

ABSTRACT

The dynamic resistance measurement was developed as a supplementary measurement in order to analyse the switching process of the on-load tap changer. The article considers the importance of on-load tap changers and their main testing methods with the focus on dynamic resistance measurement.

KEYWORDS

power transformer, on-load tap changer, OLTC, dynamic resistance measurement, DRM

Dynamic analysis and testing of on-load tap changer

Dynamic resistance measurement

Introduction

Power transformers represent the most expensive link between generation and utilization of electric power. One very important component of a power transformer is the on-load tap changer (OLTC). As its name suggests, an OLTC permits tap changing, and hence regulating voltage without interrupting the load current. This can be accomplished in various ways, resulting in considerably diversified tap changer designs. The two most common ones are the so-called inductive and resistive type tap changers.

Studies, as shown in Figure 1, show that about 30 % of reported failures of substation power transformers are related to the aging effects on OLTCs. Due to this high failure rate, it is very important to monitor the condition of the power transformer's OLTC closely. Unlike other more static components in a transformer, the OLTC consists of numerous moving parts. Manufacturers typically recommend a maintenance cycle that mostly depends on the total number of switching operations.

1. Types of OLTCs

To analyse and assess the dynamic resistance measurement (DRM) in a proper manner, it is important to know the type and the construction of the OLTC. There are two common OLTC technologies in the market. The inductive ones, which are typically used in the North America on the low-voltage side, and the resistive OLTCs, which are often used in the rest of the world on the high-voltage side.

This article focuses on resistive type tap changers. In general, there are two different types of resistive tap changers: diverter switch and selector switch type, as shown in Figures 2 and 3.

The diverter switch types have two parts: a tap selector at the top to select the next tap within the main transformer tank, and a

diverter switch at the bottom to switch the load current with its own oil volume. With this OLTC type, the tap selector is switched before the diverter switch, and the type is mostly used in higher power ratings.

The selector switch type combines the function of the diverter switch and the tap selector, within its own oil volume, separated from the oil of the main transformer tank.

2. Common methods for OLTC testing

Power transformer OLTCs need close monitoring of their condition due to their high failure rate. As a basis for the analysis, the following diagnostic methods can be used:

▪ Static winding resistance measurement of the individual taps (offline)

The static winding resistance measurement is a very important diagnostic measurement tool and the most commonly used testing method. A conventional static resistance measurement can be used to check the winding as well as all of the internal connections, such as the connection from the bushings and the tap changer mobile contacts to the winding, the contacts of the tap selector and the main contacts of the diverter switch. An assessment can be made by comparing the results with the factory report or by

calculating the deviation from the average of the three phases.

▪ Vibro-acoustic measurements by using acceleration sensors (offline/online)

The vibro-acoustic method is used to detect acoustical signals caused by mechanical movement. The recorded profiles, which range up to 10 seconds and between 10 Hz – 100 kHz in time and frequency domain are compared with existing reference profiles to identify certain failure modes [3].

▪ Position and torque measurement on the drive axis (offline/online)

The OLTC's drive mechanism, comprising of a motor, drive shaft and gear, operates the selector switch while charging a spring to actuate the diverter or selector switch, respectively. The position and torque measurement uses motor supply parameters (current and voltage) to detect mechanical problems and aging of the drive mechanism. The results can be compared with a reference profile or between the taps.

▪ Dissolved Gas Analysis (DGA) of the oil in the tap changer compartment (offline/online)

The DGA in the OLTC compartment has become more common. During the switching process of an OLTC, discharge and heating occurs which generally leads to a higher concentration of gasses in the

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The dynamic resistance measurement was developed in order to analyse the dynamic switching process of on-load tap changers

