



Parameter Identification of Equivalent T-Circuit of Three Phase Transformers Using Real Time Measurements

Hasan Dirik^{1*}, Cenk Gezeğin²

^{1,*} Sinop University, Vocational School, Department of Electric and Energy, Sinop, Turkey

²Ondokuz Mayıs University, Engineering Faculty, Electrical and Electronics Engineering, Samsun, Turkey

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Abstract

Transformers are monitored for various purposes such as monitoring losses, stability analysis, and fault prediction. An equivalent circuit model consisting of passive elements is usually used for this aim. Steinmetz's transformer model has the ability to represent well the behavior of transformers at low frequencies. In this study, a new method to obtain the Steinmetz model parameters of a 3-phase transformer under load is presented. In the method, calculations are done by considering each leg of a 3-phase transformer as equivalent to a single-phase transformer. The calculations use the current and voltage of the winding in each leg as input parameters. Equations of the method are given first for single-phase transformer and then for 3-phase transformers with Δ/Δ and Δ/Y connections. Since it is not possible to measure the winding currents on the delta connected side in practice, a new method to obtain winding currents using line currents is also given in this paper. The validity and accuracy of the method has been demonstrated by the simulation studies carried out in Matlab/Simulink environment.

Key words: Transformer monitoring, parameter identification, delta-star connected, real time monitoring

1. Introduction

Monitoring of transformers, which is one of the important and expensive equipment of power systems, is a popular topics of recent years. Generally, an equivalent circuit model is used for monitoring. Equivalent circuits of transformers are copies of transformers, usually consisting of passive circuit elements that can represent linear or non-linear behaviors of them under various conditions. The methods used in transformer monitoring are usually based on calculating the parameters of a transformer model from offline measurements or online operating data. Monitoring of these parameters is mostly done for the purposes such as stability analysis, monitoring of losses, improvement of design or fault diagnosis. At this point, the equivalent circuit used in monitoring is vital. In order to predict the behavior of a transformer in a power system, the equivalent circuit of the transformer and the values of its parameters are needed. Furthermore, the equivalent circuit parameters of the transformer must be known for the analysis of circuits containing transformers. The dynamic behavior of transformers in some cases such as inrush, saturation, ferroresonance can be examined using a nonlinear

model [1-3]. Linear models are sufficient to analyze non-dynamic behavior.

The approaches used in the literature to obtain equivalent circuit parameters are based on either the data of the experiments carried out in the laboratory environment [4] or the calculations over the design/label values [5-6]. However, it is not possible to conduct experiments by separating the currently operating transformer from the system it is connected to, and the design parameters of most transformers are not available [4]. An important approach for obtaining parameters is to use an optimization technique. Practical Swarm Optimization [7], Genetic Algorithm [8], Imperialist Competitive Algorithm [9], Gravitational Search Algorithm [9], Bacterial Foraging Algorithm [10], Artificial Bee Colony Algorithm [11] and Chaotic Optimization Approach [4] are some of them. Some other methods used to obtain transformer parameters are the finite element method [12], frequency response analysis [3], gray box modeling [13] and state space approach [14]. However, these methods are not easy to apply to a transformer as it is mostly under load. Although there are many studies proposed for the parameter

* Corresponding author:

Email: hasan_dirik@hotmail.com

estimation of transformer operating under load [6, 7, 15-19], single-phase transformers are considered in these methods.

The most well-known transformer model in the literature is the one developed by Steinmetz [20]. This model is well representative of the behavior of the transformer at low frequencies. The well-known classical way to obtain the parameters of the Steinmetz model is to apply open-circuit and on-load experiments to the transformer. A major disadvantage of this method is that experiments can only be performed offline.

In this study, a new method is presented that enables the equivalent circuit parameters of 3-phase transformers to be obtained using real-time operating data. The prominent advantages of the method are that it can be applied to transformers under load using real operating data, that it does not require transformer design parameters, and that it can be applied to 3-phase transformers. The method is developed by considering each leg of the 3-phase

transformer as a single-phase transformer. The equations used in the calculations are given for the single-phase transformer first and then for the star-star and delta-star connected transformers respectively. Calculations are made using primary and secondary winding currents and voltages on the windings. In practice, since it is not possible to measure the winding currents of the delta connected side; a method for the calculation of the winding currents using line currents is also given. The performance of the method has been demonstrated by the simulations made in Matlab/Simulink environment. The results clearly showed that the method can calculate Steinmetz parameters of 3-phase transformers very well.

