Indirect Measurement of Transformer Winding Resistance

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Abstract

Resistance measurement of transformer windings is an important diagnostic tool in the transformer condition assessment. It is one of the basic offline diagnostic methods which allows detecting winding turn-to-turn faults, inter-winding faults, as well as the OLTC faults. Dynamic resistance measurement which was first developed for the analysis and fault diagnostics of the HV circuit breakers, are used very successfully for detecting degradation and defects within Tap changers. There are basically two methods of dynamic resistance measurement of power transformer windings, direct and indirect methods. This paper presents the main characteristics of indirect measurements, as well as the basic benefits of its application.

Transformer model

A transformer consists of magnetically and electrically coupled windings. In the case of a three-phase two windings transformer, there are six windings which are electrically connected three by three into two groups. They are arranged following a magnetic standard so that they are on the same core leg, two windings of different groups of electrically connected windings.

The winding distribution of a three-legged magnetic core is presented in figure 1.

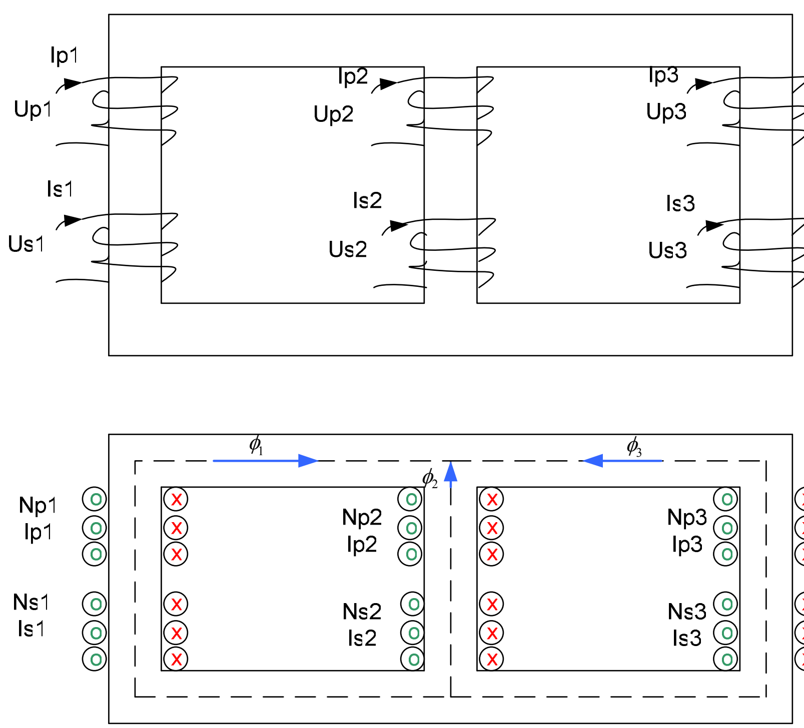

Figure 1. The winding arrangement of a three-legged magnetic core

When voltage sources are connected, currents flow through windings, forming magneto motive forces which affect the flow of appropriate magnetic fluxes. Equivalent scheme of magnetic paths is presented in figure 2.

