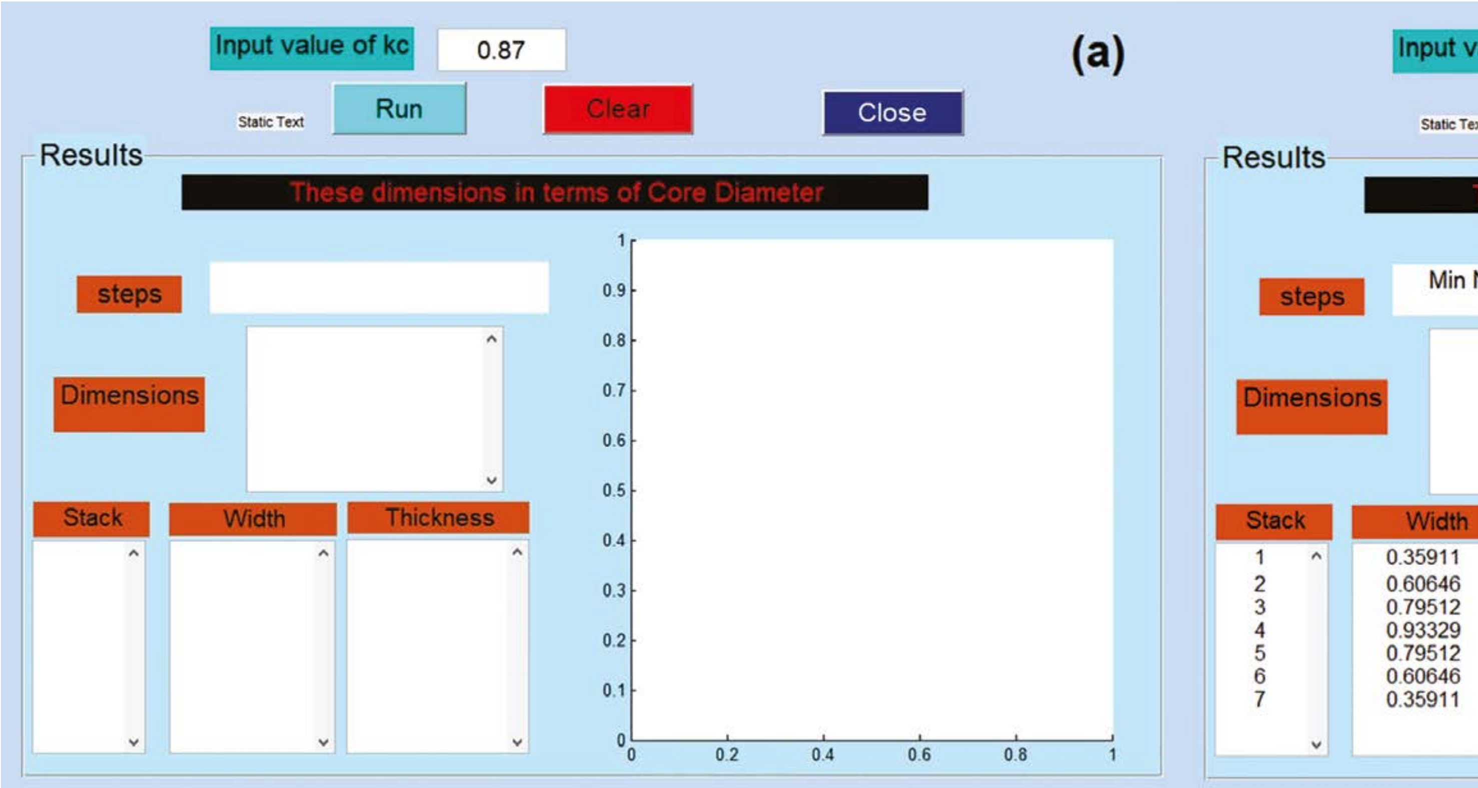


ABSTRACT

It is known that the deployment of highly efficient power transformers is crucial for the minimization of overall network losses. Hence, the curriculum of an elective senior-level course was developed for Cairo University students. This curriculum was developed by industrially experienced faculty members to mimic typical tasks encountered by power transformer manufacturers. In addition to classical methodologies, the course offers students hands-on experience in relevant finite-element analysis tools and newly introduced artificial intelligence techniques. Examples of student-developed design software packages are given. It is evident that linking the course content to actual real-life industrial scenarios results in outstanding student performance.

