A Monitoring Method for AC Winding Resistance of Distribution Transformers Using Terminal Measurements

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Abstract: Transformers are vital and expensive components of power systems. Therefore, monitoring of transformers has become one of the most important issues in recent years. With the transformer monitoring systems, it is generally aimed to detect transformer faults, to determine the remaining life, to measure losses and to see whether the winding temperatures are under the specified limits. For this aim, one of the most important parameters that must be measured is the AC resistance of transformer windings. In this paper, a new method that provides to monitor AC winding resistance for this purpose has been described. The method that has been developed by considering the equivalent circuit of transformer uses voltages and currents of both sides of single and three-phase transformers. In the paper, firstly, mathematical background of the presented method explained and steps of procedure have been given. Then, results of a simulation work that has been done in Matlab/Simulink environment and experimental works have been executed on two distribution transformers have been presented. Lastly, the results are interpreted. Results of simulation and experiments clearly demonstrate that the method allows accurate monitoring of AC resistances of transformer windings and can be used in such monitoring systems.

Keywords: AC resistance, distribution transformer, equivalent circuit of transformer, real time monitoring.

I. INTRODUCTION

The current density of a conductor in which the direct current (DC) flows is the same throughout the cross section. However, if the current flowing in the same conductor is alternating current (AC), the density of current flowing in the conductor increases in the outer portions and decreases in the inner portions due to the skin and the proximity effects. This causes an increase in the active resistance of the conductor. This increase also depends on the frequency of the flowing currents. This resistance is called AC resistance of conductor. Therefore, the losses caused by the currents flowing through the windings of the transformers, which are the most important parts of AC power systems, increase. This means that transformer load losses (copper losses) are closely related to their AC winding resistance [1]-[3]. Taking this relation into account, two studies aiming to reduce the AC resistance values and hence the losses in the design stage of the transformers can be reached in [4] and [5]. The AC resistance of windings also gives important information about the condition of the transformer windings. There is also a close relationship between the deformation occurring in the transformer windings and the AC resistance. There are a number of studies in the literature to monitor the state of the windings via the short-circuit impedance (it includes the AC resistance of windings) of the transformers [6], [7]. In these studies, it is assumed that the AC resistance of windings changes depending on the frequency. However, due to the temperature increase during real-time operation, it is expected that the DC resistance of windings and accordingly AC resistance of the winding are changed. In addition, real-time monitoring of this change will increase the usability of methods for the detection of winding faults and the condition monitor. Therefore, in this study, a new method for the monitoring of AC resistances of transformer windings during real time operation is presented. The mathematical equations used by the method are given for both single-phase and three-phase transformers. The simulations and experimental works that have been done clearly demonstrated the validity of the method.

II. AC RESISTANCE OF TRANSFORMER WINDINGS

As is known, the ohmic loss in a conductor is equal to the multiplication of the square of the current flowing through it and the resistance value of the conductor. This equality is completely true if the flowing current is DC. But this equation will not be true with the same DC current value if the flowing current is AC. Thus, in order to maintain this equality, it is necessary that the value of winding resistance should be greater than the value of winding resistance measured by the application of DC voltage. Although the current density of a conductor carrying DC current is uniform throughout the its cross section, when the same conductor carries AC, the current density does not remain the same throughout the cross section of the conductor. The main reasons for phenomena are the proximity and skin effects. These effects cause a decrease in current density from the surface of the conductor to the center and a decrease in effective cross section of the conductor used. This means that the resistances (R_{ac} and R_{dc}) of the conductors while carrying AC and DC currents are different. This difference is more evident in the large power transformers due to the greater effects of the proximity and skin effects. The increase in the winding resistance of transformers due to skin and proximity effects is called stray resistance (R_s). Thus, for the value of this resistance, the following equation is valid.

$$R_s = R_{ac} - R_{dc} \tag{1}$$

According to IEC, Eddy and other stray losses outside the DC losses (P_{dc}) are called additional losses [8]. The same losses are called stray losses according to IEEE [9]. That is, copper losses (or load losses, P_{LL}) of a transformer windings caused by their DC resistance are called ohmic losses, while additional losses caused by stray resistance are called stray losses (P_s).

