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In order to compensate for network voltage variations, transformers are equipped with tap-changers to adjust the voltage ratio by changing the turns ratio

Tap-changer diagnostics: Present state and new developments

ABSTRACT

The primary function of power transformers is to transform voltage levels for transmission and distribution. Often, transformers are equipped with a device to adjust the voltage ratio by changing the turns ratio: the tap-changer. About 30 % of all European substation transformer failures are attributed to tap-changer failure, as well as about 22 % of the failures in which a fire or explosion has occurred. Although the contribution of tap-changer failures has decreased over the years, it justifies appropriate measures to timely identify tap-changer defects and mitigate failure risks. In this paper, we present an overview of tap-changer diagnostic options, and discuss recent developments, in particular concerning improved techniques for dynamic resistance measurement.

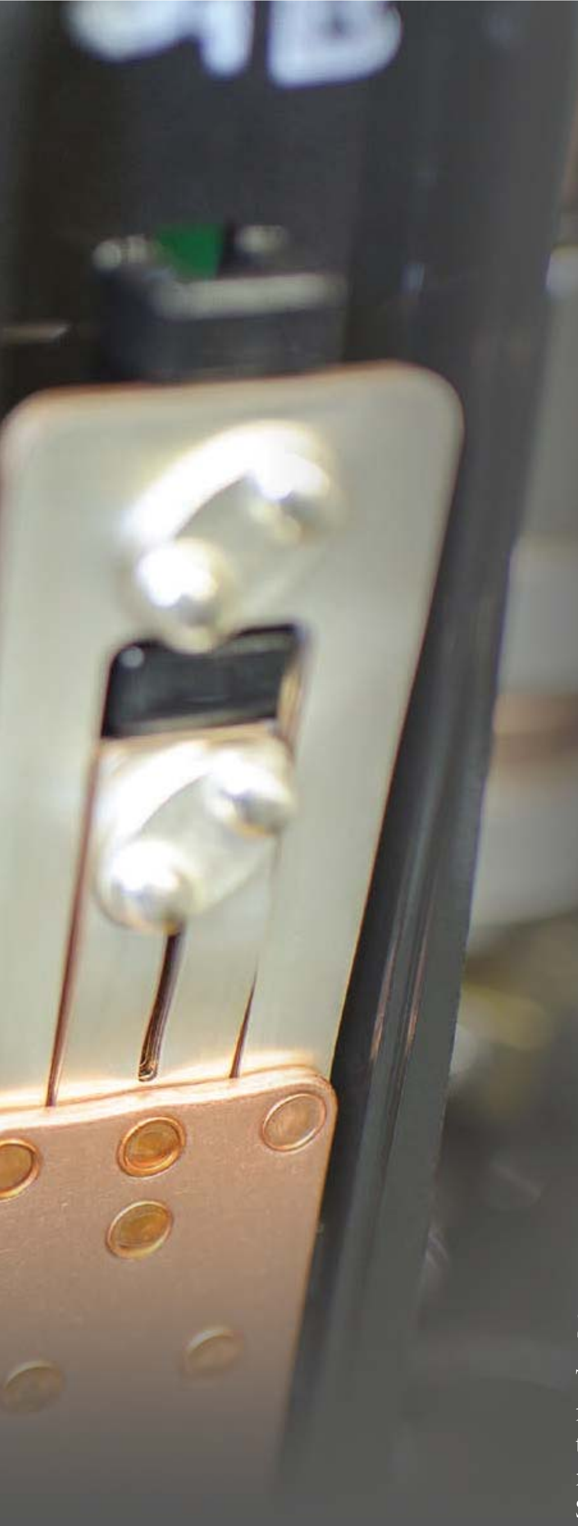
KEYWORDS

diagnosis, dynamic resistance measurement, power transformer, tap-changer

1. Introduction

The primary function of power transformers is to transform voltage levels for transmission and distribution. The ratio between input and output voltage is determined by the turns ratio. During operation, network voltages vary as a result of power fluctuations in the grid, thereby possibly inducing additional losses and stability issues. In order to compensate for this, transformers are equipped with a device to adjust the voltage ratio by changing the turns ratio: the tap-changer.

