature enhances the tool's flexibility and reveals that its main target is not only the accuracy of the calculations during BLDC motor's performance estimation, but also the effective management and the interpretation of the results in order to maximize the learning benefits. In this way, students are able to validate the design methodology and the results obtained in the lecture assignments and compare these data with the theoretical models, which are provided in the literature sessions.

The main window of the developed GUI is depicted in Figure 3. In the same figure the basic menu of the tool is also presented in exploded view. As it can be seen, user has the choice of saving, opening, or creating a new project. To enhance the educational purpose of this tool and reduce the complexity of this topic a discrimination of the input and output data is necessary. By clicking on specific menu items, namely "Motor Specifications," "Design Parameters," and "Material Data," individual windows appear in order the students to enter the corresponding input data. The post-processing analysis of the derived results is enabled through "Results" and "Parametric Sweep" menu items. Moreover, the user has the opportunity to adjust mesh specifications and consequently the simulation process characteristics (i.e.,

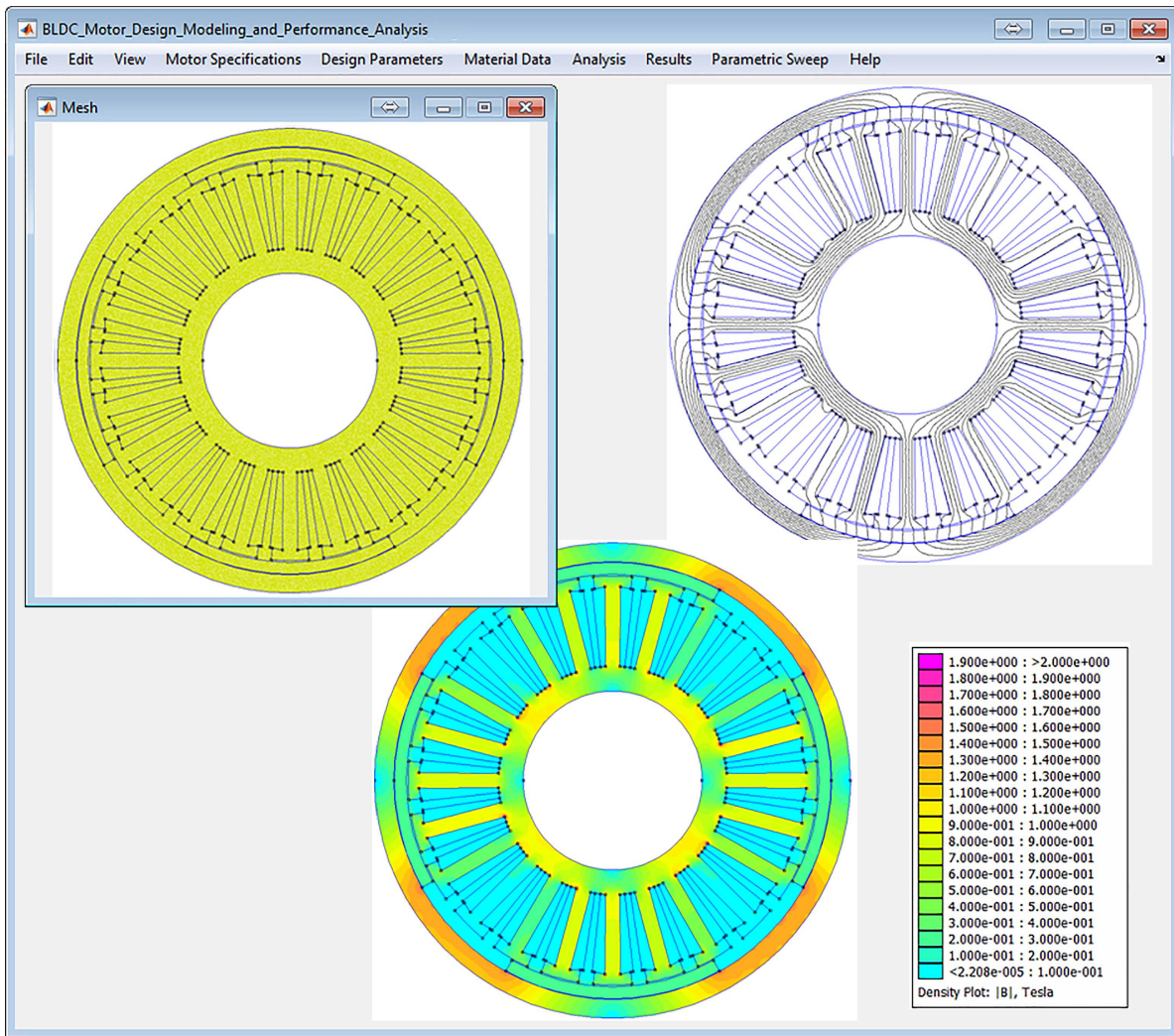


FIGURE 7 Graphical results representations from post-processing window (i.e., mesh illustration, flux lines distribution, and flux density distribution of the examined motor)

simulation time and solution accuracy) by modifying the total number of the developed triangular elements and the number of nodes. A brief help is also available at the menu of the main window in order to explain sufficiently each geometrical parameter and electromechanical quantity involved in BLDC motor design and performance analysis procedure.