KEYWORDS

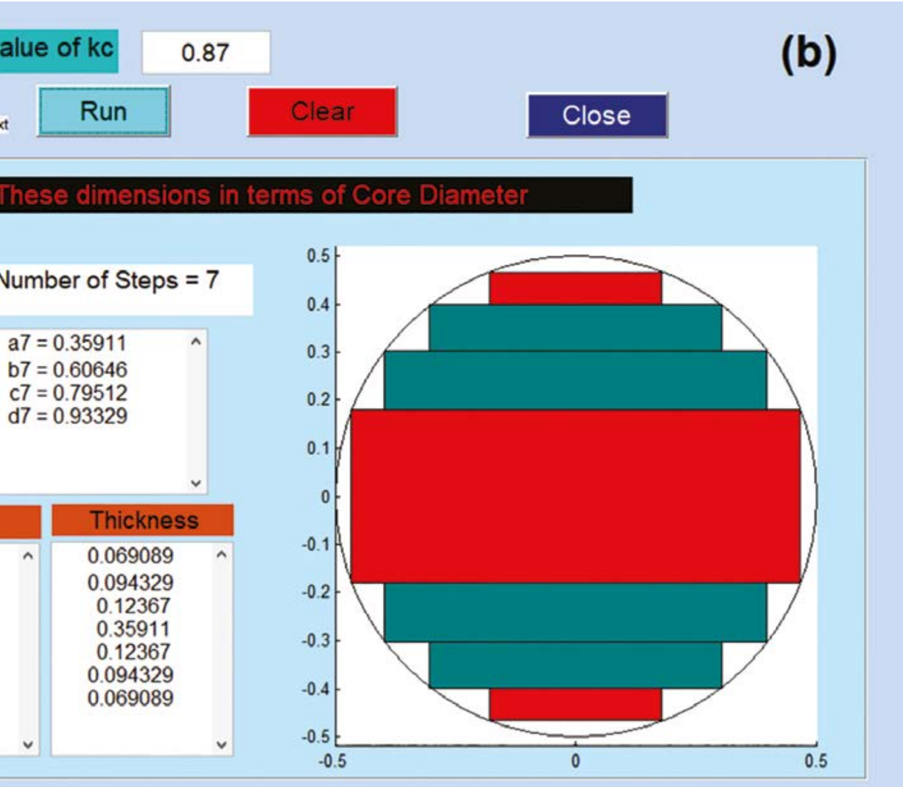
artificial intelligence techniques, computer-aided design, design optimization, transformer design methodologies

Computer-aided transformer design capacity building

A sample industry-oriented senior level university course

1. Introduction

Power transformers are considered among the most important components in any power network. Obviously, deployment of highly efficient power transformer units is indispensable for minimization of overall network losses. While most of the relevant power engineering curricula focus on power transformer operation and maintenance technicalities, availability of design methodologies know-how is crucial to fulfilling national and regional transformer manufacturers' job needs as well as to support efforts aiming at boosting the value added in national industries. Within the aforementioned context, a curriculum of an elective senior-level course was developed a few years ago for Cairo University Power Engineering students. Unlike traditional courses covering the same topic, the curriculum was developed by industrially experienced faculty members to mimic typical tasks encountered in design and research and development (R&D) offices of power transformer manufacturers. It should be mentioned that, in addition to power transformer design methodologies, the aforementioned course is entitled: "Computer-Aided De-



sign (CAD) of Electrical Machines" and also exposing students to design methodologies related to fractional horse-power (HP) induction motors (i.e., ratings less or equal to 1 HP) [1]. The unique nature of the course curriculum and teaching strategies with regards to power transformers design mechanism are discussed in the following sections.

