

Detailed modelling and simulation of single-phase transformers for research and educational purposes

Saif Sabah Sami¹, Mazin T. Muhssin², Zeyad Assi Obaid³, Ali N. Hussain⁴

^{1,4}College of Electrical and Electronic Engineering Techniques, Middle Technical University, Iraq

¹Research and Studies Department, Mayoralty of Baghdad, Iraq

²Faculty of Engineering, Mustansiriyah University, Iraq

³College of Engineering, University of Diyala, Iraq

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ABSTRACT

COVID-19 pandemic, despite its devastating impact, accelerated the shift to e-learning in higher education. Particularly in the electrical machines courses, that often include laboratory experiments. However, no detailed models of transformers, developed in Simulink/MATLAB®, were reported in the literature. Hence, in this paper, a virtual laboratory consists of models of single-phase transformers was built for the first time. The proposed models are easy to use and modify, and allow all machines' parameters to be altered for students to replicate easily to support and enhance the learning process of electrical machines courses. Consequently, the developed models are effective tools for educational and research purposes. Dynamic models of single-phase, two-winding, transformers and step-up and step-down auto-transformers were developed using Simulink/MATLAB®. Two different approaches for modelling were proposed, the block diagram representation and Simscape based models. The two modelling methods were validated against the built-in transformer model. The developed models have been successfully integrated into electrical engineering courses at Middle Technical University, Baghdad, Iraq. Therefore, all developed models are freely available online at a dedicated repository.

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Corresponding Author:

Saif Sabah Sami

College of Electrical and Electronic Engineering Techniques

Middle Technical University

Al-Dora, Baghdad, Iraq

Email: engsaif07@gmail.com

1. INTRODUCTION

In the light of challenges posed by COVID-19 worldwide spread, i.e. closing of universities campuses, which led to a reduction in students' physical engagement in laboratory experiments. Specifically in electrical machines courses, where students should be able to comprehend the construction and principle of operation and measure various quantities under different settings. An alternative active learning approach that can take the form of a virtual laboratory is required. Computer-aided software, like Simulink/MATLAB®, is important for effective learning of electrical machines courses [1]-[9], particularly dynamic models of these machines [10], [11]. Simulink offers a graphical environment to model dynamic systems easily, using block diagrams or Simscape blocks that mimic the characteristic of electrical and mechanical components. In addition to built-in models which represent power system components, e.g. two-winding transformers.

Although, built-in models of transformers in Simulink/MATLAB® are used to conduct various tasks, such as conventional tests, i.e. no-load, short-circuit [12], [13] and through-fault tests [9], simulating

magnetizing inrush current [14], converting three-phase to seven-phase waveforms [15], successfully. However, these built-in models or blocks has a limited ability to adopt certain changes needed for particular tests [16]-[18], simulate unbalanced operating conditions [19], analyse the transient behaviour [20]. Also, the built-in blocks are not suited to model special types of electrical machines [21] or to represent specific physical characteristics of electrical machines [22]. In addition, no Simscape library-based models of transformers were presented in the literature, which are more visually related to electrical circuits' components that students are familiar with and no detailed models of auto-transformers were reported in the literature. Consequently, detailed mathematical and Simscape library-based models of transformers are vital to create a virtual laboratory of transformers for learning, research and training purposes. Hence, in this paper, a virtual laboratory consists of models of auto-transformers were built for the first time. Additionally, mathematical models are an essential part of any system analysis and control.

A transformer is an essential component of the power system, it facilitates the transfer of power from the generation to the demand economically by changing voltage levels of its terminals. Power transformers have different types and designs, which include two-winding transformers and auto-transformers. Two-winding, single-phase, transformers are often found at distribution networks [23]. Autotransformers are frequently used to connect parts of distribution networks operating at different, yet close, voltage levels [24], [25].

The contribution of this paper is to present simple and modifiable packages for modelling and simulation of different types of single-phase transformers. This paper introduces, for the first time, a virtual laboratory of dynamic models of single-phase, (I) two-winding transformers, (II) step-up and (III) step-down auto-transformers developed using Simulink/MATLAB. Using this virtual laboratory, different settings and operating conditions of these transformers can be investigated. Three different methods to model the three types of transformers, in Simulink/MATLAB environment, are presented. Firstly, the block diagram of the transformer is presented using transfer function blocks. In the second approach, blocks represent electrical components from Simscape library are utilized to build the model. Finally, the built-in linear transformer block is used to build the model. The third approach is used for validation of the first and second modelling approaches. In this study, mathematical models of transformers are developed to relate the supply voltage to the output voltage of the transformers. All models were depicted clearly for undergraduate students to be replicated easily to support and enhance the learning process of electrical machines modules. Consequently, all models and simulation files are freely available online as a GitHub repository [26]. The developed models have been successfully integrated into electrical engineering courses at Middle Technical University, Baghdad, Iraq.