Using this software program both inner and outer rotor topologies can be examined, while surface permanent magnets are always considered to lie on rotor circumference. Several permanent magnets arrangements, such as interior-mounted, buried, V-shaped, or multi-layer magnets, are going to be incorporated in a later version of this tool. For demonstration purposes, a four poles BLDC motor with outer rotor topology and surface-mounted permanent magnets has been considered as a case study in this context. The design specifications of this motor, including rotor assembly and permanent magnets arrangement, as well as motor's output requirements (i.e., rated speed and output torque) are presented in Figure 4, where "Motor Specifications" window is illustrated. In this window,

the user can also set plenty crucial characteristics, such as the number of poles and slots, the maximum dc-link voltage, and motor's expected operating temperature. Furthermore, the windings parameters have to be determined. Students can select among different available windings configurations (e.g., lap, wave, concentrated, or distributed winding). The number of winding layers (single or double), the number of parallel branches and stator slots fill factor have likewise to be specified. Several combinations can be derived by varying the values of the aforementioned quantities aiming the students to understand their influence on motor's performance.

Next, the user can proceed with the insertion of the rest input parameters using "Design Parameters" and "Material Data" windows, as shown in Figure 5. In the first window, motor's basic dimensions, stator slots geometrical characteristics, airgap length, permanent magnets width, and height can be specified. A cross-section of the investigated motor's assembly is also depicted in order to facilitate the perception of the above geometrical quantities. In the latter window, the

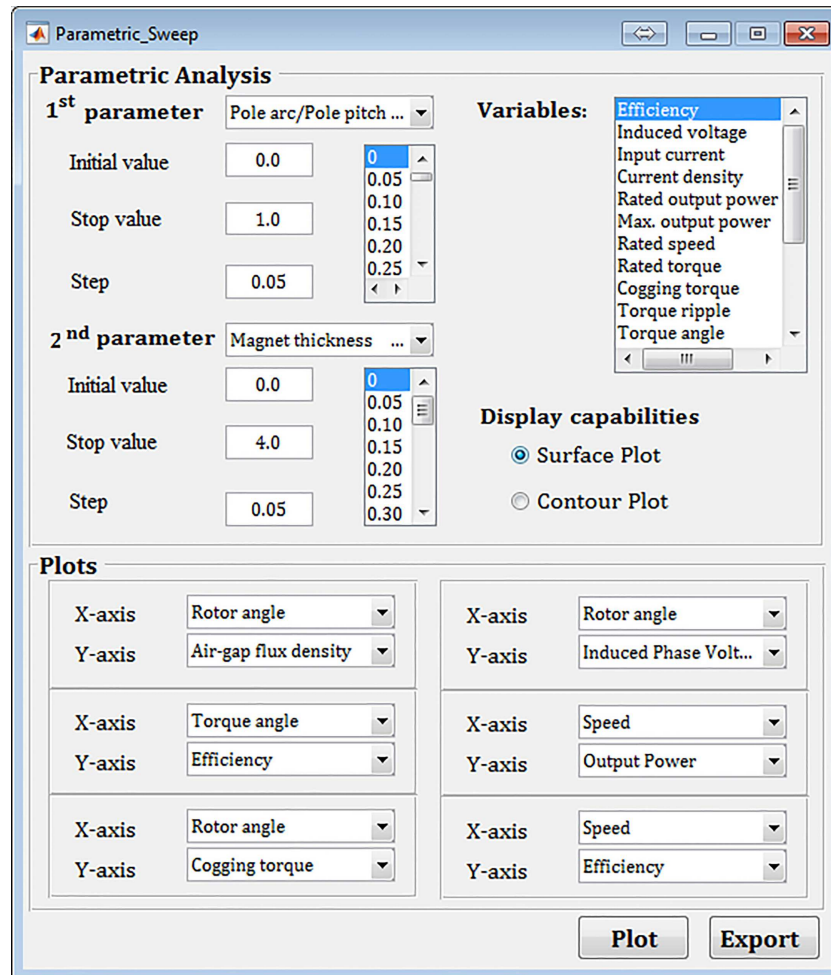


FIGURE 8 Parametric and sensitivity analysis window of the proposed tool

determination of materials' density, conductivity, relative permeability, magnets' remanent flux density, steel's stacking factor, and lamination thickness is conducted. Standard lamination sheets have thickness of 0.35, 0.50, 0.65, or 1.0 mm. Therefore, user can select a value for this parameter among the aforementioned ones. The uploading of B-H curve of commercial available non-linear steels is feasible by clicking on the "Load" button.