According to a CIGRÉ Transformer



Reliability Survey from 2015 [1], and a statistical analysis of the results [2], 30 % of all European substation transformer failures are attributed to tap-changer failure. The same survey shows that tap-changer failure is responsible for 22 % of the failures in which a fire or explosion has occurred. Although the relative contribution of tap-changer failure has decreased over the last decades, the present percentages still justify appropriate measures to timely identify and mitigate tap-changer defects.

In this paper we will present an overview of tap-changer diagnostic options, and discuss some recent developments.

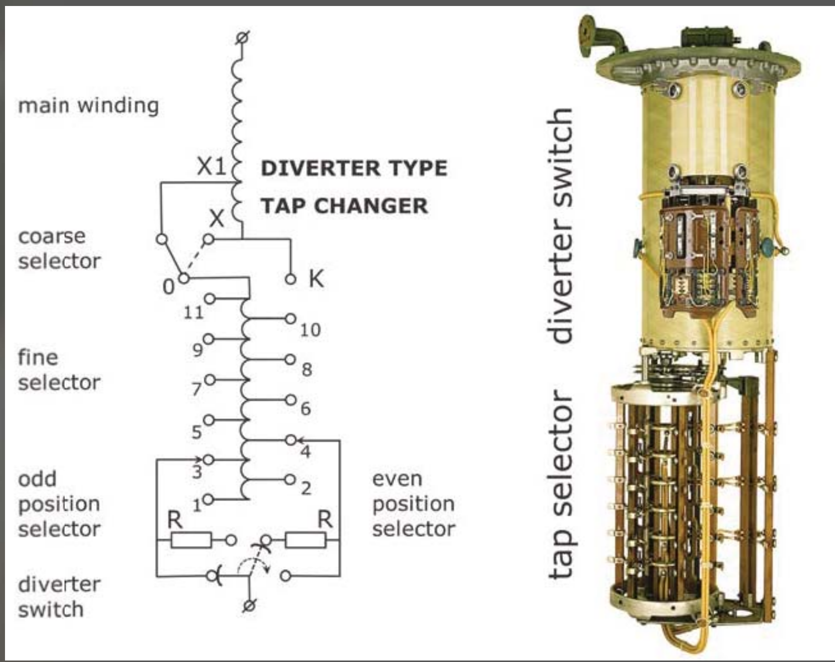


Figure 1. Diverter switch type tap-changer: schematic diagram (left), and an example (right); *Image courtesy of Maschinenfabrik Reinhausen*

The predominant failure mechanisms of tap-changers are either related to contact quality or to defects in the mechanical drive mechanism

2. Tap-changer designs

The high voltage winding of the transformer is provided with a number of taps, and the tap-changer selects the right tap to produce a given turns ratio. Several tap-changer designs are in use today [3]. The first distinction is between de-energized tap-changers and on-load tap-changers:

- **De-Energized tap-changer (DETC)** In case of a de-energized tap-changer, the transformer is first taken off-line before the tap position is adjusted, after which the transformer is put into operation again. This type of tap-changer is used if changing the tap position occurs only rarely.

- **On-load tap-changer (OLTC)** In case of an on-load tap-changer the turns ratio is adjusted while the transformer stays in operation. The transition between taps requires a mechanical mechanism consisting of an electric motor drive and its controls. During the transition from one tap position to another the current is limited by the use of a damping resistor or reactance (resistor-type versus reactance-type tap-changer). The resistor-type OLTC is suitable for high voltages but requires high speed switching (50-150 milliseconds), whereas the reactor-type OLTC is limited in voltage but can sustain higher loads and allows a longer transition time.