The copper losses change in proportion to the square of the winding current (I_w). Therefore, the following equation can be written.

$$P_{LL} = I_w^{\,2} \cdot \left(R_{dc} + R_s\right) \tag{2}$$

Some studies on transformer losses showed that the resistance R_s which is a result of stray losses changes with the harmonic content of the winding currents of transformers. This also means the resistance R_{ac} of transformer windings changes depending on the harmonic content of winding currents [10], [11]. Thus, provided that the effective value of the winding current in equation (2) is the same, the load losses caused by the harmonic current will be greater than those in the case without harmonics. Therefore, it can be seen that the resistance R_s changes depending on the harmonic content of the current. In this study, resistance values that correspond to only fundamental frequency component of the winding current are taken into consideration, because it is intended to determine the winding AC resistances independently of the harmonic components of the current. Accordingly, for the resistances to be obtained by using only the fundamental frequency components of current and voltage, equation (3) can be written.

$$R_{ac1} = R_{dc} + R_{s1} \tag{3}$$

The subscripts ***1*** of each resistance in the last equation represent the fundamental frequency components.

III. Computation of Ac Resistances of Single-Phase Transformer Windings

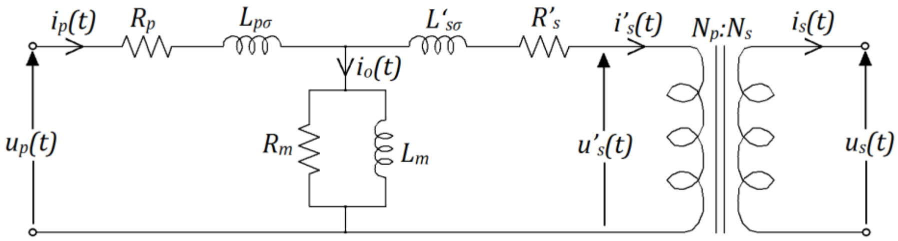

Fig. 1. Equivalent circuit of single-phase transformer

Let us consider the equivalent circuit of single-phase transformers given in Fig. 1. By using voltage and current of secondary side (u_s(t) and i_s(t)) in (4) and (5), voltage and current values of secondary side referred to the primary side (u'_s(t) and i'_s(t)) can be obtained.

$$u'_s(t) = t \cdot u_s(t) \tag{4}$$

$$i'_s(t) = i_s(t) / t \tag{5}$$

In these equations, the variable *t* represents the turns ratio of transformer and it is equal to the ratio of number of primary turns to the ratio of number of secondary turns.

$$t = N_p / N_s \tag{6}$$

Voltages and currents of the primary side and the secondary side referred to the primary side are given to DFT (Discrete Fourier Transform) as input to obtain amplitudes and phase angles of their fundamental frequency components. That is, amplitudes and phase angles of voltages and currents are found with DFT as $u_{p1} = U_{p1}\angle\alpha_{p1}$, $i_{p1} = I_{p1}\angle\beta_{p1}$, $u'_{s1} = U'_{s1}\angle\alpha_{s1}$ ve $i'_{s1} = I'_{s1}\angle\beta_{s1}$. For the voltage drop between the terminals of transformer windings, the following equation can be written by considering the equivalent circuit of transformer given in Fig. 1.

$$u_{p1} - u'_{s1} = i_{p1}Z_{p1} + i'_{s1}Z'_{s1} \tag{7}$$

Here, the variables Z_{p1} and Z'_{s1} represent the fundamental component impedances of primary winding and secondary winding referred to the primary side respectively. The current i_o in the equivalent circuit is the no-load current of the transformer and is very small as compared to the nominal currents. Therefore this current can be neglected in distribution transformers. Thus, the currents i_{p1} and i'_{s1} can be considered to be equal. In order to minimize the error caused due to this assumption, instead of both currents their averages can be used. By doing so in (7), the following equation is obtained.

$$u_{p1} - u'_{s1} = \frac{i_{p1} + i'_{s1}}{2}\left(Z_{p1} + Z'_{s1}\right) \tag{8}$$

Total impedance in the right side of the last equation is the total AC impedance of transformer windings (primary and secondary side windings) seen by the primary. If we denote it by Z_{ac1}, then it can be found by the following equation.