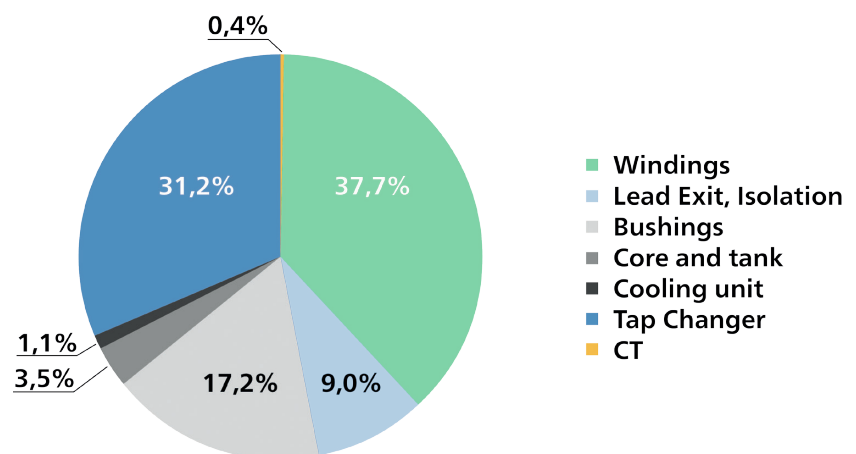


Figure 1. Failure location of substation transformers based on 536 failures [1]

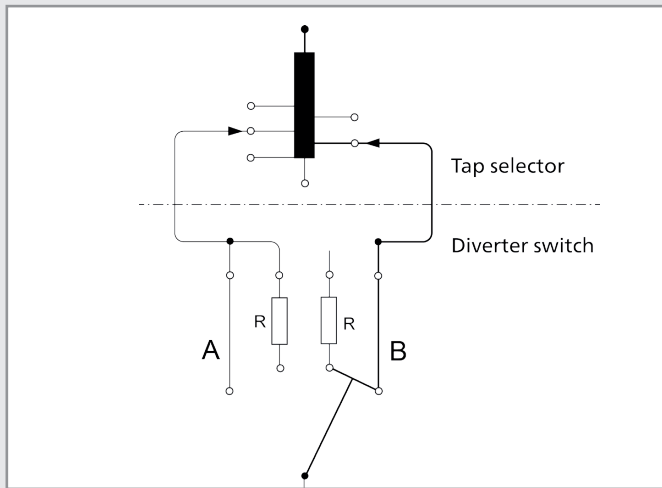


Figure 2. Diverter switch with two resistance contacts [2]

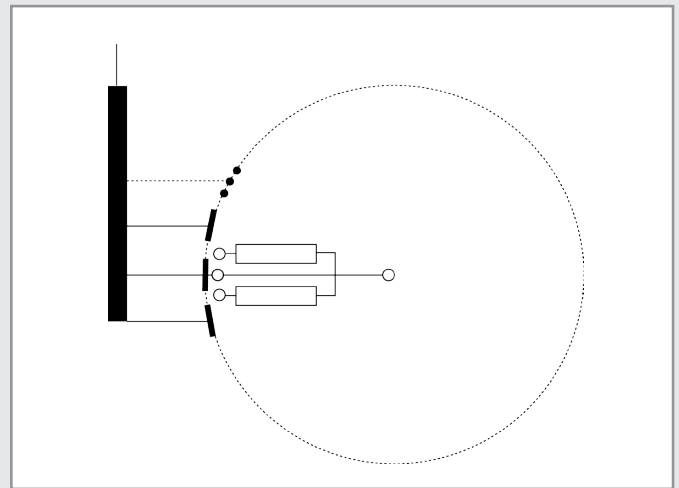


Figure 3. Selector switch with two resistance contacts [2]

tap changer compartment compared to the main tank during normal operation. Thus the interpretation of gas levels significantly varies from the interpretation of gas levels obtained from the main tank of the power transformer [4].

Each measurement method is important to analyse the condition of OLTCs.

3. Dynamic Resistance Measurement (DRM)

Typical switching times of the diverter or selector switch between 40 and 60 ms make it difficult to detect any effects during the switching process using a conventional static winding resistance measurement, which might take a few minutes. Therefore, the principal of the DRM was developed as a supplementary diagnostic method for this specific use.