2. Computation of Equivalent Circuit Parameters of Single Phase Transformer

A similar method given in this section is also given in [15] and [16]. Consider the equivalent T-circuit of a single-phase transformer given in Figure 1.

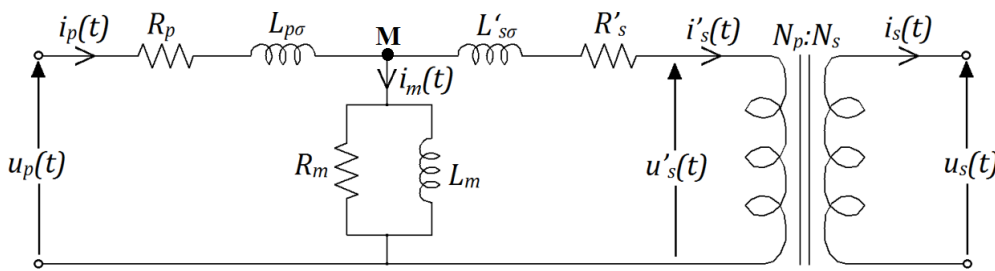


Figure 1. Equivalent T-circuit of single-phase transformer

Let's assume that the primary and secondary side voltages and currents (u_p , i_p , u_s and i_s) of a transformer operating under a certain load are

sampled with a sampling period T_s . Vectors of sampled voltages and currents will be as follows

$$u_p = [u_p(t_0), u_p(t_1), \dots, u_p(t_{N-1}), u_p(t_N)] \tag{1}$$

$$i_p = [i_p(t_0), i_p(t_1), \dots, i_p(t_{N-1}), i_p(t_N)] \tag{2}$$

$$u_s = [u_s(t_0), u_s(t_1), \dots, u_s(t_{N-1}), u_s(t_N)] \tag{3}$$

$$i_s = [i_s(t_0), i_s(t_1), \dots, i_s(t_{N-1}), i_s(t_N)] \tag{4}$$

Where N is the number of samples taken during a fundamental period T . The conversion of u_p to complex form that consists of only two numbers can

be done with the help of a component decomposition technique by the following equations:

$$U_{px} = \frac{1}{N \sin\left(\frac{\omega T_s}{2}\right)} \sum_{k=1}^N \left[(u_p(t_k) - u_p(t_{k-1})) \left(\cos(\omega t_k) \cos\left(\frac{\omega T_s}{2}\right) + \sin(\omega t_k) \sin\left(\frac{\omega T_s}{2}\right) \right) \right] \tag{5}$$

$$U_{py} = \frac{1}{N \sin\left(\frac{\omega T_s}{2}\right)} \sum_{k=1}^N \left[(u_p(t_k) - u_p(t_{k-1})) \left(\cos(\omega t_k) \sin\left(\frac{\omega T_s}{2}\right) - \sin(\omega t_k) \cos\left(\frac{\omega T_s}{2}\right) \right) \right] \quad (6)$$

$$U_p = U_{px} + jU_{py} \quad (7)$$

The last three equations are derived from equations of the individual harmonic extraction method given in [21]. The same calculations can be made for I_p , U_s , and I_s and obtained in the form of complex numbers. These values in complex numbers are used in the calculation of the winding parameters of the single-phase transformer. For this, let's consider Figure 1. First, the secondary side of the transformer voltage and current values are referred to primary side using the turn ratio r by the following equations:

$$r = \frac{N_p}{N_s} \quad (8)$$

$$U_s' = r \cdot U_s \quad (9)$$

$$I_s' = \frac{I_s}{r} \quad (10)$$

Parameters R_m and X_m seen in Figure 1 are magnetization parameters and have very large values besides the winding parameters (R_p , $L_{\sigma p}$, R_s' and $L_{\sigma s}'$). Therefore, the magnetizing current (i_m) can be neglected. In this case, the averages of the primary and secondary currents can be used as the winding current. Therefore, the voltage difference from primary to secondary can be written as:

$$U_p - U_s' = \left(\frac{I_p + I_s'}{2} \right) \left[(R_p + R_s') + j(X_{\sigma p} + X_{\sigma s}') \right] \quad (11)$$

