

Transformer Tests Using MATLAB/Simulink and Their Integration Into Undergraduate Electric Machinery Courses

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ABSTRACT: This article describes MATLAB/Simulink realization of open-circuit and short-circuit tests of transformers that are performed to identify equivalent circuit parameters. These simulation models are developed to support and enhance electric machinery education at the undergraduate level. The proposed tests have been successfully integrated into electric machinery courses at Drexel University, Philadelphia, PA and Nigde University, Nigde, Turkey. © 2006 Wiley Periodicals, Inc. *Comput Appl Eng Educ* 14: 142–150, 2006; Published online in Wiley InterScience (www.interscience.wiley.com); DOI 10.1002/cae.20077

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INTRODUCTION

Electrical machinery courses at the undergraduate level typically consist of classroom and laboratory sections. The classroom section generally covers the steady-state operation of transformers in which the per-phase equivalent circuit is used to compute

various quantities such as losses, efficiency, and voltage regulation. The laboratory section includes open-circuit, short-circuit tests conducted to determine no-load losses and equivalent circuit parameters, and load test to study transformer performance under various loading conditions.

The Electrical and Computer Engineering (ECE) Department of Drexel University offers a pre-junior level machine course (ECE-P 352 Electric Motor Control Principles) that concentrates on the fundamentals of electromechanical energy conversion and related control theory. This 5-h course, required for

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those who are in the power and control track, has both lecture (3 h) and laboratory (2 h) sections that must be taken in the same quarter. Similarly, the Department of Electrical and Electronics Engineering at Nigde University offers a 5-h (3-h lecture and 2-h laboratory sections) junior-level machinery course, EEM 308 Electric Machinery, which mainly focuses on transformers and induction motors. The authors' experience while teaching electric machinery and transformers at Drexel and Nigde Universities indicates that students generally have difficulty when they come to the laboratory to carry out transformer experiments even though the corresponding theory is extensively covered in the classroom section with a detailed hand-out describing laboratory facilities and the procedure of the experiments, given to them at least a week before the laboratory. Students are not familiar with such a laboratory environment that contains large machines, transformers; and relatively complex measurement methods, and devices as compared with other laboratories they have been to before. The time constraints during the laboratory exercise are also a difficult adjustment. In a usual 2-h laboratory section, students are required to set up and perform three transformer experiments, to take the necessary measurements, and to investigate steady-state performance of the transformer under various loading conditions. Because of the time limitations, students often rush through the experiments in order to finish them on time, which unfortunately prevents them from getting a true feeling of transformer operation and from appreciating what has been accomplished during the laboratory practice.

In order to prepare students for physical experiments and to give them insight into the experimental procedure, a software laboratory is designed and developed. It includes simulation models of transformer, induction motor, and DC motor experiments. This article presents simulation models of open and short-circuit tests of transformers as a part of the software laboratory. The simulation models are developed as stand-alone applications using MATLAB/Simulink [1] and SimPowerSystems toolbox [2]. As will be discussed later in this article, for the load experiment, students are required to write a computer program using MATLAB's M-file programming for the equivalent circuit to compute operating quantities or to modify Simulink model of the no-load test by adding a load for simulating load test. This assignment improves students' programming skills that would be helpful in other classes as well.

Such an approach to enhance the instruction of transformers and induction machines has been suggested and employed by various educators [3–7].

Various software tools such as MATLAB and MathCad have been used to model the steady-state or transient operation of transformers [5] and induction motors [6,7], which mainly improves the classroom lectures. The authors' approach [8] differs from those in the way that the computational laboratory as a part of laboratory experiments provides students with simulation models of physical experiments to be conducted in an actual laboratory environment. The proposed simulation models developed by using Simulink/SimPowerSystem toolbox enhances laboratory experience by providing students with the opportunity to verify results of laboratory experiments and compare them with those obtained by computer simulations. Such a comparison opportunity helps students realize the limitations of hardware experiments and, as a counterpoint, appreciate that computer simulations cannot substitute for actual hardware experiments as they might not exactly represent the operation of transformers because of some modeling assumptions. Moreover, an undergraduate electric machinery course that integrates up-to-date computer hardware and software tools in both lecture and laboratory sections also meets the expectations of today's students who want to use computers and simulation tools in every aspect of a course, and thus, possibly attracts more students.