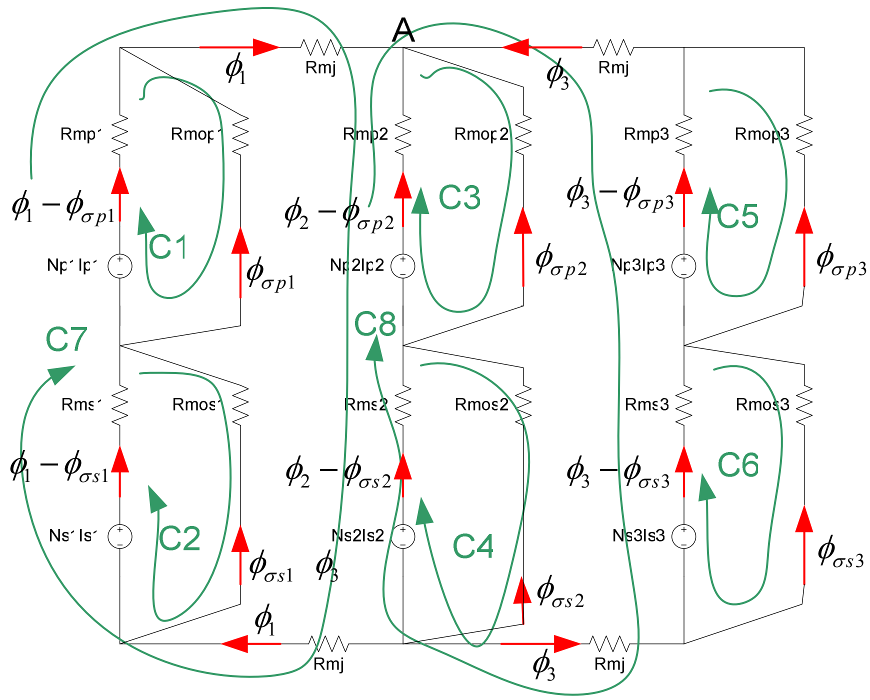

Figure 2. Equivalent scheme of magnetic paths for three-legged magnetic core

The leakage fluxes are also taken into account [2], [3]. For equivalent circuit formed like this corresponding equations can be set:

C1: $N_{p1}i_{p1} - R_{mp1}\left(\phi_1 - \phi_{\sigma p1}\right) + R_{m\sigma p1}\phi_{\sigma p1} = 0$

C2: $N_{s1}i_{s1} - R_{ms1}\left(\phi_1 - \phi_{\sigma s1}\right) + R_{m\sigma s1}\phi_{\sigma s1} = 0$

C3: $N_{p2}i_{p2} - R_{mp2}\left(\phi_2 - \phi_{\sigma p2}\right) + R_{m\sigma p2}\phi_{\sigma p2} = 0$

C4: $N_{s2}i_{s2} - R_{ms2}\left(\phi_2 - \phi_{\sigma s2}\right) + R_{m\sigma s2}\phi_{\sigma s2} = 0$

C5: $N_{p3}i_{p3} - R_{mp3}\left(\phi_3 - \phi_{\sigma p3}\right) + R_{m\sigma p3}\phi_{\sigma p3} = 0$

C6: $N_{s3}i_{s3} - R_{ms3}\left(\phi_3 - \phi_{\sigma s3}\right) + R_{m\sigma s3}\phi_{\sigma s3} = 0$

C7:

$$N_{s1}i_{s1} - R_{ms1}\left(\phi_1 - \phi_{\sigma s1}\right) + N_{p1}i_{p1} - R_{mp1}\left(\phi_1 - \phi_{\sigma p1}\right) - N_{s2}i_{s2} + R_{ms2}\left(\phi_2 - \phi_{\sigma s2}\right) - N_{p2}i_{p2} + R_{mp2}\left(\phi_2 - \phi_{\sigma p2}\right) - 2R_{mj}\phi_1 = 0$$

C8:

$$N_{s2}i_{s2} - R_{ms21}\left(\phi_2 - \phi_{\sigma s2}\right) + N_{p2}i_{p2} - R_{mp2}\left(\phi_2 - \phi_{\sigma p2}\right) - N_{s3}i_{s3} + R_{ms3}\left(\phi_3 - \phi_{\sigma s3}\right) - N_{p3}i_{p3} + R_{mp3}\left(\phi_3 - \phi_{\sigma p3}\right) - 2R_{mj}\phi_3 = 0$$

$$\phi_1 + \phi_2 + \phi_3 = 0$$

For each of the windings, voltage balance equation is valid:

$$U_{p1} = R_{p1}i_{p1} + N_{p1}\frac{d\phi_1}{dt} + N_{p1}\frac{d\phi_{\sigma p1}}{dt}$$

$$U_{s1} = R_{s1}i_{s1} + N_{s1}\frac{d\phi_1}{dt} + N_{s1}\frac{d\phi_{\sigma s1}}{dt}$$