Stating total winding impedance (Z_t) by

$$Z_t = R_t + jX_{t\sigma} = (R_p + R_s') + j(X_{\sigma p} + X_{\sigma s}') \quad (12)$$

total winding resistance (R_t) and total leakage reactance ($X_{t\sigma}$) can be obtained by the following equation.

$$R_t = \text{Re} \left[\frac{2(U_p - U_s')}{I_p + I_s'} \right] \quad (13)$$

$$X_{t\sigma} = \text{Im} \left[\frac{2(U_p - U_s')}{I_p + I_s'} \right] \quad (14)$$

Assuming that the parameters of primary side and the secondary side reduced to primary are equal ($R_p = R_s'$ and $X_{\sigma p} = X_{\sigma s}'$), the equivalent circuit parameters can be calculated with the following two equations.

$$R_p = R_s' = \text{Re} \left[\frac{U_p - U_s'}{I_p + I_s'} \right] \quad (15)$$

$$X_{\sigma p} = X_{\sigma s}' = \text{Im} \left[\frac{U_p - U_s'}{I_p + I_s'} \right] \quad (16)$$

From Figure 1., voltage at the point M can be expressed as

$$U_m = \frac{U_p + U_s'}{2} \quad (17)$$

Also, magnetizing current (I_m) will be equal to difference between the currents I_p and I_s' :

$$I_m = I_p - I_s' \quad (18)$$

The impedance (Z_m) of the magnetizing branch in the equivalent T-circuit is obtained by dividing the voltage by the current:

$$Z_m = \frac{U_m}{I_m} = \frac{U_p + U_s'}{2(I_p - I_s')} \quad (19)$$

The real and imaginary components of the impedance will give the series R-L values:

$$R_{sm} = \text{Re}[Z_m] \tag{20}$$

$$X_{sm} = \text{Im}[Z_m] \tag{21}$$

Finally, the following equations are used for the conversion to parameters consisting of parallel connected R-L elements.

$$R_m = \frac{R_{sm}^2 + X_{sm}^2}{R_{sm}} \tag{22}$$

$$X_m = \frac{R_{sm}^2 + X_{sm}^2}{X_{sm}} \tag{23}$$

3. Computation of Equivalent Circuit Parameters of Three Phase Transformer

Since the primary and secondary windings on each leg of three-phase transformers are exposed to the same magnetic flux as in single-phase transformers, each leg of a three-phase transformer can be considered as a single-phase transformer. In practice,

it is not always possible to directly measure the current flowing through each winding of 3-phase transformers and the voltage across the windings. However, the current and voltage of each winding should be used for the correct calculation of the parameters. In star-connected windings, line currents are equal to winding currents and can be measured directly, but this is not possible in delta-connected windings. Similarly, while the phase-to-phase voltage in delta-connected windings is also equal to voltage on winding, it is not possible to directly measure the winding voltage in star-connected windings whose star point is not present. Therefore, in this section, it is discussed how to obtain equivalent circuit parameters by the line currents and phase-to-phase voltages of transformer. For this aim, two different transformers with λ/λ and Δ/λ connections, which are frequently used, are considered.

3.1. Star-Star Connected Transformer

Let's consider the circuit diagram of the star-star connected transformer given in Figure 2-a.