The remainder of the article is organized as follows: Section II describes simulation models of no-load and short-circuit tests together with necessary theory. Section III compares the equivalent circuit parameters determined using simulation data with those obtained from experimental data. Section IV explains how these simulation models are integrated into undergraduate electric machinery courses at authors' institutions, and Section V presents a survey designed to evaluate whether simulation models were helpful in understanding the transformer theory and experiments while the last section concludes the article.

TRANSFORMER TESTS: EXPERIMENTAL SETUPS AND SIMULINK MODELS

The steady-state operating characteristics of transformers are investigated using an equivalent circuit as shown in Figure 1 [9,10]. In this circuit, R_1 and X_{11} represent the primary winding resistance and leakage reactance; R_2 and X_{12} denote the secondary winding resistance and leakage reactance; R_C resistance stands for core losses, X_M represents magnetizing reactance; and a denotes the transformer turns ratio. The equivalent circuit is used to facilitate the computation

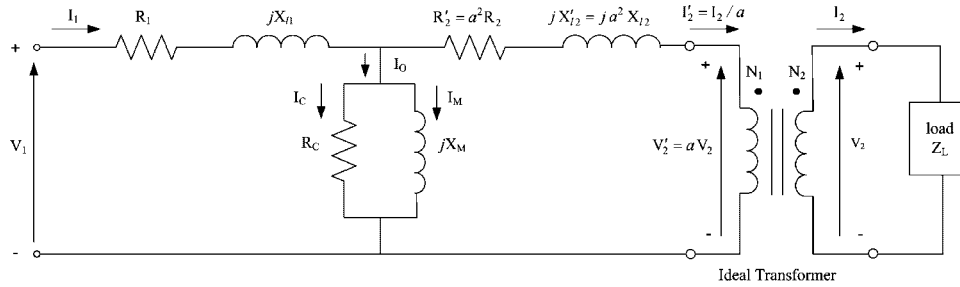


Figure 1 Equivalent circuit of a transformer referred to the primary side.

of various operating quantities such as losses, voltage regulation, and efficiency. The parameters of the equivalent circuit can be obtained from the open-circuit and short-circuit tests. In the following, the experimental setup and Simulink/SimPowerSystems model of each test are described.

The SimPowerSystems toolbox is a useful software package to develop simulation models for power system applications in the MATLAB/Simulink environment. With its graphical user interface and extensive library, it provides power engineers and researchers with a modern and interactive design tool to build simulation models rapidly and easily. MATLAB and Simulink/SimPowerSystems have been widely used by educators to enhance teaching of transient and steady-state characteristics of electric machines [5,7,11,12], modeling of power electronic converters [13], power system transient stability and control [14–16]. Other commercial software packages, such as Maple and MathCad, are commonly used in electrical engineering education with their advantages and disadvantages [17,18]. The reason that MATLAB with its toolboxes was selected is that it is the main software package used in almost all undergraduate courses in the authors' institutions as a computation tool to reinforce electrical engineering education. Therefore, students can easily access MATLAB, and they already have the basic programming skills to use the given Simulink models and to

write computer programs when required before coming to the machinery class.

Open-Circuit Test

The open-circuit test is performed in order to determine exciting branch parameters (i.e., R_C and X_M) of the equivalent circuit, the no-load loss, the no-load exciting current, and the no-load power factor. As shown in Figure 2, while one of the windings is open-circuited (in our case secondary winding is open-circuited), a rated voltage is applied to the other winding (in our case it is the primary winding), and the input voltage, V_{OC} ; input current, I_{OC} ; and input power, P_{OC} , to the transformer are measured.

Figure 3 shows the Simulink/SimPowerSystems realization of the open-circuit test. A single-phase transformer model whose equivalent circuit parameters could be specified using transformer dialog box is used. A single phase AC voltage source is applied to the primary side. Since in Simulink environment, all elements must be electrically connected, the secondary side of the transformer cannot be left open and a load has to be connected. In order to simulate no-load condition, constant impedance model to reflect loading is used, and the resistance and inductance values are set to very large numbers while the value of the capacitor is set to a very small number. The resulting secondary current will be approximately

