Simulation modeling of a two-winding three-phase voltage transformer in the MATLAB program

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Abstract. The article calculates the parameters of the transformer according to the technical characteristics of domestic manufacturers of power equipment. Simulation modeling of a three-phase voltage transformer in the idle mode by the Tree-Phase Transformer (Two Windings) block and at various load factors is carried out. The constructed simulation model of the transformer is recommended to be used as a basis for the subsequent study of processes in the rural power supply system.

1. Introduction
Simulation modeling is a description of the behavior of an object in time in the form of mathematical relationships. Simulation modeling allows you to conduct various experiments with the model using computer programs. To date, there are many software systems that allow, through calculations and graphical representations of the results, to simulate the behavior of an object when exposed to various factors. Such systems include the mathematical laboratory MATLAB. Modeling of power supply systems is possible using typical elements of the power supply system from the Simulink application. The Simulink package consists of pre-set graphical blocks and the SimPowerSystems extension that allows you to model high power power systems.

2. Materials and methods
When modeling transformers, an equivalent circuit is used in which electromagnetic couplings are replaced by electrical ones. More reliable, but inconvenient for manual calculations, is the T-shaped equivalent circuit (figure 1). It is this scheme that is used when modeling a transformer in the MATLAB program [1-3].

The elements of the longitudinal branch are represented by active and inductive resistances R1, X1 of the primary and R2, X2 of the secondary windings. The transverse elements are presented in the form of active Rµ and inductive Xµ resistances, which express the active component of the current Ia and reactive Iµ, components of the magnetizing current of the transformer Ix. In turn, Ia is determined by the power losses in the steel of the transformer, and Iµ is determined by the magnetizing flux of the mutual induction of the transformer windings.

3. Results and Discussion
To find the parameters of the transformer according to the data of domestic manufacturers of electrical equipment, calculation formulas are used to determine the reduced values of the parameters of a two-winding transformer, which are necessary for modeling in MATLAB. As the base voltage Ub, we accept...
such a voltage, to which all resistances are reduced - \( U_b = 10kV \). In this case, the resistances and inductances of the primary and secondary windings are reduced to one basic voltage level (table 1) [4-6].

![Figure 1. T-shaped equivalent circuit of the transformer.](image)

| Parameter                                      | Designation | Meaning | Units |
|------------------------------------------------|-------------|---------|-------|
| Number of phases                               | \( m \)     | 3       | -     |
| Transformer Rated Power                        | \( S_{nt} \) | 100     | kVA   |
| Rated network frequency                        | \( f_n \)   | 50      | Hz    |
| Short circuit voltage                          | \( U_k\% \) | 4.5     | %     |
| Short circuit loss                             | \( \Delta P_{kz} \) | 1.97    | kW    |
| Idle loss                                      | \( \Delta P_x \) | 0.29    | kW    |
| No-load current                                | \( I_x\% \) | 2.2     | %     |
| Winding connection diagram                      | Y/Yn        |         |       |

The parameters of transformers in the MATLAB program are set in named units; for this, the active and inductive resistance of each winding must be brought to its rated voltage. Calculation of the parameters of the T-shaped equivalent circuit of the transformer for simulation in the MATLAB program [7-10].

Active winding resistance:

\[
R_{16} = R_{26} = \frac{\Delta P_{kz} U_b^2}{2 \cdot S_{nr}} = 9.9 \text{ Ohm} \quad (1)
\]

\[
R_{1*} = R_{2*} = \frac{\Delta P_{kz}}{2 \cdot S_{nr}} = 0.0099 \text{ o.e.} \quad (2)
\]

Winding impedance:

\[
Z_{1b} = Z_{2b} = \frac{U_k\%}{100} \frac{U_b^2}{2 \cdot S_{nr}} = 22.50 \text{ Ohm} \quad (3)
\]

\[
Z_{1*} = Z_{2*} = \frac{U_k\%}{200} = 0.0225 \text{ o.e.} \quad (4)
\]