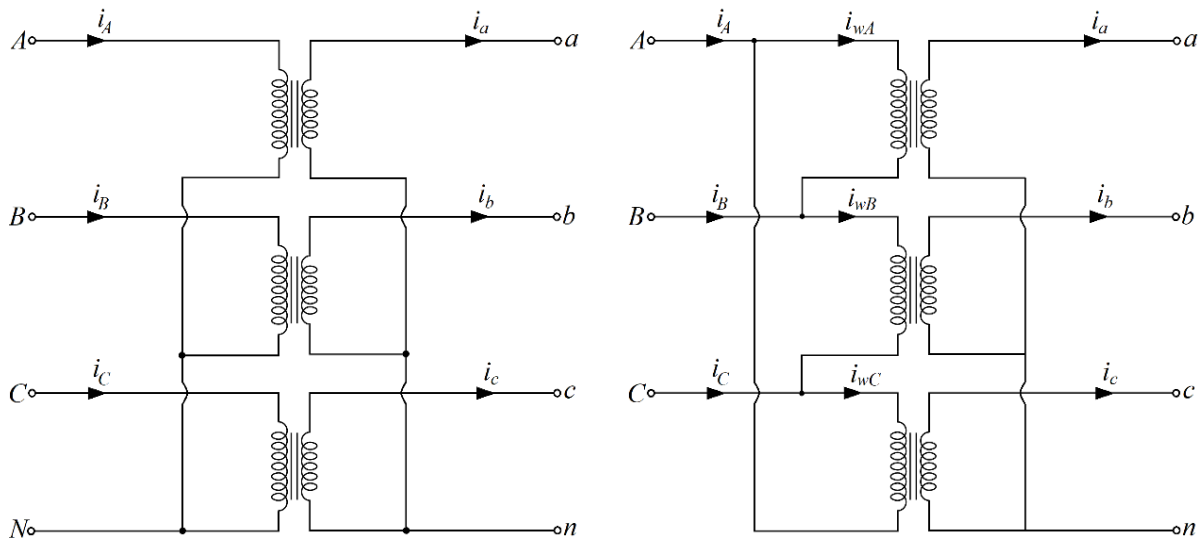


Figure 2. Winding structure of transformers with λ/λ and Δ/λ connection groups

By considering the windings on each leg of the transformer as a single-phase transformer, parameters can be obtained for each leg separately. To do this, the primary and secondary side voltages of the transformer must be measured as phase to neutral ($u_{AN}, u_{BN}, u_{CN}, u_{an}, u_{bn}$ and u_{cn}). Also, the line (or winding) currents (i_A, i_B, i_C, i_a, i_b and i_c) must be measured. The sampled voltages and currents are converted to complex values denoted by $U_{AN}, U_{BN},$

$U_{CN}, U_{an}, U_{bn}, U_{cn}, I_A, I_B, I_C, I_a, I_b$ and I_c using equations (5), (6) and (7). From these values, the secondary side currents and voltages are referred to the primary side with the help of equations (12) and (13), and the values $U'_{an}, U'_{bn}, U'_{cn}, I'_a, I'_b$ and I'_c are obtained. Finally, using these complex values, the equivalent circuit parameters can be calculated respectively for each leg of the transformer with the help of the following equations:

$$R_A = R_a' = \text{Re} \left[\frac{U_{AN} - U_{an}'}{I_A + I_a'} \right] \tag{24}$$

$$R_B = R_b' = \text{Re} \left[\frac{U_{BN} - U_{bn}'}{I_B + I_b'} \right] \tag{25}$$

$$R_C = R_c' = \text{Re} \left[\frac{U_{CN} - U_{cn}'}{I_C + I_c'} \right] \tag{26}$$

$$X_{\sigma A} = X_{\sigma a}' = \text{Im} \left[\frac{U_{AN} - U_{an}'}{I_A + I_a'} \right] \tag{27}$$

$$X_{\sigma B} = X_{\sigma b}' = \text{Im} \left[\frac{U_{BN} - U_{bn}'}{I_B + I_b'} \right] \tag{28}$$

$$X_{\sigma C} = X_{\sigma c}' = \text{Im} \left[\frac{U_{CN} - U_{cn}'}{I_C + I_c'} \right] \tag{29}$$