2. Course objectives and teaching methodologies

The main objectives of the course under consideration are:

- to make students acquainted with the materials and theories related to specifications-oriented transformers design,
- to give students hands-on experience with some CAD tools currently used at R&D and / or design offices of power transformer manufacturers (see, for example, [2, 3]),
- to introduce students to typical optimization and / or cost reduction challenges encountered by manufacturers. It should be mentioned here that optimization reduces to minimum both the construction and running costs which are usually achieved by fulfilling the required design specifications yet competing pricewise in sales tenders.

In other words, the course objectives tend to help potential power transformer design engineers acquire necessary technical capacity relevant to the industry as well as to give them a flavour of what design challenges should be expected in real life.

2.1 Specifications-oriented power transformers design approach

In real-life situations, whether a sophisticated Finite Element Analysis (FEA) transformer design software tool or a simplistic analytical design approach is adopted, the main challenge is to identify the detailed design specifics that would result in fulfilling a set of required specifications at the minimum possible cost (refer, for instance, to [4, 5]). Obviously, the trade-off for using a simplistic analytical design approach is the involvement of safety factors to guarantee fulfilment of the required specifications at the expense of uncertainty in achieving the minimum cost design. Nevertheless, such analytical approach could yield a very good initial design details for more sophisticated transformer design software tools in addition to offering a fast high-level assessment of how design details may change as a result of a variation of certain design parameters, such as specific losses of utilized steel sheets.

Availability of design methodologies know-how is crucial to fulfilling transformer manufacturers' job needs as well as to support efforts aiming at boosting the value added in national industries

Aside from covering all basics related to power transformer materials, the theory of operation and effect of the properties of every single component on the operation performance [1], a recently compiled specifications-oriented design methodology is mainly adopted [6]. According to this methodology, the main specification requirements may be directly correlated to four main design parameters. More specifically, the Volt-Ampere Rating (*S*), the overall ohmic Copper Losses (*Pcu*), the ohmic No Load Losses (*Pnl*), and the ohmic Reactance per Phase (*X*) may be correlated to the Window Height (*Hw*), the Limb Diameter (*D*), the maximum Core Flux Density (*Bc*), and the average conductors' Current Density (*J*) in accordance with the following equations:

$$S = C_1 f_1(J, Bc, D, Hw) \quad (1)$$

$$Pcu = C_2 f_2(J, D, Hw) \quad (2)$$

$$Pnl = C_3 f_3(Bc, D, Hw) \quad (3)$$

$$X = C_4 f_4(J, D, Hw) \quad (4)$$

It is extremely important to give students hands-on experience with some CAD tools currently used at R&D and / or design offices of power transformer manufacturers

In the era of the fourth industrial revolution and its far-reaching consequences it is extremely important to expose students to non-traditional artificial intelligence (AI) transformer design techniques

In (1)-(4), C_1, C_2, C_3 and C_4 represent equation constants which take into account other design parameters such as: frequency, voltages, winding connections, window space factor, steel core stacking factor, conductor resistivity, copper and steel densities and specific core losses (please refer to [6]).

Obviously, several approaches may be taken to solve the above four equations to directly meet the main operating specifications. More specifically, equations may be solved simultaneously or iteratively to offer a very good initial detailed design guess. There is no doubt that a solid technical background of design limitations is required to sort out non-realistic solutions that may be a consequence of unachievable specifications requirements. Examples of such non-realistic solutions may include a maximum core flux density (*Bc)* exceeding the saturation range of the utilized steel core magnetization curve and / or practical current density of copper windings. It should be stated that once the four unknowns are determined, all other design specifics, such as the number of turns and winding cross-sections, may be calculated from other parameter inter-relations.

2.2 Hands-on experience with different CAD tools relevant to transformer design

A considerable percentage of the course work grade was related to the development of friendly software packages equipped with graphical user interfaces (GUI) that would support real-life activities carried out in transformer manufacturer design and / or R&D divisions.

Typical programming assignments included the development of software packages offering fast design support based on the previously discussed specifications-oriented analytical approach. Other examples involved optimization techniques to maximize gross core cross-sectional area within a given winding inner diameter.