After setting the input parameters and defining mesh characteristics, the 2D simulation performance follows. The user can access all motor output parameters under full and no load operation through a post-processing window, which is presented in Figure 6. The "Results" window consists of five blocks. The first block involves the full load motor's behavior parameters. Crucial electromagnetic quantities for a BLDC motor are given among others, for example, the armature current density, the input dc-link current, the maximum output power, the torque constant, and ripple. The second block displays the no-load data, such as flux densities at different motor's parts (e.g., airgap, rotor yoke, and stator teeth) and cogging torque. The next two blocks present the

motor parts weights and important windings specifications respectively, for example, the fundamental winding factor, the wire diameter, the number of conductors, and the armature phase resistance. The last block contains a set of buttons. By clicking on these buttons the drawing of various plots is enabled (e.g., mesh, flux density, flux lines distribution, field intensity, and current density). The above quantities are firstly determined under different running conditions through finite element analysis using FEMM. Then the derived results are illustrated using Matlab capabilities and according to user's demands. "Settings" button at the bottom of the depicted window enables user to define the plots characteristics. In Figure 7 the mesh, flux lines, and magnetic flux distribution are indicatively depicted. These figures can be saved, exported, and edited by user as any Matlab figure. As it can be seen, the user can easily vary the geometrical specifications, perform a new simulation, and interpret effectively the results. Thus, the final derived topology satisfies the imposed constraints and problem requirements as the user takes advantage of the previously described tool's capabilities.

Furthermore, the proposed here tool enables the conduction of parametric and sensitivity analysis by modifying one or two essential parameters. The above can be done through “Parametric Sweep” window, which is depicted in Figure 8. In the presented case study, user had selected from an available parameters list to vary simultaneously the value of pole arc to pole pitch ratio (for the sake of space also called embrace) and permanent magnet thickness. For this purpose, the initial and stop values of these two variables as well as the variation step have been defined. Then the influence of parameters variation on plenty output variables is investigated. The derived results can be illustrated by two different ways (i.e., surface and contour plots). This flexibility permits each student to choose the display capability, which is more effective, allows him to validate the theoretical background and extract more easily useful conclusions. Figures 9 and 10 depict the corresponding results of such a parametric analysis conducted for our case by using surface and contour plots respectively. Finally, by selecting an embrace-magnets thickness combination several plots depicting various electromechanical quantities can be created, as shown in Figure 11. User can select the quantities that will

be depicted on both x and y-axis of each single plot. For demonstration and completeness purposes, air-gap flux density versus rotor angle, efficiency versus torque angle, cogging torque versus rotor angle, induced phase voltage versus rotor angle, output power versus speed, and efficiency versus speed have been consecutively selected for further investigation.

4 | OVERALL ASSESSMENT OF THE EDUCATIONAL TOOL

4.1 | Description of the applied learning process

As already mentioned, the described here software program has been developed in Electrical Machines Laboratory of DECE at Democritus University of Thrace. It was intended to provide students an interactive and quite useful tool in order to study and validate BLDC design and performance analysis procedure aiming to stimulate their interest in broaden electrical machines area. For this purpose, this tool was integrated in learning process of the “*Advance topics in Electrical Machines Design*” course at post-graduate level