$$Z_{mA} = \frac{U_{AN} + U_{an}'}{2(I_A - I_a')} \tag{30}$$

$$Z_{mB} = \frac{U_{BN} + U_{bn}'}{2(I_B - I_b')} \tag{31}$$

$$Z_{mC} = \frac{U_{CN} + U_{cn}'}{2(I_C - I_c')} \tag{32}$$

$$R_{mA} = \frac{\text{Re}[Z_{mA}]^2 + \text{Im}[Z_{mA}]^2}{\text{Re}[Z_{mA}]} \tag{33}$$

$$R_{mB} = \frac{\text{Re}[Z_{mB}]^2 + \text{Im}[Z_{mB}]^2}{\text{Re}[Z_{mB}]} \tag{34}$$

$$R_{mC} = \frac{\text{Re}[Z_{mC}]^2 + \text{Im}[Z_{mC}]^2}{\text{Re}[Z_{mC}]} \tag{35}$$

$$X_{mA} = \frac{\text{Re}[Z_{mA}]^2 + \text{Im}[Z_{mA}]^2}{\text{Im}[Z_{mA}]} \tag{36}$$

$$X_{mB} = \frac{\text{Re}[Z_{mB}]^2 + \text{Im}[Z_{mB}]^2}{\text{Im}[Z_{mB}]} \tag{37}$$

$$X_{mC} = \frac{\text{Re}[Z_{mC}]^2 + \text{Im}[Z_{mC}]^2}{\text{Im}[Z_{mC}]} \tag{38}$$

3.2. Delta-Star Connected Transformer

Consider the circuit diagram of the delta-star connected transformer given in Figure 2-b. Here, a parallelism can be established between the equations of star-star and delta-star connected transformers in order to calculate the equivalent circuit parameters of the delta-star connected transformer. In fact, the main

difference between both transformers is that in star connection, the voltage on each primary winding is phase to neutral voltage, while in delta connection it is phase-phase voltage.

In addition, since it is not possible to measure the winding currents (I_{wA} , I_{wB} and I_{wC}) on the delta connected primary side, currents on the primary side winding must be calculated over the primary side line currents (I_A , I_B and I_C) and the secondary side winding currents (I_a' , I_b' and I_c') that are possible to be measured. For this aim, the following calculations are done. First, let's write the primary side winding currents as the sum of the secondary side winding currents and magnetizing currents (I_{mA} , I_{mB} and I_{mC}).

$$I_{wA} = I_a' + I_{mA} \tag{39}$$

$$I_{wB} = I_b' + I_{mB} \tag{40}$$

$$I_{wC} = I_c' + I_{mC} \tag{41}$$

Considering the connections in Figure 2, we can calculate the line currents of the delta connected side by the differences of the winding currents as follows.

$$I_A = I_{wA} - I_{wC} = I_a' - I_c' + I_{mA} - I_{mC} \tag{42}$$

$$I_B = I_{wB} - I_{wA} = I_b' - I_a' + I_{mB} - I_{mA} \tag{43}$$

In the last two equations the unknowns are I_{mA} , I_{mB} and I_{mC} . If the sum of these currents is assumed to be zero, a third equation necessary for the solution is written.

$$I_{mA} + I_{mB} + I_{mC} = 0 \tag{44}$$

Computing the unknowns from the last three equations, we have the followings:

$$I_{mA} = \frac{I_A - I_B - 2I_a' + I_b' + I_c'}{3} \tag{45}$$

$$I_{mB} = \frac{I_A + 2I_B + I_a' - 2I_b' + I_c'}{3} \tag{46}$$

$$I_{mC} = \frac{-2I_A - I_B + I_a' + I_b' - 2I_c'}{3} \tag{47}$$

Substituting the values found in (39)-(41) equations,

currents on the delta connected windings are obtained as follows,

$$I_{wA} = \frac{I_A - I_B + I_a' + I_b' + I_c'}{3} \quad (48)$$

$$I_{wB} = \frac{I_A + 2I_B + I_a' + I_b' + I_c'}{3} \quad (49)$$

$$I_{wC} = \frac{-2I_A - I_B + I_a' + I_b' + I_c'}{3} \quad (50)$$

Finally, the equations required for the calculation of the parameters can be written as follows, similar to the equations in the previous section.