For the on-load tap-changer, we distinguish between two types dependent on the way the contacts are selected and switched to, namely: the diverter switch type and the selector switch type tap-changer:

- In a **diverter switch** (or transfer switch) tap-changer, the next tap position is selected in a circuit that does not carry current, after which the load current is transferred to that circuit by the diverter switch;

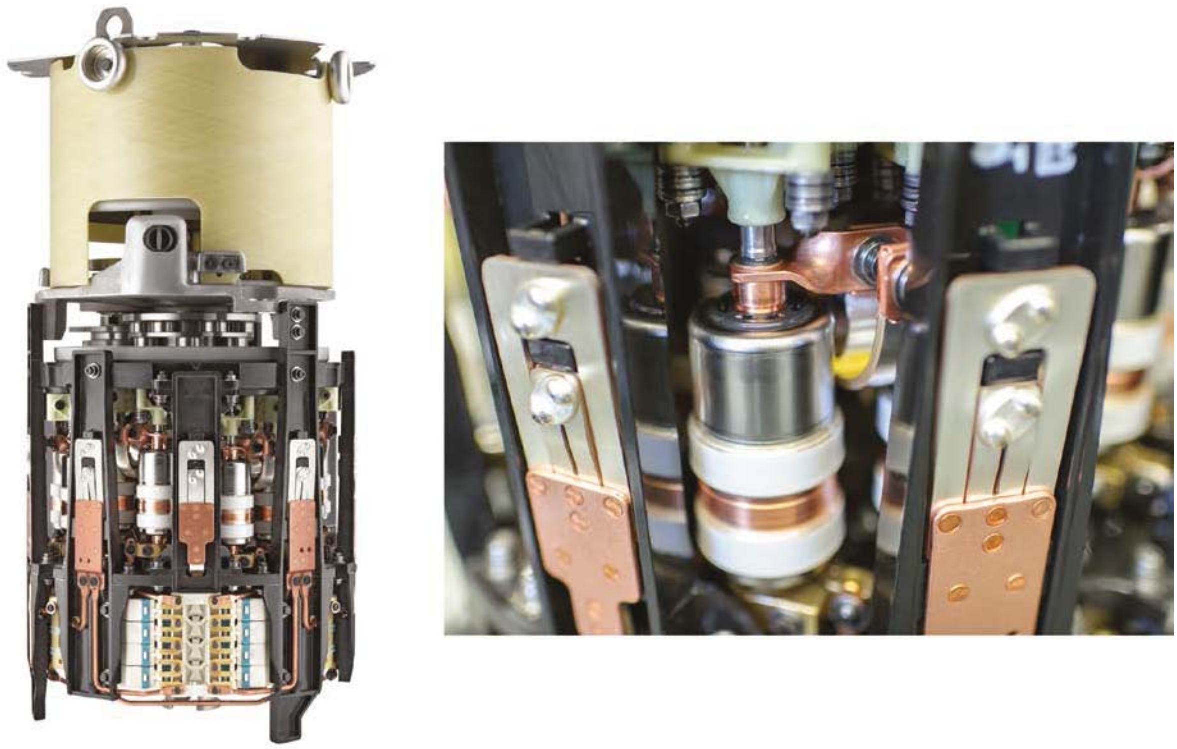


Figure 2. Diverter switch insert with vacuum technology (left) and a detail of the vacuum switch (right); *Images courtesy of Maschinenfabrik Reinhausen*

- In a **selector switch** (or arcing tap switch) tap-changer, tap selection and load switching occurs at the same time.

Figure 1 shows the schematic diagram and an example of a diverter switch type tap-changer.

At present, in existing transformers the tap-changer including the tap contacts and the switches is mostly immersed in oil. Often the tap-changer is placed in a separate oil compartment in order to prevent pollution of the transformer oil by tap-changer contaminants and vice versa. However, in older transformers the active transformer parts and the tap-changer share the same oil compartment. Modern designs of the diverter switch type tap-changer use vacuum switching: the vacuum tap-changer. Further, new designs are available in which the oil is not only replaced as a switching medium but also as the insulation medium: the dry-type vacuum tap-changer and the SF6-insulated vacuum tap-changer. Figure 2 shows an example of a diverter switch insert with vacuum technology.

