Evaluating the effect of using synchronous machine simulations to support traditional teaching methodology in electrical engineering degree courses

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Abstract

Based on the equivalent electrical circuits, synchronous machine concepts are abstract and difficult to understand. Many studies highlight the difficulty that engineering degree students have understanding electrical circuits, and propose different methodologies to address this.

This study aims to show how the use of computer assisted teaching improves general understanding of synchronous machines, in accordance with the following hypothesis: “complementing the traditional approach to teaching synchronous machines courses (based on theory lessons and practical laboratory sessions), with computer simulations, improves conceptual understanding and, consequently, course success rates”. In order to test the effectiveness of the proposed teaching methodology, a controlled experiment was conducted. The students were separated into two groups, control and experimental, and their responses compared. The former followed traditional teaching methodology, while the latter utilised the proposed complementary computer assisted simulations. Both groups were evaluated according to the same test comprised of a list of comprehension questions. The results of the z-test analysis show that $z = 4.365$, $p < 0.001$, meaning the null hypothesis can be rejected and a significant contrast between the two groups can be recognised. The effect size, evaluated using Cohen's d, is $d = 0.816$, again indicating that the difference between the groups is significant. The posttest results reveal that the experimental group outperformed the control group in all three of the dimensions under analysis: theory, problems and complete test.

Keywords: Simulation, undergraduate, electrical engineering, isolated synchronous machine

1. Introduction

As synchronous machines are present in almost everything powered by electricity, knowledge of them plays a key role in electrical engineering education and, synchronous machines courses are part of undergraduate electrical engineering programmes the world over. In the traditional teaching paradigm, laboratory experiments are used to support theory courses and, nowadays, the use of computer based tools is commonplace. In the case of synchronous machines, computer based tools are an attractive option since they allow the student to interact with the synchronous machine, avoiding the risk of short circuits, damage to devices and equipment, and, most importantly, injury to users (Rosa et al., 1999).

Studies have identified quite a high failure rate for synchronous machines courses, as students have difficulty applying previously taught knowledge, such as electric circuit analysis and mathematical competences (De La Hoz i Casas and De Blas del Hoyo, 2015; Lumpur et al., 2018). Computer based tools contribute to the acquisition of basic knowledge and offer significant advantages in terms of engineering degrees (Brophy et al., 2013; Yetilmezsoy, 2017). Brophy et al. (2013), showed how the use of computer based tools to study system function under different conditions, provides an important mental representation, which can be used to predict the performance of complex systems.. As the authors state, this approach can be generalised to other learning experiences designed to help students apply fundamental abstract engineering principles, such as the foundations of synchronous machines.

Electricity, despite being a cumbersome, perplexing concept, is ever-present in people's lives. Its impalpable nature leads students to develop false ideas about the way electrical systems function and, though many studies have been conducted and many similes exist, it remains a complex area of study. Indeed, many students still have difficulty understanding all the aspects of the way electrical systems, regardless of size, function (Hart, 2008).

Interest in research on the challenges faced by students in understanding electrical concepts goes back several decades. In order to check university students' understanding of the basic concepts of electricity after having completed an introductory physics course which included electrical circuits and Ohm's Law, McDermott, (1991), developed a test consisting of one single question about a simple DC circuit. Despite having both previous knowledge and experience using Ohm's Law to solve more complex problems, only a small percentage answered correctly. The author found that most of the errors arose from misunderstandings which affected the ability to reason when faced with unexpected situations.

In subsequent work, McDermott and Shaffer, (1992), studied the difficulties faced by students when analysing simple electrical circuits, such as the inability to apply basic concepts related to current, voltage and resistance. Students lacked the conceptual framework to enable them to make qualitative inferences about the way electrical circuits behave when modified. For example, if the original circuit was modified, students focused only on the point where the change was made, and were unable to understand that this change altered the behavior of the rest of the circuit. More recent studies have produced similar results, with students continually failing to acquire a proper conceptual understanding of the behavior of electrical systems (Andre and Ding, 1991; Asoko, 1996; Başer and Durmuş, 2010; Gunstone et al., 2009; Hart, 2008; T. Jaakkola et al., 2010; T Jaakkola and Nurmi, 2008; Tomi Jaakkola et al., 2011; Osborne, 1983; Shipstone, 1984; Streveler et al., 2008; Zacharia and Constantinou, 2008).

Appropriate conceptual perception allows pupils to deduce how a circuit will behave when subject to change (R. Cohen et al., 1983; Frederiksen et al., 1999; Streveler et al., 2008). Rittle-Johnson et al. (2001) defined the conceptual understanding of engineering concepts as: "an implicit or explicit understanding of the principles that govern a domain and of the interrelations between units of knowledge in a domain." Streveler et al. (2008), use this as a basis for their definition with understanding being based, on the one hand, on knowledge of quantities and, on the other hand, knowledge of the relationships between them. Moreover, Lindström et al. (1993), and de Jong et al. (1998) showed that as conceptual understanding deepens, there a corresponding increase in the capacity to accurately evaluate the relationships built between quantities in circuits whose parameters are subject to change.

