Degradation Effects and Diagnosis of On-load Tap Changer in Power Transformers

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Abstract—By performing diagnostics on on-load tap changers by means of dynamic resistance measurements, a condition diagnosis of high-speed resistor-type tap changers can result in pre-failure detection of contact degradation. It provides the measurement parameters that are most suitable for detecting these defects, such as the presence of a contact film, contact wear and pitting. The resistance curves of OLTCs are interpreted, to determine the occurring degradation mechanisms, which can be used to support strategic decisions about the maintenance or overhaul of the tap changer.

I. INTRODUCTION

The primary function of an on-load tap changer (OLTC) is to select another tap position without interrupting the load current. This can be accomplished in various ways, resulting in a considerable diversity of tap changer designs. An overview of OLTC ageing and degradation mechanisms and some examples of diagnosis performed that indicated ageing will be discussed. The role of the on-load tap changer is to transfer the load current during switching and they are therefore equipped with an arcing switch. Two different arcing switch principles are:

1. Diverter switch
2. Selector switch

The main difference between these designs is that a diverter switch type OLTC uses a tap selector to pre-select taps without switching current, in combination with a diverter switch to switch the load from the selected to the pre-selected tap. A selector switch type OLTC combines the selection of fine tap windings with the switching of the load current.

In several countries the tap changer has the highest contribution in the failure statistics of power transformers [2, 3]. This emphasizes the need to understand tap changer degradation and to be able to perform sensitive diagnostics to detect upcoming problems.

II. TAP CHANGER TECHNOLOGIES

A. Selector switch type

Selector switch type OLTCs combine the switching of the load current with the selection of fine winding taps. Selector switches can be used in a stand-alone manner but their voltage regulating range can also be extended with a (multiple) coarse change-over selector. When all of the fine tap windings are selected by the selector switch, a coarse tap winding can then be inserted before the selector switch can continue.

An example of a selector switch type OLTC is shown in Figure 1, with its selector switch on top of the coarse change-over selector. The selector switch is accessible at the top of the transformer, while the coarse change-over selector is mounted deeper within the transformer tank, underneath the selector switch. Therefore can the selector switch be checked during regular maintenance by removing the rotor insert, the oil can be replaced, the selector switch inspected and its arcing contacts renewed when necessary.
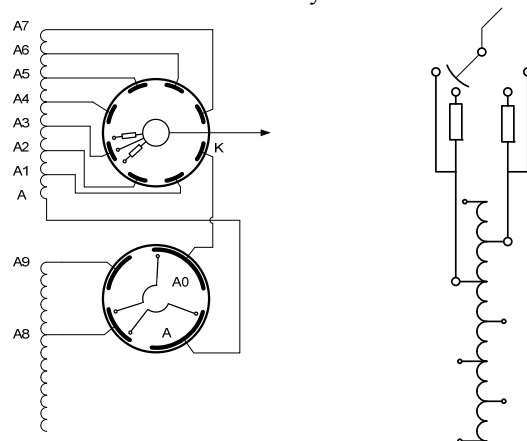

Figure 1. Left: Selector switch type OLTC with coarse change-over selector, Right: Diverter switch with transition resistors (top) and a tap selector (bottom).

The selector switch and the coarse change-over selector both consist of a stator on which the static contacts are mounted. These contacts are connected to the taps on the transformer windings. The rotor is located inside the stator and rotated by the drive system. The rotor makes a connection between the stator contacts. The total operating time of the selector switch movement will take about 30-200 ms.

The selector switch changes the voltage ratio with one voltage step at a time. The coarse change-over selector shown in figure 1 makes a voltage change of 8 steps when switching from coarse tap A8 to A9. The current is brought to the selector switch stator by the rotor of the coarse change-over

selector (by using contact A). The selector switch has selected three fine tap windings using tap A3. The transition resistors are necessary to prevent the short circuit of adjacent fine tapped windings and to provide a non-interrupted current path for the load current during the switching operation. The circulating current is determined by the step voltage and the resistance of the selector switch.

B. Diverter switch type

A diverter switch type OLTC combines a diverter switch and a tap selector. The tap selector has two sets of contacts available for tap selection. One of the two contacts is selected by the diverter switch and is under load. The other contact selects the next tap without switching current. Diverter switch type OLTCs use transition resistors to limit the circulating current in the diverter switch. Figure 1 shows a tap selector and a diverter switch. By switching the reversing change-over selector, one can add or subtract the selected transformer windings, thus doubling its range. A coarse change-over selector can add a section of the regulating winding to the main winding, in this way changing the voltage of all tap selector contacts.

In contrast to the selector switch type tap changer, most diverter switch type OLTCs have no rotor inside the arcing switch. A stationary insert is used instead. The diverter switch can easily be maintained by removing the diverter switch insert. Similar with the selector switch type tap changers, the oil can be replaced, the diverter switch inspected and its arcing contacts replaced.

III. DEGRADATION MECHANISMS

An OLTC has sets of contacts that switch different currents at different recovery voltages. For example, the main contacts of the arcing switch are designed to transfer the load current to the transition contacts. The arcing contacts of the arcing switch are designed to break the load current and the circulating current. The contacts of the tap selector and the change-over selector are not designed to switch current. Therefore these sets of contacts wear differently.

