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A DRM technique for OLTC testing by the transformer secondary winding DC voltage curve

***Abstract**. The dynamic resistance measurement (DRM) method was developed as a supplementary for testing the transformer on-load tap changer (OLTC) and has become popular in recent years. The DRM method has proven to be an effective method for early detecting potential faults in tap changers. The traditional DRM method is based on a DC current being injected through a transformer winding and a tap changer as it moves from the tap to tap. The measurements are carried out in the tested transformer winding under shorted secondary winding. The article presents a new conception of the DRM method, where the OLTC condition is tested by a voltage curve, that is logged on the no-load secondary transformer winding.*

***Streszczenie.** Metoda dynamicznego pomiaru rezystancji (DRM) została opracowana jako uzupełnienie badania przełącznika zaczepów pod obciążeniem transformatora (OLTC) i stała się popularna w ostatnich latach. Metoda DRM okazała się skuteczną metodą wczesnego wykrywania potencjalnych usterek przełączników zaczepów. Tradycyjna metoda DRM opiera się na analizie przepływu prądu stałego przez uzwojenie transformatora i przełącznik zaczepów podczas jego przełączania od zaczepu do zaczepu. Pomiary wykonywane są w badanym uzwojeniu transformatora pod zwartym uzwojeniem wtórnym. W artykule przedstawiono nową koncepcję metody DRM, w której stan przełącznika zaczepów jest badany za pomocą krzywej napięcia, która jest rejestrowana na uzwojeniu wtórnym nieobciążonego transformatora. (**Technologia DRM do testowania przełącznika zaczepów pod obciążeniem przy wykorzystaniu krzywej napięcia stałego uzwojenia wtórnego transformatora)**.*

Keywords: power transformer, on-load tap changer, dynamic resistance measurement, contact failure.
Słowa kluczowe: transformator mocy, podobciążeniowy przełącznik zaczepów, dynamiczny pomiar rezystancji, uszkodzenie styków.

Introduction

Power transformers in power systems are used to convert the parameters of AC electrical energy and interconnect power grids that perform transmission and distribution functions. Power flow variations in electrical grids cause changes in voltage levels in the grid nodes and on the electrical energy consumer buses, which tend to problems in maintaining the power system operation and deterioration in the quality of power supply to consumers. To compensate for voltage changes in the grid, power transformers are equipped with devices for on-load changing the transformer voltage ratio by changing the ratio of windings turns. These devices are called on-load tap-changers (OLTCs). By switching the taps of the transformer windings without load current interruption they change the ratio between the number of turns of the transformer windings. Various designs of tap changers are known in practice. The two most common are inductive and resistive type on-load tap changers. The presented article is devoted to the resistive type OLTCs.

Power transformers are very reliable and important components of electrical systems. However, many transformers have been in operation for a long time and some of them have today exceeded their design life. Transformer failures happen with a certain frequency and depend on many factors. Unlike static transformer components, the on-load tap-changer consists of numerous moving parts. Therefore, the number of damages to the on-load tap-changer is relatively large. Studies, reported in [1], show that about 30 % of substation power transformers outages are related to OLTCs damages. Because of this high failure rate, it is very important to periodically monitor the condition of the power transformer OLTC and perform their maintenance.

Methods for OLTC testing

It is known from operating experience that the predominant causes of tap changer failures are either damage to the contacts or defects in the operation of the mechanical drive [2]. The tap selector contacts and the transfer switch are subject to degradation due to the so-called "long-term effect" that occurs, which is caused by oil secretions and friction. Repetitive sparking can damage the contacts of the tap selector switch. The drive mechanism is also subject to wear and constant friction, the spring can lose springiness, which can cause the mechanism to be damaged.

The following diagnostic methods can be used for transformer OLTC testing.

Static winding resistance measurement of the individual taps [3]. The static winding resistance is an important indicator of the condition of the winding as well as all internal connections such as the connection from the inputs and moving contacts of the tap changer to the winding, the tap selector contacts and the main contacts of the diverter switch. The evaluation of the test results is carried out by comparing the results with the factory report or by calculating the deviation from the average value of the three phases. This method is relatively time-consuming because after moving the tap contacts to the next position one needs to stabilize the current due to the large time constant of the measurement circuit.