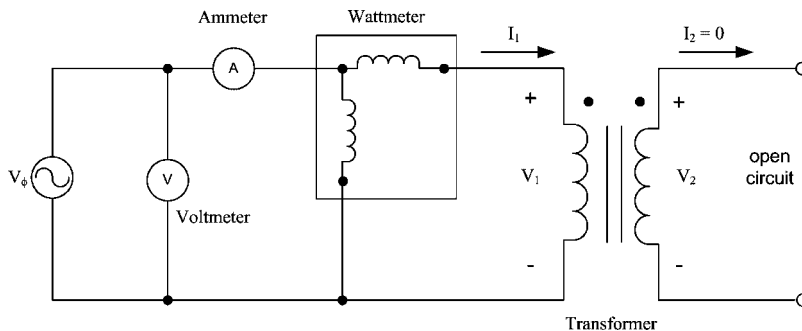


Figure 2 Experimental setup of the open-circuit test.

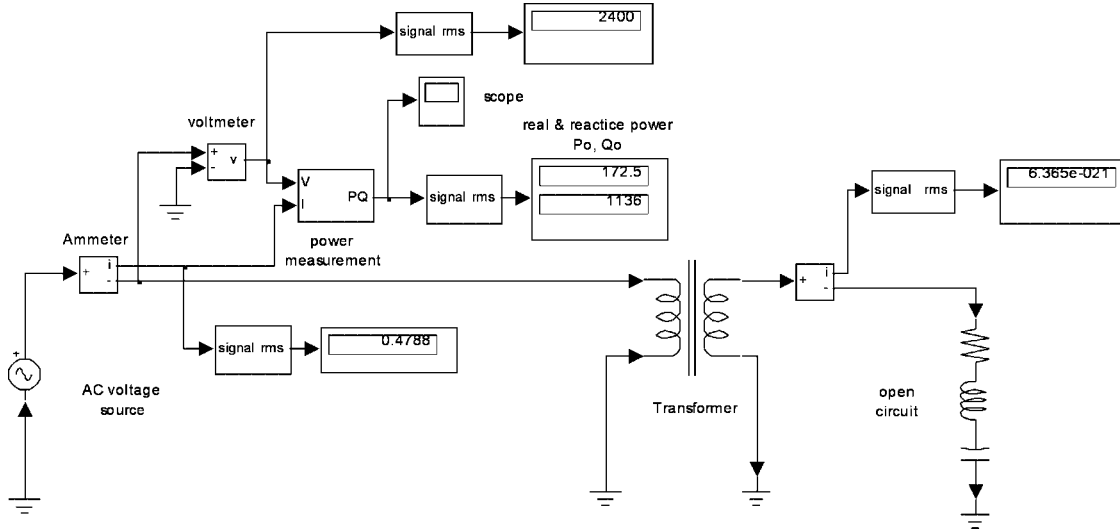


Figure 3 Simulink/SimPowerSystems implementation of the open-circuit test.

zero. On the primary side, current, and voltage measurement blocks are used to measure the instantaneous current and voltage. The output of each meter is connected to a root mean square (rms) block, *signal rms*, to determine the rms values of primary current and voltage. The rms block computes the rms value of its input signal over a running window of the one cycle of the fundamental frequency. The display boxes read these rms values of the open-circuit current, I_{OC} , and voltage, V_{OC} . The outputs of the current and voltage measurement blocks are connected to a power measurement block, *power measurement*, that measures the active power, P_{OC} , and reactive power, Q_{OC} , of the primary side. The output of this block is connected to a display box to read P_{OC} and Q_{OC} . In order to measure the secondary current, which is approximately zero, a current measurement block with an rms block and display is used.

These measurements either from experiment or from simulation enable the approximate computation of the resistance R_C and reactance X_M of the excitation branch referred to the primary side. The magnitude of the excitation admittance from the open-circuit voltage and current is computed as

$$|Y_E| = G_C - jB_M = \frac{I_{OC}}{V_{OC}} \quad (1)$$

where G_C is the conductance of the core-loss resistor and B_M is the susceptance of the magnetizing inductor. The phase angle of the admittance can be found from the knowledge of the power factor. The open-circuit power factor, PF_{OC} , is given by

$$PF_{OC} = \cos\theta = \frac{P_{OC}}{V_{OC}I_{OC}} \quad (2)$$

Once the power factor angle θ is known, R_C and X_M can easily be computed as follows:

$$G_C = |Y_E|\cos\theta, R_C = \frac{1}{G_C} \quad \text{and} \\ B_M = |Y_E|\sin\theta, X_M = \frac{1}{B_M} \quad (3)$$

Short-Circuit Test

The short-circuit test is conducted by short-circuiting the secondary terminal of the transformer, and applying a reduced voltage to the primary side, as shown in Figure 4, such that the rated current flows through the windings. The input voltage, V_{SC} , current, I_{SC} , and real power, P_{SC} , are measured.