Using the same setup (Figure 4a), the dynamic resistance measurement measures the fast switching process of the diverter

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switch. DRM can detect arcing contacts, switching times of the diverter switch, switching interruptions, due to broken commutating resistors or broken leads for example, and the complete wear of contacts. Therefore, it provides a deeper insight into the OLTC's dynamic condition.

By analysing the recordings, it is possible to draw a number of conclusions related to the condition of the OLTC. There are three different ways to display the dynamic behaviour of the diverter switch:

- (1) Current curve
- (2) Voltage curve
- (3) Resistance curve

In further contemplation we will refer only to the current curve.

Current curve

The current curve, as seen in Figure 4b, is the most common way to interpret DRM measurements, as it is widely used for static resistance measurement and gives the possibility to detect current interruptions.

By applying a short circuit to the opposite side of the transformer, the current signal becomes more sensitive, as the current drop (ripple) increases as shown in Figures 7 and 8. This is a result of a lower time constant due to the shorted main inductance. A direct comparison of the current signal is difficult when measuring with different test equipment, as the ripple is dependent on the dynamic properties of the current source. But the principle and the different stages of the switching process are always visible, regardless of the source parameters.

Voltage curve

Alternative to the current signal, the dynamic behaviour can also be assessed

Table 1. Common methods for OLTC testing [5]

Measurement method	Application/ purpose	Problems
Static winding resistance	Check the windings as well as the internal connections	Contacts alignment, contact wear
Vibro-acoustic	Detect acoustical signals caused by mechanical movement	Linkage/gears, Timing/Sequence, contacts alignment, arcing, overheating/coking, contact wear, transition
Position and torque	Detect mechanical problems and aging of the drive mechanism	Linkage/gears, control/relays, motor, brake, lubrication, contacts alignment
Dissolved gas analysis	Detect higher concentration of gasses in the tap changer compartment	Arcing, overheating/coking
Dynamic resistance	Measure the fast switching process of the diverter switch	Timing/sequence, contact wear, transition

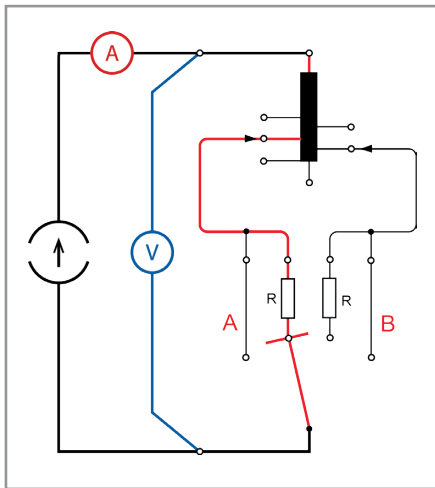


Figure 4a. Typical measurement setup of DRM - current curve

using the voltage or resistance curve. By injecting a DC current, as shown in Figure 5, the recorded voltage signal seen in Figure 6A can be obtained. When using the voltage curve, however, it is crucial to make sure that the voltage signal does not get cut off due to a voltage limiter of the source, which would make it difficult to analyse the signal. In addition to the cut-off voltage, transients as shown in the example of Figure 6A between stage 1 and 2 would not be seen as clearly if the voltage limit was reached. Analog to the current curve, a direct comparison of the measured curves is not possible when measuring with different test instruments.

Resistance curve

The resistance curve, as seen in Figure 6B cannot be measured directly, but is a calculation derived from the measured voltage and current based on the setup shown in Figure 5. A short circuit on the opposite transformer terminals can be applied to