Taking everything into account, it is clear that conceptual understanding is of paramount importance in the competence and experience of engineering students (Streveler et al., 2008). However, it seems that traditional energy engineering instruction fails to furnish students with a sufficiently detailed conceptual understanding of electrical circuits.

Traditional electrical engineering curricula are composed of two elements: theory lessons, based on textbooks and problem solving, and practical laboratory sessions. In the former, topics are often approached from a facts and calculations perspective; students are taught laws and definitions in the form of equations, which can be used to solve basic electrical circuit problems (Frederiksen et al., 1999; Gunstone et al., 2009; Tomi Jaakkola et al., 2011; McDermott and Shaffer, 1992). Consequently, problems in textbooks are often focused on “the ability to execute action sequences to solve problems” (Rittle-Johnson et al., 2001). Conversely, in the latter, students build electrical circuits and measure magnitudes, practices fundamental to acquiring the dexterity and experience with real devices that results in true conceptual understanding of the field. Nevertheless, laboratory practices have limitations. Where circuits are involved, students typically focus on building them correctly, as opposed to concentrating on understanding the relationships between input and output variables (Hodson, 1993; Schauble et al., 1992). Furthermore, interaction with real circuits inevitably leads to unpredictable situations which deviate from those taught in theory classes. If both the measuring equipment and the elements of which the circuit is composed are not ideal, the measurements will deviate from the theoretically calculated outputs, resulting in potential misunderstandings.

It is evident that the traditional combination of theory classes and practical sessions fails to provide the students with the tools to gain an adequate conceptual understanding of electrical engineering. Therefore, the introduction of additional teaching methodologies which advance conceptual understanding may be an appropriate step. Papadouris and Constantinou (2009), showed that frequent practice with real systems through experimentation, inquiry and interpretation established a basis for the improvement of conceptual understanding. Steinberg (2000), also highlighted the importance of experimentation for students in engineering education, identifying two decisive learning points:

Firstly, successful learning relies on interpreting how students understand the subject, i.e., learning must take into account the students' preconceptions on the subject. In this respect, the role of the teacher is key in helping the students develop their own ideas and use them as a basis for learning. Secondly, students must actively participate in the learning process, rather than passively observe what they are being taught. That is to say, they must collaborate under an inquiry-based learning methodology (Binns et al., 2010; Bliss and Ogborn, 1994; Capps et al., 2013; Chi et al., 1994; Chinn and Brewer, 1998; Hake, 1998; T. Jaakkola et al., 2010; Pollock, 2009; Ronen and Eliahu, 2000; Vosniadou, 2003).

In inquiry-based learning, one of the most effective ways to gain conceptual understanding (Bok, 2006), students are taught through exploration and the use of scientific deduction. Information and Communications Technology (ICT) could be used to enhance this process by, for example, allowing students to perform computer simulations to investigate, test and collect data (Betrancourt, 2005; Binns et al., 2010; de Jong, 2006; De Jong et al., 1998; R. E. Mayer, 2002; Rieber, 1996; Vosniadou, 2003).

Simulations facilitate the study of any real system. They allow for the modification of the input variables, such as the source voltage in a circuit, and the subsequent examination of the way this effects the rest of the variables, such as the current intensity. A range of different tests can be run resulting in rapid results. The simulation can be configured and modified with speed and ease, allowing the student to focus on the analytic process unhindered. Through systematic trials consisting of the change in magnitude of the variables in an electrical circuit, students can analyse the characteristics of the implemented model, as well as Ohm's and Kirchhoff's laws (de Jong, 2005, 2006; Jong and Joolingen, 1998). In addition, observing what happens in the simulation helps the students to validate their own visual representation and recognise those characteristics in need of improvement. Ultimately, this process can help students establish relationships between simulated and real systems (Papadouris and Constantinou, 2009; White and R. Frederiksen, 1998).

Although two of the main features of using simulators for inquiry-based learning are considered to be proactive participation and representative teaching (Halpern, 1994; Menges and Svinicki, 1991), the latter does not necessarily happen of its own accord. Grove and Bretz, (2012), and Lee and Thompson (1997), concur that only specific cognitive actions can foster representative teaching. To ensure that students develop appropriate cognitive responses, and to prevent these from weakening, training is essential (Bell and A Davis, 2000; de Jong, 2005, 2006; De Jong et al., 1998; Golan et al., 2000; Hogan and Pressley, 1997; Holbrook and Kolodner, 2000; Quintana et al., 2002). The incorporation of cognitive aids within the scope of teaching can direct students through the inquiry process (de Jong, 2006), and where solutions to problems are incorrect, simulators can provide students with invaluable information (Steinberg, 2000).