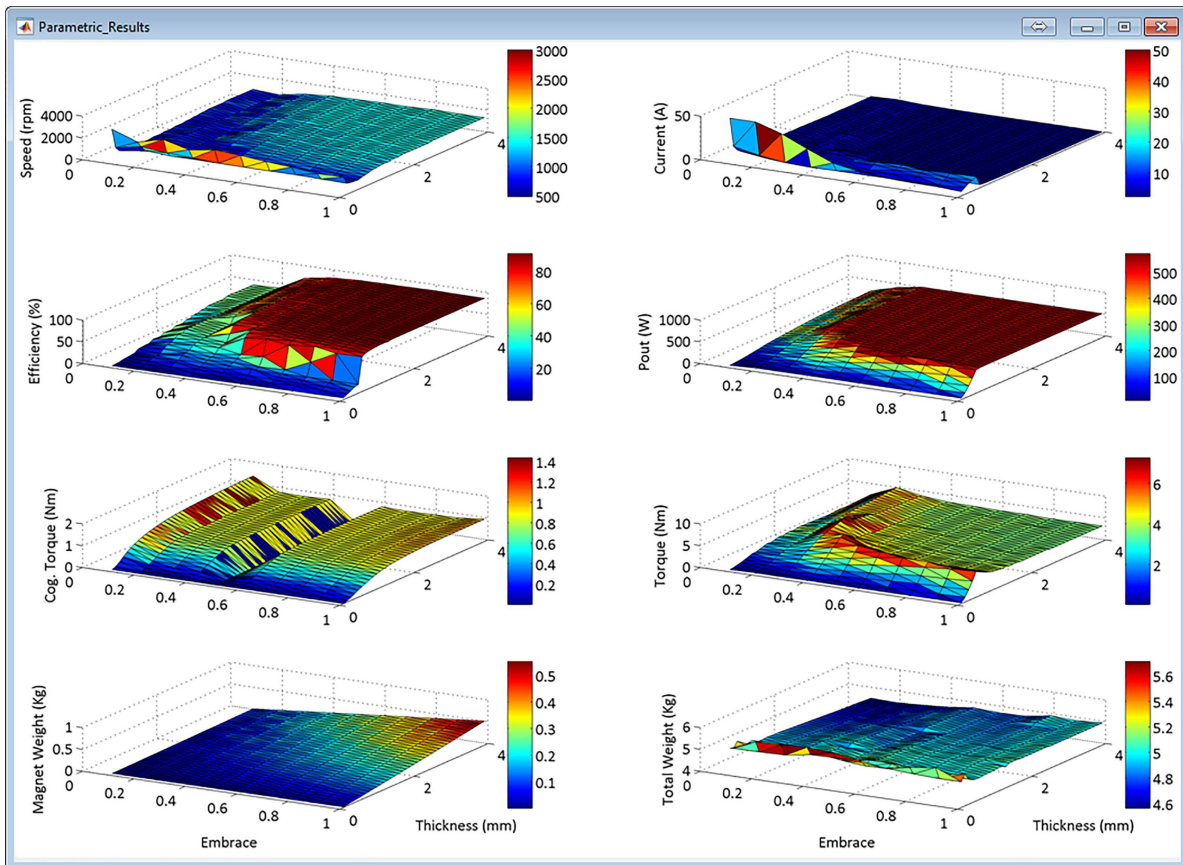


FIGURE 9 Results window (when surface plots is selected) of embrace and magnets thickness variation on: speed, efficiency, cogging torque, magnets weight, input current, output power, output torque, and total motor's weight

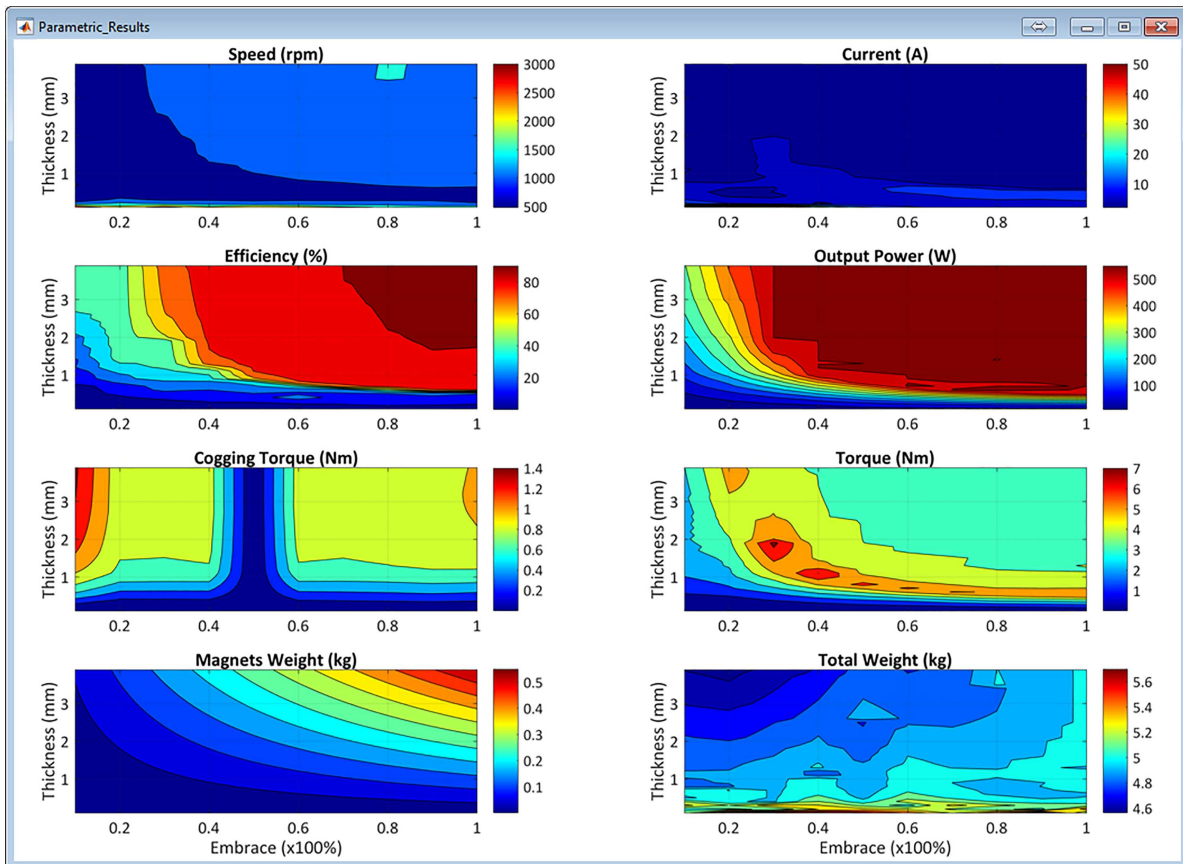


FIGURE 10 Results window (when contour plots is selected) of embrace and magnets thickness variation on: speed, efficiency, cogging torque, magnets weight, input current, output power, output torque, and total motor's weight

(MSc and PhD degree). During the spring 13-weeks semester of the 2014–2015, 2015–2016, and 2016–2017 academic year, 36 students attended the specific course. According to the syllabus, the course consists of a 4-hr session in a weekly basis. As it can be seen in Figure 12, where the course schedule is presented, the specific course is organized in three different parts (Part 1–3). The first 4 weeks (Part 1) are devoted to provide students with the necessary theoretical background that governs this topic. Specifically, in these theoretical lectures, a thorough discussion and analysis is conducted pertaining to (a) the fundamental principles of BLDC machines operation; (b) the equivalent electrical and magnetic circuit; (c) the aforementioned design methodology; and (d) the involved equations. At the end of Part 1 (fourth week) a test is administrated to the students. The main purpose of this «pre-tool» test is to assess the students' fundamental knowledge of BLDC machines and ascertain if the theoretical background was well received by them.