Vibro-acoustic measurements by using acceleration sensors [4]. Vibro-acoustic measurements are based on the detection of mechanically generated acoustic signals. Sensors installed on the transformer capture the vibro-acoustic signal and comparing its shape with the reference characteristic can provide valuable information about the condition of the tap changer, such as problems in the arcing switch, preselector and wear in the tap changer. Any variation from the signature waveform can be indicative of a fault in the OLTC.

Motor power/current measurement [5]. By measuring the power or current of the motor, one can detect mechanical problems and the aging of the drive mechanism. The results can be compared with a signature or between the taps. Anomalies in the measured waveform may indicate problems such as increased friction and loss of lubrication when moving between tap positions during selection. Defects in the charging of the spring used in the OLTC to quickly switch the load current from one circuit to another can also be detected.

Dissolved Gas Analysis (DGA) [6]. Thermal impulses or electrical discharges in the on-load tap-changer or transformer tank release gases that dissolve in the oil. The composition of dissolved gases depends on the level of temperature increase and the discharge energy. DGA is the most widely used diagnostic method for transformer diagnostics. The advantage of DGA is that it indicates the presence of degradation; the disadvantage is that it does not reflect the location of the defect and the scale of damage.

Dynamic resistance measurement (DRM) [5, 7]. Dynamic resistance measurement is a method to examine the condition of the OLTC contacts under its motion. The dynamic measurement is not as accurate as the static resistance measurement, but provides more relevant information on the state of the contacts and takes less time. The typical switching time of a selector switch is 40 to 60 ms. Unlike measuring the static resistance of a winding, which typically takes several minutes, detecting a change in contact resistance is difficult. Therefore, the DRM principle is considered an additional diagnostic method.

Logging electrical parameters during the switching process make it possible to analyze the state of the tap changer. There are three ways to display the dynamic behaviour of the diverter switch:

- current curve;
- voltage curve;
- resistance curve.

The traditional DRM method uses connecting a DC voltage source to the winding of a transformer with an on-load tap-changer. The measurement must be made in such a way that the core remains energized during the test. The measurement is performed by switching the OLTC through all taps. During the test, the secondary winding of the power transformer is short-circuited to increase safety and to provide a rate of current change in the circuit under test in response to changes in circuit impedance [5, 8].

The outline of the DRM testing is presented in Fig.1

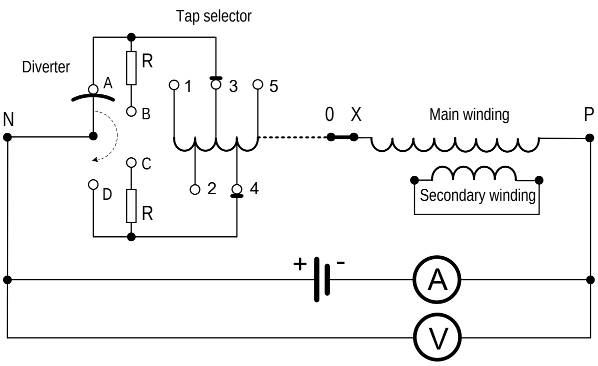

Fig.1. The outline of the standard DRM testing

Current curve. The current curve is used as the most common interpretation of DRM measurements because of allowing the detection of current interruptions during the tap switching.

Voltage curve. The dynamic behaviour can also be analysed by the voltage curve. Variation of direct current during tap switchings produces an adequate voltage signal. When using the voltage curve, however, it is crucial to ensure that the measured voltage signal does not get cut off due to a voltage source limiter, making it difficult to analyse the transients during tap switchings. Similar to the measurement of the current curve, a direct comparison of the obtained curves is not possible when using different measuring instruments.

Resistance curve. The resistance curve cannot be measured directly but is obtained by calculation through the measured voltage and current. The shorted transformer secondary provides reduces the time constant of the tested winding. Due to the high parasitic inductance, the inductive voltage that occurs during switching introduces a significant error in the measurement of the resistance curve. To compensate for this effect, a method was proposed for determining the inductive component of the voltage [3]

A proposed method for dynamic OLTC testing

A typical scheme of logging parameters during OLTC tap switchings, based on the standard DRM method, applies measuring instruments directly in the tested winding of the transformer with its secondary winding shorted.