The idea of using simulators to teach electrical engineering is nothing new. In fact, studies have already shown the effectiveness of using them to help primary school children grasp electricity concepts (Başer and Durmuş, 2010; Engelhardt and Beichner, 2004; T. Jaakkola et al., 2010; T Jaakkola and Nurmi, 2008; Tomi Jaakkola et al., 2011). Other studies focused on university students, specifically engineering undergraduates (De La Hoz i Casas and De Blas del Hoyo, 2015; Notaroš et al., 2018; Rosa et al., 1999). Rosa et al. (1999), presented simulation software for synchronous machines and power electronics designed to offer a quick and easy introduction to simulation and lab experiments. However, its effectiveness as a complementary teaching tool has never been properly assessed.

De La Hoz I Casas and De Blas del Hoyo, (2015), proposed a “learning by doing” methodology as a way of improving students' practical results. This methodology linked laboratory experiments with active modelling to enhance understanding of synchronous machines, resulting in a noticeable improvement. More recently, Notaroš et al. (2018), used MATLAB as a tool to develop the creativity of electrical engineering students (defined as the integration of research, design and optimisation) on electromagnetics courses. This study differed from previous ones in that, instead of conducting experiments according to a prescribed model, students created their own programs.

The aforementioned studies all relate to elemental electricity courses concerning the analysis of electric circuits. Therefore, as we focus on the teaching of synchronous machines courses, and these machines can be represented by equivalent electric circuits, they provide a good starting point for our study.

However, focusing only in synchronous generators, there are very few previous works that propose the use of simulations as a tool for its teaching (Temiz and Akuner 2009; Vahidi and Bank Tavaloki 2009) as it is proposed in this study. Temiz and Akuner (Temiz and Akuner 2009) used computer aided teaching to explain the rotating air gap between rotor and stator of the induction motor. They compared the conventional way of teaching (based only in technical drawing) with simulations that visualized the rotation of the air gap step by step to the students. The evaluation process indicated that the students of the class in which the subject was taught by computer aided simulation could get higher grades than the one which was taught conventional way. In the case of Vahidi and Bank Tavaloki (Vahidi and Bank Tavaloki 2009), a “prepared simulator” (a graphical user interface created in Matlab Simulink) is provided to the students to assist them to solve some exercises related to the understanding of synchronous generator performance. From this study, it is concluded that visualized education, with the help of computer, eases to understand the subject and causes longer memorization. From the analysis of these works, it can be highlighted some novelties that this work offers in comparison to them. Regarding the first work (Temiz and Akuner 2009), it is focused on teaching a very specific aspect of electrical machines, the rotation of the air gap between the rotor and stator, while ours is focused on the global understanding of the electrical machine operation. Besides, in (Temiz and Akuner 2009), the computer tool was developed by the teachers and simply provided to the students to use it whereas we propose that the students build their own model following a manual with instructions. With regard to the work presented in (Vahidi and Bank Tavaloki 2009), the teaching topic coincides with ours (the general understanding of synchronous generators' operation), the computer tool proposed is also Matlab Simulink and the methodology to compare the teaching approaches is quite similar to ours. However, in (Vahidi and Bank Tavaloki 2009), the students were provided with a "prepared simulator" that had to be configured to answer some questions while in our case the simulator has to be built by the students as part of the learning process and then, configured to answer some questions.

Taking everything into consideration, the main novelty of this study lies not only in the proposed use of computer assisted teaching to improve the global understanding of synchronous machines but also in a "learning by doing" based approach: the students were provided with a guide enabling them to construct their own models from zero. Once the model is built, it is configured to answer some questions whose objective is easing the understanding of synchronous generator operation. Finally, the effectiveness of the methodology was evaluated by means of a controlled experiment.

This study is the result of the "Synchronous machines modelling and analysis" project supported by a teaching innovation programme developed in 2018 by a Spanish university. A team of three educators implemented this approach to enhance the understanding of the operation of synchronous machines using computer based tools.

2. Methods and material

2.1.Participants

This study was conducted in the 2017-2018 academic year with the participation of 114 Electrical Engineering undergraduates divided into two groups: one following the traditional approach, and the other, using the proposed methodology. The subsequent data collected from those following the traditional approach was used as reference against which the suitability of the proposed approach was measured.

