

Simulation of Synchronous Generator on MATLAB-SIMULINK for Teaching Performance Characteristics to Undergraduate Students*

B. VAHIDI, M. R. BANK TAVAKOLI

Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran. E-mail: vahidi@aut.ac.ir

For accurate knowledge of a synchronous generator characteristic it is essential to have an idea of its operation conditions. This paper presents an approach for teaching electric machines used in the laboratory specially designed exercises that can be done with MATLAB-SIMULINK. This MATLAB-SIMULINK-based technology will simulate a synchronous generator in order to determine its performance characteristics. By using a prepared simulator, four groups of students have been tested via designed question sheets to determine the effectiveness of the method for teaching the synchronous generator performance concept. This evaluation is very positive in terms of students' developing confidence and their better understanding of the tests and theoretical concepts.

Keywords: MATLAB-SIMULINK, synchronous generator, power factor, load.

INTRODUCTION

COMPUTER SIMULATION plays an important role in engineering course teaching. Nowadays, a variety of software tools are available to simulate electrical circuits; one of them is MATLAB. Many simulations of different aspects of a power system and engineering application using MATLAB have been presented by different researchers [1–7]. Some researchers used different methods for instruction in electrical machines [8–10].

A synchronous generator, being a vital piece of equipment in an electric system, requires critical attention from the standpoint of its performance under steady state operation; therefore, it is highly desirable to observe the behavior of a synchronous generator during operation [11–13].

Performing such tests is the responsibility of power system engineers; students of power system engineering should therefore be familiar with testing synchronous generators and other electric machines. Electrical machinery courses at undergraduate level typically comprise four theoretical classroom courses:

- 1) Electrical machine I (dc machines)
- 2) Electrical machine II (transformers + induction machines)
- 3) Electrical machine III (synchronous machines)
- 4) Special machines.

And three laboratory courses:

- 1) DC machines laboratory
- 2) AC machines laboratory
- 3) Special machines laboratory.

Students take theoretical courses on each electric machine module in over 15 weeks (three hours per week) plus 10 weeks (three hours per week) of laboratory work for each laboratory module. In each laboratory section with three effective hours per week, students are required to set up and perform a test. In practice, it is not possible to understand the engineering concepts of electrical machinery by taking only theoretical courses and a laboratory course for electrical machinery should be designed. For this, we will need laboratory test machines, and special safety regulations. Even so, it is not possible to test everything (such as very high field currents) because there are risks of damage to machines. With this in mind, the testing bands for students are limited. We designed a simulator in a virtual library format for testing synchronous generator performance in computers. This teaching method was tested on four groups of students by use of special test sheets and questions. It revealed that using the simulator improved their level of understanding.

Electrical machine III

This module consists of a 15 weeks theoretical course. In this course three-phase transformer, synchronous motor and generator are taught. Due to the importance of a synchronous generator in a power system, 40 per cent of course time is spent on this component. The important perfor-

* Accepted 6 December 2008.

mance characteristics of synchronous generator are:

- output power—load angle (P - Δ) (δ)
- internal generated voltage—field current ($E - I_f$)
- terminal current—field current ($I_t - I_f$)
- power factor—field current ($\cos(\phi) - I_f$).

These subjects should be taught in a synchronous generator course [11–13]. According to authors' experience in the field of electrical machinery is that instructors have too little teaching time for this subject in the classroom or laboratory. They find that students generally have difficulty carrying out laboratory experiments and in understanding the theoretical course as well. Therefore, finding a new instruction method for this subject could help educators to be successful in their teaching.

Components of electric machines for laboratory use are expensive; therefore, computer simulation can be an efficient tool for teaching when the budget is limited, or to serve as useful preparatory exercises before students come to the laboratory. Also, in many cases, performing or viewing actual tests on a large machine in the rating of power plant generators is not possible for undergraduate students, so simulation is a better alternative.

The authors of this paper have used MATLAB-SIMULINK as an instructional tool to teach testing method of synchronous generators to undergraduate students at electrical machine III course. This method of instruction has enabled students to understand the techniques of these tests. The success rate of students in understanding the tests shows the ability of this method.

Of course there are some differences between the hardware setup and the MATLAB-SIMULINK model; i.e. per-phase-based power is measured in the simulation model, while in the experiment the total three-phase value is measured. However, this difference is not significant since under the three-phase balanced operation; computations are usually completed using the per-phase quantities.