Students were also exposed to free student version two-dimensional (2D) FEA packages [2, 3]. This was especially important to give them a head start in comprehending mathematical basics and limitations of such packages as well as to introduce them to how more sophisticated FEA packages may be well utilized within power transformer manufacturer plants to further refine preliminary design details that lead to the ultimate minimization of production material and, consequently, cost. It should be stated here that some assignments focused on using the FEA packages in the assessment and visualization of stray fields leading to eddy current losses in winding top and bottom edges, something hard to convey without such tools. Such FEA assignments focused on demonstrating that minimization of the previously mentioned losses related to the transformer window height to width ratio.

Given the implications of the Fourth Industrial Revolution [7], it was also extremely important to expose students to non-traditional artificial intelligence (AI) design techniques. In line with this mandate, feedforward artificial neural networks (FFANN) were introduced, and means of training and usage were covered. Some assignments involved using an FFANN with inputs and outputs conforming to the eight variables given in equations (1)-(4) to recommend design details for a given set of required specifications [8]. Obviously, this was possible by training the same FFANN using a set of top-quality power transformers having different specifications and with known design details.

2.3 Sample assignments and student work

In addition to a total of 45 contact hour lectures, and 15 contact hour tutorials, 112 students registered in the Spring 2020 semester were subdivided into 22 different groups. It should be mentioned that the course topic proved to be appealing to students interests since the registered students represented 70 % of the total final year students despite the fact that two other elective courses were offered. Different mini projects were assigned to the student groups, where more than one group was assigned the same project. This was especially important to highlight the possibility of adopting different optimization logic and / or design methodologies to achieve the same ultimate goal. All mini projects involved the development of a software tool equipped with a user-friendly GUI. A very brief listing of some of those mini projects, which had to be accomplished within a month duration, is given below:

- Development of a software package that can maximize the transformer core cross-sectional area for 5, 7 and 9 step steel lamination stacks,
- Development of a software package capable of identifying the minimum number of lamination stacks required to achieve a certain required stacking factor,
- Getting acquainted with a free student version of a 2D electromagnetic FEA package to construct an energized power transformer having specific dimensions and use the package to identify eddy current losses in winding edges as well as to plot leakage flux and flux density distribution at central parts of the core limbs,
- Development of a transformer design FFANN capable of identifying design details corresponding to the required specifications, provided that these specifications fall within extreme specification values of a given set of 20 different transformers used for the neural network (NN) training purposes,
- Development of a transformer design software package based on the taught specifications-oriented analytical methodologies.

Clearly and as previously stated, such mini projects were carefully chosen to give the students a flavour of what they might encounter in case they join a transformer manufacturer design and / or R&D office.

An example of the delivered student mini projects is shown in the cover figure where the number of core steel stacks and their dimensions relative to the winding inner diameter is calculated to achieve a given stacking factor. This package involved both a GUI and an optimization routine. The figure clearly highlights the input data in the image (a). Once the "RUN" button is clicked, detailed dimensions are calculated and given, as shown in the image (b). It should be mentioned that this tool has been developed to fulfil assignment requirements for a group of 3 students.

An alternative for steel stacking is shown in Fig. 1. where the number of stacks, inner winding diameter in addition to the dimensions of the steel laminations are identified. The developed student mini-project software tool then computes the stacking factor, dimensions of the various steel stacks in addition to the wasted steel laminations as a result of a mismatch between the lamination and stack dimensions. Once more, Fig. 1.a highlights the input. Once the "CALCULATE" button is clicked, detailed dimensions are calculated as in Fig. 1.c, as per the dimensioning scheme of Fig. 1.b. It should be stated that this tool has been developed by a group comprised of 5 students.