$$U_{p2} = R_{p2}i_{p2} + N_{p2}\frac{d\phi_2}{dt} + N_{p2}\frac{d\phi_{\sigma p2}}{dt}$$

$$U_{s2} = R_{s2}i_{s2} + N_{s2}\frac{d\phi_2}{dt} + N_{s2}\frac{d\phi_{\sigma s2}}{dt}$$

$$U_{p3} = R_{p3}i_{p3} + N_{p3}\frac{d\phi_3}{dt} + N_{p3}\frac{d\phi_{\sigma p3}}{dt}$$

$$U_{s3} = R_{s3}i_{s3} + N_{s3}\frac{d\phi_3}{dt} + N_{s3}\frac{d\phi_{\sigma s3}}{dt}$$

For each of the six windings, different electrical coupling schemes exist, in two different groups, N_{p1}, N_{p2} and N_{p3} in one, and Ns_1, Ns_2 and Ns_3 in another group [8].

Method for transformer winding resistance measurement

If the DC voltage source is connected to the N_{p1} and all other windings are open, then it is possible to measure winding resistance in two different ways [5]:

1. By measuring the voltage and current of winding N_{p1} at the end of the transition process and calculating the resistance - direct method;
2. By measuring the voltage and current of winding N_{p1} and voltage of the winding N_{s1}, and calculating the resistance - indirect method.

Applying the first method, selected voltage and current level correspond to the part of magnetic circuit in saturation. The resistance is then calculated as:

$$R_{p1} = \frac{U_{p1}}{i_{p1}}$$

It should be noted that in the second measurement method transition process may not be completed, and with neglecting leakage flux and inductance, resistance of the winding Np1 can be calculated as:

$$R_{p1} = \frac{U_{p1} - \frac{N_{p1}}{N_{s1}}U_{s1}}{i_{p1}}$$

In this case, the voltages U_{p1} and U_{s1} correspond to windings on the same limb. This means that the vector group of transformer should be considered, so that for example for a group Yd the phase voltage U_p is considered, and line voltage U_s is measured.

In the case of 9 windings in zigzag group, situation is more complex and should be considered specifically.

Diagrams of voltage and current as a function of time, when a DC voltage source is applied on winding N_{p1} are presented in figure 3.

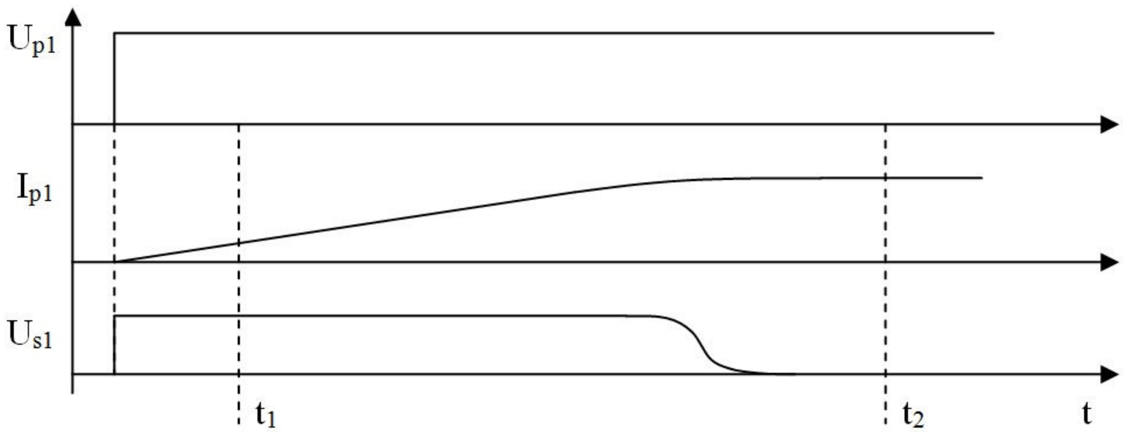

Figure 3. Diagrams of electrical parameters with constant voltage source

Resistance measurements by direct method require transition process to be completed, for example, in a moment of time t_2, but the indirect method can be carried out before the end of the transition process, for example in a moment t_1. It is important to note that completion of the transition process depends on the connection type. Thus, for example, for a vector group Yd it can last much longer than for the group Yy. Additionally, the level of DC voltage directly affects the rate of current increase. Therefore it is justified to use much higher voltage level during the transition process then necessary to achieve $U_{p1R}=I_{p1}R_{p1.}$ When desired current level is achieved, it is necessary to reduce voltage level to a value $U_{p1R}=I_{p1}R_{p1}$.