SYNCHRONOUS GENERATOR

A synchronous generator is a synchronous machine used as a generator. It converts mechanical power to three-phase electric power. The source of mechanical power, the prime mover, may be a diesel engine, a steam turbine, a water turbine, or any similar devices. Whatever the source is, it must have the basic property that its speed is almost constant regardless of the power demand. If this were not so, then the resulting power system's frequency would wander [11, 12]. Not all the mechanical power going into a synchronous generator becomes electric power out of the machine. The difference between output power and input power represents the losses of the machine.

It is worth noting here that synchronous generators are classified in two types. The first is the low

speed (engine or water driven) type, which is characterized physically by having salient poles, a large diameter and small axial length. The second is the turbo generator, which uses the steam turbine as the prime mover.

In a single phase representation, if the armature resistance is ignored (since $X \gg R$) a very useful equation can be derived to approximate the output power of generator [11, 12].

$$P = \frac{V_t E \sin \delta}{X} \quad (1)$$

$$\delta = \sin^{-1} \left(\frac{P X}{V_t E} \right) \quad (2)$$

From phasor diagram of generator (Fig. 1) the following equations can be obtained [11, 12].

$$\tan(\varphi) = \frac{\sqrt{V_t^2 E^2 - P^2 X^2} - P R - V_t^2}{P X + \frac{R}{X} \sqrt{V_t^2 E^2 - P^2 X^2}} \quad (3)$$

$$I_t = \frac{P}{V_t \cos(\varphi)} = \frac{P}{V_t} \sqrt{1 + \tan^2(\varphi)} \quad (4)$$

From mathematics:

$$\cos(\varphi) = \frac{1}{\sqrt{1 + \tan^2(\varphi)}} \quad (5)$$

SOFTWARE ORGANIZATION

The MATLAB base software is prepared by authors to evaluate the synchronous generator performance.

Before starting any simulation, it is important for students to know the theoretical aspects of a synchronous generator. A brief description of software in one session is also required to get them involved before the simulations start. The following are required for students to do before the simulations:

- 1) They should be able to describe the concept of generator performance in general.
- 2) They should be able to use SIMULINK modules in graphical interfaces to handle the available simulator.

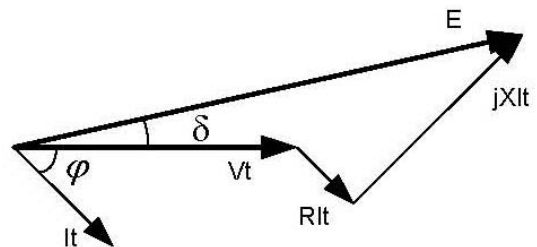


Fig. 1. Phasor diagram of generator.

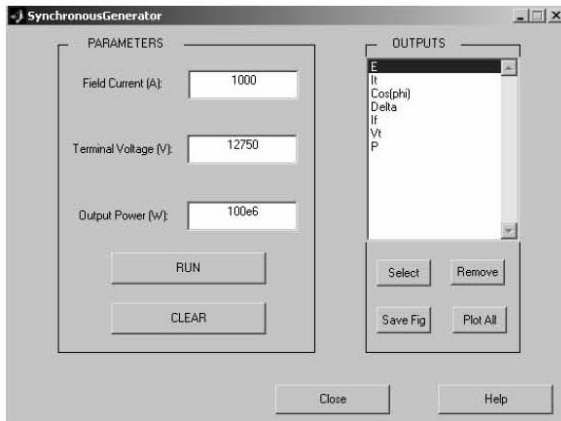


Fig. 2. GUI configuration.

- 3) Students are also required to be familiar with data handling and output/input facilities in MATLAB software.
- 4) To fulfill the above items, some sessions about software and data handling may be required based on the feedbacks of present knowledge of pupils.

Graphical user interface

A graphical user interface (GUI) is a user interface built with graphical objects and components of the GUI such as buttons, text files, sliders and menus. By providing an interface between the user and the application's underlying code, GUIs enable the user to operate the application without knowing the commands which would be required by a command line interface. For this reason, applications that provide GUIs are easier to learn and use than those that are run from the command line. The MATLAB graphical user interface development environment provides a set of tools for creating GUIs. These tools greatly simplify the process of laying out and programming a GUI [14]. Figure 2 shows the GUI for the present job. By running the software for several cases and saving the graph (**Save Fig**), the **Plot All** key will be active and can plot several graphs in one page.