$$Z_{ac1} = \frac{2(u_{p1} - u'_{s1})}{i_{p1} + i'_{s1}} \tag{9}$$

Real part of this impedance is equal to the AC resistance (R_{ac1}) of total windings seen by the primary side of transformer. Therefore, total AC resistance of windings can be found using fundamental components of voltages and currents as in (10).

$$R_{ac1} = \mathrm{Re}\left[\frac{2(u_{p1} - u'_{s1})}{i_{p1} + i'_{s1}}\right] \tag{10}$$

This equation provides to obtain AC resistance of a single-phase transformer from the measured voltages and currents during real time operation.

IV. Computation of AC Resistances of Three-Phase Transformer Windings

Since both primary and secondary windings of the three-phase transformers are exposed to the same magnetic flux as they are in the single-phase transformers, each limb of a three-phase transformer can be considered as a single-phase transformer. In practice, it is not always possible to measure the currents and voltages on each winding of 3-phase transformers. For accurate computation, the voltage and current of each winding of transformer must be used. In three-phase windings with star-connection, line currents are equal to the winding currents. This allows the measurement of current flowing in the winding. But, this is not possible in winding with delta-connection. Similarly, since the phase to phase voltages are equal to voltage on the each winding, the voltages between terminals of each winding can be easily measured. But, in windings with star connection and without neutral conductor, it is not possible to measure the voltage on the windings from terminals. Thus, it is explained the method to obtain the AA winding resistance through the line currents and phase-to-phase voltages of the transformer in this section. For this aim, two different transformers with star-star and delta-star connections, which are frequently used, have been considered. The winding structures of the transformers for both connection groups are given in Fig 2.

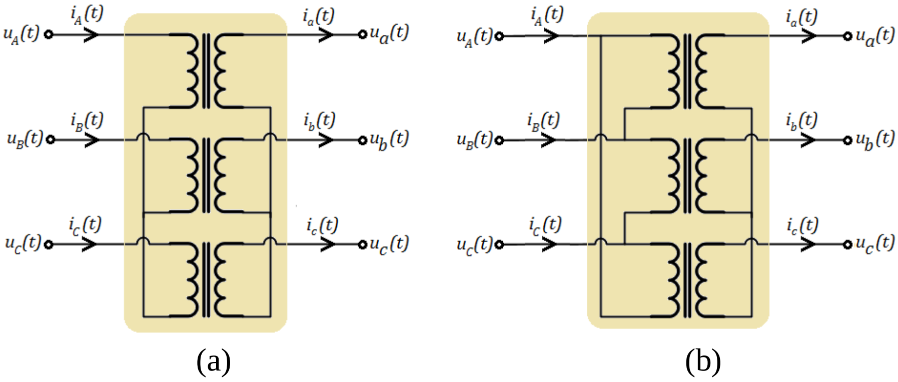

Fig. 2. Winding structures of transformers with star-star and delta-star connection

A. Star-Star Connected Transformers

Equivalent winding structure of star-star connected transformer is given in Fig. 2. We can consider each limb of this transformer as a single-phase transformer. Here, fundamental impedance components of each winding of limbs are Z_{Aac1}, Z_{Bac1} and Z_{Cac1} respectively. Therefore, the equations used in single-phase transformers can be written in the form of equations (11) - (13).

$$u_{AN1} - u'_{an1} = Z_{Aac1} \frac{i_{A1} + i'_{a1}}{2} \tag{11}$$

$$u_{BN1} - u'_{bn1} = Z_{Bac1} \frac{i_{B1} + i'_{b1}}{2} \tag{12}$$

$$u_{CN1} - u'_{cn1} = Z_{Cac1} \frac{i_{C1} + i'_{c1}}{2} \tag{13}$$

These equations provide the computation of AC winding resistances of each limb (R_{Aac1}, R_{Bac1} and R_{Cac1}) as in (14)-(16).