$$R_A = R_a' = \text{Re} \left[\frac{U_{AB} - U_{an}'}{I_{wA} + I_a'} \right] \quad (51)$$

$$R_B = R_b' = \text{Re} \left[\frac{U_{BC} - U_{bn}'}{I_{wB} + I_b'} \right] \quad (52)$$

$$R_C = R_c' = \text{Re} \left[\frac{U_{CA} - U_{cn}'}{I_{wC} + I_c'} \right] \quad (53)$$

$$X_{\sigma A} = X_{\sigma a}' = \text{Im} \left[\frac{U_{AB} - U_{an}'}{I_{wA} + I_a'} \right] \quad (54)$$

$$X_{\sigma B} = X_{\sigma b}' = \text{Im} \left[\frac{U_{BC} - U_{bn}'}{I_{wB} + I_b'} \right] \quad (55)$$

$$X_{\sigma C} = X_{\sigma c}' = \text{Im} \left[\frac{U_{CA} - U_{cn}'}{I_{wC} + I_c'} \right] \quad (56)$$

$$Z_{mA} = \frac{U_{AB} + U_{an}'}{2(I_{wA} - I_a')} \quad (57)$$

$$Z_{mB} = \frac{U_{BC} + U_{bn}'}{2(I_{wB} - I_b')} \quad (58)$$

$$Z_{mC} = \frac{U_{CA} + U_{cn}'}{2(I_{wC} - I_c')} \quad (59)$$

$$R_{mA} = \frac{\text{Re}[Z_{mA}]^2 + \text{Im}[Z_{mA}]^2}{\text{Re}[Z_{mA}]} \quad (60)$$

$$R_{mB} = \frac{\text{Re}[Z_{mB}]^2 + \text{Im}[Z_{mB}]^2}{\text{Re}[Z_{mB}]} \quad (61)$$

$$R_{mC} = \frac{\text{Re}[Z_{mC}]^2 + \text{Im}[Z_{mC}]^2}{\text{Re}[Z_{mC}]} \quad (62)$$

$$X_{mA} = \frac{\text{Re}[Z_{mA}]^2 + \text{Im}[Z_{mA}]^2}{\text{Im}[Z_{mA}]} \quad (63)$$

$$X_{mB} = \frac{\text{Re}[Z_{mB}]^2 + \text{Im}[Z_{mB}]^2}{\text{Im}[Z_{mB}]} \quad (64)$$

$$X_{mC} = \frac{\text{Re}[Z_{mC}]^2 + \text{Im}[Z_{mC}]^2}{\text{Im}[Z_{mC}]} \quad (65)$$

4. Simulation Works

The proposed parameter identification method has been examined with simulations made in Matlab/Simulink environment. In Figure 3, the view of the Simulink file used in the examination is given. Here, a transformer with Δ - λ winding connection is used, and the mask parameters of this transformer of the Simulink model are shown in Figure 4. The "CALCULATIONS" block is the block where the calculations of the method are made, and the inner view of this block is given in Figure 5.

In each calculation step, 400 samples were obtained from each voltages and currents of the 3-phase transformer with a sampling frequency of 20 kHz. The simulation was carried out using both Δ - λ and λ - λ connections of the transformer. The real and simulated values are given in Table I. As can be seen from this table, the method can calculate the equivalent circuit parameters of the transformer almost perfectly for both connection types.