Interface parameters can be changed from a GUI window. After running a case with desired points, to start a new one, variables can be cleared using the **Clear** button.

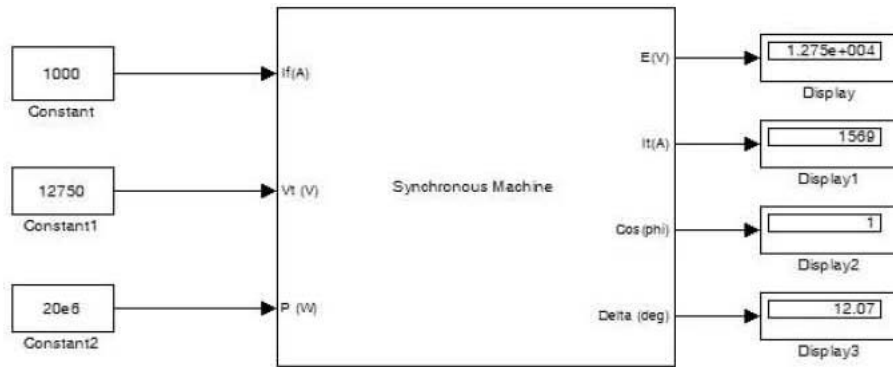


Fig. 3. Block diagram representation of synchronous machine.

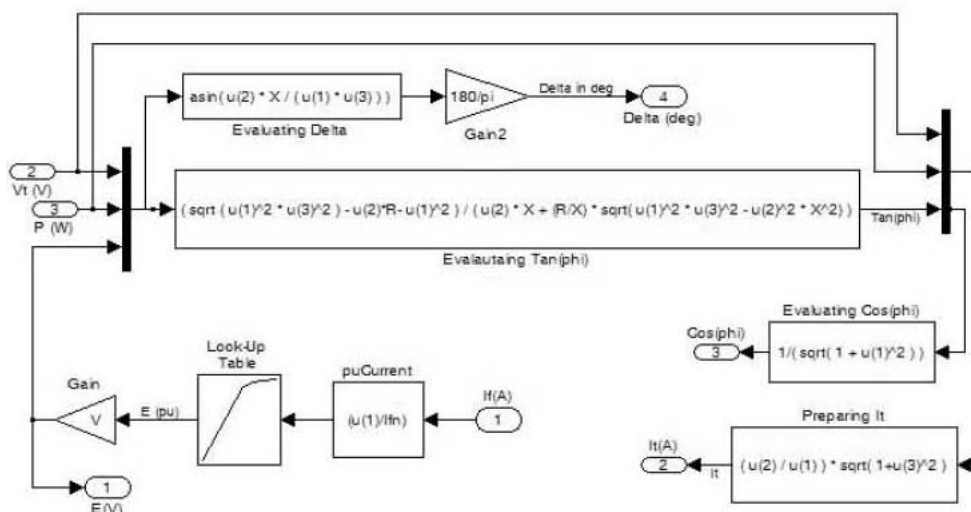


Fig. 4. Simulated block diagram of synchronous machine.

SIMULATION

Simulated circuit

The circuit that is simulated on MATLAB-SMULINK is shown in Figure 3 and Figure 4 [14].

Generator parameters

Generator parameters are set out in the menu in Figure 5.

Obtaining results

To obtain results:

- 1) Parameters of generator should be chosen (Figure 5).
- 2) Also choose parameters on GUI (Figure 2).
- 3) Press **RUN** key (Figure 2).
- 4) On GUI the following outputs will appear (Figure 2).
 - E
 - I_t
 - $\cos(\phi)$
 - Delta
 - If
 - V_t
 - P
- 5) Change desired parameters and press **RUN** again to create next point and follow this procedure until enough points being generated.