Figure 5 shows the Simulink/SimPowerSystems implementation of the short-circuit test. This model is almost the same as simulation model of open-circuit test shown in Figure 3. The only difference is that secondary side is short-circuited. Several measurement blocks are used to obtain short-circuit real power, voltage, and current. The value of the AC voltage source is adjusted until the current in the short-circuited winding is equal to its rated value.

Since a reduced voltage is applied to the primary windings, a negligible current flows through the excitation branch. Ignoring this current, the magnitude of the series impedance referred to the primary side of the transformer can easily be computed as

$$|Z_{eq}| = |Z_{SC}| = \frac{V_{SC}}{I_{SC}} \quad (4)$$

Neglecting the core loss at the low value of V_{SC} , the

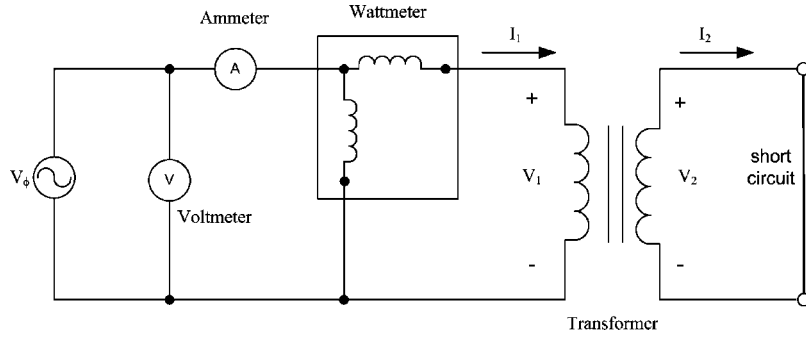


Figure 4 Experimental setup of the short-circuit test.

equivalent series resistance and leakage reactance can be found by

$$R_{eq} = R_{SC} = \frac{P_{SC}}{I_{SC}^2}, \quad X_{eq} = X_{SC} = \sqrt{|Z_{eq}|^2 - R_{eq}^2} \quad (5)$$

Using the circuit notations provided in Figure 1, the equivalent resistance and reactance are the sum of resistance and reactances of the primary and secondary referred to the primary side:

$$R_{eq} = R_1 + a^2 R_2, \quad X_{eq} = X_{l1} + a^2 X_{l2} \quad (6)$$

It is worth mentioning here that there is no easy way to split the series impedance into primary and secondary components. It is generally assumed that the primary and secondary windings have the equal contribution to the total resistance and reactance [9,10] although such separation is not necessary to compute transformer operating quantities such as losses, voltage regulation, and efficiency.

COMPARISON OF EQUIVALENT CIRCUIT PARAMETERS

To illustrate the effectiveness of the proposed simulation models, one compares the equivalent circuit parameters determined by simulations with those obtained from hardware experiments. The transformer used for this purpose is a 50 KVA 2400–240 V 50 Hz transformer located at electric machinery laboratory of Nigde University. The open-circuit and short-circuit tests are first performed to obtain equivalent circuit parameters that will be used in simulations. Resulting circuit parameters are given in Table 1.

For the transformer tested, the simulation models of the open-circuit and short-circuit tests were run. The simulation data is given in Table 2 where voltage, current, and power values measured are provided. Table 3 gives the equivalent circuit parameters computed using the simulation data and the corresponding errors relative to those obtained