The remaining sections of the paper is organised as follows; in section 2, the basic equations of transformers are presented. Section 3 presents the modelling of each of the three types of transformers using the three aforementioned methods. Simulation results of all models are depicted and discussed in section 4. Finally, a summary of this study was presented in the conclusion section (i.e. section 5).

2. FUNDAMENTAL EQUATIONS OF TRANSFORMERS

2.1. Fundamental equations of two-winding transformers

A single-phase transformer consists of two windings placed over a laminated silicon steel core, which are called primary, secondary windings. Figure 1 shows the equivalent circuit of a two-winding, single-phase, loaded transformer. As shown in Figure 1, the primary and secondary windings have impedances represented by (Z_1) and (Z_2) respectively.

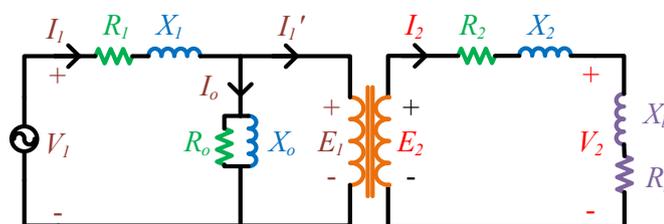


Figure 1. Equivalent circuit of single-phase, two-winding transformer (adopted from [27], [28])

These impedances are responsible for some voltage drop in the primary and secondary windings [29]:

$$V_1 = E_1 + I_1 Z_1 \quad (1.a)$$

$$Z_1 = R_1 + jX_1 \quad (1.b)$$

$$V_2 = E_2 - I_2 Z_2 \quad (2.a)$$

$$Z_2 = R_2 + jX_2 \quad (2.b)$$

where

V_1 : primary winding terminals voltage

E_1 : self-induced emf in the primary winding

R_1, X_1 : resistance and self-reactance of the primary winding

I_1, I_2 : primary and secondary currents, respectively

V_2 : secondary winding terminals voltage

E_2 : mutually induced emf in the secondary winding

R_2, X_2 : resistance and self-reactance of the secondary winding

If an inductive load is connected to the secondary winding terminals, with impedance (Z_{l2}):

$$Z_{l2} = R_{l2} + jX_{l2} \quad (3.a)$$

$$V_2 = I_2 Z_{l2} \quad (3.b)$$

where

R_{l2}, X_{l2} : resistance and self-reactance of the load connected to the secondary winding

When no current flows in the secondary winding ($I_2=0$), a small current flows in the primary winding to feed the iron losses (hysteresis and eddy current losses), often called the magnetizing or no-load current [29], [30]. The no-load current (I_0), has two components; the active or working component (I_w) and the reactive of magnetising component (I_{mag}):

$$I_0 = E_1 Y_0 \quad (4.a)$$

and

$$Y_0 = \frac{1}{R_0} + \frac{1}{jX_0} \quad (4.b)$$

where shunt admittance (Y_0) represents the exciting admittance of the transformer that carries no-load current I_0 . The resistance (R_0) is related to the hysteresis and eddy current losses and the reactance (X_0) is associated with the magnetization of the core [30].

When current flows in the secondary winding (I_2), it is proportional to the primary current (I_1'). Similarly, induced emf in the secondary winding is proportional to the primary induced emf:

$$N_1 I_1' = N_2 I_2 \quad (5.a)$$

$$K = \frac{N_2}{N_1} = \frac{E_2}{E_1} = \frac{I_1'}{I_2} \quad (5.b)$$

and

$$I_1 = I_1' + I_0 \quad (5.c)$$

where

N_1, N_2 : the number of turns of the primary and secondary windings, respectively

K : transformation ratio of the transformer or the turn ratio

2.2. Fundamental equations of auto-transformers

A single-phase auto-transformer can be constructed when the two windings of a transformer are connected electrically, consequently, the connection leads to their voltages aid or oppose one another [31]. Consequently, in addition to the energy transfer from one winding to the other by magnetic induction, direct energy flows by conduction. Alternatively, an auto-transformer can be constructed using a single continuous

common winding for both the primary and secondary sides. Auto-transformers main disadvantage is the loss of electrical isolation between the primary and secondary circuits [32]. While the main advantage of auto-transformers is the ability of a larger apparent power transfer [30].

When a conventional two-winding transformer is converted to an auto-transformer by connecting the two windings electrically in series with additive polarity between the two windings, a step-up auto-transformer is constructed as shown in Figures 2(a) and 2(b). When the two windings are connected electrically in series with the subtractive polarity between the two windings, a step-down auto-transformer is constructed as shown in Figures 2(c) and 2(d).

