Teaching Calculation of Transformer Equivalent Circuit Parameters using MATLAB/Simulink for Undergraduate Electric Machinery Courses

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Abstract

Background/Objectives: Computer-based educations have become popular thanks to their useful and flexible structures in classroom environment. Methods/Statistical analysis: This paper presents MATLAB/Simulink implementation of transformer tests, namely dc, open-circuit, and short-circuit tests performed to identify equivalent circuit parameters and effective education of transformer modeling at electric machinery courses and reinforcement of the theoretical concepts given at these courses. Results: The proposed method has been successfully integrated into electric machinery courses at Author University with very encouraging results. The results show that relative errors are negligible, and the proposed simulation models accurately predict equivalent circuit parameters. Conclusion/Application: This method will be very helpful for students when they carry out hardware laboratory experiments in electric machinery courses.

Keywords: Computer based Education, Electric Machinery, Power System Blockset (PSB), Root-Mean-Square (RMS), Simulink, Transformer Equivalent Circuit, Undergraduate Courses

1. Introduction

Computer-based education is an interactive tool in the classroom that makes the students continuously active, the learning much more stable and flexible. Because these advantageous properties, these tools have been increasingly used in educating students of hard engineering subjects such as computer, electrical and mechanical engineering of the past years1-4. The computer simulations as a part of laboratory experiments enhance laboratory experience by providing students with the opportunity to verify the results of laboratory experiments and compare them with those obtained by computer simulations. It helps students to realize the limitations of hardware experiments5-9.

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Electrical machinery courses at the undergraduate level typically consist of laboratory and classroom sections8. The classroom section covers the steady-state operation of the one phase transformer in which the equivalent circuit is used to compute various transformer quantities, such as input current and power, voltage regulation percentage and efficiency according to load types. The computations require the knowledge of equivalent circuit parameters. These parameters are obtained by performing open-circuit, short-circuit and dc tests on the transformer in a typical laboratory experiment11.

The laboratory section helps students to become familiar with the transformer operation and to obtain measurement experiences. The author experience at Aliabad Katoul Islamic Azad University (AKIAU) shows that educating students usually have difficulty when they carry out these experiments in the laboratory even though the corresponding theories are extensively covered in the classroom with a detailed procedure of the experiments, given to them before the laboratory. Students are not familiar with a laboratory environment and relatively measurements. The time circumscriptions during the laboratory practice are also a difficult adjustment. In a
two-hour laboratory section, students usually needed to set up and perform four transformer experiments, to take the necessary measurements, and to study performance of the transformer under various loading conditions. Because of the time constraints, students often hurry through the experiments in order to finish them on time, which unfortunately prevents them from getting a true feeling of transformer operation.

Thus, simulation-based tools must be developed for transformer experiments to provide appropriate preparatory exercises before students come to the laboratory. The goal of this paper is to present simulation models of these transformer experiments to design a virtual laboratory environment. The dc, open-circuit, and short circuit simulation models are developed as stand-alone applications using MATLAB/Simulink and Power System Blockset (PSB).

This paper is organized so that a description of the open-circuit, short circuit, and dc tests is included in section 2. First, the experimental setup for each test is presented with a brief explanation of how these tests are performed and how the corresponding measurements are used to obtain the equivalent circuit parameters. Then, the corresponding Simulink/PSB model is presented and compared with the actual laboratory setup. Section 3 compares the equivalent circuit parameters calculated using simulation tool and data obtained from laboratory experiments. Section 4 describes how to incorporate these simulations into undergraduate electric machinery course at AKIAU, while the conclusion is drawn in section 5.

2. Experimental Setups and Simulink/PSB Models of Transformer Tests

The equivalent circuit of a transformer referred to its primary side is shown in Figure 1. In this circuit, $R_p$ and $X_p$ represent primary coil resistance and leakage reactance, respectively; $R_s$ and $X_s$ denote the secondary coil resistance and leakage reactance, respectively; $R_c$ resistance stands for core losses; $X_M$ represents magnetizing reactance; $N_p$ and $N_s$ denotes number of turns on primary and secondary coils, respectively where $a = \frac{N_p}{N_s}$ is transformer turn ratio.