The corresponding diagrams of voltage and current are given in figure 4.

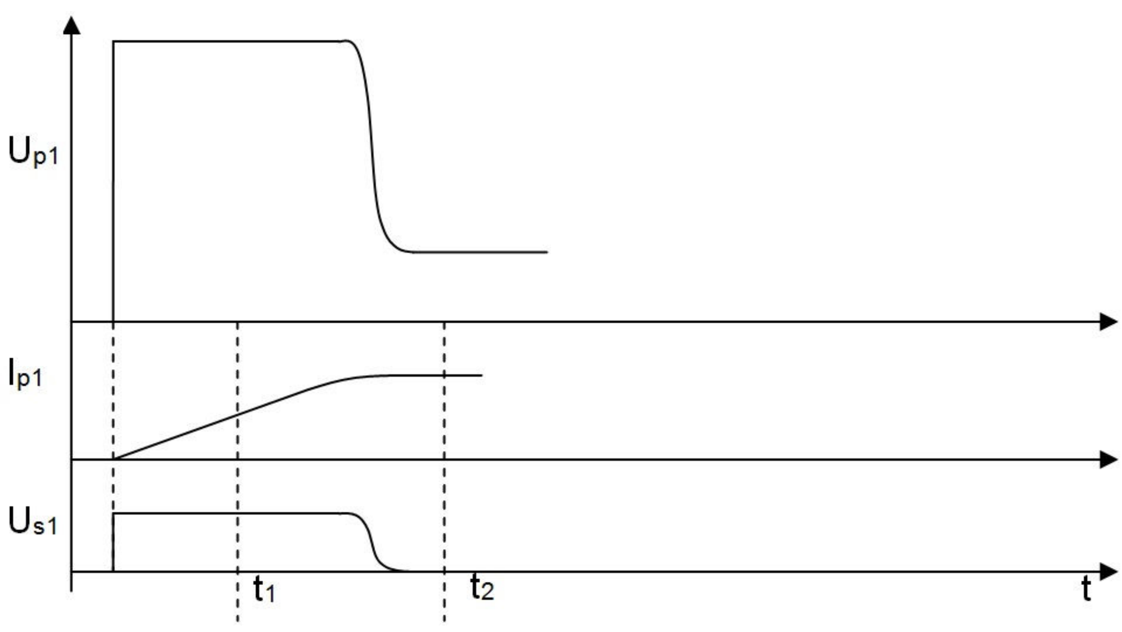

Figure 4. Diagrams of electrical parameters with variable voltage excitation

Considering the above mentioned facts it is justified to use a controlled voltage source with adjustable current limitation. Furthermore, as the measurement by the direct method is more accurate (the leakage flux of primary winding is not neglected), it should be used for measurement in case of specific transformer vector groups, where it can provide a relatively short time to reach the required current level. The indirect method of measurement has to be used in the event of unacceptably long period of transition process.

Characteristics of the indirect method of measurement are:

1. Selecting the measurement point t_1 in a moment with sufficiently large value of current and appropriate accuracy.

2. In a defined time interval Δt, before the moment of time t_1, the secondary voltage does not change. This is an indication of the linear part of the magnetic characteristics.

3. Time sampling of primary and secondary voltage and current of the primary winding must be synchronized (without delay).