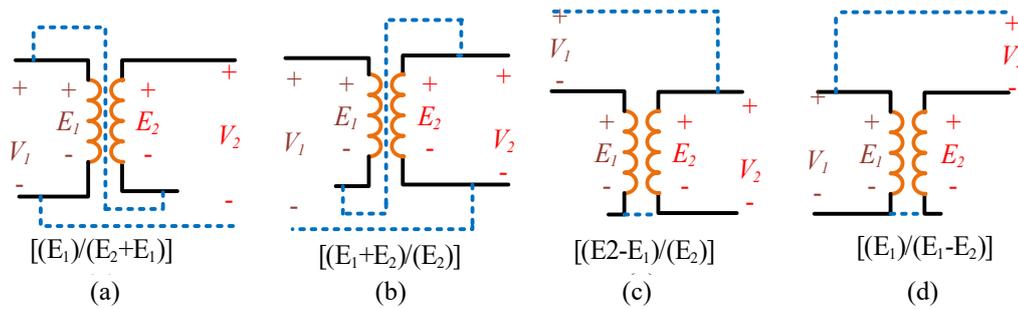


Figure 2. Conversion of two-winding transformers to (a) and (b) step-up auto-transformers, (c) and (d) step-down auto-transformers (adopted from [29], [32])

2.2.1. Auto-transformers constructed by additive polarity (step-up auto-transformers)

As depicted in Figure 2, two arrangements are possible to convert two-winding transformers into step-up auto-transformers. In this paper, the connection scheme in Figure 2(a) is adopted and shown in Figures 3(a)-(c). The converted two-winding transformer to an auto-transformer can be analysed in a similar manner to a two-winding transformer, where the primary impedance (Z_1), secondary impedance (Z_2) and shunt admittance (Y_o) at the primary circuit remain as:

$$Z_1 = R_1 + jX_1 \quad (6.a)$$

$$Z_2 = R_2 + jX_2 \quad (6.b)$$

$$Y_o = \frac{1}{R_o} + \frac{1}{jX_o} \quad (6.c)$$

The supply voltage to the primary circuit of the auto-transformer, shown in Figure 3(c), is (V_1)

$$V_1 = E_1 + (I_1 - I_2)Z_1 \quad (7)$$

and

$$I_1 - I_2 = I'_1 + I_o \quad (8.a)$$

where

$$I_o = E_1 Y_o \quad (8.b)$$

$$I'_1 = kI_2 \quad (8.c)$$

On the secondary side of the auto-transformer, the output voltage (V_2) is the result of the transferred inductive and conductive energies:

$$V_2 = E_2 - I_2 Z_2 + V_1 \quad (9.a)$$

If a simple RL load is applied to the secondary circuit of the auto-transformer:

$$Z_l = R_l + jX_l \tag{9.b}$$

Then

$$V_2 = I_2 Z_l \tag{9.c}$$

In (9.a) and (9.c) yields:

$$\begin{aligned} I_2 Z_l &= E_2 - I_2 Z_2 + V_1 \\ \therefore I_2 &= \frac{E_2 + V_1}{Z_2 + Z_l} \end{aligned} \tag{9.d}$$

2.2.2. Auto-transformers constructed by subtractive polarity (step-down auto-transformers)

Figure 2 shows two connection schemes that are possible to convert two-winding transformers into step-down auto-transformers. In this paper, the arrangement presented in Figure 2(d) is implemented and shown in Figures 3(d)-(f). The supply voltage to the primary circuit of the auto-transformer, shown in Figure 3(f), is (V_1).

$$V_1 = E_1 + I_1 Z_1 \tag{10}$$

and

$$I_1 = I'_1 + I_o \tag{11.a}$$

as

$$I_o = E_1 Y_o \tag{11.b}$$

$$I'_1 = k I_2 \tag{11.c}$$

On the secondary side of the auto-transformer, the output voltage (V_2) is the result of the transferred inductive and conductive energies:

$$V_2 = V_1 - E_2 - I_2 Z_2 \tag{12.a}$$

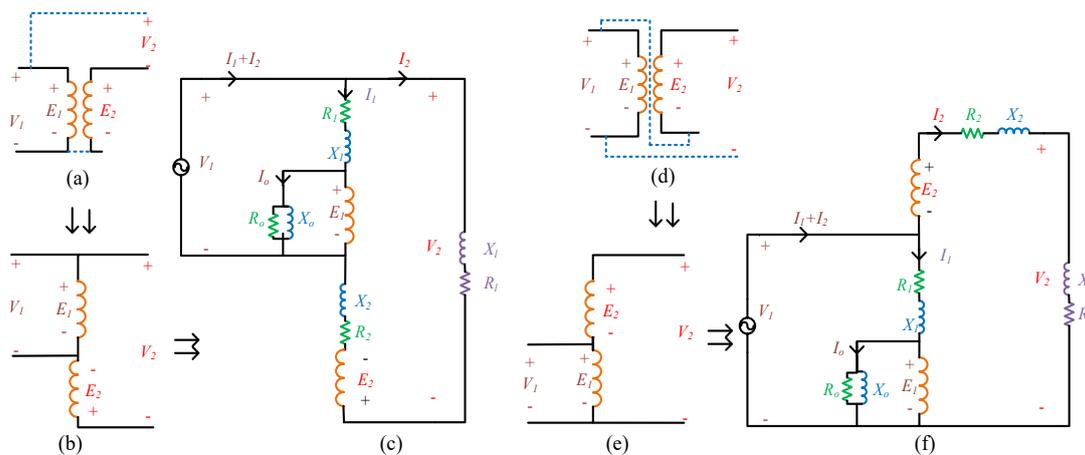


Figure 3. (a) An ideal single-phase two-winding transformer converted to, (b) an ideal step-up auto-transformer, (c) a converted loaded practical step-up auto-transformer (adopted from [29], [32]), (d) An ideal single-phase two-winding transformer converted to (e) an ideal step-down auto-transformer (f) a converted loaded practical step-down auto-transformer (adopted from [29], [32])