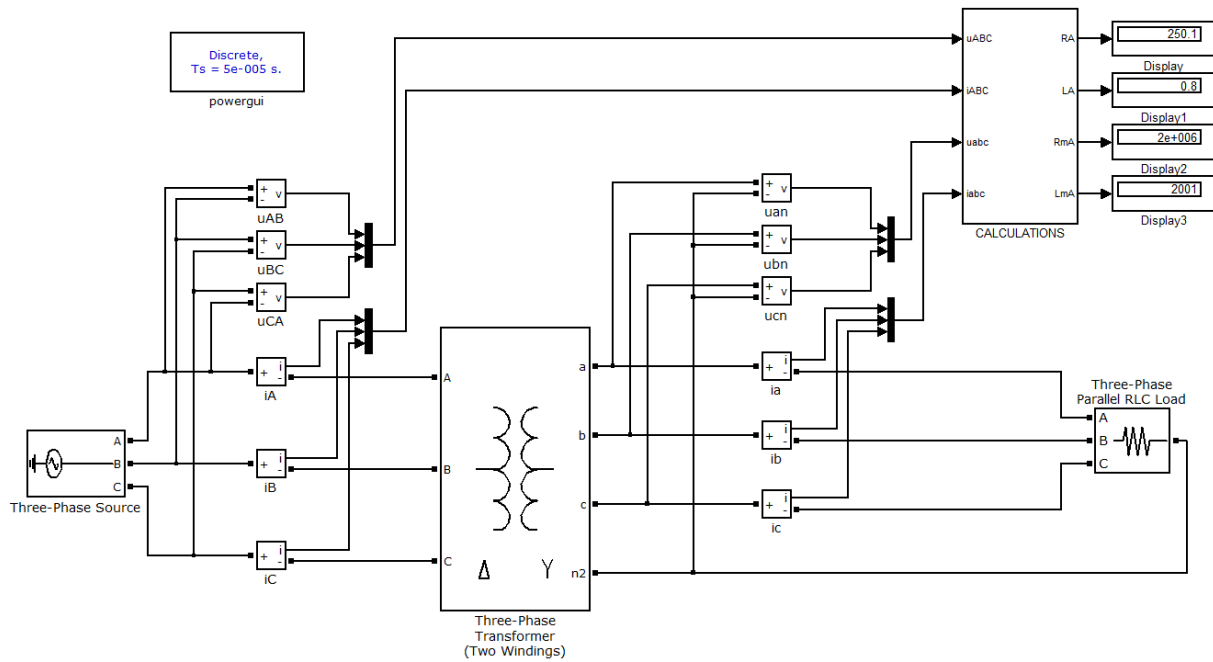


Figure 3. View of the Simulink file used in the simulation of the transformer

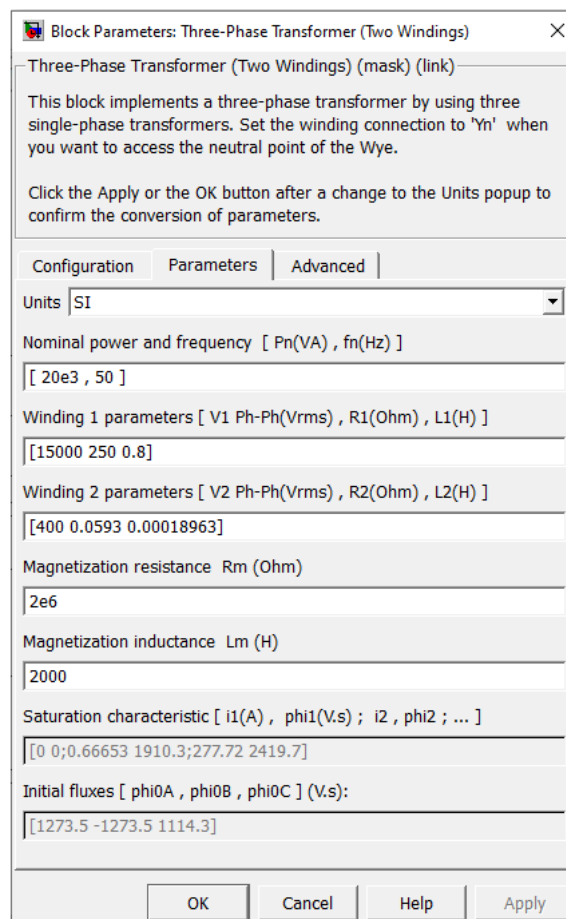


Figure 4. Matlab/Simulink parameters of the 3-phase transformer used in the simulations