Another example is shown in Fig. 2, where a non-iterative software tool equipped with a GUI was developed to automate the analytical specifications-oriented transformer design approach. In Fig. 2.a., symbols *Kc*, *SW* and *CFe* represent the stacking factor, the window space factor and a constant correlating the steel sheets losses per kg weight as per the expression $CfeBc^2$, respectively. Once the "CALCULATE" button is clicked, design details are computed as shown in Fig. 2.b. In this figure, *Ww*, *Hw*, *N1*, *N2*, *A1*, *A2*, *I1* and *I2* represent the window width, the window height, primary winding number of turns, secondary winding number of turns, primary winding cross-section, secondary winding cross-section, primary current, and the secondary current respectively. Moreover, *R*, *Rc* and *Xm* represent the equivalent winding resistance per phase, equivalent core loss resistance per phase, and the magnetizing reactance per phase, respectively, all referred to the high voltage side. Please note that the tool also offers an insight into how the quality of steel laminations would affect the overall design details through the shown curves demonstrated once the "PLOT" button is clicked. It should be mentioned that development of this tool was assigned to a different group of 6 students enrolled in the course.

Within the course, students are developing software packages for the transformer-related mini-project, which include a GUI and a solution using advanced computational techniques such as optimization

Alternatively, Fig. 3 demonstrates a different iterative software tool equipped with a GUI which was developed to automate the analytical specifications-oriented transformer design approach. The required design specifications are entered as shown in Fig. 3.a. Once the "CALCULATE" button is clicked, design details are given as shown in Fig. 3.b. This design tool and its GUI was developed by yet another group comprised of 6 students.

Overall, it was clear that linking the course content and assignment requirements to actual real-life industrial scenarios has resulted in boosting student motivation and the will to deliver high-quality work. This is indeed in the very best interest of both the students within their future job search efforts as well as for power transformer manufacturers in search of new qualified and talented manpower.