The aim of diagnostics is to measure the contact quality and the mechanical behaviour, or to identify the presence of degradation mechanisms through their symptoms

3. Tap-changer failure mechanisms

The predominant failure mechanisms of tap-changers are either related to contact quality or to defects in the mechanical drive mechanism [4]:

- The contacts of the tap selectors and the transfer switch are subject to degradation due to discharges and friction. The previously occurring so-called "long-term effect", which is caused by oil film formation and coking, is mostly solved these days by using silver plated contacts.
- Apart from this, the contacts of the arcing switch of a selector-type tap-changer are subject to regular arcing, thereby causing arcing damage to the contacts.
- The drive mechanism is subject to wear and friction, whereas the spring may lose its spring power.

As a result, many diagnostics are aiming at measuring the contact quality of contacts (resistance) and the mechanical behaviour (motion diagrams, transition times), or at identifying the presence of degradation mechanisms through their symptoms (indicators): DGA as an indicator for arcing and heating, motor power and vibrations as indicators for mechanical friction or wear.

4. Tap-changer diagnostic techniques

CIGRÉ brochure 445 (Guide for transformer maintenance) presents an overview of the different diagnostic

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techniques for different OLTC types and different types of tap-changer defects [3].

Motor power / current measurement: the method consists of measuring the motor power or current needed for the motor to perform its motion, and thereby identify mechanical issues. Anomalies in the measured waveform may indicate problems such as increased friction and loss of lubrication while moving between tap positions during selection. Also, defects in charging the spring that is used in a diverter type tap-changer to quickly transfer load from one circuit to another may be identified.

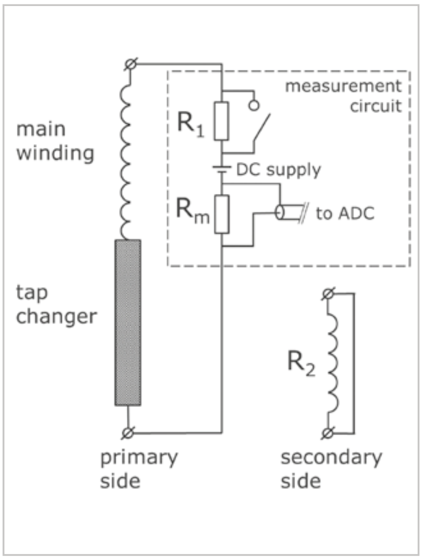

Figure 3. Alternative measurement circuit for dynamic resistance measurement

Static resistance measurement: static resistance measurement is an off-line measuring technique to measure the static contact resistance in a fixed position. The method is relatively time-consuming because every time the tap-changer is moved to a new position, it takes time before the current is stabilized due to the high L/R time.

Dynamic resistance measurement: dynamic resistance measurement is an off-line technique to examine the condition of the contacts of the on-load tap-changers during its motion (hence dynamic). This technique was originally designed, and is still in use, for high voltage circuit breakers. The measurement is not as accurate as the static resistance measurement, but provides more relevant information and takes far less time. We will further discuss this method later.

Dissolved Gas Analysis (DGA): whenever thermal or discharge effects occur in oil, they produce gases that are dissolved in the oil. The composition of the dissolved gases depends on temperature increase (by heating, arcing and coking) and discharge energy. DGA is the most widely used diagnostic technique for transformer diagnosis, and interpretation schemes such as Duval's Triangle have been developed for both transformers and tap-changers, and are still being improved [5-9]. The advantage of DGA is that it indicates degradation mechanism; the disadvantage is that is does not reflect the location of the defect, or the amount of damage done.