If a simple RL load applied to the secondary circuit of the auto-transformer:

$$Z_l = R_l + jX_l \quad (12.b)$$

Then

$$V_2 = I_2 Z_l \quad (12.c)$$

In (12.a) and (12.c) yields:

$$\begin{aligned} I_2 Z_l &= V_1 - E_2 - I_2 Z_2 \\ \therefore I_2 &= \frac{V_1 - E_2}{Z_l + Z_2} \end{aligned} \quad (12.d)$$

3. MODELLING OF THE SINGLE-PHASE TRANSFORMERS

Two different approaches to model single-phase, two-winding transformers, step-up and step-down auto-transformers were developed. In the first approach, the block diagram of transformers is presented using transfer function blocks. The second approach relies on Simscape/Simulink blocks, which represent electrical components, to build the model. To validate these two modelling approaches, the built-in linear (two or three windings) transformer block is used.

The transfer function of linear, time-invariant, differential equations systems can be found using the four following steps [33]:

- Finding the equations which describe the system.
- Identifying the system input and output variables, undoubtedly, currents and voltages of the primary, secondary and tertiary circuits.
- Taking Laplace transform of these equations, assuming zero initial conditions.
- The transfer function of the system, or subsystem, is the ratio of the output to the input variables.

3.1. Modelling of the two-winding, single-phase, transformer

3.1.1. Modelling transformers using block diagrams

To represent the two-winding transformer using transfer function blocks, (1) through 5 are used to describe the system in the Laplace domain. Considering the initial conditions to be zero, the following equations were produced, which can be simply put into a block diagram form:

$$V_1(s) = E_1(s) + I_1(s)(R_1 + sL_1) \quad (13.a)$$

$$I_o(s) = I_1(s) - I'_1(s) \quad (13.b)$$

$$I'_1(s) = KI_2(s) \quad (13.c)$$

$$E_1(s) = \frac{I_o(s)}{\left(\frac{1}{R_o} + \frac{1}{sL_o}\right)} \quad (13.d)$$

$$E_2(s) = KE_1(s) \quad (13.e)$$

$$V_2(s) = E_2(s) - I_2(s)(R_2 + sL_2)$$

$$V_2(s) = I_2(s)(R_{l2} + sL_{l2}) \quad (13.f)$$

$$E_2(s) = I_2(s)((R_{l2} + R_2) + s(L_2 + L_{l2}))$$

$$V_2(s) = E_2(s) \frac{(R_{l2} + sL_{l2})}{((R_{l2} + R_2) + s(L_2 + L_{l2}))} \quad (13.g)$$

Figure 4 shows a representation of the equivalent circuit in Figure 1 using transfer function blocks Simulink library.

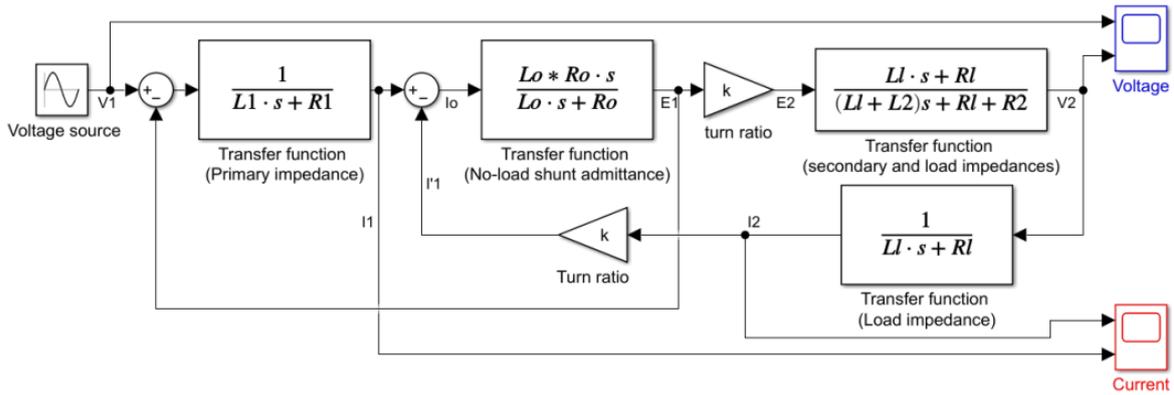


Figure 4. A single-phase, two-winding, transformer model by transfer function blocks Simulink

3.1.2. Modelling transformers using Simscape blocks

Two-winding transformers can be represented by electrical circuits (i.e. inductors and resistors), in addition to components that imitate the characteristic of an ideal transformer. Some components from the Simscape/Simulink library have been chosen to build the model as shown in Figure 5(a).