$$R_{Aac1} = \mathrm{Re}\left[\frac{2\left(u_{AN1} - u'_{an1}\right)}{i_{A1} + i'_{a1}}\right] \tag{14}$$

$$R_{Bac1} = \mathrm{Re}\left[\frac{2\left(u_{BN1} - u'_{bn1}\right)}{i_{B1} + i'_{b1}}\right] \tag{15}$$

$$R_{Cac1} = \mathrm{Re}\left[\frac{2\left(u_{CN1} - u'_{cn1}\right)}{i_{C1} + i'_{c1}}\right] \tag{16}$$

If we want to use the last three equations, it is necessary to measure 6 different phase-neutral voltages of the transformer. But, in practice, phase-phase voltages are usually measured instead of phase-neutral voltages. Due to this fact, a second alternative approach for the obtaining AC winding resistances using 4 phase-phase voltage measurements is presented. Let us suppose that the voltages $u_{AC}(t)$, $u_{BC}(t)$, $u_{ac}(t)$, $u_{bc}(t)$ and currents $i_A(t)$, $i_B(t)$, $i_a(t)$, $i_b(t)$ are measured simultaneously from the primary and secondary side of the transformer in Fig. 2-a. If voltages and currents of secondary side of the transformer are referred to the primary side by using turns ratio of transformer as in (4) and (5), the values of $u'_{ac}(t)$, $u'_{bc}(t)$, $i'_a(t)$ and $i'_b(t)$ are obtained. Then, the fundamental frequency components of voltages and currents (u_{AC1}, u_{BC1}, u'_{ac1}, u'_{bc1} and i_{A1}, i_{B1}, i'_{a1}, i'_{b1}) are found using DFT in terms of amplitudes and phase angles. If we subtract (13) from both (11) and (12), we obtain the equations (17) and (18).

$$u_{AC1} - u'_{ac1} = \frac{i_{A1} + i'_{a1}}{2} Z_{Aac1} - \frac{i_{C1} + i'_{c1}}{2} Z_{Cac1} \tag{17}$$

$$u_{BC1} - u'_{bc1} = \frac{i_{B1} + i'_{b1}}{2} Z_{Bac1} - \frac{i_{C1} + i'_{c1}}{2} Z_{Cac1} \tag{18}$$

In the last two equations, there are three unknown variable (Z_{Aac1}, Z_{Bac1} and Z_{Cac1}) in two equations. In this stage, in order to solve this problem, we will assume that the winding impedances of outer limps (limb A and limb C) of transformer have the same values. With this assumption, the number of unknown variables will be reduced to two. This assumption, in fact, is true, due to the symmetrical structure of three-phase transformer. Thence, these two equations can be easily solved and give two AC resistances ($R_{Aac1} = R_{Cac1}$ and R_{Bac1}) as in (19) and (20).

$$R_{Aac1} = R_{Cac1} = \mathrm{Re}\left[\frac{2\left(u_{AC1} - u'_{ac1}\right)}{\left(2i_{A1} + i_{B1}\right) + \left(2i'_{a1} + i'_{b1}\right)} \right] \tag{19}$$

$$R_{Bac1} = \mathrm{Re}\left[\frac{2}{\left(i_{B1} + i'_{b1}\right)} \left(\left(u_{BC1} - u'_{bc1}\right) - \frac{\left(i_{A1} + i_{B1} + i'_{a1} + i'_{b1}\right)\left(u_{AC1} - u'_{ac1}\right)}{2i_{A1} + i_{B1} + 2i'_{a1} + i'_{b1}} \right) \right] \tag{20}$$

B. Delta-Star Connected Transformers

Let us consider the circuit of delta-star connected transformer given in Fig. 2-b. According to circuit structure, it is not possible to measure the winding currents from transformer terminals on the delta connected side of windings. It is also not possible to obtain winding currents using line currents. Meanwhile, by considering equivalent circuit of single phase transformers, no-load current of a transformer is equal to the difference between the currents of primary and secondary sides. In real, no-load currents of transformers are too small as compared to the winding currents and thus these currents can be neglected. No-load currents of distribution transformers are usually smaller than 0.5% of nominal currents. Therefore, in the computation of winding resistances from real time data, winding currents of delta connected side are not considered and it is assumed that the primary side currents equal to the secondary side currents.