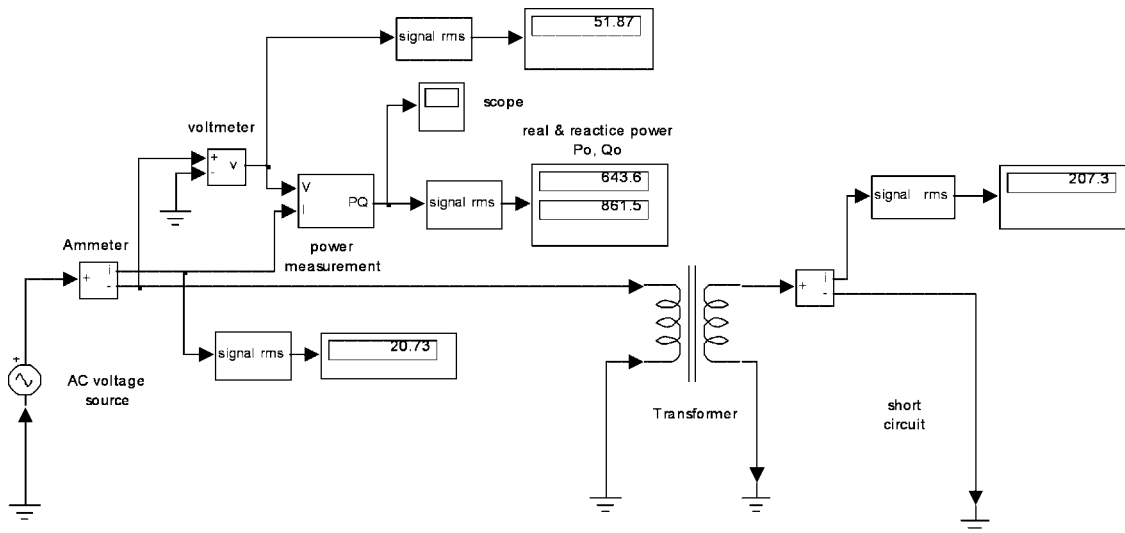


Figure 5 Simulink/SimPowerSystems implementation of the short-circuit test.

Table 1 Equivalent Circuit Parameters of the Transformer Tested

R_1 (Ω)	R_C (Ω)	X_{11} (Ω)	X_M (Ω)	R_2 (Ω)	X_{12} (Ω)
0.7488	33,391	1.00224	5,008	0.007488	0.0100224

experimentally. The error computations assume that equivalent circuit parameters determined experimentally are accurate. The results indicate that relative errors are negligible and the proposed simulation models accurately predict equivalent circuit parameters. The largest error occurs in the resistance of the windings, since one assumes that the two resistances have equal contributions to the total series resistance referred to the primary side, which might not be the real case.

INTEGRATION OF SIMULATION MODELS INTO ELECTRIC MACHINERY COURSES

In this section, the authors describe the integration of these simulation models into electric machinery courses at two different universities, Drexel University and Nigde University. The lecture section of the electric machinery course (ECE-P 352) offered at the ECE Department of Drexel University introduces students to operation principles of transformers, induction motors, DC motors, and various motor control techniques including power electronics based ones. In the laboratory section, students are required to perform various experiments for which the necessary theoretical background is developed in the lecture section. The experiments conducted during the term at the Interconnected Power System Laboratory (IPSL) [19] of Drexel University include open-circuit, short-circuit, and load tests for transformers, speed control experiments for DC motors, and induction motor tests. Similarly, the electric machinery course (ECE 308) offered at the Department of Electrical and Electronics Engineering of Nigde University introduces students to operation of transformers, induction motors, and motor speed control methods. In the laboratory section, students are asked to conduct transformer and induction motor tests at the Electric Power Engineering Center (EPEC) of Nigde University. The EPEC consists of a small-scale machinery

laboratory and a power electronic laboratory that includes various experimental setups for power engineering courses.

At both universities, in order to incorporate simulation models of transformer tests into the course, the laboratory section is divided into two main components, each of which is a 2-h section, software laboratory and hardware laboratory. After being introduced to the theory and operating characteristics of the transformers, the equivalent circuit, voltage regulation, losses, efficiency, and three-phase transformers, students simulate the open-circuit and short-circuit tests and record the data required to compute equivalent circuit parameters. A week before the software laboratory, the Simulink/SimPowerSystem models of the tests, equivalent circuit parameters of the transformer located at the laboratory and a detailed hand-out describing how each simulation model is to be simulated are made available to students.

For the load test, in order to determine voltage regulation and efficiency an assignment is given to students either to develop steady-state model of the transformer using MATLAB’s M-file programming or to modify the presented simulation model of the open-circuit (or short-circuit) test by including a load at the secondary terminal of the transformer. Based on their skills, students are allowed to choose one of these two options. Figure 6 depicts a typical voltage regulation profile for lagging, unity and leading power factor loads, and an efficiency curve generated by the program developed by students. Such an assignment enables students to gain experience and confidence in transformer operation under various loading conditions, which will be helpful for them when they conduct the loading experiment in the hardware laboratory in the following week. Moreover, this assignment helps students to better understand effects of load type and load power factor on transformer voltage regulation and efficiency.