The transformer model shown before is often more complex than necessary in order to get good results in practical engineering applications. The excitation branch of the model adds another node to the circuit and the solution will be more complex. The excitation branch has a very small current compared to the load current of the transformers. In fact, it is so small that under normal circumstances it causes a completely negligible voltage drop in $R_p$ and $X_p$. Because this is true, the excitation branch is simply moved to the front of the transformer, and the primary and secondary impedances are left in series with each other. These impedances are just added, creating the approximate equivalent circuits in Figure 2.

The equivalent circuit is used to facilitate the computation of various operating quantities, such as branch currents, losses, percentage of voltage regulation and efficiency. The parameters of the equivalent circuit can be obtained from the dc, open-circuit and short circuit tests.

In the following, both experimental setup and Simulink/PSB models of each test are presented. The PSB is an effective software package to develop simulation models for power system studies in the MATLAB/Simulink environment. Simulink/PSB has been widely utilized by teachers to enhance teaching of electrical engineering courses. Of course, other commercial software packages, such as EMTP and PSCAD, are commonly used in electrical engineering education. The reason that MATLAB with its toolboxes was selected is that it is the main software package utilized in almost all undergraduate courses.
in the authors’ university as a simulation tool. Therefore, educating students may easily access to MATLAB, and they already have the basic programming proficiencies to use the given Simulink/PSB models.

2.1 Open-circuit Test

In the open-circuit test, a transformer’s secondary winding is open-circuited, and its primary winding is connected to a full-rated line voltage. Look at the equivalent circuit in Figure 1. Under the conditions described, all the input current must be following through the excitation branch of the transformer. The series elements \( R_p \) and \( X_p \) are too small in comparison to \( R_c \) and \( X_M \) to cause a significant voltage drop, so essentially all the input voltage is dropped across the excitation branch.

Figure 3 illustrates the experimental setup of the open-circuit test. And Figure 4 shows the Simulink/PSB realization of the open-circuit test, where a one-phase 220 V/50 Hz ac source voltage is applied to the primary winding of the transformer, and the input voltage, input current, and input power to the transformer are measured. From this information, it is possible to determine the power factor of the input current and therefore both the magnitude and angle of the excitation impedance.

The easiest way to calculate the values of \( R_c \) and \( X_M \) is to look first at the admittance of the excitation branch. The conductance of the core-loss resistor is given by

\[
G_C = \frac{1}{R_C}
\]

(1)

And the susceptance of the magnetizing inductor is given by

\[
B_M = \frac{1}{X_M}
\]

(2)

Since these two elements are in parallel, their admittances add, and the total excitation admittance is

\[
Y_E = G_C - jB_M = \frac{1}{R_C} - j \frac{1}{X_M}
\]

(3)

The magnitude of the excitation admittance (referred to primary circuit) can be found from the open-circuit test voltage and current:

\[
|Y_E| = \frac{I_{OC}}{V_{OC}}
\]

(4)

The angle of the admittance can be found from knowledge of the circuit power factor. The open-circuit power factor is given by

\[
PF = \cos \theta = \frac{P_{OC}}{V_{OC}I_{OC}}
\]

(5)

And the power factor angle \( \theta \) is given by

\[
\theta = \cos^{-1} \left( \frac{P_{OC}}{V_{OC}I_{OC}} \right)
\]

(6)

The power factor is always lagging for a real transformer, so the angle of the current always lags the angle of the voltage by \( \theta \) degrees. Therefore, the admittance \( Y_E \) is

\[
Y_E = \frac{I_{OC}}{V_{OC}} \angle -\theta
\]

(7)

By comparing equations (3) and (7), it is possible the values of \( R_c \) and \( X_M \) directly from the open circuit test data.

The equivalent circuit parameters can be obtained from experimental data or PSB simulation. In Simulink/PSB setup, the output of each current or voltage measurement block is connected to a root-mean-square (rms) block, called signal rms, to calculate the rms value of parameters. This block computes the rms value of the input signal over the one cycle. The outputs of the voltage measurement block and the current measurement block are connected to a power measurement block, called the active and reactive power measurement that computes the...
active and reactive powers. In addition, the output of this block is connected to a display block to show the values of open-circuit test.