Here, the equations to be used in the calculation of AC resistances of windings can be written in a format similar to the equations of star-star connected transformers.

$$u_{AB1} - u'_{an1} = Z_{Aac1} \cdot i'_{a1} \tag{21}$$
$$u_{BC1} - u'_{bn1} = Z_{Bac1} \cdot i'_{b1} \tag{22}$$
$$u_{CA1} - u'_{cn1} = Z_{Cac1} \cdot i'_{c1} \tag{23}$$

Hereby, subtracting (23) from (21) and (22) yield the following two equations.

$$2u_{AC1} - u_{BC1} + u'_{ac1} = Z_{Aac1} i'_{a1} - Z_{Cac1} i'_{c1} \tag{24}$$
$$u_{BC1} + u_{AC1} - u'_{bc1} = Z_{Bac1} i'_{b1} - Z_{Cac1} i'_{c1} \tag{25}$$

There are three unknown variable (Z_{Aac1}, Z_{Bac1} and Z_{Cac1}) in the last two equations. These equations can be solved if we reduce the number of unknown variables by assuming that $Z_{Aac1} = Z_{Cac1}$ in the basis of the information given in the previous section. In this condition, the desired AC resistances can be computed by solving the subjected equations and taking real parts as in (26) and (27).

$$R_{Aac1} = R_{Cac1} = \mathrm{Re}\left[\frac{2u_{AC1} - u_{BC1} + u'_{ac1}}{2i'_{a1} + i'_{b1}}\right] \tag{26}$$
$$R_{Bac1} = \mathrm{Re}\left[\frac{1}{i'_{b1}}\left(u_{BC1} + u_{AC1} - u'_{bc1} - (2u_{AC1} - u_{BC1} + u'_{ac1})\frac{i'_{a1} + i'_{b1}}{2i'_{a1} + i'_{b1}}\right)\right] \tag{27}$$

V. Simulation and Experimental Works

In this chapter, a simulation that has been done in the Matlab/Simulink environment and experimental works that have been done on two different distribution transformers have been given. Simulation of developed method has been done on linear transformer model. Nominal values of transformer that used in the simulation are 1-phase, 1000 VA, 50 Hz, 220 V/22 V, R_p=0.2 Ω, R'_s=0.002 Ω, $L_{p\sigma}$=10 mH, $L'_{s\sigma}$=0.1 mH, R_m=400 Ω and L_m=10 H. Simulation has been executed by connecting a resistance with 5 Ω to the secondary side winding and by applying the voltage in the Fig. 3 to the primary side winding of transformer. In the simulation, voltages and currents of both sides of transformer measured and the series winding resistance (the total of primary to secondary winding resistances, AC resistance) of transformer has been computed by using the method explained above. As can be seen in Fig. 3, applied voltage is pure sinusoidal in the first 0.1 second while it consist of harmonics in the time interval of 0.1-0.2 seconds. This voltage has been increased at the time instant of 0.2 second. The AC winding resistance is computed as 0.4 Ω throughout the simulation except for the transition moments as can be seen in Fig 3. Actual series winding resistance (AC resistance) must be 0.2+0.002x $(220/22)^2$=0.4 Ω. Therefore, the simulation done in Matlab / Simulink environment shows that the presented method can accurately calculate the series winding resistance using real time current and voltage data. This also means that series winding resistance (AC resistance) of a transformer can be theoretically found correctly by using real time terminal measurements.