3.1.3. Modelling transformers using the built-in transformer block

Simulink provides a ready to use linear transformer block, which can mimic two or three windings transformers. This block will be used directly to model this machine and validate the two early built models. Figure 5(b) shows a representation of a single-phase, two-winding, transformer using the built-in transformer block.

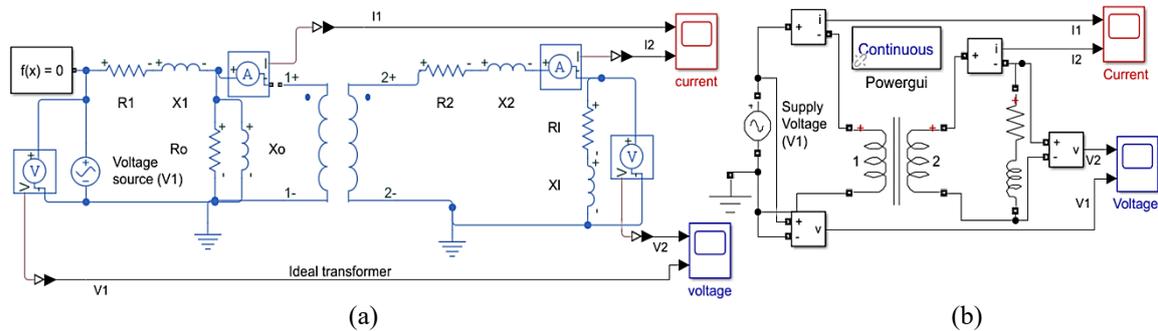


Figure 5. A single-phase, two-winding, transformer (a) model by Simscape blocks and (b) model using the built-in transformer block in Simulink.

3.2. Modelling of the step-up, single-phase, auto-transformer

3.2.1. Modelling transformers using block diagrams

To represent the step-up auto-transformers, constructed using single-phase transformers by the additive polarity of its two windings, using transfer function blocks, (6) through (9) are used to describe the system in the Laplace domain. Considering the initial conditions to be zero, the following equations were produced, which can be simply put into a block diagram form:

$$V_1(s) = E_1(s) + (I_1(s) - I_2(s))(R_1 + sL_1) \tag{14.a}$$

$$I_o(s) = (I_1(s) - I_2(s)) - I'_1(s) \tag{14.b}$$

$$I'_1(s) = KI_2(s) \tag{14.c}$$

$$E_1(s) = \frac{I_o(s)}{\left(\frac{1}{R_o} + \frac{1}{sL_o}\right)} \tag{14.d}$$

$$E_2(s) = KE_1(s) \tag{14.e}$$

$$V_2(s) = V_1(s) + E_2(s) - I_2(s)(R_2 + sL_2) \tag{14.f}$$

$$V_2(s) = I_2(s)(R_1 + sL_1) \tag{14.g}$$

$$E_2(s) + V_1(s) = I_2(s)((R_1 + R_2) + s(L_2 + L_1)) \tag{14.h}$$

$$V_2(s) = (V_1(s) + E_2(s)) \frac{(R_1+sL_1)}{((R_1+R_2)+s(L_2+L_1))} \tag{14.i}$$

Figure 6 shows a representation of the equivalent circuit in Figure 3(c) built using transfer function blocks in Simulink.

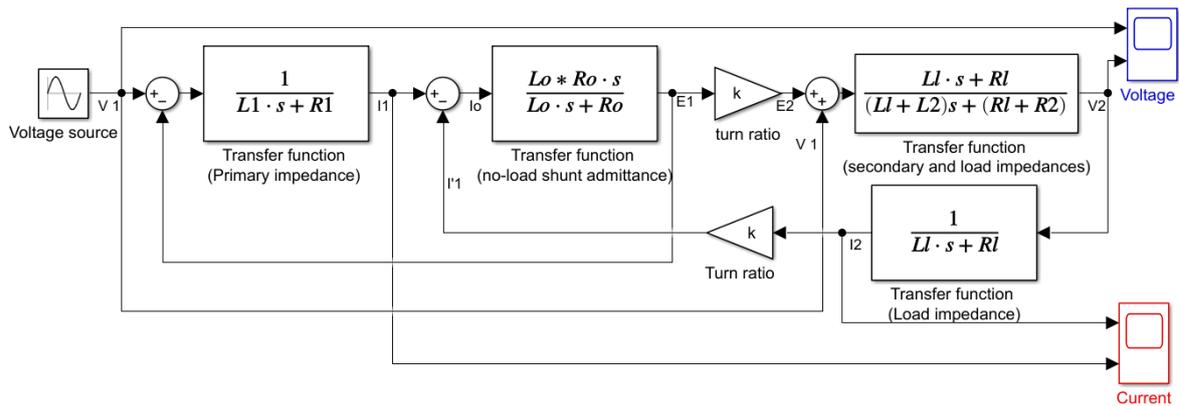


Figure 6. A single-phase, step-up, auto-transformer model by transfer function blocks Simulink

3.2.2. Modelling transformers using Simscape blocks

Auto-transformers can be represented by electrical circuits (i.e. inductors, resistors and an ideal two-winding transformer). Some components from the Simscape/Simulink library have been chosen to build the model as shown in Figure 7(a).