Course's Part 2 follows next. During this part students are trained to use the developed educational tool and acquire practical experience by solving various design problems. Three weekly projects are assigned to them and the derived results are thoroughly interpreted and discussed in the

classroom after the homework's deadline according to the schedule (Figure 12). Except from these weekly projects, one final project (FP) is assigned to each post-graduate student. This project includes the design of a BLDC motor, which is supposed to be suitable candidate for various industrial and electromotive applications. For example, in the last academic year (i.e., 2016–2017) students had to develop a direct-drive traction system for an electric scooter designing a BLDC outer rotor motor with surface-mounted magnets. Taking advantage of the tool's capabilities (e.g., parametric and sensitivity analysis, provided graphical feedback, etc.), students had to ensure that the final motor configuration will satisfy a large amount of constraints in agreement with the specific application requirements. The target of this procedure is the students to conclude to a motor assembly close to the optimal one through the appropriate post-processing analysis and by applying engineering judgment. The final deliverables involve a technical report in which the analysis of the derived motor topology is conducted along with a presentation. All students present their work in the last two sessions of the course (Part 3). Furthermore, a «post-tool» test is administrated to them. This exam involves the same questions with the «pre-tool» test, since the correct answers of

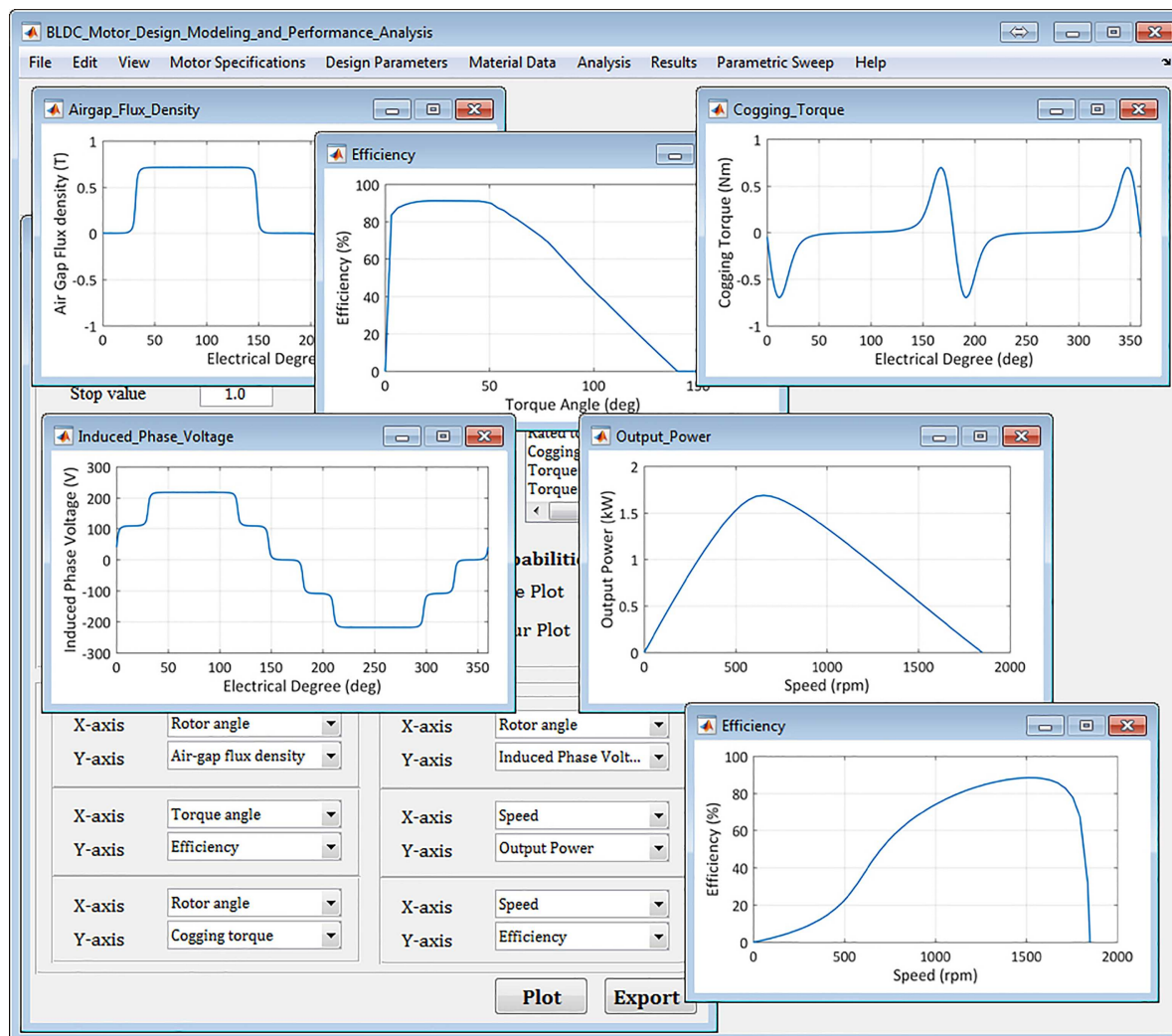


FIGURE 11 Plots window which depicts several electromechanical quantities for a given embrace-permanent magnets thickness combination. From left to right and top to bottom: airgap flux density versus rotor angle, efficiency versus torque angle, cogging torque versus rotor angle, induced phase voltage versus rotor angle, output power versus speed, and efficiency versus speed

	Week	1	2	3	4	5	6	7	8	9	10	11	12	13
Part 1														
	Theory	✓	✓	✓	✓									
	Exam				✓									
Part 2														
	Tool training				✓	✓	✓	✓	✓	✓	✓	✓		
	1 st weekly assignment				✓									
	1 st students deliverable					✓								
	2 nd weekly assignment						✓							
	2 nd students deliverable							✓						
	3 rd weekly assignment								✓					
	3 rd students deliverable									✓				
	FP assignment				✓									
	FP deliverable										✓			
Part 3														
	FP presentation											✓	✓	
	Exam												✓	✓
	Questionnaire's filling out													✓

FIGURE 12 “Advance topics in Electrical Machines Design” course's semester schedule and organization

the «pre-tool» test and students' performance had not yet been revealed to them. The aim of this procedure is to estimate sufficiently the impact of tool's incorporation on the learning process and the improvement of students' knowledge on BLDC machines fundamentals. The final grade that each student will receive is determined by taking into account his performance on: (a) «post-tool» exam; (b) weekly assignments; and (c) final project by 20%, 30%, and 50%, respectively.