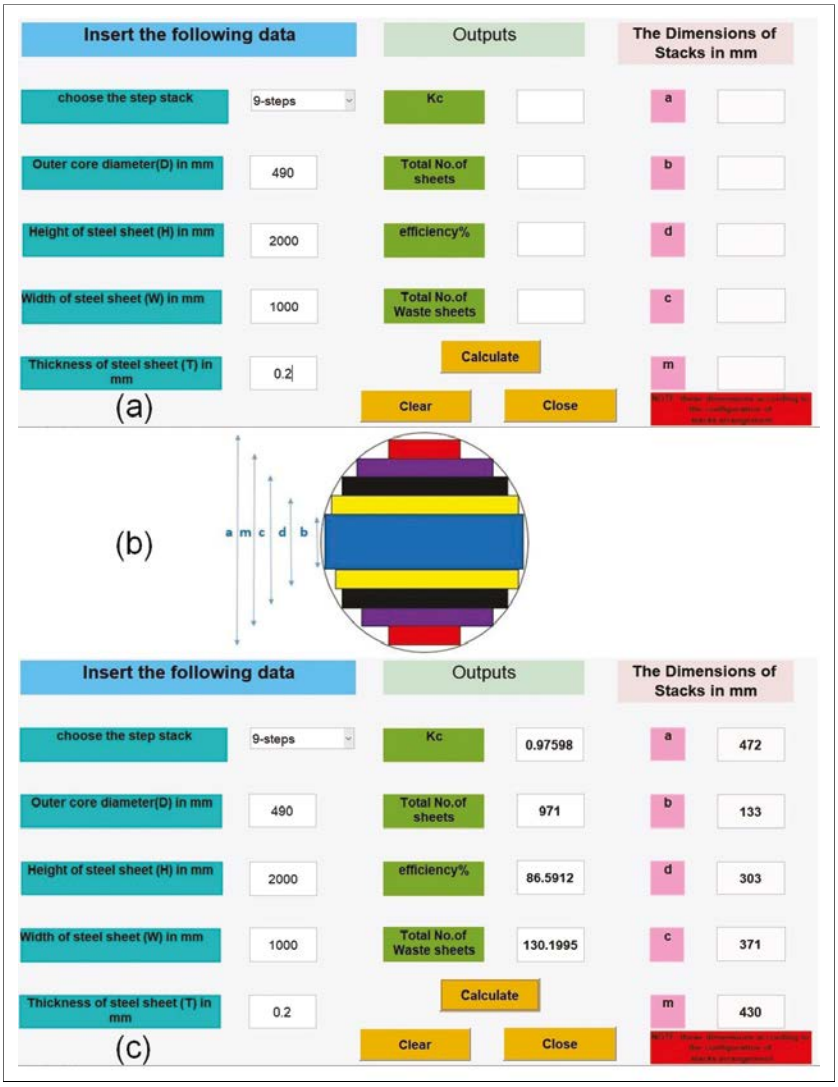


Figure 1. A delivered student mini-project where, given the number of stacking steps, the inner diameter of windings and steel lamination dimensions (a), the tool identifies the steel stack dimensions as identified in (b) in addition to the stacking factor and wasted steel laminations (c).