In the hardware laboratory, students are asked to set up and conduct three transformer tests: the open-circuit test, short-circuit test, load test. Similar to what is performed in the software laboratory, they take measurements required to compute equivalent circuit parameters and to examine the transformer operating characteristics under varying load. During the laboratory section, students appear to be familiar with transformer theory, experiments, and operation because of

Table 2 Simulation Results of the Transformer Tests

Test	V (V)	I_1 (A)	I_2 (A)	P (W)	Q (VAR)
Open-circuit test	2,400	0.4847	1.677×10^{-19}	171.1	1148
Short-circuit test	51.87	20.83	208.3	642.1	864.3

Table 3 Equivalent Circuit Parameters Determined by Simulation and the Corresponding Errors

	R_1	R_C	X_{11}	X_M	R_2	X_{12}
Value (Ω)	0.73992	33,670	1.00124	5006	0.007392	0.0100124
Error (%)	1.188	0.835	0.1002	0.0399	1.188	0.1002

the experience gained during the software laboratory. A week after they complete hardware experiments, students are required to submit a report that must combine results from both simulations and experiments. The emphasis is that the report should compare simulation results with experimentally recorded data, mainly focusing on the differences/similarities. One can assume that parameters obtained from simulation data would be the same as those obtained from experimental data since transformer parameters determined from experimental data are used in simulations. However, as can be seen in Table 3, this equivalency is not the case and negligible errors are observed. In their reports, students are encouraged to provide explanations for these errors. These errors might be the result of modeling of the transformer in Simulink, or round-off in computation, or measurements errors often observed in the hardware experiments. Nevertheless, the proposed simulation models give students insight into as to the experimental procedure and the expected results before they go into the electric machinery laboratory to perform the actual experiments.

SURVEY AND STUDENT RESPONSE

In order to find out student response to the designed simulation models and to determine whether models were actually helping them in the understanding of transformer theory and experiments, students who attended the EEM 308 class in the past 2 years (80 students) were asked to fill out a questionnaire at the end of the term, which is presented in the Appendix. It must be stated here that there is no good control group for statistical assessment since these simulation models were introduced for all students within a course.

The first group of questions (questions from 1 to 5) aims to determine the students' previous knowledge of MATLAB/Simulink and to evaluate whether they were able to use the Simulink models easily and effectively. Survey results indicate that a great majority of the students (80%) were familiar with MATLAB/Simulink in general. This could be easily attributed to an introductory control system class taken before where Simulink was extensively used.

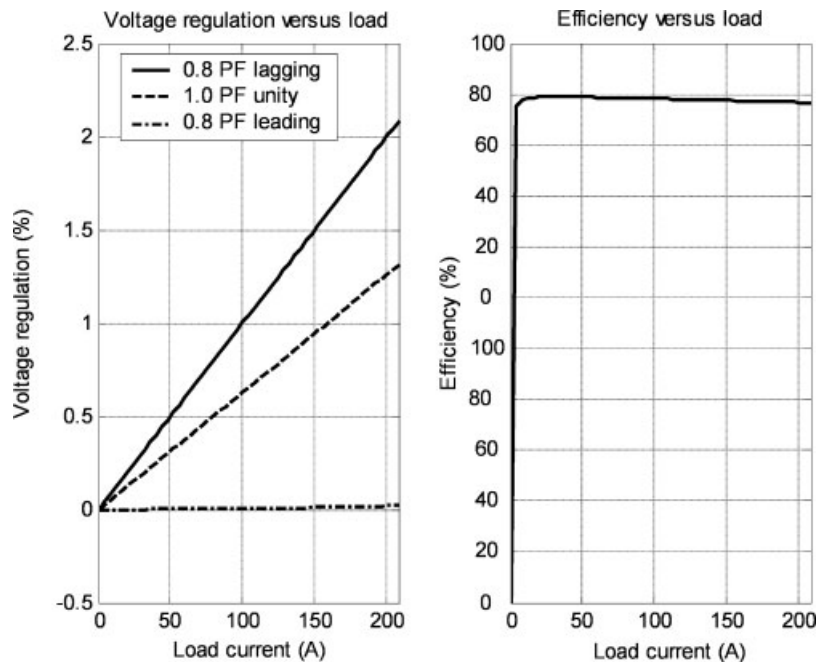


Figure 6 Voltage regulation curves for lagging, unity, and leading load power factor and efficiency curve.