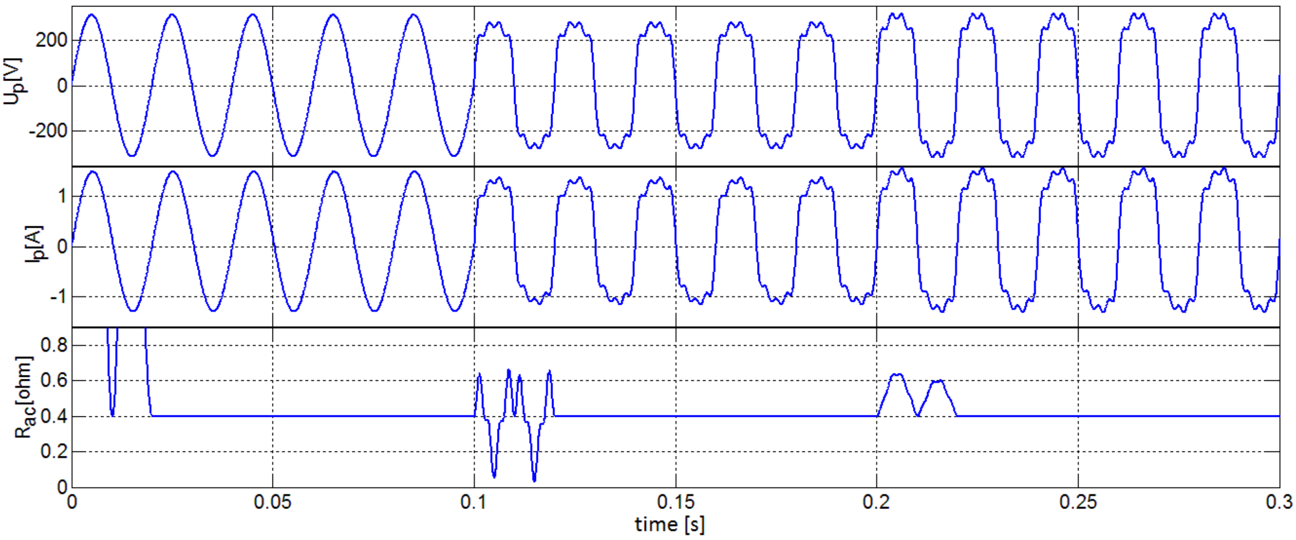

Fig. 3. Voltage, current and R_{ac} of simulated transformer throughout the simulation

The method explained in this paper has been tested on two distribution transformer experimentally. One of them is three-phase with Delta-star connection and the other is a single-phase. As the temperature of test environment is 30 °C, DC resistances have been referred to this temperature.

Rated values of single-phase transformer are 60 kVA, 27.5 kV /460 V, 2.18 A/130.4 A. According to the factory test report, DC resistances of primary and secondary windings are 126.7 Ω and 20.57 mΩ at 10 °C. Considering the turns ratio of transformer (59.7825), total series resistance of this transformer at the temperature 10 °C is obtained as 200.2 Ω. This value can be referred to temperature 30 °C as 215.67 Ω.

Rated values of three-phase transformer are 250 kVA, Dyn11, 6.3 kV/400 V, 22.91 A/360.8 A. Average values of DC winding resistance at each sides have been measured as 0.6437 Ω and 2.73 mΩ by using a micro-ohm-meter at the temperature of 20 °C. Turns ratio of the transformer has been also measured as 15.7155. Thus, total series DC resistance of windings at 20 °C is 1.3179 Ω and the referring this value to the temperature of 30 °C the value of 1.3688 Ω is computed.

Total AC resistances of both transformers have been obtained by two experimental methods. First method is short-circuit test method while the other is the presented method in this paper. In the short-circuit tests, only the primary voltages and currents have been measured and used for the computation of AC resistance. The results of tests are summarily given in Table 1.

Table 1. Results of experimental works

	1-phase TR	3-phase TR
R_{dc} (at 30 °C)	215.67 Ω	1.3688 Ω
R_{ac1} (short-circuit test)	226.71 Ω	1.4015 Ω
R_{ac1} (presented method)	226.15 Ω	1.3908 Ω

According to the results of experiments, AC resistances of both transformers have been obtained as bigger than their DC winding resistances. This is an expected result due to skin and proximity effects. Results of that obtained by short-circuit tests are almost the same as the results of presented method in this paper. This means that AC resistances of single or three-phase transformers can be successfully obtained by the method and demonstrates its effectiveness.

VI. CONCLUSION

In this paper, it is explained to how to obtain the AC winding resistances of single-phase and three-phase transformers using real time current and voltage measurements. Presented method is based on the equivalent circuit of transformer. Due to stray losses emerged from skin and proximity effects; there is always a difference between AC and DC winding resistances of transformers. As this difference is also related to the frequency of applied voltage, AC resistance of windings have been obtained by using fundamental frequency components of voltages and currents of windings. Being the results of short-circuit tests and the presented method very close to each other demonstrates the effectiveness of presented method. Thus, this method can be used for the monitoring of AC winding resistances of single and three phase transformers in their real time operations.

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