4.2 | Tool's evaluation and discussion of the results

In this section, the evaluation of the previously described educational computer-aided tool's effectiveness is analytically discussed. For this purpose all the necessary data on students' performance are provided. Figure 13 depicts the

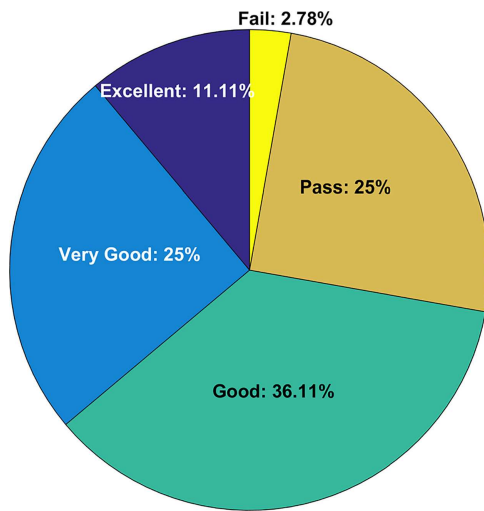


FIGURE 13 Overall (3-semester) students' grade distribution on post-graduate course "Advanced Topics in Electrical Machines Design"

grade distribution for the 36 post-graduate students who attended the specific course over the last three academic years. According to DECE's grading scale system it is supposed that a student fails a course when his grade is less than or equal to 49% of the maximum grade that the student could receive. Thus, in the grading scale of 0–100 points a "Fail" corresponds to a total score less than or equal to 49 points, a "Pass" grade varies from 50 to 64 points, while "Good," "Very Good," and "Excellent" performance corresponds to 65–74, 75–84, and 85–100 points, respectively. Based on the performance results, only one of the 36 students failed to receive an accessible score as he did not meet the requirements of the final project. On the other hand, 9 students attained "Pass" and "Very Good" as final grade, 13 students attained "Good," while the performance of four students was considered to be "Excellent," which corresponds to 11% of

the post-graduate students. Therefore, the overall students' performance can be judged satisfactory. Also, this feature can be considered as preliminary evidence about the accomplishment of the educational goals and the successful implementation of the proposed here tool in engineering education. Moreover, the overall satisfactory students' performance indicates that they also have achieved high scores at the final project, in which the deep understanding of the various design parameters on motor's performance is of great importance. The effective interpretation of the tool-based derived results is also one of the three main educational goals that have been set during the development of this computer-aided tool.

In order to highlight even more the tool's impact on the improvement of students' learning attitude and their academic performance, the results of the "pre- and post-tool" tests are presented in Figure 14. In these tests, students were asked to answer ten exam questions (EQs) with scalable difficulty. The results of the two tests are significantly different to each other. Indicatively, the number of correct answers in the case of «post-tool» test is increased by 6.45% for the easiest question (EQ1) and by 87.50% for the most difficult one (EQ10) compared to the corresponding ones of the "pre-tool" test. Analogous results are valid for all the other questions. Thus, it is clearly indicated that students' knowledge on BLCD machines fundamentals was enhanced after using this tool.