By choosing one of above outputs, which is available in right-hand sub-window, and pressing the **Select** button, the x-axes variable will be set and

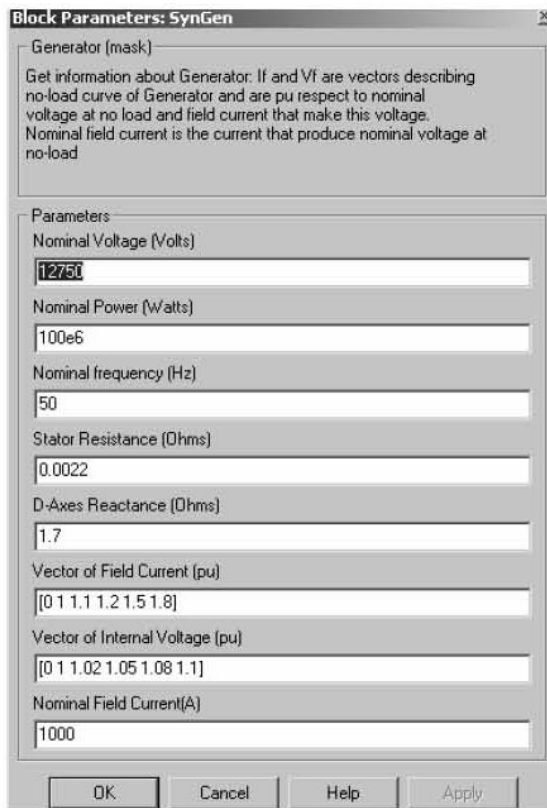


Fig. 5. Menu for choosing the generator parameters.

the **Plot** button will appear. By selecting the y-axes variable from the sub-window and clicking **Plot**, a graph will be drawn (e.g. E – If).

RESULTS AND STUDENT FEEDBACKS

The E – If is shown in Figure 6.

The figures can be shown in MATLAB or be exported from MATLAB figure windows in any other format (e.g. bmp) and be inserted in other documents to prepare report. Output power versus delta (δ) for different terminal voltages are shown in Figure 7.

Terminal current (I_t) versus field current (I_f) for different output powers are shown in Figure 8.

Power factor ($\cos(\phi)$) versus field current (I_f) for different output power are shown in Figure 9.

Some performance characteristics of a synchronous generator such as V curves are shown through simulation and the results are helpful for discussing performance characteristics.

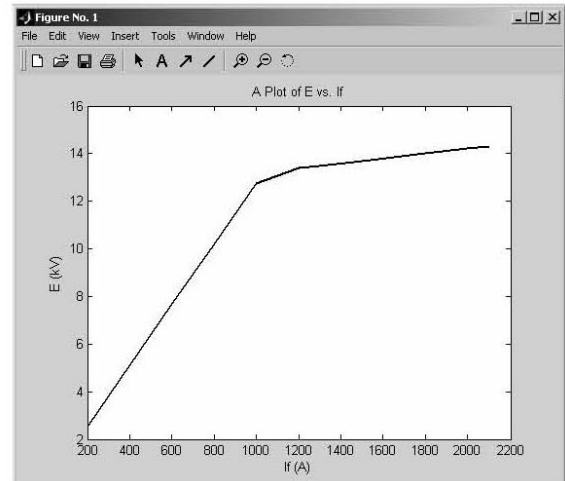


Fig. 6. E versus If.

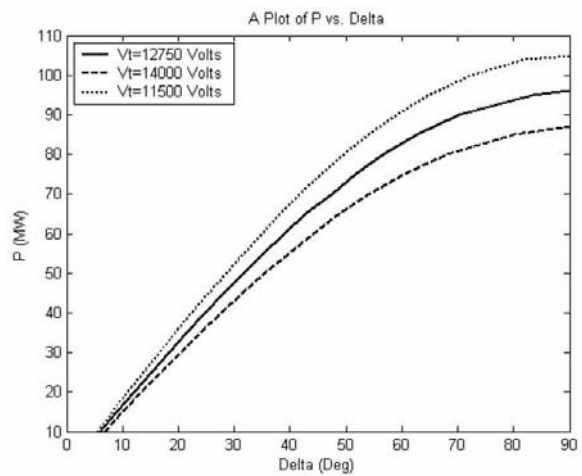


Fig. 7. Output power versus delta (δ) for different terminal voltages.

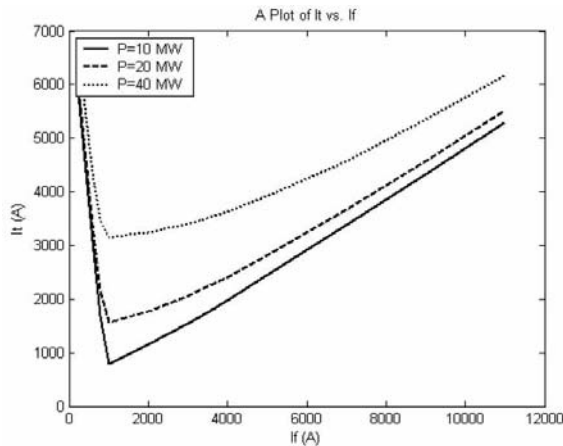


Fig. 8. It versus If for different output power.