On the other hand, very few students (15%) had some experience with Simulink/SimPowerSystems. This is not surprising since the EEM 308 is the first course where they are introduced to the SimPowerSystems toolbox. With regard to the use of Simulink models, 70% of students felt that they had no difficulties in simulating transformer tests with the help of the associated simulation handout. However, a relatively large number of students (45%) thought that a tutorial on Simulink and SimPowerSystems toolbox at the beginning of the term would be much more helpful. For this reason, a 3-h tutorial concentrating on the use of SimPowerSystems is put in perspective. Such a tutorial will evidently refresh the knowledge of those who are somewhat familiar with Simulink and more importantly, will help all students explore the capabilities of Simulink/SimPowerSystems and learn how to develop and simulate power system models. Finally, 72% of the students felt that the use of simulation models helped them improve their experience and skills on how to use Simulink.

The second group of questions is to assess the effectiveness of the simulation models in terms of helping students in actual transformer experiments. The survey results show that 70% of the students thought that simulating transformer tests before hardware experiments helped them clearly understand experimental procedure and save time in conducting the actual experiments, which was the most important reason for designing these models. On the other hand, only 45% of them felt that simulations helped them increase their understanding of transformer theory. A great deal of students (85%) thought that simulation models and physical experiments complement each other. Most of the students used M-file programming to obtain voltage regulation and efficiency since obtaining these by using Simulink takes much more time. In general, students found simulation models were very helpful and suggested that MATLAB and Simulink/SimPowerSystems should be used in other power system courses as well.

CONCLUSIONS AND FUTURE WORK

In this article, the authors present simulation models of transformer tests performed to obtain equivalent circuit parameters. Each Simulink/SimPowerSystems model is explained in detail and compared with the corresponding experimental setup. Circuit parameters obtained from simulation results are compared with those obtained from hardware experiments. The error studies show that MATLAB with Simulink/SimPowerSystems toolbox is a good simulation tool to model transformer tests and to evaluate steady-state characteristics of

transformers. Furthermore, a successful integration of simulation models is described in a software laboratory in an electric machines course, which complements classroom lecture and laboratory practice. The following future work is put in perspective: (i) Simulation models will be modified to analyze quantitatively the waveforms of various transformer connections under steady-state no-load conditions while taking into account the non-sinusoidal voltage supply. (ii) The software laboratory will be extended to include Simulink/SimPowerSystems models of speed control experiments of DC motors, and experiments for synchronous machines so that a complete computational laboratory will be available to support electric machinery education at authors' institutions.

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APPENDIX

Survey for junior students (EEM 308 Electric Machinery):

1. Were you familiar with Matlab and Simulink before taking this class? (Circle one.)
YES SOME LITTLE NO
2. Have you used SimPowerSystems toolbox of Simulink before?
YES SOME LITTLE NO
3. Do you think that Simulink model of transformer tests are easy to understand and to simulate?
YES SOME LITTLE NO
4. Were the simulation handout easy to follow and helpful to simulate the transformer tests?
YES SOME LITTLE NO
5. Do you think that the use of Simulink models helped you improve your knowledge on Matlab and its Toolboxes in general?
YES SOME LITTLE NO
6. Do you think that the simulation models and experience you gained from them helped you understand better the experimental procedure of the transformer tests and save you time in conducting hardware experiments?
YES SOME LITTLE NO
7. Do you think that Simulink models helped you increase your understanding of transformer characteristics and equivalent circuit theory?
YES SOME LITTLE NO

8. Do you think that simulations of transformer tests complement the laboratory practice?
YES SOME LITTLE NO
9. In order to determine voltage regulation and efficiency which one did you use and why?
M-file programming Modified one of given Simulink model of the tests
10. Do you think that measurements and results of simulations were comparable with those of actual experiment?
YES SOME LITTLE NO
11. Any additional comments and suggestions as to improve the simulation models and software laboratory in general would be appreciated.

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BIOGRAPHIES



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