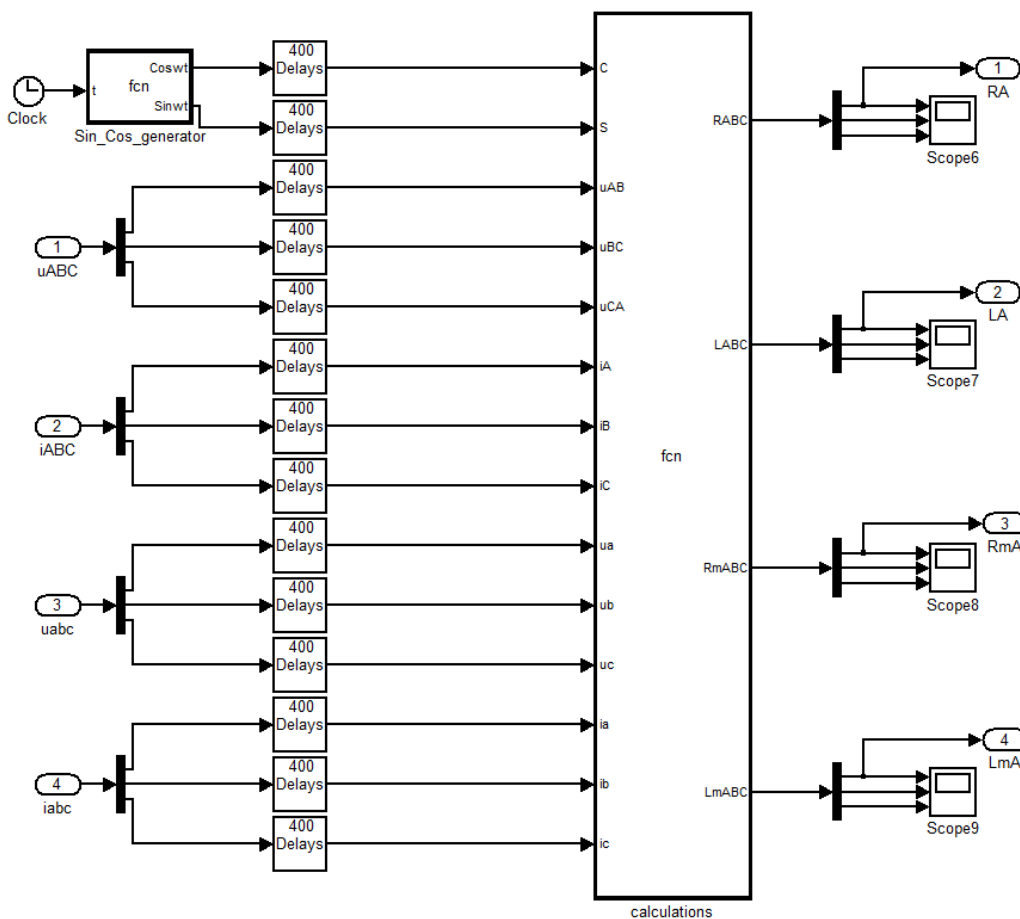


Figure 5. Internal view of the “CALCULATIONS” block

5. Conclusion and Discussion

Transformer monitoring is one of the important and popular topics of recent years. A model is usually used for monitoring. Steinmetz's linear model has the ability to well represent the behavior of transformers at low frequencies. The classical method used to obtain the Steinmetz model parameters of a transformer is to apply open-circuit and on-load tests to the transformer. However, since these tests require the transformer to be separated from the power system to which it is connected, it is not possible to apply this method to existing transformers. Almost all of the methods suggested in the literature to monitor the equivalent circuit parameters of the transformer are for single-phase transformers, and there is no method to monitor the Steinmetz model parameters of the 3-phase transformer in real time.

In this study, a new method is presented to obtain

parameters of Steinmetz's equivalent T-circuit model of 3-phase transformers operating under load. The method is developed by considering each leg of the 3-phase transformer as a single-phase transformer. The input variables of the method are the primary and secondary side voltage and currents. Calculations are made using the currents and voltages of the transformer windings. Since it is practically not possible to measure winding currents in delta-connected windings, a new method to calculate winding currents by line currents is presented in this paper. In the method, the sampled voltage and current values are first converted to complex values with the help of a complex number conversion process and parameter calculations are made with complex numbers. The validity of the method was evaluated with the help of simulation studies in Matlab/Simulink environment and its accuracy was clearly demonstrated.

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