To quantitatively assess tool's impact and its acceptance on the above learning process and clarify students' satisfaction level a survey was undertaken at the last session of the course for three consecutive academic years. Students were asked to fill a questionnaire, in which they had to grade the 13 questions form according with the five-level Likert scale, where "1" means strongly disagree, "2" means disagree, "3" means neither agree or disagree, "4" means agree, and "5" means strongly agree. Thus, they were able to express their opinion about tool's usefulness in consolidating their knowledge of this field. Students' feedback is essential, since

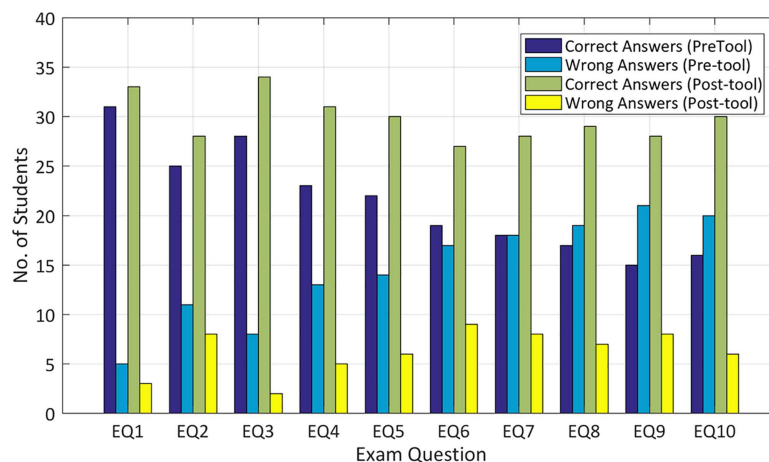


FIGURE 14 Overall performance results of "pre-" and "post-" tool test

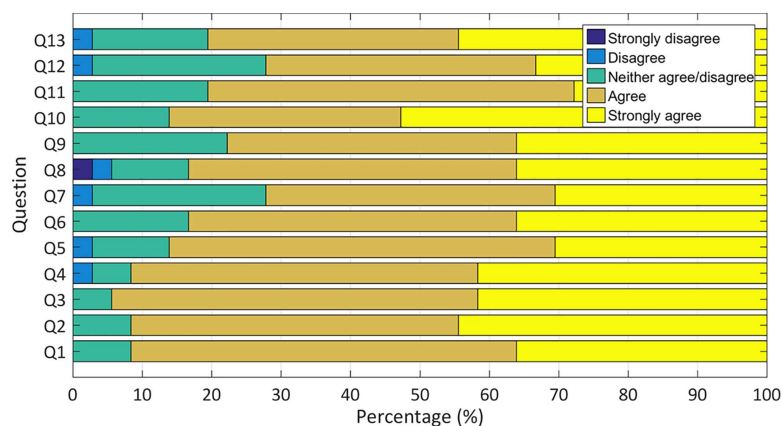
TABLE 1 Students' survey questions and the corresponding results

No.	Question	1	2	3	4	5	Average
Q1	The BLDC design tool is user friendly and quite educative.	0	0	3	20	13	4.28
Q2	The problem's input data can be easily inserted.	0	0	3	17	16	4.36
Q3	The graphical interface is effective and permits the better interception of the results.	0	0	2	19	15	4.36
Q4	I did not need any further instructions and help in order to use this tool.	0	1	2	18	15	4.31
Q5	This tool helped me to improve previously acquired knowledge on BLDC machines design.	0	1	4	20	11	4.14
Q6	Computer-aided sessions were well organized and strongly related to the main topic of this course.	0	0	6	17	13	4.19
Q7	The time devoted to theoretical and practical sessions is properly defined.	0	1	9	15	11	4.00
Q8	The followed teaching approach let me developed technical and practical skills that will be useful in other university courses.	1	1	4	17	13	4.11
Q9	The overall learning process satisfied my expectations.	0	0	8	15	13	4.14
Q10	I would recommend similar tools to be used in other electrical machinery courses.	0	0	5	12	19	4.39
Q11	I would use this tool in future extracurricular projects.	0	0	7	19	10	4.08
Q12	I am interested to explore deeper electrical machines performance and design topic.	0	1	9	14	12	4.03
Q13	I believe that I have successfully completed the BLDC motor design project.	0	1	6	13	16	4.22

it gives instructors the proper guidance about which characteristics of teaching approach and especially in our case which tool's specifications should be modified or not. Therefore, the conduction of several crucial improvements for forthcoming sessions is enabled. Moreover, the interaction between students and educators ensures the effectiveness of the course, the maintenance of the quality of university education and permits them to reflect upon their experiences among others. The 13 imposed questions and the corresponding students' responses obtained through evaluation sheets are summarized in Table 1. Additionally, the same Table shows the average of each question. The cumulative results of students' survey are also depicted in Figure 15.