2.2.Theoretical background

An alternator phasor diagram provides a graphical representation of the relationship between the electromotive force, *Emf*, and the terminal voltage of one phase under different operating regimes. Furthermore, it facilitates the study of the interaction between the excitation and induced magnetomotive forces, *Mmfs*, which leads to the resultant *Mmf* that generates the magnetic flux in the air gap (Chapman, 2011; Fraile Mora, 2003). This phasor diagram is analysed using a synchronous machine with a uniform air gap (cylindrical rotor), simplifying the operation of the machine, since the armature reaction is not dependent upon the position of the rotor (i.e. the reluctance is identical in all positions). In addition, it is assumed that the dispersion reactance, X_σ, is constant and the hysteresis iron losses can be neglected. This last condition is equivalent to saying that the resulting *Mmf* (F_r) is in phase with the magnetic flux it produces.

Let's consider a synchronous machine operating in generator mode with a voltage per phase, *V*, and an inductive current in the armature, *I*, with a phase shift of φ degrees. To determine the resulting *Emf* (E_r), the voltage drops across the resistance (*R*) and dispersion reactance must be added to the terminal voltage, as shown in the circuit of Fig. 1a, resulting in:

$$\overline{E}_r = \overline{V} + R\overline{I} + jX_\sigma\overline{I} = \overline{V} + \overline{Z}_\sigma\overline{I} \tag{1}$$

Fig. 1b, where the terminal voltage has been taken as the reference on the real axis, shows the resulting geometrical composition.

The magnetic flux required to produce the above-mentioned *Emf* leads the E_r by 90° and, if the magnetic hysteresis is omitted, the direction of the magnetic flux is the same as the resulting *Mmf*. In addition, F_r is the sum of the excitation *Mmf*, F_e, and the *Mmf* corresponding to the armature reaction, F_i, expressed as:

$$\bar{F}_r = \bar{F}_e + \bar{F}_i \tag{2}$$

Consequently, the excitation *Mmf* is obtained by a vector sum of F_r and $-F_i$. Fig. 1b shows the resulting phasor diagram, taking into account that F_i and the current that generates it, I, are in phase,.

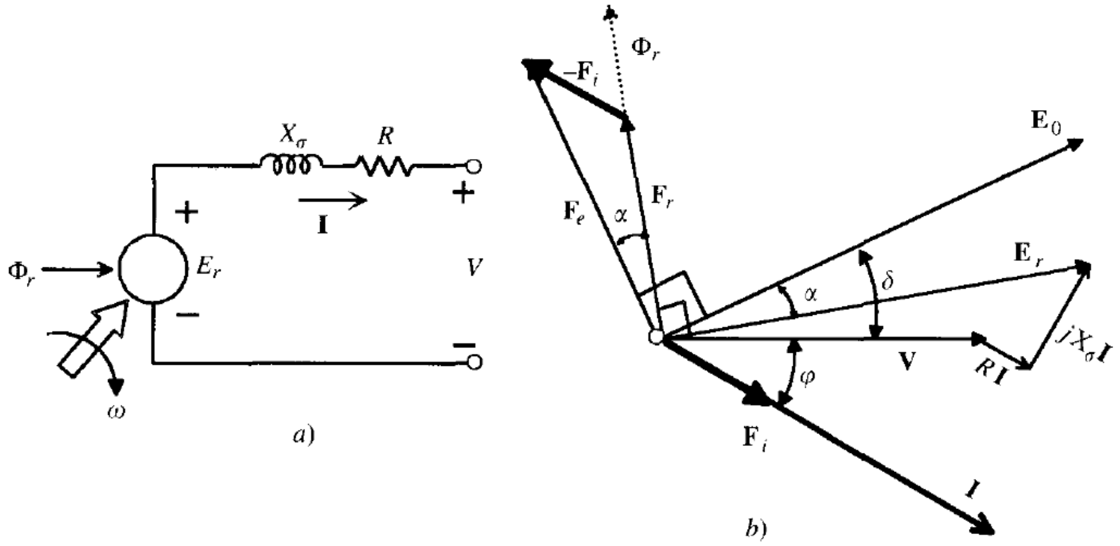

Figure 1. a) Equivalent circuit of an alternator. b) Phasor diagram.

When the machine is operating under open circuit conditions, with the same excitation, represented by F_e, there is no armature reaction, i.e. $F_i = 0$. Thus, F_e becomes the resulting *Mmf*, $F_e = F_r$, and the magnetic flux in the air gap increases in phase with Fe (Fig. 1b), and is determined by means of the open circuit characteristic curve of the synchronous machine. This process constitutes the usual method to calculate the necessary *Mmf* in the excitation when the machine supplies a current, *I*, at a certain voltage, *V*.

In fact, the physical process is inverse, starting from the excitation *Mmf*, and obtaining the output voltage and current from the load characteristics. Fig. 2 shows an illustrative diagram of the resulting functional relationships, including a feedback loop (representing that the output interferes with the input). Initially, an excitation current I_e is injected, which produces a F_e and, when the rotor rotates, an *Emf* is generated. When a load is connected across the armature, an output current *I* is obtained.