Inductive reactance of windings:


\[ X_{1b} = X_{2b} = \sqrt{Z_{1b}^2 - R_{1b}^2} = 20.23 \, \text{Ohm} \]  \hspace{1cm} (5)

\[ X_{1*} = X_{2*} = \sqrt{Z_{1*}^2 - R_{1*}^2} = 0.0202 \, \text{o.e.} \]  \hspace{1cm} (6)

Winding inductance:

\[ L_{1b} = L_{2b} = \frac{X_1}{2 \cdot \pi \cdot f} = 0.0644 \, \text{Hz} \]  \hspace{1cm} (7)

\[ L_{1*} = L_{2*} = X_{1*} = 0.0202 \, \text{o.e.} \]  \hspace{1cm} (8)

Total power loss in the idle mode of the transformer:

\[ \Delta S_x = \frac{I_{x\%}}{100} \cdot S_{HT} = 2.2 \, \text{kVA} \]  \hspace{1cm} (9)

\[ \Delta S_{x*} = \frac{I_{x\%}}{100} = 0.022 \, \text{o.e.} \]  \hspace{1cm} (10)

Transformer magnetizing power:

\[ \Delta Q_x = \sqrt{\Delta S_x^2 - \Delta P_{xx}} = 2.181 \, \text{qvar.} \]  \hspace{1cm} (11)

\[ \Delta Q_{x*} = \sqrt{\Delta S_{x*}^2 - \Delta P_{xx}^*} = 0.02181 \, \text{o.e.} \]  \hspace{1cm} (12)

Active resistance of the magnetizing circuit:

\[ R_{\mu} = \frac{U_b^2}{\Delta P_{xx}} = 344827.59 \, \text{Ohm} \]  \hspace{1cm} (13)

\[ R_{\mu*} = \frac{S_{HT}}{\Delta P_{xx}} = 344.83 \, \text{o.e.} \]  \hspace{1cm} (14)

Inductive reactance of the magnetizing network:

\[ X_\mu = \frac{U_b^2}{\Delta Q_x} = 45855 \, \text{Ohm} \]  \hspace{1cm} (15)

\[ X_{\mu*} = \frac{1}{\Delta Q_{x*}} = 45.85 \, \text{o.e.} \]  \hspace{1cm} (16)

Magnetizing circuit inductance:

\[ L_{\mu} = \frac{X_\mu}{2 \cdot \pi \cdot f} = 146 \, \text{Hz} \]  \hspace{1cm} (17)

\[ L_{\mu*} = X_{\mu*} = 45.85 \, \text{o.e.} \]  \hspace{1cm} (18)

The resulting calculated values of the two-winding voltage transformer will be entered into Block Parameters: Three-Phase Transformer (figure 2).
Let's check the accuracy of calculating the parameters of the magnetization circuit of a two-winding transformer, for this we need to build a virtual model of the transformer in the MATLAB program and take the necessary measurements in idle mode (figure 3), then compare the results with the data of the manufacturer (table 1).

Where Three-Phase Source - models a three-phase voltage source; Three Phase V-I Measurement - performs measurement of currents and voltages in three-phase networks; Powergui - allows you to control the state of model variables at the time of initialization and after simulation; Multimeter - performs the measurement of electrical parameters; Power - block for calculating active and reactive power; Display - designed to display the numerical values of the measured values; Three-Phase Transformer is a block model of a power three-phase two-winding transformer.

Display 1 displays readings on active power losses in the idle mode of the transformer $\Delta P_{x,\text{mod}} = 288.55$ W, and on Display 2 reactive power $\Delta Q_{x,\text{mod}} = 2176.17$ var. Thus, the error in the values of power losses in the simulation model of the transformer and the loss parameters set by the manufacturer are within the range of permissible errors [11].