### 2.2 Short-circuit Test

The short-circuit test is carried out to calculate some of its equivalent circuit parameters. In this experiment, the secondary terminals of the transformer are short-circuited, and the primary terminals are connected to a fairly low-voltage source, as shown in Figure 5. The input voltage is adjusted until the current in the short-circuited winding is equal to its rated value. The input voltage, current, and power are again measured.

Since the input voltage is so low during the short-circuit test, negligible current flows through excitation branch. If the excitation current is ignored, then the entire voltage drop in the transformer can be attributed to the series elements in the circuits. The magnitude of the series impedances referred to the primary side of the transformer is

\[ |Z_{SE}| = \frac{V_{SC}}{I_{SC}} \]  

(8)

The power factor of the current is lagging. Thus, the current angle is negative, and overall impedance angle \( \theta \) is positive:

\[ \theta = \cos^{-1} \left( \frac{P_{SC}}{V_{SC} I_{SC}} \right) \]  

(9)

Therefore,

\[ Z_{SE} = R_{eq} + jX_{eq} = \frac{V_{SC}}{I_{SC}} \angle \theta \]  

(10)

It is possible to determine the total series impedance referred to the primary side using this technique. To split the \( R_{eq} \) into primary and secondary components the dc test is performed. In addition, the \( X_{eq} \) approximately can be split to:

\[ X_p = a^2 X_s = \frac{X_{eq}}{2} \]  

(11)

The experimental setup of the short-circuit test is not shown here since it is similar to that of the open-circuit test shown in Figure 3. Several measurements blocks are utilized to measure the current, voltage, and active/reactive powers.

### 2.3 dc Test

The voltmeter-ammeter method is the most common method used for transformer winding resistance measurement. Resistance-measuring systems employing computer-controlled digital voltmeters, current measuring shunts, and/or digital ammeters of appropriate accuracy are commonly used for cold-resistance measurements and in connection with temperature-rise determinations. To use this method, the following steps should be taken:

Measurement is made with direct current, and simultaneous readings of current and voltage are taken using the connections in Figure 6. The required resistance is calculated from the readings in accordance with Ohm's Law. Resistance is recommended to be measured at intervals of 5 s to 10 s, and the readings used shall be after the current and voltage have reached steady-state values.

The primary winding resistance determined from the dc test is an approximate value of the actual one since the skin effect and temperature effects are not taken into consideration. However, this approximation is acceptable enough for teaching purposes.

When the three tests are performed, equivalent circuit parameters can simply be computed:

- The primary resistance is directly calculated from the dc test.
- The open-circuit test gives the magnetizing resistance and reactance referred to primary side.
- The short-circuit test gives the series impedances.

Figure 5. Simulink/PSB implementation of short-circuit test.

Figure 6. Simulink/PSB implementation of the dc test.
To validate the proposed simulation models, one compares the equivalent circuit parameters calculated by simulations with those obtained from experimental setups. The transformers used for this goal are the one-phase 50 Hz, and the 120 VA located at Aliabad University’s Electrical Machine Laboratory (EML) and shown in Figure 7. A set of hardware experiments are first performed (i.e., dc, open-circuit, and short-circuit tests) on two transformers to obtain appropriate equivalent circuit parameters for software simulations. The resulting parameters are presented in Table 1.

For each transformer validated the Simulink/PSB models of the dc, open-circuit, and short-circuit tests were run. The simulation result of the tests for transformer 1 is shown in Table 2, where calculated quantities, such as voltage, current and power required for computing equivalent circuit parameters, are presented. For example, the dc test simulation data for transformer 1 is as follows: 22 V and 7.097 A. The simulation data for the other one is similar to that of transformer 1 and, thus, is not given here.

Table 3 presents the equivalent circuit parameters determined using the simulation tool and the corresponding errors relative to those obtained experimentally. The error computations suppose that equivalent circuit parameters calculated experimentally are exact. The results show that relative errors are negligible, and the proposed simulation models accurately predict equivalent circuit parameters.