This current, shown in Fig. 1b, represents the current of one phase only (the “a” phase, for example), when, actually, there are three currents, one per phase, with the same module. These currents are 120° out of phase and also circulate across electric windings deviated 120° in space. Thus, a rotating *Mmf* armature reaction, F_i, is produced, which rotates in synchronism with the excitation *Mmf*, F_e. These two *Mmfs* interact and result in another *Mmf* (F_r), which, through the iron magnetisation curve of the machine, produces a final magnetic flux, Φ_r, which generates the resulting *Emf* in the armature winding, E_r (in each phase). Due to the existence of the resistance, *R*, and dispersion reactance, X_σ, a lower voltage *V* than E_r is obtained.

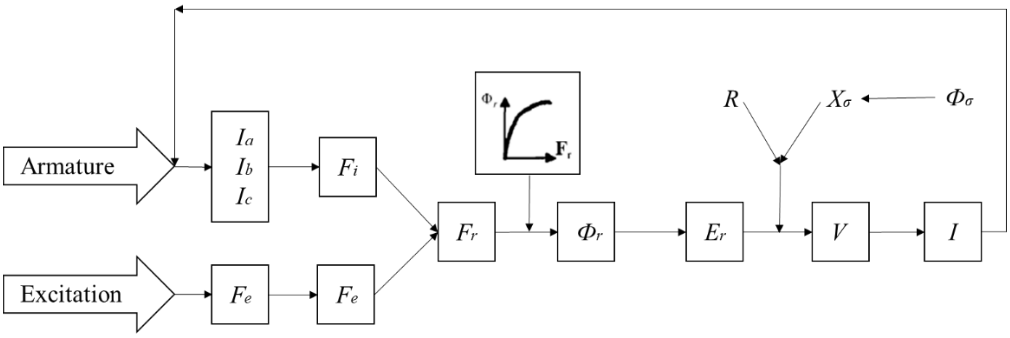

Figure 2. Functional relationships between the variables of a synchronous machine.

2.3.Material: MATLAB® and Simscape Electrical® Toolbox

MATLAB® was chosen as the software tool for this study for several reasons. Firstly, it has been proven easy to use (Majid et al., 2012). Secondly, its toolboxes and graphical interface, Simulink, are widely used in industry for multiple modeling domains, and it includes tools for design, implementation, verification, and validation (Mathworks, 2019). Around the world, thousands of engineers and scientists rely on Simulink for modeling and simulating complex systems thus, it will serve as an advantage to the students throughout their professional careers.

Simscape Electrical® Toolbox was chosen as it provides a smooth graphical environment for the students, allowing them to program actions in the model, simulate different case studies and visualize the results with ease. Furthermore, its component libraries contain the necessary electrical components for the development of electrical machines tests, such as synchronous machines, passive elements (resistors, inductors and capacitors) and measurement devices.

Different assignments guide the students in the design of circuits representing different synchronous generator tests based on different criteria. Each assignment contains a unique set of questions designed to lead the students in the analysis of the results. The circuits are simulated using the SimPowerSystems library of MATLAB/Simscape. The ease of manipulation allows the student to follow a “what if” philosophy and learn about the behaviour of the electric machines through experimentation.

All the participants of this study had prior knowledge of the software, having used it in other subjects.

3. Analysis and results

3.1.Modelling

The objective of this experiment was to build a model of a synchronous machine working as a generator and check its performance under different conditions: 1) operating with a real load, and 2) operating with no load to determine its no-load curve.

The proposed model can be extrapolated to any size machine. In this study a machine with the following characteristics was chosen: a three-phase wye connected alternator of 3000 kVA, 6600 V phase to phase and 50 Hz, an armature resistance of 0.07 Ω and a dispersion reactance of 0.7 Ω / phase. The relationship between the generated *Emf* and the *Mmf* in the air gap is defined as follows:

$$Emf = \frac{5800 \cdot Mmf}{Mmf + 9300} \tag{3}$$

where *Emf* is the electromotive force per phase generated in the machine in V, and *Mmf* is the magnetomotive force in the air gap in AT.

This is an electric model of the machine, which does not take the mechanical model into account, i.e., the rotation speed is considered to remain constant at all times.

The model, based on the Fig. 2 diagram, is predicated on the theoretical background outlined above, particularly equations (1) and (2), which in turn are represented in the Fig. 1b phasor diagram. To simplify the model, the E_r variable is considered the origin of the phases. Thus, the resulting phasor diagram will be rotated δ-α degrees with respect to Fig. 1b.