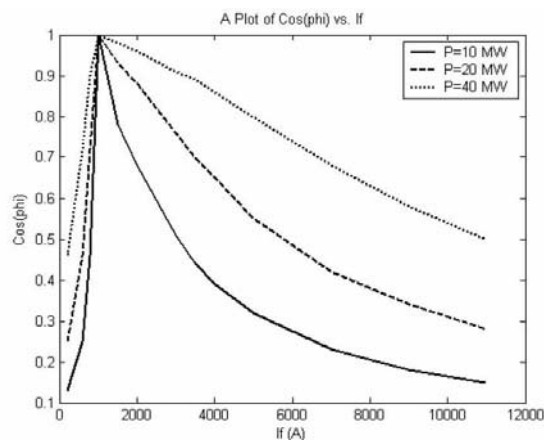


Fig. 9. Cos (phi) versus If for different output power.

Assessment of learning outcomes refers to specific processes through which learners demonstrate their attainment.

During a course, the instructor requires learners to demonstrate that they have attained the learning outcomes. To assess the depth of learning about synchronous generator performance, we prepared a question sheet. Students are required to answer the questions after the theoretical sessions and before using the simulator. The same questions are asked of students after each try on the simulator. Note that working with simulator is taught first and questions are based only on the synchronous generator itself. A student is said to understand the concept, if he or she answers all the questions correctly.

The following questions are used for testing students whether they understood all the concepts or not:

- 1) If the output power (P) is to be fixed, how does increasing the field current affect the output power factor?
- 2) An operator of a synchronous generator suddenly sheds some load by mistake. If the load characteristics force the generator to operate with constant power factor, how will the generator field current change?

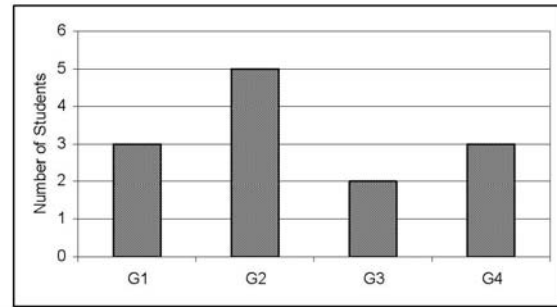


Fig. 10. Number of students who understood the concept before using the simulator.

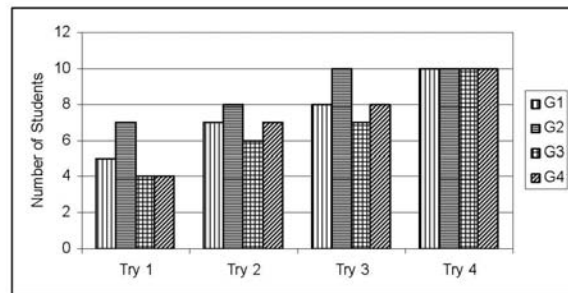


Fig. 11. Number of students who understood the concept in four successive tries on the simulator.

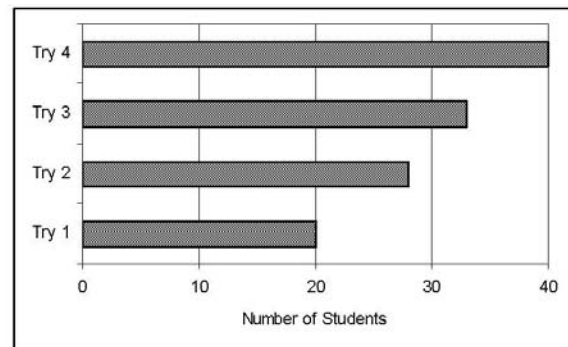


Fig. 12. Understanding of all students.

- 3) How will the generator terminal current change if the field current increases and output power (P) remains constant?
- 4) Because of cooling, a synchronous generator is assigned to work at minimum terminal current. If the output power (P) increases, how should the field current be adjusted for safe operation?
- 5) If the load angle of a generator increases, how will its output power change?
- 6) During a short circuit in the supply which is connected to the synchronous generator, the generator terminal voltage drops. However, the output power is assumed to remain constant. How will the load angle of the generator change?