In the method developed by the authors, it is proposed to measure the voltage on the transformer secondary no-load winding when switching taps in the primary winding with direct current. A schematic diagram of the measurement method is shown in Fig. 2.

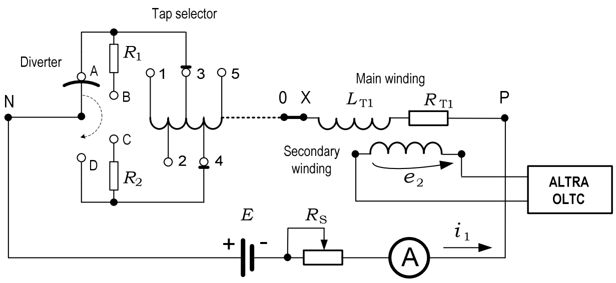

Fig.2. Schematic diagram of the measurement method

During testing the behaviour of tap switchings the voltage change oscillogram on transformer secondary winding is logged. The main value that is strictly controlled under OLTC operation is the time of tap switchings which determines the time of transformer winding operating current flow through the current-limiting resistor of low rated power. The open secondary winding of the transformer causes a high inductance of the primary circuit, and during a tap switching, the change in direct current is minor due to the short switching time (2-3 cycles of the operating frequency). But there will be a change in the voltage on the primary winding of the transformer, proportional to the change in voltage across the current-limiting resistor when a tap switching.

Before starting testing in the primary circuit of the transformer, it is necessary to stabilize the direct current. The switching sequence of the diverter contacts during the transition from tap 3 to tap 4 is as follows. First, current from the DC source flows through diverter contact A and then contact B is connected to it. After contact A opens, current flows through resistor R_1 and contact B. Then contact C closes and current flows through two resistors R_1 and R_2 connected in parallel by contacts B and C. Next, contact B opens and current flows through resistor R_2. Connecting the contact D shunts resistor R_2, and after opening contact C, the main winding of the transformer is connected to tap 4 through normally closed contact D.

Computer simulations were carried out using the Matlab-Simulink software to study the transients in the transformer winding circuits when switching OLTC taps.

In the simulation was used transformer of a type TDN 10000/115/11 ± 9×1,78% with the next rating data:

S_{nom} = 10 MVA; U_{1nom} = 115 kV;
U_{2nom} = 11 kV; I_{μ} = 0,7 %;
R_{T1} = 3,98 Ω; R_{T2} = 0,11 Ω;
X_{T1} = 69,5 Ω; X_{T2} = 1,9 Ω.

Fig. 3 and Fig. 4 show voltage and current curves obtained by simulating the OLTC tap switchings with the transformer's shorted and no-load secondary winding according to the described contacts A, B, C, and D sequence.

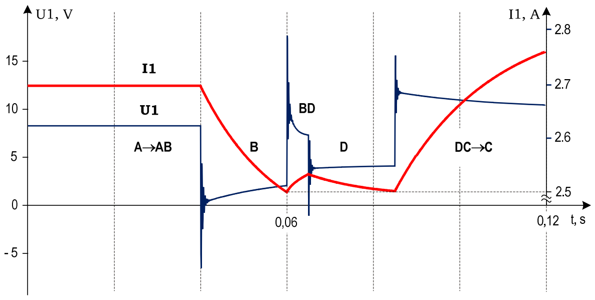

Fig.3. Primary voltage (U1) and current (I1) curves under shorted transformer secondary winding

As one can observe from Fig.3 during switching a tap under shorted transformer secondary testing current changes within 0,25 A (9%). The primary winding voltage curve depends on the current change and the transformer impedance time constant.