Since the I_e and load are known, the solution of equations (1) and (2) is obtained as follows:

- Equation (1): $\overline{E}_r = \overline{V} + R\overline{I} + jX_\sigma \overline{I} = \overline{V} + \overline{Z}_\sigma \overline{I}$; All the variables of the second member are known, therefore, they can be used to calculate the E_r vector. However, taking into account that the origin of the phases is placed in the E_r, all the other vectors have to rotate at an angle equal to that obtained as a result of the operation.
- Equation (2): $\overline{F}_r = \overline{F}_e + \overline{F}_i$; In this equation, the F_r modulus and the F_e angle are unknowns. The equation can be reformulated as $|F_r|\angle\beta = |F_e|\angle\gamma + |F_i|\angle\varphi$,where β is equal to the angle of E_r plus 90º (in this case β = 90º), and F_e and F_i are calculated as $F_e = N_e \cdot I_e$ and $F_i = N_i \cdot I$. The angle φ is the same as the load (or armature) current. Therefore, there are two equations with two unknowns, which can be solved by substitution:

$$\begin{aligned} |F_r| &= \frac{|F_e|\sin\gamma + |F_i|\sin\varphi}{\sin\beta} \\ \frac{\sin\gamma}{\tan\beta} &- \cos\gamma = K \end{aligned} \tag{4}$$

Where K is:

$$K = \frac{|F_i|\left(\cos\varphi - \dfrac{\sin\varphi}{\tan\beta}\right)}{|F_e|} \tag{5}$$

It is a system of nonlinear equations, the solution to which requires iterative methods.

Fig. 3 shows the circuit to be implemented in Simulink, composed of those elements shown in Table 1. This model can be downloaded from https://es.mathworks.com/matlabcentral/fileexchange/74125-synchronous-generator .

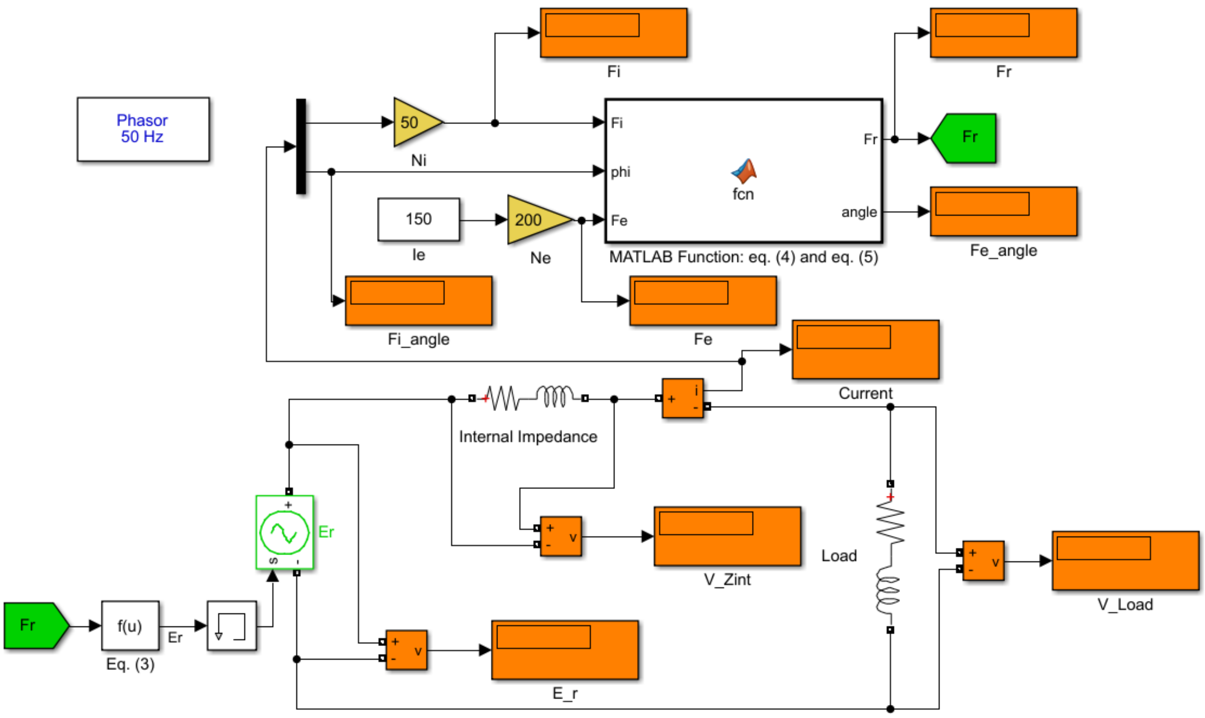

Figure 3. Simulink model.

Table 1. Characteristics of the elements that make up the model.