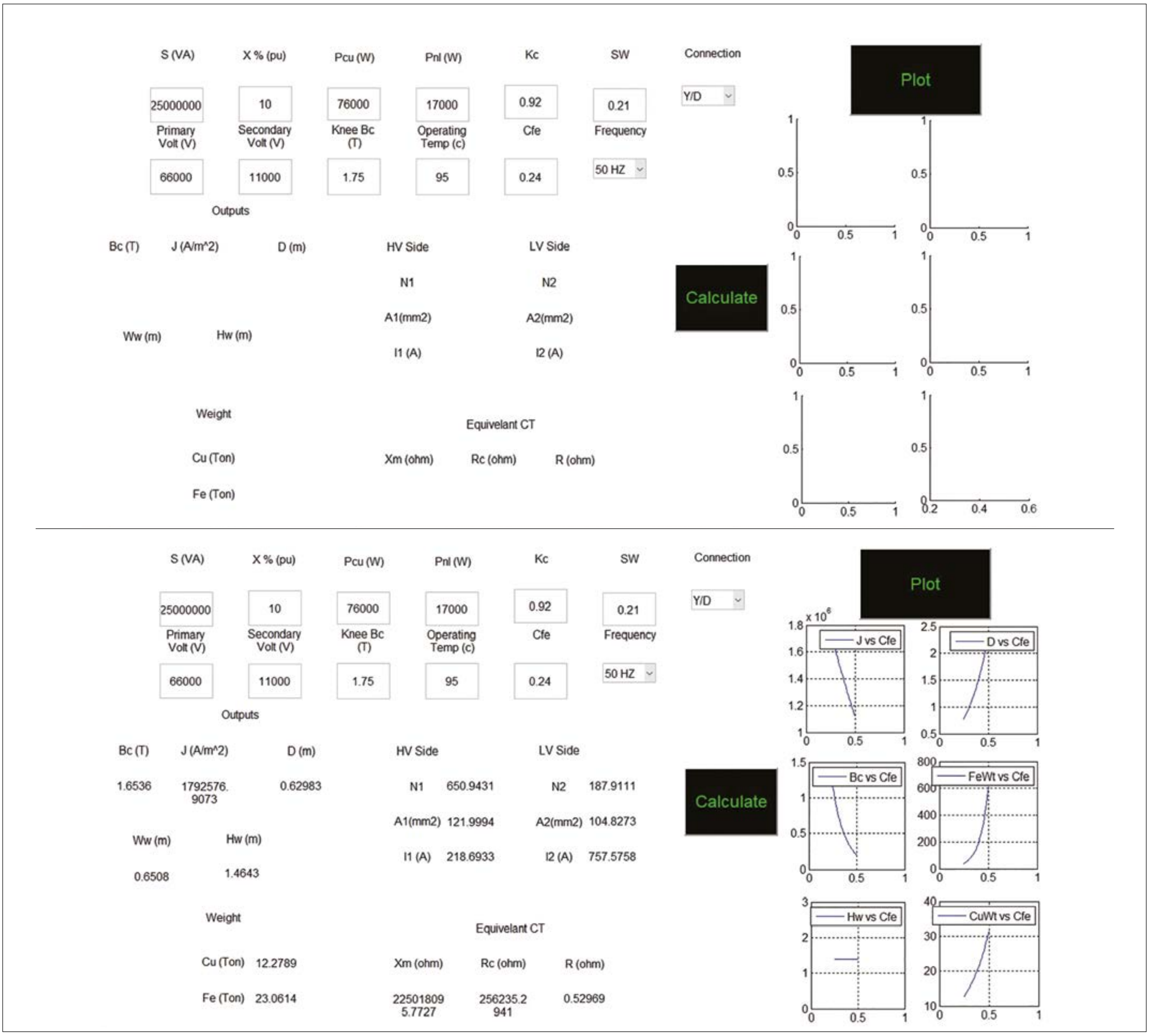


Figure 2. Non-iterative automation of the analytical specifications-oriented transformer design approach where, for a set of required specifications as shown in (a), it is possible to obtain detailed design details in addition to an account of how the quality of steel sheets material could affect those details (b).

Conclusion

This article has highlighted the need for developing transformer design curricula reflecting real-life industrial design challenges. On a quest for these capacity-building efforts, hands-on knowledge transfer related to electromagnetic software packages and newly introduced artificial intelligence approaches is a must. Outstanding mini projects developed by the students suggest that adopting the aforementioned curricula results in boosting the students' motivation. Tertiary and / or tap changers windings are also planned in future versions of the course. The author would like to conclude this article by acknowledging the great work of all 112 students who enrolled in the reported Spring 2020 course (of which sample design tools have been reported in this article) as well as the support of Dr. H. Hassan and Eng. A. Abbas who participated in the teaching efforts.

Expect outstanding work from students as a result of being motivated by linking the course content and assignment requirements to actual real-life industrial scenarios

Bibliography

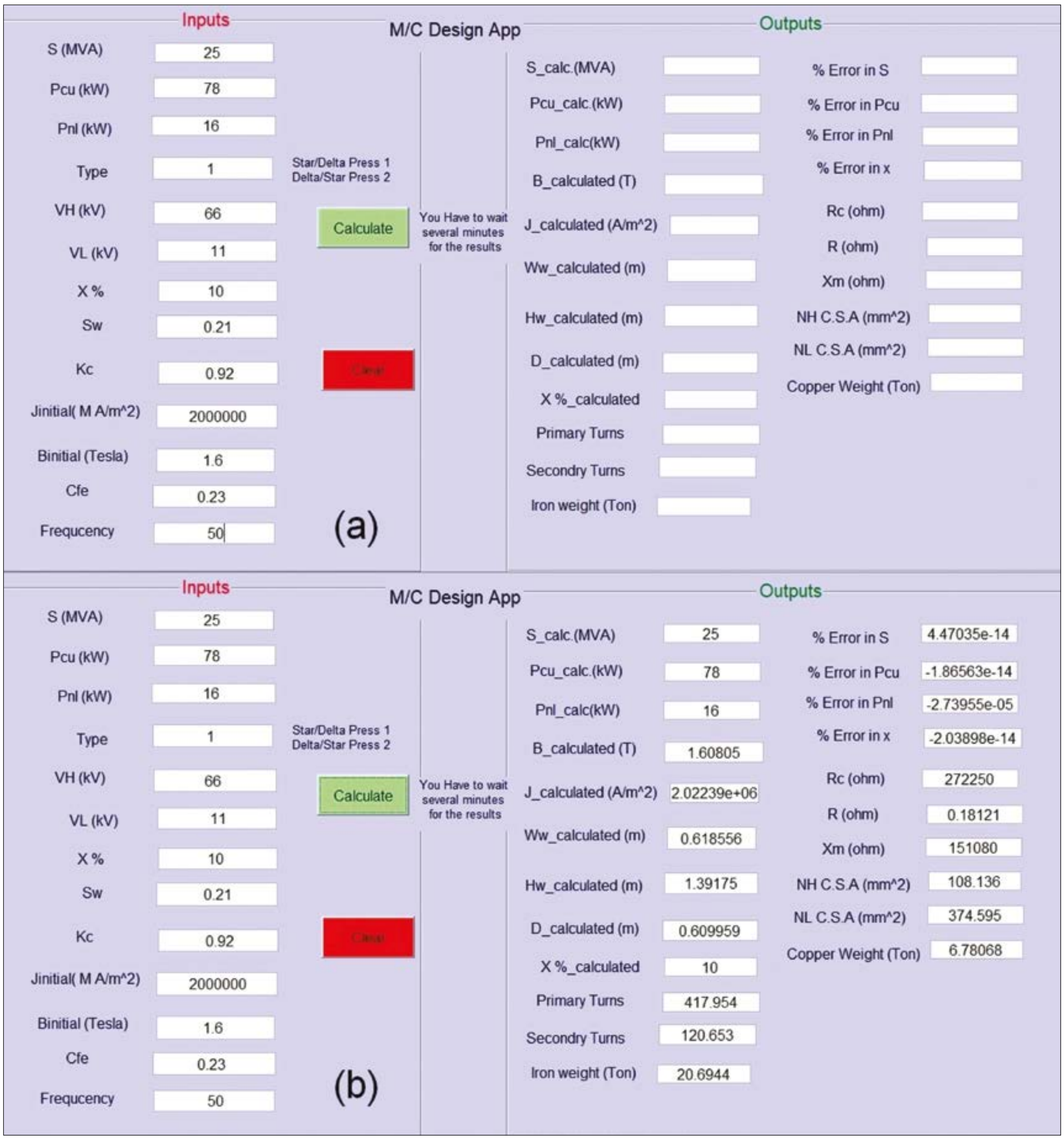
[1] A. K. Sawhney, *A course in electrical machine design*, Dhanpat Rai & Sons, Delhi, 1984