As it can be seen, the average grade of each question is equal or higher than 4.00 in the 1.00–5.00 scale. This feedback indicates quite positive learning experience and

great interest by students. According to the results (Questions 1–3), students at first place found that the educational tool is very user friendly, since they mentioned that its interface has been well-designed allowing them to insert easily the required input data and change the geometrical and operational parameters of the machine. The particularly high average attained in Question 3 highlights the effectiveness of the developed graphical interface. Furthermore, it points out that instructors' great effort so that to enhance tool's flexibility and incorporate various results display capabilities has been positively appreciated by students. At this point, it should also be mentioned that the tool's enhanced display capabilities, the inclusion of parametric analyses ability, the inclusion of a brief help at each menu of the tool and the capability of plots creation which depict simultaneously several electromechanical quantities, were implemented in order to help post-

**FIGURE 15** Cumulative results of students' survey

graduate students to save time while developing their knowledge on BLDC machines. Taking into account their positive feedback through their responses and their comments, it is clearly revealed that the educational goal of time savings while developing the knowledge has been fulfilled.

The next item (i.e., responses to Question 4) shows that almost all users think that the software program presents low complexity and consequently is easy to use, which is a very important feature for the acceptance of any educational tool. As stated by post-graduate students, less guidance and assistance was required by instructors during the tool's training sessions and the implementation of this tool. It is already known that the educator's role consists of providing students with the appropriate tool in order to find the best way to solve a problem rather than guiding them to the solution. It should be considered as a general recommendation for other instructors who would like to implement a similar teaching approach that students have to be able to easily use or try the tool either in the laboratory of electric machinery courses or at home.

By examining further the derived responses (i.e., Questions 5 and 9) it is also revealed that the proposed teaching approach received good rates from the students concerning the success in understanding sufficiently the provided theoretical background, gaining great sympathy from them, stimulating their learning interest, improving their problems solving ability, and fulfilling or even overcoming the learning expectations. Tool's incorporation in educational process facilitates a topic that was quite difficult to be computationally assessed by students allowing it to become more visual. Therefore, the majority of students found BLDC machines design aspect more attractive and stated that they are willing to use this specific computer-aided tool in extracurricular projects (Question 11) and would recommend similar tools to be developed and used in other electrical machinery courses (Question 10). Many of them would like also to carry out further research in this area based on their responses to Question 12.

Moreover, the responses to Questions 5–8 indicate that the practical sessions and the tool's incorporation in the education process enable students to enhance their technical skills and this could be of great use for future engineers and other universities courses. The above feature has been achieved through the proper design of this subject in respect to the efficient organization and scheduling of both theoretical and practical lectures. The time devoted to each type of lectures was equal and therefore constructive dialogue and the desirable interaction has been performed between students and educator. Questionnaire results show that the majority of students believe that the presented here teaching method can bring results that cannot be achieved in the traditional class. In particular, skills such as engineering judgement, problem solving ability, long-term knowledge,

and self-confidence are significantly enhanced when non-conventional educational approaches are implemented. For instance, it is remarkable that most of the students were confident that they have successfully completed the BLDC motor design final project based on their answers given to Question 13.

Regarding the overall survey results, it is obvious that the obtained feedback is very promising and encourages software developers and instructors to produce computer-aided tools for educational purposes and develop new projects. In our case, students seem to satisfactorily approve the proposed here teaching approach and recommend the incorporation of aid tools and practical experience in the learning process of other engineering subjects. Based on the above, the integration of additional capabilities into the current version of this tool and the developing of similar software programs for the design and performance analysis of other machine types, such as induction, switched reluctance and permanent magnet synchronous motors, are included in the forthcoming plans of DECE's Electrical Machines Laboratory.

5 | CONCLUSIONS

Nowadays, engineering curriculums and especially electrical machinery courses are upgraded with the incorporation of technology motivated strategies in the learning process. Following, this tendency, which is gaining increasing attention, a new simulation based educational tool for the design and performance analysis of BLDC machines was introduced in this study. The proposed computer-aided tool was developed for post-graduate students in order to permit the practical experience that students are looking for and enhance the competence of the theoretical lectures and the fundamental principles that are provided there. This practical approach is based on simulation and numerical analysis using a Matlab GUI with flexible structure and an open source finite element method software. At first, a step-by-step design procedure was analytically described and a teaching methodology based on a simple but effective algorithm was also presented in order to make this difficult topic more visual and comprehensible for students. The outline of the proposed educational tool, its menus and its capabilities were thoroughly presented and also an indicative application of this tool was given. Then, the applied teaching approach and students' attainments were analyzed. Next, positive feedback about the tool's effectiveness for attaining the educational goals was measured by a Likert scale survey, in which several indicative guiding research questions has been imposed to students. Taking into account students' responses and their performance on an exam (before and after the tool's usage) as well as of the assigned projects it has been revealed that tool's advanced capabilities, such as the

various results display options, the conduction of parametric and sensitivity analysis, the interactive graphical feedback and the user-friendly interface, essentially improves students' motivation and performance in electrical machines design subjects. Therefore, it was obvious the three main educational goals which have been primarily set have been achieved. Based on the above, it is aimed to expand the integration of computer-aided tools in the electrical machines courses by developing similar software programs for other types of motors and generators. Moreover, a revised version of the proposed tool, which will incorporate new capabilities and characteristics regarding with subsequent students' feedback, is also planned to be released.

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