### 3. Comparison of Equivalent Circuit Parameters

In this section, the author presents the application of these simulation models in electric machinery courses at Aliabad Katoul University, Iran. The Electrical Engineering Department of Aliabad Katoul University offers a pre-junior-level machine courses in two levels. Level 1 focuses on the fundamentals of electromechanical energy conversion and dc motor, and level 2 concentrates on transformers and induction motors. This research is presented for level 2. This five-hour course required for both lecture and laboratory sections. The lecture section (three hours a week) introduces students to operation principles of transformers and induction motors. In the laboratory section (two hours a week), students need

![Figure 7. EML set up.](image)

Table 1. Equivalent circuit parameters of the transformers

<table>
<thead>
<tr>
<th></th>
<th>(R_P) (Ω)</th>
<th>(X_P) (Ω)</th>
<th>(R_S) (Ω)</th>
<th>(X_S) (Ω)</th>
<th>(R_C) (kΩ)</th>
<th>(X_M) (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer 1</td>
<td>3.1</td>
<td>3.18</td>
<td>2.7</td>
<td>0.421</td>
<td>6.914</td>
<td>1.294</td>
</tr>
<tr>
<td>Transformer 2</td>
<td>2.9</td>
<td>6.43</td>
<td>2.56</td>
<td>0.85</td>
<td>6.453</td>
<td>1.244</td>
</tr>
</tbody>
</table>

Table 2. Simulation results of the transformer tests for transformer 1

<table>
<thead>
<tr>
<th></th>
<th>(V) (V)</th>
<th>(I) (A)</th>
<th>(P) (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-circuit test</td>
<td>220</td>
<td>0.1725</td>
<td>7.053</td>
</tr>
<tr>
<td>Short-circuit test</td>
<td>13.3</td>
<td>0.5477</td>
<td>7.006</td>
</tr>
<tr>
<td>Dc test for Primary winding</td>
<td>22</td>
<td>7.097</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Equivalent circuit parameters and relative errors

<table>
<thead>
<tr>
<th></th>
<th>(R_P) (Ω)</th>
<th>(Err.) (%)</th>
<th>(X_P) (Ω)</th>
<th>(Err.) (%)</th>
<th>(R_S) (Ω)</th>
<th>(Err.) (%)</th>
<th>(X_S) (Ω)</th>
<th>(Err.) (%)</th>
<th>(R_C) (kΩ)</th>
<th>(Err.) (%)</th>
<th>(X_M) (kΩ)</th>
<th>(Err.) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer 1</td>
<td>3.099</td>
<td>0.032</td>
<td>3.32</td>
<td>4.5</td>
<td>2.678</td>
<td>0.81</td>
<td>0.44</td>
<td>4.8</td>
<td>6.86</td>
<td>0.75</td>
<td>1.298</td>
<td>0.31</td>
</tr>
<tr>
<td>Transformer 2</td>
<td>2.899</td>
<td>0.034</td>
<td>6.535</td>
<td>1.63</td>
<td>2.526</td>
<td>1.3</td>
<td>0.86</td>
<td>1.61</td>
<td>6.44</td>
<td>0.12</td>
<td>1.252</td>
<td>0.64</td>
</tr>
</tbody>
</table>
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In order to integrate simulation models of transformer tests into the course, the laboratory section is divided into two main parts, each of which is a two-hour section: software laboratory and hardware laboratory. After being introduced to the theoretical principals and operating behaviors of the transformer, including per-phase equivalent circuit, students simulate three transformer tests presented in the previous section and record the data required to determine per-phase equivalent circuit parameters.

The Simulink/PSB models of the tests and a detailed hand-out are made available to students, before the software laboratory. Using the simulation tool, students investigate transformer characteristics under varying conditions. Examples of simulations obtained by students’ computer programs for the transformer 1 is presented in Figure 8 that shows transformer efficiency as a function of current for three power factors. This work will be very helpful for student when they carry out hardware laboratory experiments in the next week at the EML.

5. Conclusion

The paper presented simulation models of transformer tests performed to determine parameters of the equivalent circuit of transformers. Each Simulink/PSB model developed in detail and compared with the corresponding laboratory setup. Circuit parameters calculated from simulation results are compared with those obtained from laboratory hardware experiments. The error studies show that Simulink/PSB is a precise simulation tool to model transformer. Moreover, a successful incorporation of simulation models is explained in a software laboratory in an electric machinery course, which complements classroom lecture and laboratory experience.

6. References