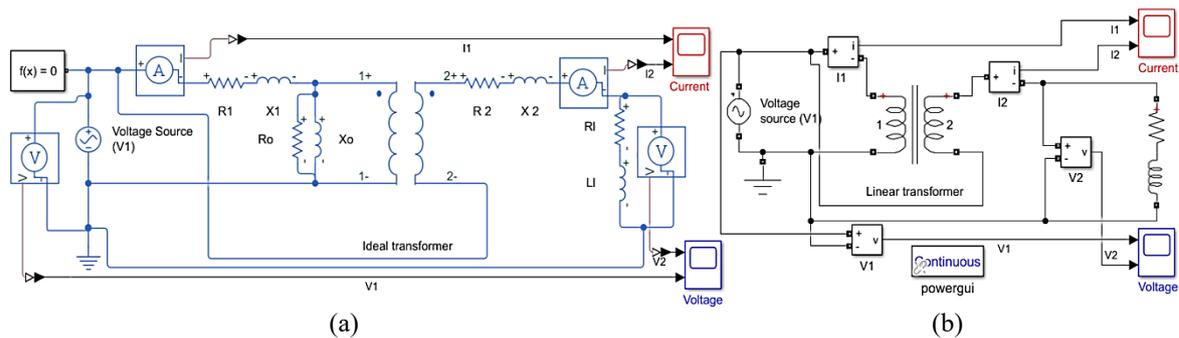


Figure 7. A single-phase, step-up, auto-transformer (a) model by Simscape blocks and (b) model using the built-in linear transformer block in Simulink

3.2.3. Modelling transformers using the built-in transformer block

The built-in linear, two-winding, transformer block was used to construct the step-up, single-phase, auto-transformer. This block was used to model this machine and validate the two early built models. Figure 7(b) shows a representation of a single-phase, step-up, auto-transformer using the built-in linear transformer block.

3.3. Modelling of the step-down, single-phase, auto-transformer

3.3.1. Modelling transformers using block diagrams

To represent the step-down auto-transformers, constructed using single-phase transformers by the subtractive polarity of its two windings, using transfer function blocks, in (6), (9) and (12) are used to describe the system in the Laplace domain. Considering the initial conditions to be zero, the following equations were produced, which can be simply put into a block diagram form:

$$V_1(s) = E_1(s) + I_1(s)(R_1 + sL_1) \tag{15.a}$$

$$I_o(s) = I_1(s) - I'_1(s) \tag{15.b}$$

$$I'_1(s) = KI_2(s) \tag{15.c}$$

$$E_1(s) = \frac{I_o(s)}{\left(\frac{1}{R_o} + \frac{1}{sL_o}\right)} \tag{15.d}$$

$$E_2(s) = KE_1(s) \tag{15.e}$$

$$V_2(s) = V_1(s) - E_2(s) - I_2(s)(R_2 + sL_2) \tag{15.f}$$

$$V_2(s) = I_2(s)(R_l + sL_l) \tag{15.g}$$

$$V_1(s) - E_2(s) = I_2(s)((R_l + R_2) + s(L_l + L_2)) \tag{15.h}$$

$$V_2(s) = (V_1(s) - E_2(s)) \frac{(R_l + sL_l)}{((R_l + R_2) + s(L_l + L_2))} \tag{15.i}$$

Figure 8 shows a representation of the equivalent circuit in Figure 3(f) built using transfer function blocks in Simulink library.

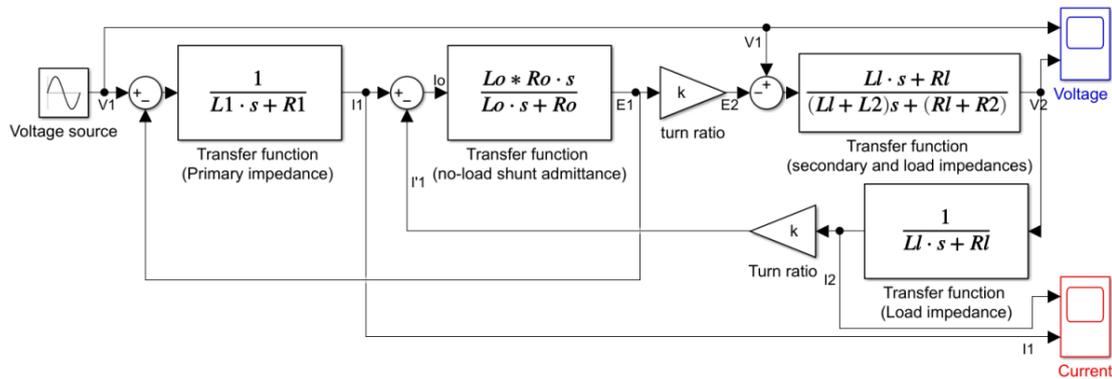


Figure 8. A single-phase, step-down, auto-transformer model by transfer function blocks Simulink

3.3.2. Modelling transformers using Simscape blocks

Auto-transformers can be represented using electrical circuits (i.e. inductors, resistors and an ideal two-winding transformer). Some components from the Simscape/Simulink library have been chosen to build the model as shown in Figure 9(a).