Dynamic resistance measurements

During dynamic resistance measurements of OLTC, a relatively low value of the test current is used. Figure 5 shows a typical example of DRM (Dynamic Resistance Measurements) graph in the case of aged tap changer contacts. Basically, the graph can show the effects of resistance that can be divided into four categories [5], [6], and [9]:

1. The effect of the transformer winding resistance. Appears as expected value during each operation of OLTC. The measured resistance value changes during selection or de-selection of winding taps.

2. The effect of transition resistors. Given that these resistors are in each circuit of OLTC operation, test current is briefly reduced during the transition from one position to the another.

   Characteristic data are crossing time deviation and the problems of synchronization between the phases.

3. The effect of the contact resistance. In this part of the graph the problems related to the contact resistance can be seen, as well as the phenomenon of contact films or overheating.

4. The effect of open contacts. In this occasion test currents drops to zero, given the substantial increase in resistance between the contacts.

The first two effects exist during a normal operation of an OLTC, also without experiencing degradation problems [7], [10].

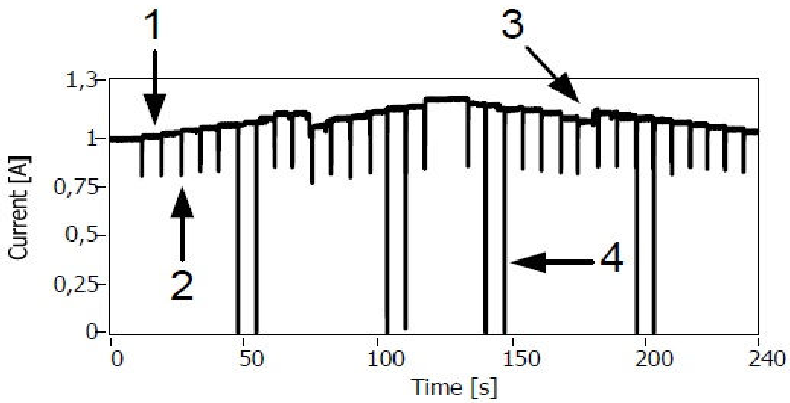

Figure 5. Example of dynamic resistance measurements of aged OLTC contacts [7]

Generally, there are two methods of measuring the dynamic resistance of OLTC:

1. Measuring voltage and current during transition process on the side of the transformer with the OLTC - direct method.

2. Measuring voltage and current during transition process on the secondary side of the transformer (the side without OLTC) - indirect method.

Direct method is often performed with a short circuit on the secondary winding. The change of current during direct measurement of resistance depends on two effects. One of them is related to a rapid current change, during which current flows in a winding on the secondary side. An equivalent circuit is shown in figure 6 and during this effect, current changes depend on the time constant T_1, which has the following form:

$$T_1 = \frac{2(1-k)L_1}{R_1 + m^2 R_2}$$

where variables are:

m - the transformer ratio,

k - the coupling factor between the windings.

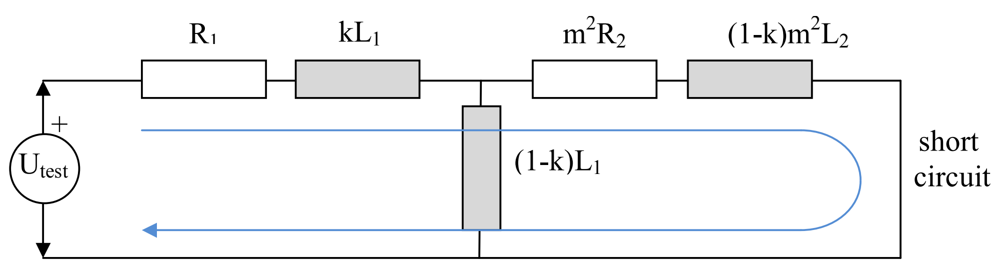

Figure 6. Transition current path with short circuited secondary winding - effect 1 [6]

The time constant has values of a few tens of milliseconds. During this period a rapid changes of current are possible, since inductance of the primary windings has no major impact.

This period is followed by a slower change of current, in the order of tens of seconds, during which the current is directly dependent on the inductance of the main winding (Figure 7). Characteristic of this effect is the increase of magnetic circuit energy with reducing the current value through the short circuit on the secondary winding to a negligible value while neglecting the influence of leakage inductance [6].