[2] QuickField simulation software by Tera Analysis Ltd., www.quickfield.com

[3] D. C. Meeker, *Finite Element Method Magnetics*, Version 4.2 (28 Feb 2018 Build), http://www.femm.info

[4] M. A. Tsili, A. G. Kladas, P. S. Georgilakis, *Computer aided analysis and de-*

Figure 3. Iterative automation of the analytical specifications-oriented transformer design approach where, for a set of required specifications as shown in (a), it is possible to obtain detailed design details in addition to an account of how the quality of steel sheets material could affect those details (b).



sign of power transformers, Computers in Industry 59 (2008) 338–350

[5] C. V. Aravind et al., *Universal computer aided design for electrical machines*, 2012 IEEE 8th International Colloquium on Signal Processing and its Applications, Melaka (2012) 99-104. DOI: 10.1109/CSPA.2012.6194699

[6] A. A. Adly, *A specifications-oriented initial design methodology for power transformers,* Energy Systems 8, 285–296 (2017), https://doi.org/10.1007/s12667-016-0197-5

[7] *Jobs Lost, Jobs Gained: Workforce Transitions in a Time of Automation,* McKinsey Global Institute, December 2017

[8] K. Mehrotra, C. K. Mohan, S. Ranka, *Elements of artificial neural networks*, Cambridge, MA: The MIT Press, 1997

Author

Amr A. Adly received B.Sc. and M.Sc. degrees in Electrical Power Engineering from Cairo University and the Ph.D. degree in Elect. Eng. from the University of Maryland, College Park, USA. He worked as a Senior Magnetics Design Scientist at LDJ Electronics, Michigan, USA, during 1993–1994. In 1994 he joined Cairo University as a faculty member and was promoted to Full Professor in 2004. He also worked in the USA as a Visiting Professor at the University of Maryland during summers of 1996–2000. He established and directed the R&D Division of the Egyptian Industrial Modernization Centre and worked as a design consultant for several motor and transformer plants in Egypt. Professor Adly is an IEEE Fellow and is currently an Associate Editor for several scientific journals including the IEEE Transactions on Magnetics. He published more than 130 reviewed papers and holds one US patent and was awarded numerous prestigious prizes and awards including the University of Maryland ECE Department Distinguished Alumnus Award. Prof. Adly has served as the PI of several joint international projects and previously as Cairo University Vice President for Graduate Studies and Research.