3.3.3. Modelling transformers using the built-in transformer block

The built-in linear, two-winding, transformer block was used to construct the step-down, single-phase, auto-transformer. This block was used to model this machine and validate the two early built models. Figure 9(b) shows a representation of a single-phase, step-down, auto-transformer using the built-in linear, two-winding, transformer block.

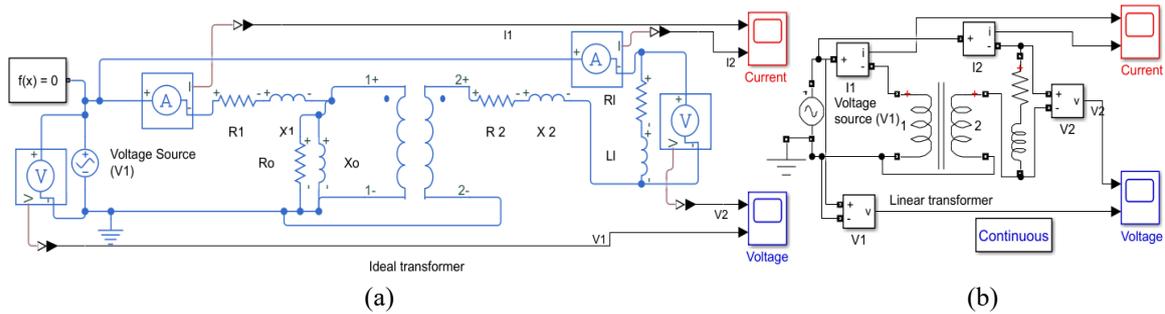


Figure 9. A single-phase, step-up, auto-transformer: (a) model by Simscape blocks and (b) model using the built-in linear transformer block in Simulink

4. SIMULATION RESULTS

Models presented in the previous section are simulated and output signals of voltages and currents are depicted and discussed in this section. All models were built and simulated using MATLAB 2018a.

4.1. Simulation of two-winding, single-phase, transformers

The developed models of two-winding transformers in section 3.1 are tested. The parameters used in the simulation of the 150-kVA transformer are presented in Table 1. Parameters presented in Table 1 were fed to models shown in Figures 4 and 5 the output voltages and currents were depicted in Figure 10. As shown in Figure 10, voltage and current signals were used to validate the first and second modelling approaches by comparing them to the third modelling approach. The three models produced identical outputs when fed by the identical input. Additionally, measured values of output voltages and currents are identical to the values presented in [34].

Table 1. Parameters of the two-winding transformer used in the simulation [34]

Parameter	Value	Parameter	Value
V_1	2455 V	R_2	0.002 Ω
R_1	0.2 Ω	L_2	0.011937 mH
L_1	1.2 mH	R_1	0.3075 Ω
R_o	10000 Ω	L_1	0.61016 mH
L_o	4.1115 H	K	240/2400
V_2	240 V	Freq	60 Hz

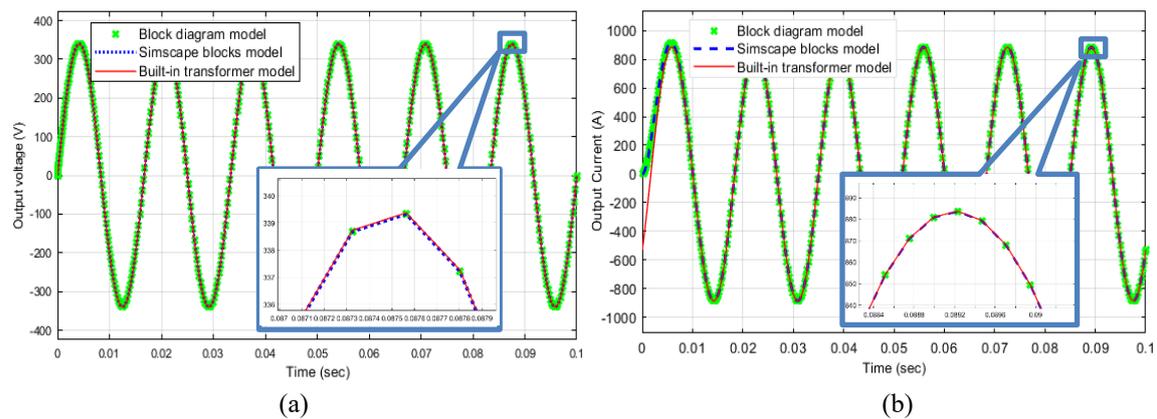


Figure 10. Single-phase, two-winding, transformer models' output signals of the secondary terminal: (a) voltage and (b) current