The test is performed on four groups (i.e. G1, G2, G3 and G4) of students (10 students per group). Before using the simulator, the understanding rate

of students is shown in Figure 10. As can be seen from this chart, the learning rate in all four groups is low (13 students out of 40). However, after the first try, the rate of understanding increases.

Figure 11 shows the understanding rate of each group of students in four successive tries. The final results are shown for the cumulative understanding rate of students during four tries in Figure 12. After four tries, all the students have understood the concepts by using the simulator utilities. During each try, the students may focus on the questions that they have not answered properly. In a different test, with different learners, it may take more than four tries for educators to teach the subject to all the learners.

DISCUSSION

Pedagogical instruction objections

There are three major instructional objectives in the present plan of learning:

- 1) Utilize user-friendly simulator software to teach tedious theoretical and relatively complicated aspects of synchronous generator to students who are encouraged to use the software as a virtual instrument instead of theoretical books.
- 2) Prepare a self-pacing laboratory course for students and evaluate its effectiveness in teaching the subject.
- 3) Make sure that near-perfect performance is achieved in learning the key aspects of synchronous generator behaviour by students using the simulator for self-learning.

Even if these objectives are attained, difficulties can still be encountered, particularly in planning first use of the simulator. As a result of different levels of student ability, not all of them understood all the matter. These showed when they next worked with the software. To overcome this, students worked with the simulator themselves before the session started. When the students were grouped, another session with these groups working on the simulators made all the students reach the desired level for starting the plan.

The instructor and students should have enough knowledge of MATLAB-SIMULINK and the instructor should use theoretical aspects of the subject in order to explain the simulation ([11–13] are helpful).

In our plan, students could see the behavior of the synchronous generator on PC monitors in the classroom. In addition, by using video projectors, instructors could display the performance of the synchronous generator during teaching and ask the students to do the same on their own computers.

From the authors' point of view this can help students to understand the subject better than only listening to their instructors.

Teaching and learning aspects of the simulator

In short, a virtual electrical machines laboratory on synchronous generators can be implemented because it is cheap and does not need special regulations and safety rules for students and instructors. Based on the authors' experience, the combination of traditional teaching methods and using the simulator is the best and most effective method in teaching. During work with the simulator the sense can be induced in students that they are in charge, operator of a machine that will show them the behavior of the generator in user-friendly graphics instead of working solely by complicated equations. By this method they can understand better the relationship between characteristic parameters such as output power and δ (see Figure 7) and output and field current (see Figure 8).

The simulator's uniqueness: aspects in the teaching process

The simulator considerably reduces the time and cost needed to teach the performance characteristics of synchronous generators; therefore, it is very useful for educational purposes where budgets are limited. What makes this simulator unique is that it can be used in distance learning and a virtual library. The focus is placed on studying the relations between characteristics parameters which can be observed in the laboratory, i.e. terminal voltage, current, output power, torque, velocity, etc.

Empirical data on assessment of the simulator

The process of testing the students' understanding of the performance of synchronous generators process is covered in successive semesters with different groups of students. The results reveal the effectiveness of using such simple simulators to achieve considerable improvements in the learning process.

Comparison with the Keller plan

As a useful final discussion, it is interesting to compare the method which was used in this paper with the Keller plan, a personalized system of instructions (PSI) teaching method which is proved to have significant effect in science education [15]:

- 1) Students using the simulator work individually with the software; they are intended to work on it until they master the instructions and answer the questions in the test sheets correctly. There are also short sessions for preparing the students to work with the simulator. Hence, this plan is an individually paced, mastery-oriented course which includes only a few lectures as compared to the basic features of Keller plan.
- 2) In Keller, the printed study guides are the main means of communicating information, compared with the virtual environment of the simulator playing the same role.

3) With us, no undergraduate tutors are assigned and all individuals are tested directly in different steps by instructors. Support is provided by the user-friendly design of the simulator which stimulates the interest of students and encourages them to play with and learn.

CONCLUSION

We have outlined and illustrated a MATLAB-SIMULINK model to simulate a synchronous generator. The method considerably reduces the time and cost needed to teach its performance characteristics. It is a very useful educational tool where budgets are limited, or to serve as useful

preparatory exercises before students come into the laboratory.