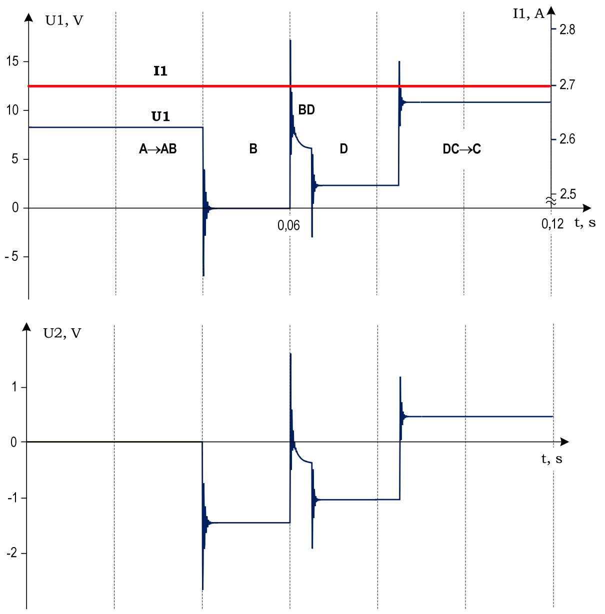

Fig.4. Primary voltage (U1) and current (I1) and secondary voltage (U2) curves under no-load secondary winding

The inductance of the measurement circuit increases significantly under the no-load transformer secondary winding, and during the OLTC tap switching, the current remains almost constant, as one can see in Fig. 4. The tested circuit's steady operating condition before tap switchings can be described by the expression:

$$E - i_1(R_s + R_{\mathrm{T1}}) = 0. \quad (1)$$

After opening contact A and inserting resistor R_1, the transient in the circuit can be described as follows:

$$E - i_1(R_s + R_{\mathrm{T1}}) - L_{\mathrm{T1}} di_1/dt - i_1 R_1 = 0, \quad (2)$$

Since the current remains almost constant during switching an OLTC tap, it can be assumed that the sum of the first two terms in equation (2) will also be equal to zero, as in equation (1). This assumption means that the voltage across the inductance of the tested winding will correspond to the change in voltage across the current-limiting resistor being switched on:

$$L_{\mathrm{T1}} di_1/dt = -i_1 R_1. \quad (3)$$

This change in voltage in the primary winding will cause an electromotive force on the transformer secondary winding that can be defined as follows:

$$e_2 = -L_{12} di_1/dt \quad (4)$$

where L_{12} – is the mutual inductance between primary and secondary transformer windings.

The secondary winding of the transformer is connected to the measuring instrument having a large input impedance and therefore the effect of the secondary winding current on the primary winding current is negligible. For low testing current in the winding, the transformer core will be far from saturation and the voltage shape on the secondary winding will repeat the shape of the voltage change on the current-limiting resistor during the tap switchings:

$$e_2 = \frac{L_{12}}{L_{\mathrm{T1}}} \cdot i_1 R_1. \quad (5)$$

It is known from experience that no more than 15% of the transformer rating current is recommended for on-load tap-changer DRM testing - a higher value will cause heating of the transformer winding, changes in resistance and inaccuracies of the measurement results. The low test currents were shown to be more sensitive to contact bouncing and the effect of residual oil coating on the contacts. This caused the current to be interrupted several times during the test, which could lead to misinterpretation of the results. Test currents in the range 3-5 A are, in most cases, sufficient to obtain a stable recording of the switching transients. In these cases, oil coating on the contacts does not impact the measurements.

Fig. 5 shows a graph of the bad operating condition of transformer OLTC, obtained by simulating a contact B switching-out, accompanied by arcing. As exploitative practice shows the arcing can be caused by coking or pitting of the contacts.

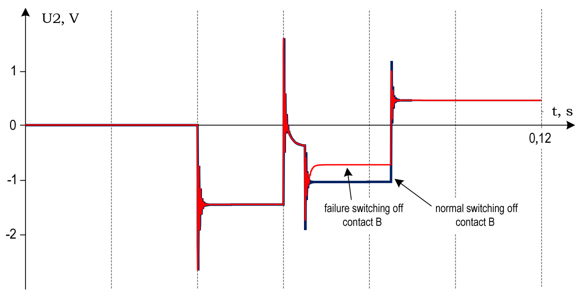

Fig.5. Voltage curve on transformer secondary winding under arcing switching-off contact B

Dynamic measurement arrangement

The layout of the proposed DRM setup is shown in Fig. 6. The testing device was developed by Lviv Polytechnic National University and the Institute of Microprocessor Control Systems for Power System Objects. The main components of the circuit are the microprocessor, the analogue-digital converter (ADC) and the power supply. The device is connected to a PC via a USB converter. The signal from the secondary winding of the transformer is fed to the input of the instrument by symmetrical a two-wire communication line type "twisted pair". The signal is fed to the amplifier that is used to suppress in-phase interference and match the input of a 16-bit serial ADC module. The microprocessor reads information from the ADC, writes information arrays into memory and provides writing the information to the PC by RS-485 interface.