4.2. Simulation of step-up, single-phase, auto-transformers

The models of single-phase, step-up, auto-transformers developed in section 3.2.1 are verified. The parameters presented in Table 2 are used to simulate the two-winding, 50-kVA rated, transformer which was converted to a 550-kVA, step-up, auto-transformer in [35]. Parameters presented in Table 2 were fed to models shown in Figures 6 and 7 the output signals were presented in Figure 11. Figure 11 depict the output voltage and current signals of the three earlier mentioned models, these signals were used to validate the first and second models by comparing them to the third model. The three models produced identical outputs when fed by identical inputs. Additionally, measured values of output voltages and currents are identical to the values listed in [35].

Table 2. Parameters of the step-up auto-transformer used in the simulation [35]

Parameter	Value	Parameter	Value
V_1	2405 V	R_2	0.007 Ω
R_1	0.72 Ω	L_2	0.023873 mH
L_1	0.0024 H	R_l	10.1794 Ω
R_o	632 Ω	L_l	0.0202 H
L_o	4.1115 H	K	240/2400
V_2	240 V	Freq.	60 Hz
$V_{secondary} (V1+V2)$	2640 V		

4.3. Simulation of step-down, single-phase, auto-transformers

The models of step-down auto-transformers developed in section 3.3.2 are simulated using the parameters presented in Table 2, however, the secondary voltage is changed to ($V_{secondary} (V1-V2) = 2160$ V). These parameters represent a two-winding, 50-kVA rated, transformer which was converted to a 450-kVA, step-down, auto-transformer. Machine parameters were adopted from [35]. Parameters presented in Table 2, with $V_{secondary} = 2160$ V, were fed to models shown in Figures 8 and 9. The output voltage and current signals of the three earlier mentioned models were fairly identical, hence these signals were used to validate the first and second modelling approaches by comparing them to the third model.

As shown in Figures 10 and 11, the coincidence of depicted curves indicates the adequacy of the developed models. Hence, the developed models can be an integrable part of a variety of systems for different studies and analyses. Additionally, the developed models can be used in coordination with other models within Simulink environment.

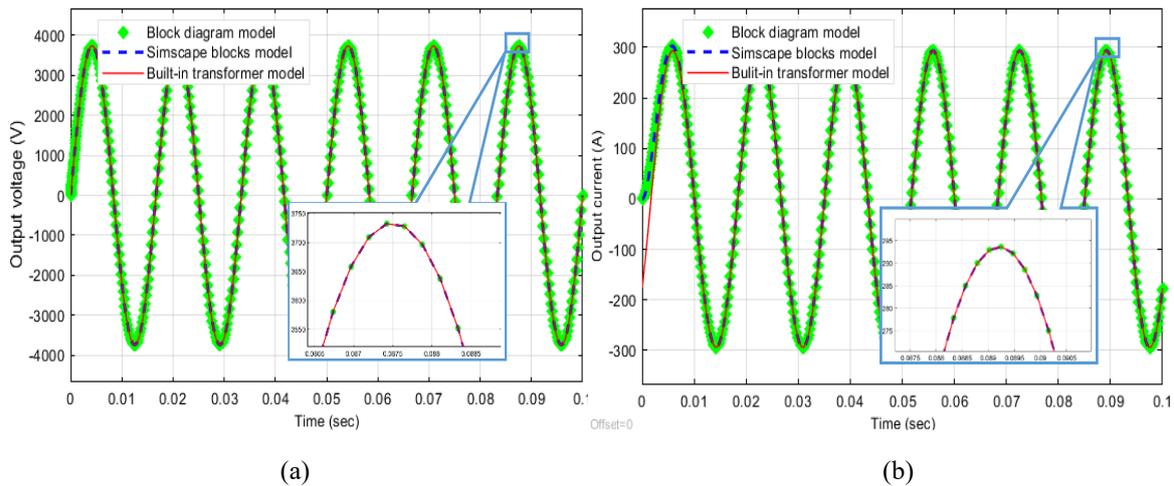


Figure 11. Single-phase, step-up, auto-transformer models' output signals of the secondary terminal: (a) voltage and (b) current

5. CONCLUSION

A virtual laboratory of models representing single-phase transformers for undergraduate education and research purposes was developed. Dynamic models of two-winding transformers and step-up and step-down auto-transformers developed using Simulink/MATLAB were presented. All models are made accessible via a publicly available GitHub repository. A block diagram modelling approach was used that allows model modification for various applications. The second modelling approach utilises Simscape library components, which mimic electrical parts of transformers, to construct models. All developed models allow all machine parameters to be changed for monitoring and evaluation purposes, hence an enhanced learning environment is created. In the third modelling approach, the Simulink built-in linear transformer block was adopted, which provide a benchmark for the first and second modelling approaches to be validated.

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