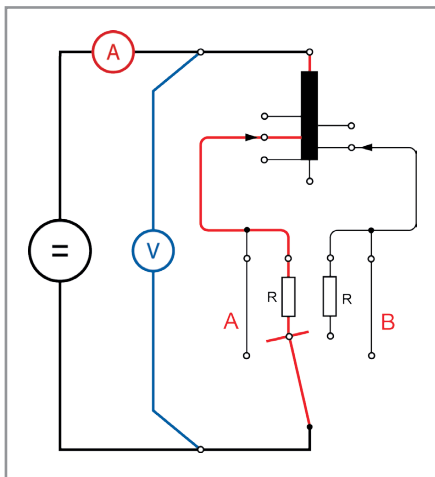


Figure 5. Typical measurement setup of DRM - voltage and resistance curve

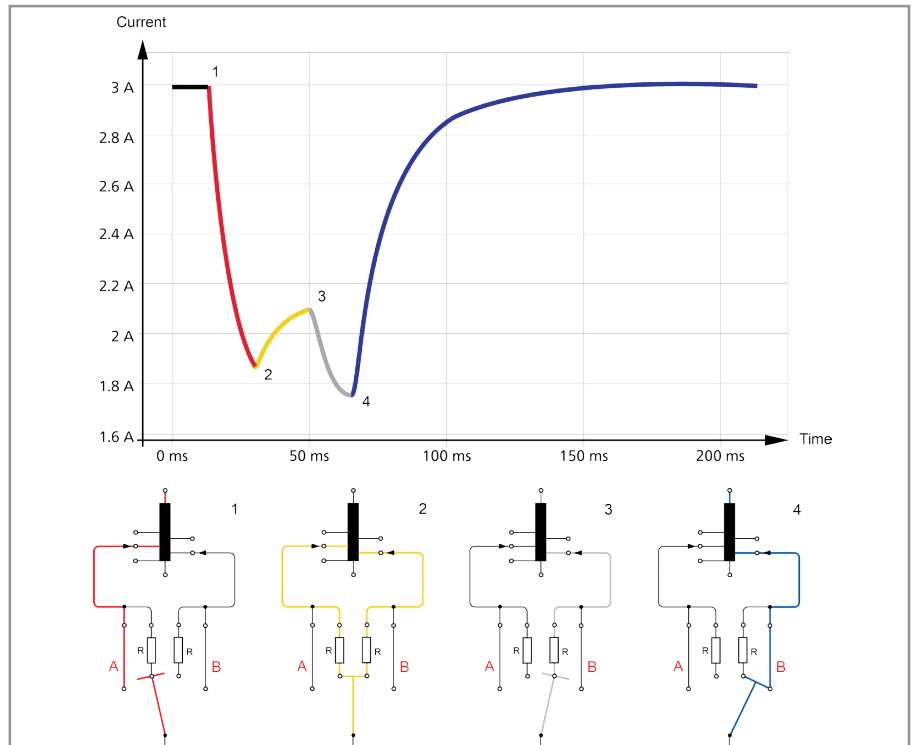


Figure 4b. Typical dynamic behaviour of the diverter switch in operation - current curve

decrease the time constant of the system. In addition, a high stray inductance may cause a significant inductive voltage, which cannot be separated from the resistive voltage part using the setup shown in Figure 5.

To compensate for this effect, a method to determine the inductive part of the voltage by simultaneously measuring the voltage on the opposite winding was introduced several years ago [6].

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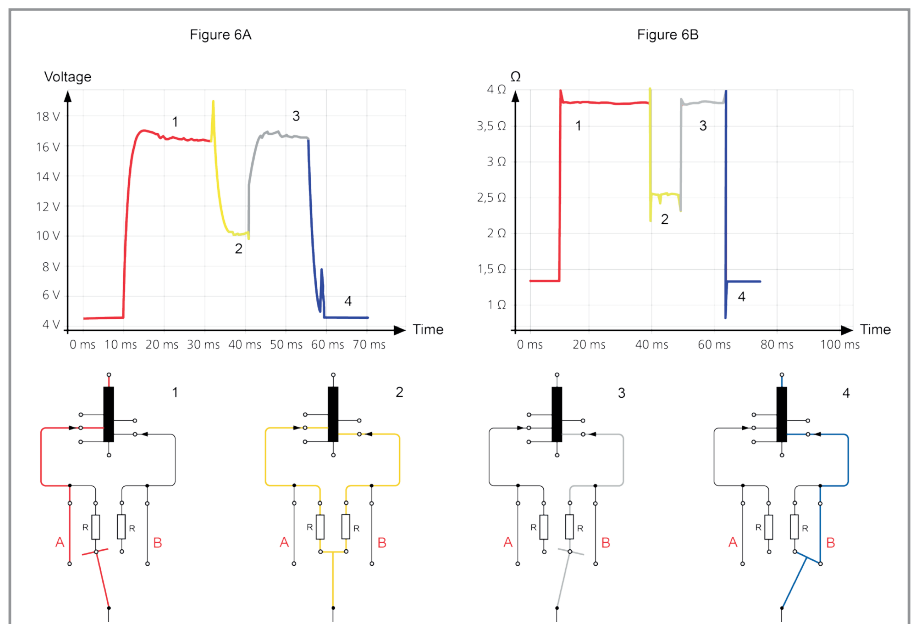