Vibro-acoustic measurements: vibro-acoustic measurement is an on-line technique to detect mechanically generated acoustic signals. Each tap-change operation produces a typical pressure wave or vibration, and by comparing measured waveforms with the reference waveforms of a healthy tap-changer, mechanical defects such as timing differences can be detected.

Dynamic resistance measurement is a powerful tool to detect actual defects before they induce a failure, whereas DGA provides an early warning by detecting the presence of degradation mechanisms. Motor power measurement is a relatively simple method that can easily be combined with a dynamic resistance measurement. We will here focus on dynamic resistance measurement.

5. Dynamic resistance measurements

The dynamic resistance measurement is regarded as an enhancement of the winding resistance test [3]. The test circuit involves a known resistor, and a DC source supplies a DC voltage. The DC current is measured continuously during the OLTC switching process. By analyzing the current response, both the timing sequence and the value of the transition resistances can be determined. One of the drawbacks of the common version of this methodology is the slow response of the measuring circuit due to the high L/R time. An accurate measurement of the resistance values requires that the current is stabilized, which enhances the measurement time. We here present a variation of the common measuring principle [10]. The circuit involves a resistor R_1 which is usually short-circuited. After each diverter switch operation the resistor is introduced in the circuit by opening the switch for a short while (typically 1 second). The resistance value is determined from the current drop, thereby shortening the required measurement time. Figure 3 shows the measuring circuit.

After disconnecting the transformer, the secondary side of the transformer is short-circuited, and the measuring circuit is connected. The current is continuously

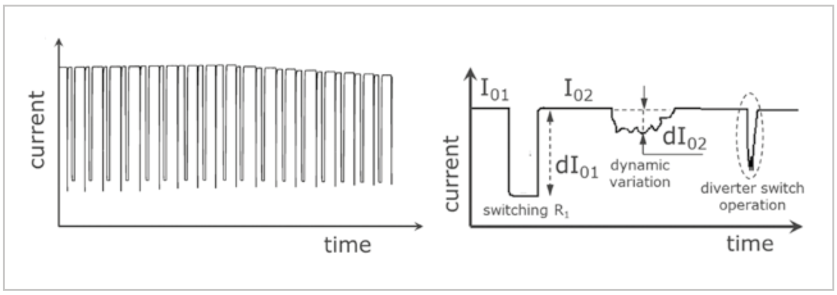

Figure 4. Typical measured waveform for a sequence of tap positions (left), and enlarged for one tap position (right)

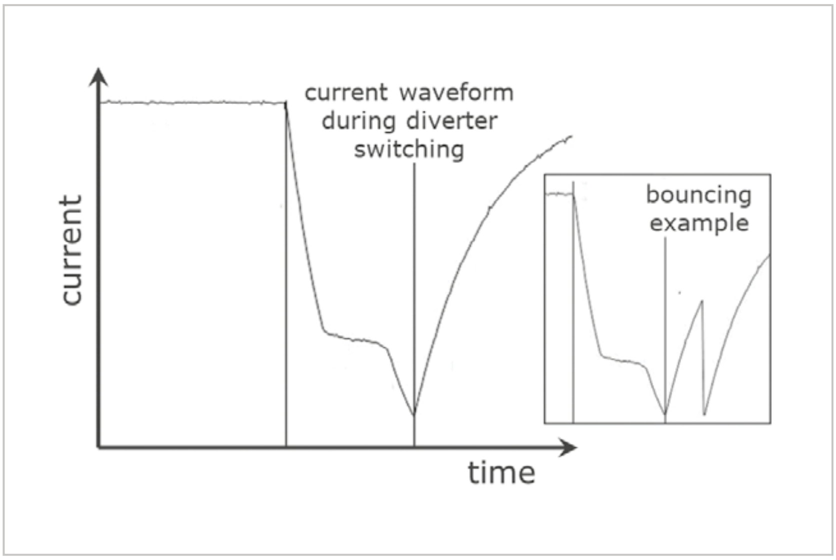

Figure 5. Typical measured waveform for a healthy diverter switch operation, and an example of deviant behaviour as a result of bouncing

Recent developments related to the interpretation of dynamic resistance measurements introduced the concept of a condition indicator for tap-changer contacts

monitored while the resistor R_1 is bypassed by a switch. After each diverter switch operation, the bypass switch is opened for a short time (in the order of 1 second), whereby R_1 is introduced causing a voltage drop. This causes a waveform as typically shown in Figure 4.