Change-over selector contacts (including tap selector contacts) do not wear as fast as arcing switch contacts that wear due to the switching of load currents. These contacts will not switch significant currents, but can show pitting of the contacts and the development of so called pyrolytic carbon. This contact degradation is not due to the arcs caused by switching the current but by a long term overheating process. Furthermore, the contacts of the change-over selector are infrequently used and can be motionless for long periods. This activates the second degradation mechanism of change-over selector contacts: a long-term aging effect on contacts under oil.
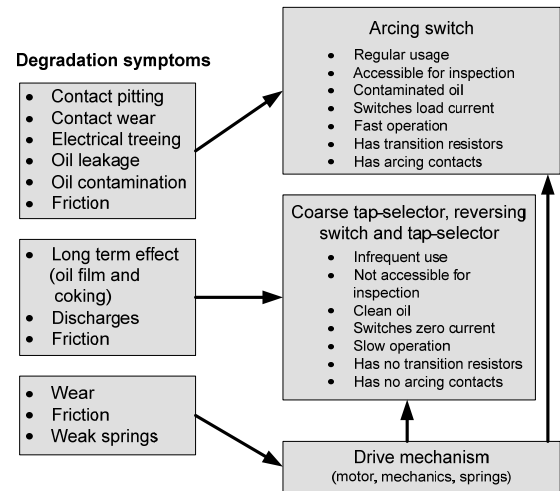

Figure 2. Tap changer degradation mechanisms [1].

In general the following four contact conditions can be present:
1. Clean contacts (good condition)
2. Contacts with a surface film
3. Contacts with high local temperatures
4. Contact failure due to overheating

A. Contacts with a surface film

The resistance of a contact will gradually increase during its lifetime. According to [4] and [8, 9] this long-term effect starts with surface oxidation and the formation of organic polymers [6]; these effects reduce the conductivity. Anorganic layers can be formed on copper contacts [6].

At higher temperatures an organic film is also formed [9]. The organic film is composed of organic compounds in the transformer oil and consists of polyacrylates and polyfurans. This layer bonds to the oxide layer formed on the contacts to give a stable film of low conductivity.
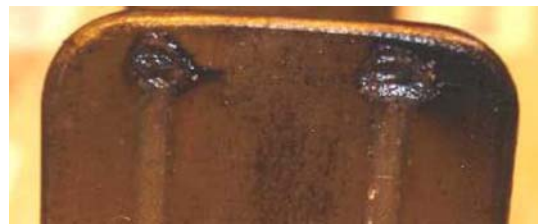

Figure 3. The long-term degradation effect on the change over selector contact.

The formation of this surface film is referred to as the early stage of the long-term aging effect. Experiments described in [5] show that the surface film grows thicker as the contacts age, and that the growth rate of this layer is strongly dependent on the surface temperature of the contacts. The contact resistance and the power losses at the contact increase as the surface film grows. At early stages of the long-term aging effect, the film can be removed by switching the OLTC through its cycle of

operation. The motion of the contacts during this cycle partially breaks down the surface contamination [7, 10] and delaying the long-term aging effect.

B. Contacts with high local temperatures

Another advanced degradation stage is the long-term aging effect due to the temperature dependence of the surface film growth rate. The contact resistance can also fall during the long-term aging, as the surface film breaks down due to discharges [7] or contact wiping. Small discharges can restore a better current path by disrupting the surface film, but the contact resistance can increase by several orders of magnitude before the contact improves again [7]. These discharges become worse as degradation proceeds, and the oil dissociates due to these discharges and the high contact temperatures. It is these effects together that constitute advanced long-term aging.

The decomposition of transformer insulation oil leads to the deposition of carbon between the contacts. This formation of pyrolytic carbon is called coking [6]. Oil cracking occurs at local temperatures above 300 °C [7]. Catastrophic conditions can thus be produced when the contact temperature rises above 300 °C, but even a rise in oil temperature near the contact to above 100-105 °C can be enough to cause serious defects [11]. The film growth and power losses increase gradually, which causes a rising temperature, until the contacts get overheated and failure occurs.

TABLE I
CAUSES AND CONSEQUENCES REGARDING THE DEVELOPMENT OF THE LONG-TERM EFFECT [8]

Cause	Consequence
Infrequent movement of the contacts	The surface film is not wiped off the contacts when the change-over selector is not operated.
High temperatures	The formation of the surface film is highly temperature-dependent.
High load current	Power losses at the contact interface increase exponentially with the load current and lead to correspondingly greater heating of the contacts.
Low contact pressure	Coking and pitting of the contacts are more likely to lead to contact jamming when the contact pressure is low. The layer of contamination on the contact surface, which can lead to contact malfunction or failure, is also more easily disrupted at high contact pressure.
Copper or brass contacts	The growth rate of the surface film is higher on copper and brass contacts than on silver contacts. Pitting and coking are reduced by silver-coating of the contact surface; however, older OLTC designs may use bare copper contacts.