Evaluation of the project involving more than 40 students confirm its benefits.

SYMBOLS

P = Output power
 E = Internal generated voltage
 V_t = Terminal voltage
 Delta (δ) = Load angle
 X = Synchronous reactance
 R = Armature resistance
 cos(φ) = cos(phi) = Power factor
 I_t = Output current
 I_f = Field current

REFERENCES

1. J. O. Attia, *Teaching ac circuit analysis with MATLAB*. 1995 Frontiers in Education Conference, Atlanta, USA, 2c6.9-2c6.12 (1995).
2. A. Azemi and Ch. Stook, *Utilizing MATLAB in undergraduate electric circuits courses*, Proceedings of FIE'96. PA, USA, (1996) pp. 599–602.
3. J. Tan, *Real-time dc motor control using the MATLAB interfaced TMS320C31 digital signal processing starter kit (DSK)*. IEEE 1999 International Conference on Power Electronics and Drive systems, PEDS'99, Hong Kong, (1999), pp. 321–326.
4. S. I. Ivanov, A. Canpeanu, A. Bitoleanu and M. Popescu, *MATLAB-SIMULINK library for ac drives simulation*. International Conference on Simulation, IEE publication No. 457, (1998), pp. 195–200.
5. S. S. Murthy and S. Acharya, *MATLAB based steady state analysis of self excited induction generator*. PEDS 2003, New Delhi, India, (2003), pp. 749–753.
6. S. Ayasun and C. O. Nwankpa, *Induction motor tests using MATLAB/Simulink and their integration into undergraduate electric machinery courses*. *IEEE Trans. Educ.*, **48**, 2005, pp. 37–46.
7. M. Hashem, F. Fatehi and V. Gerez, *Computer modeling for enhancing instruction of electric machinery*. *IEEE Trans. Educ.*, **38**, 1995, pp. 166–170.
8. T. F. Chan, *Analysis of electrical machines using Symphony*. *IEEE Trans. Educ.*, **35**, 1992, pp. 76–82.
9. A. Toumi, *An aid for teaching doubly fed synchronous machines based on the circle diagram*. *IEEE Trans. Educ.*, **45**, 2002, pp. 171–176.
10. F. S. Selkischopp and M. A. Arjona L., *An automated system for frequency response analysis with application to an undergraduate laboratory of electrical machines*. *IEEE Trans. Educ.*, **47**, 2004, pp. 57–64.
11. A. E. Fitzgerald, C. Kingsley and S. D. Umans, *Electric machinery*, 5th ed., McGraw-Hill, New York, (2000) pp. 245–305.
12. S. J. Chapman, *Electric Machinery Fundamentals*, 1st Edition, McGraw-Hill, New York, (2003) pp. 267–345.
13. S. S. Murthy, B. P. Singh, C. S. Jha and D. P. Kothari, *Laboratory manual for electromechanics*, Wiley Eastern, New Delhi, (1982), pp. 143–160.
14. MATLAB Manual, Version 6.5, Mathworks, Inc.
15. J. A. Kulik, C. L. Kulik and K. Carmichael, *The Keller plan in science teaching*, *Science*, **183**, 1974, pp. 379–383.

Professor **Behrooz Vahidi** received the B.S. in electrical engineering from Sharif University of Technology, Tehran, Iran in 1980 and M.S. degree in electrical engineering from Amirkabir University of Technology, Tehran, Iran in 1989. He also received his Ph.D. in electrical engineering from UMIST, Manchester, UK in 1997. From 1980 to 1986 he worked on high voltage in industry as chief engineer. From 1989 to present he has been with the department of electrical engineering of Amirkabir University of Technology where he is now an associate professor. He is a senior member of IEEE. His main fields of research are high voltage, electrical insulation, power system transient, lightning protection and pulse power technology. He has authored and co-authored five books and more than 120 papers on high voltage engineering and power system.

Mohammad Reza Bank Tavakoli received the B.S. in electrical engineering from Tehran University, Tehran, Iran, in 2003 and M.S. degree in electrical engineering from Amirkabir University of Technology, in 2005. Currently, he is a Ph.D. student at the department of electrical engineering of Amirkabir University of Technology. His main fields of research are power system dynamics and power system component modeling and simulation. He is also with the IGMC Company, working on extensive analysis of Iranian power system.