Figure 6. Typical dynamic behaviour of the diverter switch in operation - voltage and resistance curve

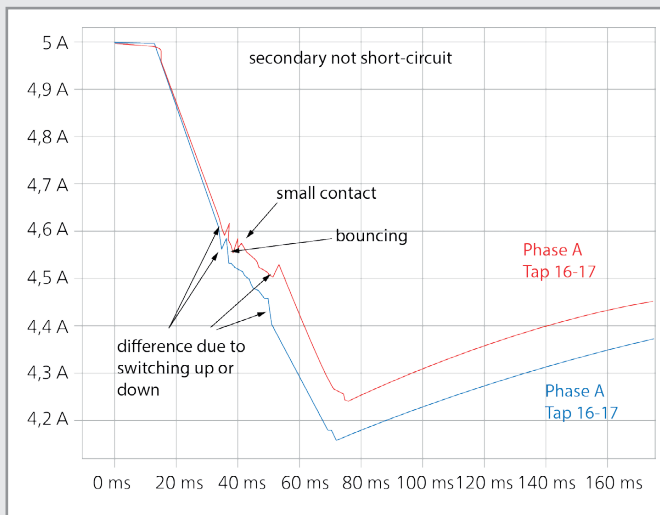


Figure 7. Difference in the DRM when switching up and down¹

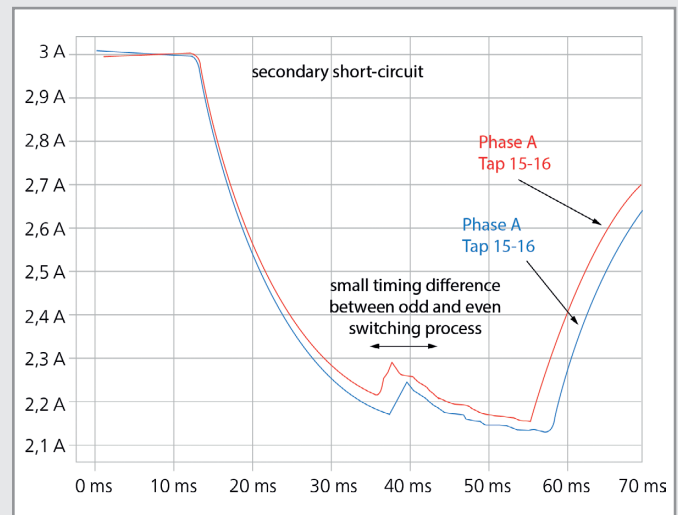


Figure 8. Difference in the DRM when switching the diverter switch in alternating directions¹

¹ Measured on MR Type DIII-200-14 27 3 GF, 1966

Test currents in the range of 3-5 A were, in most cases, sufficient to achieve a stable measurement of the switching process

The resistive curve has a big advantage of being independent from the current source used. Another advantage is that the values of the commutating resistors can be determined directly. As the induced voltage on the secondary side could be very high, it requires special protection mechanisms for the testing device.

As the current curve is currently the most commonly used way to perform DRM measurements, the following sections will focus on this method in more detail.

4. Analysis of measurement results

Based on this non-invasive testing method, failures can be detected without opening the OLTC compartment. The type and the construction of the OLTC must be known to be able to analyse and assess the DRM measurement in a proper manner. A reference "fingerprint" measurement, which is taken after commissioning or when the diverter switch is known to be in a good condition, allows efficient analysis.