#	Description	Name	Library	Values/Configuration
1	Internal impedance	Series RLC Branch	SimPowerSystem/Elements	R = 0.07 Ω L = 0.0022282 H
1	Load impedance	Series RLC Branch	SimPowerSystem/Elements	R = 12 Ω L = 0.03 H
1	Resulting *Emf*	Controlled Voltage Source	SimPowerSystem/Electrical Sources	Type: AC Initial Amplitude: 0 Initial phase: 0 Initial frequ.: 50 Hz
1	Inductor turns	Gain	Simulink/Maths Operations	200
1	Armature turns	Gain	Simulink/Maths Operations	50
1	SPS Block	Powergui	SimPowerSystem	Phasor; 50 Hz
1	Relationship between E_r and F_r	Fcn	Simulink/User-Defined functions	Equation (3)
1	Solve equations (4) and (5)	Embedded MATLAB function	Simulink/User-Defined functions	See appendix
1	Separate module and angle of I	Demux	Simulink/Signal Routing	2 outputs
1	Excitation current	Constant	Simulink/Sources	Variable value
9	Show variables	Display	Simulink/Sinks	long
2	Sending signals	Goto	Simulink/Signal Routing	Variable names
2	Receiving signals	From	Simulink/Signal Routing	Variable names

2	Voltmeter	Voltage measurement	SimPowerSystem/Measurements	Magnitude-angle
1	Ammeter	Current measurement	SimPowerSystem/Measurements	Magnitude-angle

3.2.Simulation

Having assembled the model, the students then performed the simulation and answered the following questions:

1. What excitation current produces the rated voltage? Justify the answer.
2. Check that equations (1) and (2) are met.
3. If the load is disconnected under the above excitation conditions, what voltage appears on the terminals? What excitation current would correspond to the nominal voltage at no-load terminals? If, in this last situation the load is reconnected, what voltage appears in the terminals?
4. Obtain and draw the vacuum curve, varying the excitation from zero to a level that produces 125% of the rated voltage.

Note: Support all the answers with substantiated comments.

3.3.Implementation and evaluation

The effectiveness of the proposed teaching methodology was tested by means of the following controlled experiment.

The hypothesis of this work is “complementing the traditional approach to teaching synchronous machines courses (based on theory lessons and practical laboratory sessions), with computer simulations improves conceptual understanding and, consequently, success rates”.

In order to conduct a controlled experiment, the students were separated into two groups, control and experimental, and their responses compared. The first group, comprised of 56 students, followed the traditional teaching methodology, without the complementary computer assisted simulations, while the second, comprised of 58 students, followed the proposed methodology. The experimental group participants were recruited voluntarily and received no reward for their participation. However, participation was encouraged during a presentation showcasing the new software and students were advised that it would aid them in the learning process. This way of recruiting process is common in this kind of study (Campbell et al. 2002; Pisazo et al. 2009; Tortoreli et al. 2017).

Evaluation was twofold; as well as the final course results, both groups were asked to complete a comprehensive task consisting of a list of questions related to the conceptual understanding of synchronous machines.

It must be highlighted that the experimental group took 9 additional teaching hours to complete the simulation tasks equating to a 15% increase in class time. However, in order to ensure both groups received the same total number of class hours, theory classes and problems were reduced proportionally (15%) for the experimental group.

3.4.Measurement of knowledge

Upon completion of the course, both the control and experimental groups took the same end of course exam, the results of which were used to evaluate the effectiveness of the proposed methodology.

The results were analysed through a contrast of means from the statistical distribution of the results of each group. Since both groups were big enough (N > 30), the following indicators were used.

A z-test was used to check the significance of the results:

$$z = \frac{\left|\mu_{eg} - \mu_{cg}\right|}{\sqrt{\frac{\sigma_{eg}^{2}}{N_{eg}} - \frac{\sigma_{cg}^{2}}{N_{cg}}}} \tag{6}$$

Where:

μ_{eg}, μ_{cg} are the means of the distribution of the results for the experimental and control groups, respectively.

σ_{eg}^2, σ_{cg}^2 are the standard deviation of the distribution of the results for the experimental and control groups, respectively.

N_{eg}, N_{cg} are the number of participants of the experimental and control groups, respectively.

The test was interpreted by contrasting the results with a standard normal distribution, N(0,1). The commonly considered confidence intervals are shown in Table 2.

Table 2. Confidence intervals for a standard normal distribution.

$z >$	1.96	2.57	3.30
$p <$	0.05	0.01	0.001

Thus, it can be concluded that the experimental group presents a significant change with regard to the control group when *z* is higher than a specified value (Table 2), with a probability (*p*) of the difference between both groups being random, lower than the corresponding value.

The effect size was evaluated using Cohen's *d* (J. Cohen, 1988), the value of which is calculated as:

$$d = \frac{\left|\mu_{eg} - \mu_{cg}\right|}{\sqrt{\dfrac{N_{eg}\sigma_{eg}^2 + N_{cg}\sigma_{cg}^2}{N_{eg} + N_{cg}}}} \tag{7}$$

3.5.Posttest

Both the experimental and control groups were evaluated using the same test to avoid interference with the results. This test, comprised of 15 tasks in total, was split into two parts: theory questions, and problems. In the former, the students had to answer 10 questions related to the conceptual understanding of the synchronous machine, while in the latter, the students had to use equations to solve 5 problems and show their ability to numerically predict the behavior of the synchronous machine under different conditions.