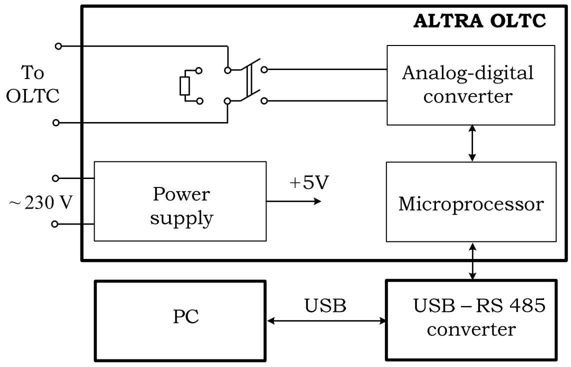

Fig.5. The layout of the proposed DRM setup

Special software GRANOS [9], installed on a PC, provides reading information from a file, displays voltage curves as time oscillograms, measures time sections of oscillograms and displays them with marked lines. The general view of the device is shown in Fig.6

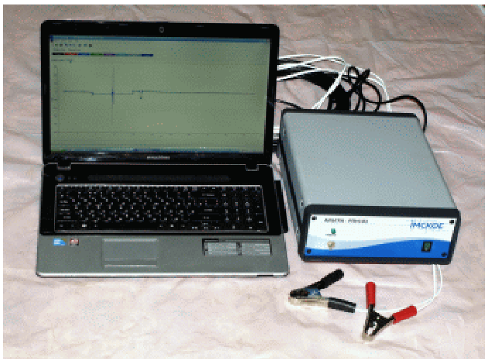

Fig.6. The general view of the device

In known DRM testing setups, such test devices are connected directly to the OLTC testing circuits, which can distort the recorded oscillograms under the switching taps. A high DRM circuit resistance results in smaller changes in the test current when a defect with a given resistance is present in the OLTC, making the readings more prone to noise [8, 10]. The developed testing device is connected to the transformer's secondary winding and captures the voltage curve. Fig. 7 shows the field oscillogram when logging the transformer OLTC tap changeover from tap 8 to tap 9.

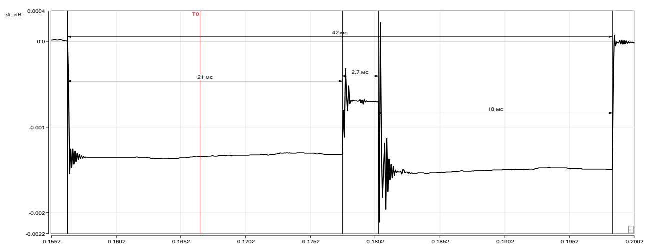

Fig.7. An example of a voltage curve recorded by the device during field testing of the OLTC

The voltage curves obtained as a result of the measurement are compared with the references. Typical records of the reference voltage curves are obtained after commissioning or when the OLTC is known to be in good condition. The output of the proposed testing device can be connected to the dispatch monitoring system of power system facilities [11] for collecting the data about OLTC conditions of grid transformers.

Conclusions

The proposed DRM method of OLTC testing, based on the analysis of the voltage curve on the transformer secondary winding, can be used as an effective tool for identifying problems associated with tap switching.

A big advantage of the proposed non-invasive testing method is the ability to external identify a problem inside the OLTC, without opening the tap changer compartment and without the need for direct access to the tap changer contacts, removing oil from the tank, etc. Analysis of the OLTC condition is carried out by comparison with reference curves.

The developed hardware and software provide fast logging of voltage change curves on the no-load secondary winding of the transformer during OLTC switching taps under the selected value of direct current in the primary winding as well as transmitting the analysed data to the dispatching database.

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