In general, two types of information can be interpreted when looking at the current profile:

• Amplitude:

Transition resistors cause the current to

vary during the switching process. In addition, contact resistance, contact movement, interruptions, winding inductance, arcing and bouncing of the contacts may influence the amplitude.

• Timing:

Differences in timing may indicate mechanical problems, excessive wear of contacts and/or contact bouncing. A certain difference may be acceptable and will greatly depend on the design and model of the OLTC.

5. Variation in the dynamic resistance results

5.1 Choosing the correct test current

When measuring the static resistance, lower test currents in the range of several amperes are preferred, especially for HV windings [7]. Although testing of low impedance LV windings may require test currents in the range of 10-20 A, it is recommended that currents should not exceed 15 % of the rated current of the winding. Larger currents may heat up the

windings. As the resistance measurement is temperature-dependent, this could lead to inaccuracies in the measured resistance [8]. In general, these considerations also apply to DRM measurements including the following:

Test currents below 3 A or 1 A have shown to be more sensitive to contact bouncing, which can lead to false interpretation of the results. A common effect which can be observed is that a residual oil coating on the contacts causes the current to interrupt several times during the test. These oil residues are usually not considered problematic when the OLTC operates under normal load conditions. In turn, test currents in this range may be able to indicate long-term aging effects such as coking at an earlier stage, but these advantages still have to be investigated further by conducting additional case studies.

Higher test currents in the range of 3-5 A were, in most cases, sufficient to achieve a stable measurement of the switching process. In these cases, minor discontinuities, for example due to oil coating on the contacts, did not affect the results. Field tests did not reveal any differences when further increasing the current to 10 A or 15 A.

DRM is a non-invasive testing method whereby failures can be detected without opening the OLTC compartment

DRM has proved to be beneficial for analysing the switching process and mobile contacts of OLTCs on power transformers

5.2 Secondary short circuit

Shorting the secondary side of the transformer can have two positive effects. First, if the current is interrupted during switching, the energy stored in the magnetic core may not be released, and the fast change in the current will not generate such a high voltage on the opposite winding. The other positive effect is that the current drop (ripple) while switching was in most cases observed to be twice as high, because the main inductance was shorted. This makes the DRM a more sensitive method, but also has an impact on the curves, making them more significant.

5.3 Switching process from tap to tap

When analysing and comparing different taps, it needs to be considered whether the curves differ in case of the OLTC switching up or down. This is important because in the former case some windings are added to the circuit, while in the latter, case windings are subtracted based on the transformer tap winding and OLTC winding, so the wiring diagram could be different for different transformers. If windings are added, the additional inductance needs to be loaded with energy, and if they are subtracted, the loaded energy in the inductance is released. This effect is much more likely if the secondary side is not shorted, as seen in Figure 7.

The measured curves also differ when switching from an odd to an even tap position, as the diverter switch is rotating in alternating directions (Figure 8). This can usually be seen as different switching times of the individual stages. In addition, bouncing of contacts can sometimes only be seen in one direction.

An example of software which allows analysis and comparison of static and dynamic resistance measurements is Primary Test Manager (PTM). PTM shows the switching process of the individual taps in a single diagram, so that they can be compared amongst each other easily. As the current signatures of many OLTC designs may vary by their phase and switching direction, the PTM software offers unique filtering options to compare up and down

operations for even and odd positions and all three phases. This enables the user to analyse measurement results for a comprehensive failure diagnosis.

Conclusion

A conventional static resistance measurement can be used to test the winding as well as all of the fixed internal connections. In some cases, however, it is not possible to detect defects using the standard winding resistance measurement [9]. Therefore, the DRM as a supplementary measurement has proved to be beneficial for analysing the switching process and mobile contacts of OLTCs on power transformers. By using the same test setup as for static resistance, the DRM function enables insight into the fast switching process of the diverter switch to detect mechanical wear-and-tear of the contacts, leads and commutating resistors without additional wiring effort. As a result, the reliability of the OLTC assessment can be improved; maintenance costs can be reduced; and most importantly, unexpected and expensive outages can be avoided.

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