During the measurement the tap-changer is operated from the first to the last contact and back again. The reason for measuring in both directions is to account for the mechanical positioning of the end contacts that switch off the motor when reaching a final position. This sequence is repeated at a different current value. The first sequence is a conditioning sequence and breaks up the oil layer that develops on the contacts in the course of time.
The interpretation consists of three steps:

1. The steady state contact resistance R_{ss} is derived from the current drop dI_{01}
2. The dynamic resistance dR is derived from the current fluctuations dI_{02}
3. The diverter switch behaviour is analyzed from the diverter switch waveform

A schematic example of the diverter switch waveform is shown in Figure 5.

6. New developments

In this section we will discuss some new developments, particularly regarding tap-changer DGA analysis and dynamic resistance measurements.

6.1 Tap-changer DGA analysis

Like for transformer DGA analysis, different interpretation methods and standards have been developed, and are still under development for tap-changer DGA analysis [5-9]. The analysis of dissolved gases for tap-changer diagnosis has not reached the maturity of transformer DGA analysis. This is, amongst others, due to the large variety of tap-changer designs and the resulting complexity of the analysis. At present, the likelihood of false positives or false negatives is too high to solely rely on DGA analysis, and the results of DGA analysis still require verification by additional testing [8]. It is expected that the interpretation methods will further evolve over the years to come. Also the introduction of new tap-changer designs making use of vacuum switching and SF_6 insulation will keep driving the further development of tap-changer DGA interpretation methods.

6.2 Dynamic resistance measurements

Recently, new developments were published related to the interpretation of dynamic resistance measurements. A first example is the introduction of the concept of a condition indicator for tap-changer contacts [11]. This proposed indicator is meant to provide a simple criterion to support decision making, and yields:

$$CI = \Delta R_{ss,max} + dR_{2,max} + \frac{(dR_{2,max})^2}{dR_{1,min}} \qquad (1)$$

where:

CI is the condition indicator;

$\Delta R_{ss,max}$ is the maximum difference in steady state contact resistance observed between phases;

$dR_{2,max}$ is the maximum dynamic contact resistance derived from dynamic fluctuations in the second sequence; and

$dR_{1,min}$ is the minimum dynamic contact resistance derived from dynamic fluctuations in the first (conditioning) sequence.

In [11] the following assessment criteria

Condition indicator range (mΩ)		
Condition	**Diverter switch**	**Selector switch**
Good	0-20	0-100
Suspicious	20-400	100-250
Bad	>400	>250

The use of condition criteria and indicators opens the way to automated defect identification algorithms for dynamic resistance measurements

are proposed for a diverter switch type tap-changer and a selector switch type tap-changer:

Similarly, criteria can be defined for the diverter switch operation waveform (providing indications for bouncing or contact degradation) and for motor power measurements (providing indications for mechanical defects such as wear, friction, spring charging issues).

As is the case for DGA analysis, also for dynamic resistance measurement interpretation criteria and indicators are being defined for newly introduced tap-changer designs making use of vacuum switching and SF6 insulation.

6.3 Integral analysis and automated interpretation algorithms

The use of condition criteria and indicators opens the way to automated defect identification algorithms, as was shown in [12] for dynamic resistance measurements. Such algorithms are used as decision support tools. Ongoing developments further include the integral evaluation of the tap-changer condition from the combined analysis of static and dynamic resistance, switching waveforms, motor power and DGA analysis. Combining integral evaluation with automated analysis will ideally lead to diagnostic software involving a library of interpretation rules and functions applicable to a variety of tap-changer designs.

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