3.6.Results

Table 3 shows the results of each part and the global results for both groups.

Table 3. Test results for the experimental and control groups.

	Control group ($N_{cg} = 56$)				Experimental group ($N_{eg} = 58$)			
	μ	σ	*Min*	*Máx.*	μ	σ	*Min*	*Máx.*
Teoretical (máx. 10)	5.768	1.716	2	8	7.190	1.721	2	10
Problems (máx. 5)	2.411	1.156	0	4	3.034	1.284	0	5
Total (máx. 15)	8.179	2.321	2	12	10.224	2.676	4	15

The results of the theory section show that $z = 4.416$, $p < 0.001$, meaning that the null hypothesis can be rejected and a significant contrast between the two groups can be recognised. The effect size is $d = 0.827$, showing a sizeable difference between the groups.

The results of the problems section show that $z = 2.728$, $p < 0.01$, likewise meaning that the null hypothesis can be rejected and a significant contrast between the two groups can be observed. The effect size in this case is $d = 0.51$, showing a moderate difference between the groups.

The overall results show that $z = 4.365$, $p < 0.001$, meaning that the null hypothesis can be rejected again and a significant contrast between the two groups can be recognised. The effect size in this case is $d = 0.816$, showing a considerable difference between the groups.

The results show that the proposed methodology, using simulations to complement the traditional teaching methods, improves the understanding of synchronous machines. The improvement was more pronounced in the understanding of theory than in the solving of problems, where the improvement was moderate.

4. Discussion and conclusions

The effectiveness of the proposed teaching methodology was tested by means of a controlled experiment comparing two groups of energy engineering students studying the same synchronous machines course; one following the traditional teaching paradigm, and the other, the proposed methodology. In the control group, theoretical instruction was complemented by practical laboratory sessions, as per the traditional approach, while in the experimental group, traditional instruction was complemented by practical sessions based on computer simulations.

This innovative software-based teaching methodology with an improved interface proposes the inclusion of examples and real-world applications, facilitating the understanding of how synchronous machines are affected by changes to input parameters. Virtual scenarios are created in Matlab/Simulink that emulate real world scenarios and provide a visual aid, showing the evolution of the main variables. This tool is used in concert with an interactive methodology that promotes discussion and the sharing of ideas between student and educator. In addition, the proposed methodology has proven easy to develop and implement without requiring deep curricular changes or financial support. Furthermore, it requires no additional credits or material/spatial resources and favors feedback and interaction.

The use of modern educational tools, such as simulation software, increased interest in the course and improved academic results. In addition, survey results showed that the students had a highly positive view of this course and indicated an interest in the use of simulation tools.

The course allowed the students to acquire advanced knowledge and skills that will be beneficial to them throughout their professional careers. The proposed methodology had a positive influence on student satisfaction, participation and initiative, and improved perception of the basic concepts of synchronous machines. Specifically, this study demonstrates that electrical engineering undergraduates can be effectively educated on the electrical behavior of power plant generators as part of their degree.

Both the control and experimental groups were evaluated using the same test, incorporating both theory and problem solving elements. A contrast of means was conducted, in order to establish whether the results of the experimental group showed an improvement over those of the control group.

The posttest results showed that the participants of the experimental group outperformed those of the control group in all three of the dimensions under analysis: theory, problems and total. In the theory and total tests this difference was highly significant, while in the problems test the difference was moderate. Although the results indicate the experimental group gained a better conceptual understanding than the control group, action could be taken to increase the significance in the problems test. For example, simulations could be performed on previously solved problems in class, and vice versa.

Appendix

This section includes the code used to solve equations (4) and (5), inserted in the block “Embedded MATLAB function” of Fig. 3.Also, see Table 1.

```
function [Fr,angle] = fcn(Fi,phi,Fe)
 angle=0;
 k=(Fi*(cosd(phi)-sind(phi)/tand(89.99)))/Fe;
 ep=1e-3;
step=0.01;
 if 0<=k&&k<=1
    for n=0:step:360
       if abs(sind(n)/tand(89.99)-cosd(n)-k)<=ep
           angle=n;
           break
       end
    end
```

```
else
 cont=0;
y=zeros(360/step+1,2);
   for n=0:step:360
       cont=1+cont;
       y(cont,1)=abs(sind(n)/tand(89.99)-cosd(n)-k);
       y(cont,2)=n;
   end
       [M,u]=min(y(:,1));
       angle=y(u,2);
end
 Fr=(Fe*sind(angle)+Fi*sind(phi))/sind(90);
```

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