Let's calculate the losses of electricity in the power transformer TMG 100/10/0.4 (table 1) at load factors $K_Z = 0.25; 0.5; 0.75; 1$ and $\cos \phi = 0.83$. 
\[ P = S_n \cdot K_Z \cdot \cos \phi \]  
(19)

\[ Q = \sqrt{S^2 - P^2} \]  
(20)

\[ \sum \Delta P_{tp} = \Delta P_{x,x} + \Delta P_{k,z} \cdot K_Z^2 \]  
(21)

Let's build a model of a two-winding transformer TMG 100/10/0.4 with \( K_Z = 0.25 \) (figure 4).

**Figure 4.** Simulation model of a two-winding transformer. Experience with \( K_Z = 0.25 \).

The results of calculations and the values obtained using the model with load factors equal to: 0.25, 0.5, 0.75, 1, we will enter in table 2

| Load factor | \( K_Z \) | 0.25 | 0.5 | 0.75 | 1 |
|-------------|---------|------|-----|------|---|
| Full power  | \( S, \text{kVA} \) | 25   | 50  | 75   | 100 |
| Active power| \( P, \text{kW} \)   | 20.75| 41.5| 62.25| 83  |
| Reactive power| \( Q, \text{kvar} \) | 13.94| 27.88| 41.83| 55.77 |

Estimated values

| Loss of electricity | \( \Delta P, \text{W} \) | 413.13| 782.5| 1398.13| 2260 |

Values obtained in the simulation

| Loss of electricity | \( \Delta P, \text{W} \) | 415 | 771.18| 1345.77| 2125.83 |

Let's build a graph of the dependence of electricity losses in the transformer on the load factor (figure 5).
4. Conclusion

Based on the calculated data, simulation modeling of a three-phase voltage transformer was performed. As a result of the experiments, a graph of the dependence of electricity losses in the transformer was built for various load factors. The graph shows that with an increase in the load factor, losses increase, while the dependence is non-linear.

Transformer substations are an important link in rural electrical networks. In this regard, modeling of transient processes is an important task. The simulation results will allow you to choose the right equipment, evaluate the impact of various transients on the quality of power supply, and choose compensating devices.

References

[1] Kostyuchenko L P 2012 Simulation modeling of rural power supply systems in the MATLAB program (Krasnoyarsk: KSAU) 215
[2] Dyakonov V P and Penkov A A 2009 MATLAB and Simulink in the power industry. (Moscow: Hotline - Telecom) 816
[3] Lurie M S and Lurie O M 2010 Electrical engineering. Simulation modeling in a laboratory workshop, course and diploma design (Krasnoyarsk: SibGTU) 2 150
[4] Leschinskaya T B and Naumov I V 2015 Agricultural power supply: textbook (Moscow: Bbcom, Translog) 656
[5] Chernyhkh I V 2008 Modeling of electrical devices in MATLAB, SimPowerSystems and Simulink (Moscow: DMK Press; St. Petersburg: Peter) 288
[6] Lykin A V 2009 Mathematical modeling of electrical systems and their elements (Novosibirsk: Publishing House of NSTU) 2 228
[7] Kryukov A V 2014 Modeling of power supply systems (Irkutsk: IrGUUPS) 142
[8] Vinogradov A V, Zaginailov V I and Mamedov T A 2020 "Consumer input-metering and distribution device as an element of power supply systems with distributed generation 0.4 kV". International technical and economic journal 6 22-30
[9] Mishuchkov V I, Pushkareva M B and Belov S I 2021 «Smart Metering and Scheduling of Electrical Loads of Buildings», Journal of Physics 2096 012132
[10] Leshtayev O V, Stushkina N A, Zaginailov V I and Sergeeva N A 2020 "Solar power station model in Matlab Simulink program". International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE) 1-5
[11] Mammadov T A and Zaginailov V I 2019 "Generalized assessment of the energy efficiency of centralized power supply and production." Energy security and energy saving 3 33-6