The time constant that describes that change has the following form:

$$T_2 = \frac{(R_1 + m^2 R_2) L_1}{R_1 \cdot m^2 R_2}$$

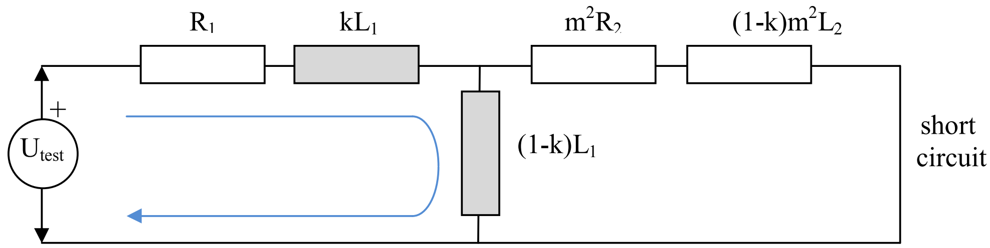

Figure 7. Transition current flow with short circuited secondary winding - effect 2 [7]

Indirect dynamic resistance measurements

The influence of large inductance of the primary winding, in which the test is performed, prevents measurements of fast current changes during the OLTC operation. One way to overcome this disadvantage is to perform an indirect measurement of the transition current, i.e. indirect dynamic resistance measurements [6]. Figure 8 shows the setup for indirect measurement.

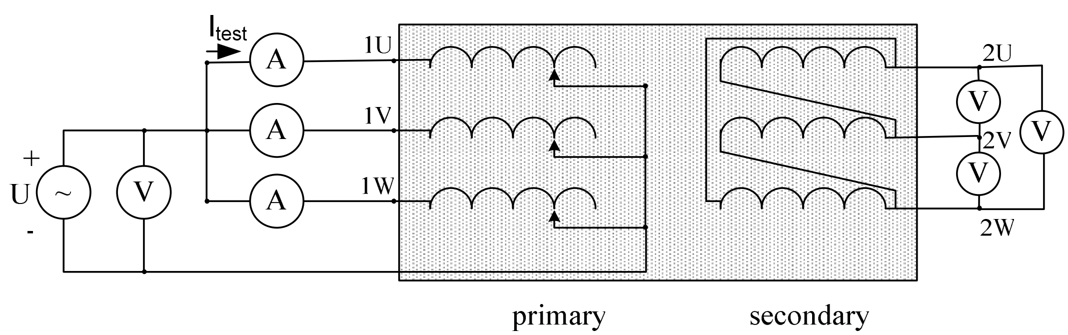

Figure 8. Setup for indirect dynamic resistance measurement

Equivalent scheme of the transition from one position to another, with the measurement of voltage on the secondary side is shown in Figure 9.

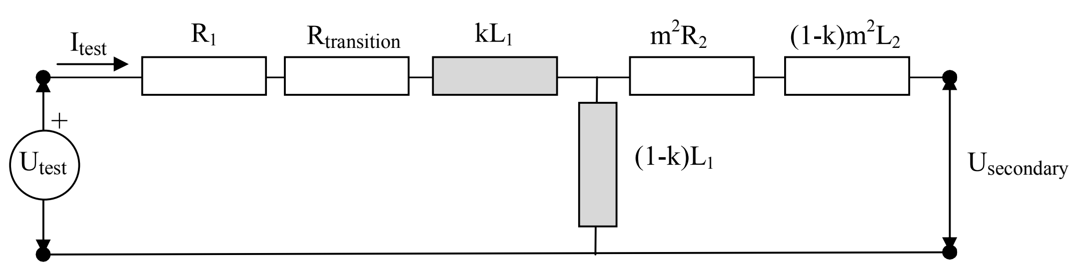

Figure 9. Equivalent diagram for indirect dynamic resistance measurement

$R_{transition}$ represents a resistor added to the circuit during transition process, when the OLTC is in operation. By setting the voltage source at a constant value, the voltage value at the transition resistor will be:

$$U_{transition} = I_{test} \cdot R_{transition}$$

The value of this voltage will be, at a constant source value, on the primary winding inductance too:

$$U_{transition} = U_{L1}$$

The voltage that appears on the primary side can be measured on the secondary winding. It has to be taken into account that with each tap position change, transformer ratio also changes, so the voltage change, measured on the secondary winding, is different for each tap. Changes in the voltage amplitude can amount to 25 % between certain positions of tap changer. Figure 10 shows the characteristic shape of the voltage on the secondary winding during the OLTC transition on the primary side. It reveals a characteristic change in amplitude and rapid response in moving of the transition resistor [7].

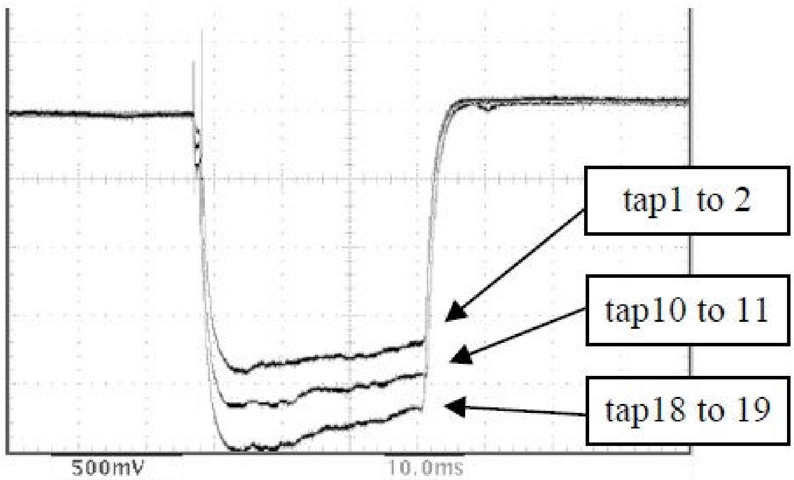

Figure 10. Characteristic shape of the secondary voltage during the OLTC transition [7]

Adding a series resistor in the primary winding circuit during a position change reduces the time constant of the primary winding. Also the change in the amplitude of the measured voltage on the secondary side is reduced, and its value quickly reaches zero when there is no induced voltage, due to stabilization of the DC current value during the test. In contrast, with the lower value of the active part of the primary windings impedance, L/R ratio also increases, which leads to increase in the time constant of the primary winding, and thus reduces the impact of inductance on current changes during OLTC transition, as the time constant is then significantly increased, compared to the time of transition from one position to another.

Conclusion

Use of indirect measurement of transformer resistance is justified when the time of the transition process is unacceptably long, and when the leakage flux can be neglected. This method of testing allows the measurement of resistance before completion of the transition process, with use of a controlled voltage source. Although it is more accurate, direct measurement of current transition is greatly affected by the inductance of the primary transformer winding. Taking this into account, direct measurement can be used in cases where the response time of a measurement signal is permitted. In contrast, the indirect measurement allows measurement and observation of rapid changes in the OLTC operation and transition process. Characteristic changes in the graphic presentation of indirect measurements can be observed by changing values of transition resistors and transformer ratio, while passing through certain tap positions.

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Biography

Nijaz Hadžimejlić was born in 1954 in Visoko, Bosnia and Herzegovina. He received the B.S., M.S. and Ph.D. degrees in 1977, 1987 and 1997, from University of Sarajevo, all in electrical engineering. From 1977 to 1998 he was with the Department of Power Electronics and Motor Control, Institute for Computer Science and Control - IRCA, Energoinvest, Sarajevo. From 1984 to 1997 he worked part time as Teaching Assistant and Senior Teaching Assistant at the Department Of Electrical Engineering, University of Sarajevo. He joined the Department Of Electrical Engineering, University of Sarajevo in 1998 where he is currently Associate Professor. Additionally, he cooperates with DV-POWER from the establishment of this company in the year 2000.

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