C. Contact failure due to overheating

The contact material wears off locally and pitted spots become visible on the contacts. The contacts are now irreversibly damaged, and cannot be repaired by switching the OLTC through all its tap positions. An overhaul is needed to undo the pitting of the contacts. Because of the infrequent movement of the change-over selector, coking can occur on all stator contacts, rotor contacts and other movable parts that carry the load current. The final stage of the long-term aging effect is thermal runaway. The coking accelerates due to increased contact resistance and the thermal resistance characteristics of the carbon [4]. Coking between moving parts of the contacts and around the springs that provide the contact pressure can cause the contacts to lose pressure. Finally, a considerable amount of contact material disappears. Coking is likely to occur when the resistance is rising rapidly [8]. The long-term aging effect can be accelerated by several factors as shown in table 1.

IV. TAP CHANGER DIAGNOSTICS WITH DRM

As shown in the previous section on-load tap changers can degrade, which affects the transformer reliability. Therefore an early detection of the irregularities with condition assessment of an OLTC is required. With off-line diagnosis accurate information on the condition can be obtained with advanced measurement systems. The focus of condition assessment techniques is to identify defects at the earliest stage, before significant damage is caused. Early discovery and remedy of defects avoids expensive consequences.

Dynamic resistance measurement is suitable for detecting irregularities in the OLTC contact resistance, as are static resistance measurements. The main difference between dynamic measurements and static measurements is that the tap changer is operated during the measurement. Important information about the importance and location of the long-term effect on the change-over selector contacts can be extracted from the measurement. The contacts do not remain at each position long enough to allow the measurement current to stabilized. Current stabilization is mostly attained after a relatively long time constant caused by a high inductance of the transformer windings. Despite the fact that DRM can be considered less accurate than static resistance measurements, it provides more information about the type and location of defects inside the OLTC. For example, a typical dynamic measurement does not allow enough time to stabilize the measurement current and cannot reveal contacts with resistance increased by 100 $\mu\Omega$, whereas static resistance measurement can do this, but cannot show irregularities in the transition time. It has been found that results of the DRM can be interpreted without quantification: the location and nature of the detected differences are sufficient to assess how serious the OLTC defect is. Four basic conditions can be given:
- OLTC in good condition
- OLTC with increased contact resistance
- OLTC with open contacts (infinite resistance)
- OLTC with deviating switch times

The location of the deviation can be used to find the cause and seriousness of the defect. Determining the seriousness of a resistance deviation before re-energizing the transformer can prevent OLTC defects to result in a failure.

V. Typical DRM Graphs

A. Normal DRM curve

Two sources of resistance variations can be identified by examination of a DRM graph without effects of degradation or OLTC defects: the transition resistors and the resistance of the tapped winding. A typical record of the test current measured on a healthy OLTC is shown in figure 4.
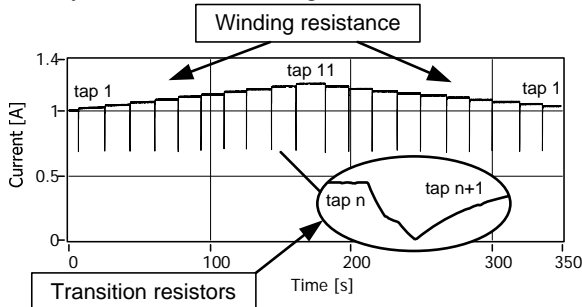
Figure 4. Typical record of DRM current on an OLTC without defects.

The winding resistance changes when regulation winding taps are subsequently deselected by the OLTC. An impedance-graph is another way to display the results of DRM, looking like a mirror reflection of the test current record since the test voltage is kept constant during the measurements.

B. Contact degradation during DRM

Contact degradation can cause increased contact resistances or deviation in the resistance during the switching operation.
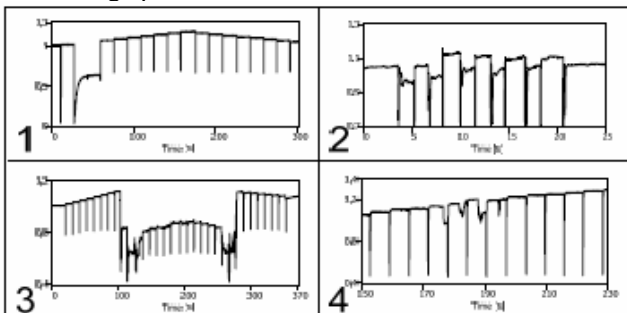
Figure 5. Four typical DRM graphs

Some examples of DRM graphs of OLTCs with deviating contact resistance, based on the four situations:
- Figure 5-1: Example of a problem in a diverter switch, no resistance deviations are measured when the changeover selector operates.
- Figure 5-2: An alternating contact resistance indicates a problem with one set of diverter switch contacts or with one of the tap-selector main contacts.
- Figure 5-3: An example of resistance deviations that only occurs when the change-over selector is operated.
- Figure 5-4: Example of a DRM graph showing one coarse tap with higher resistance than the other coarse tap.

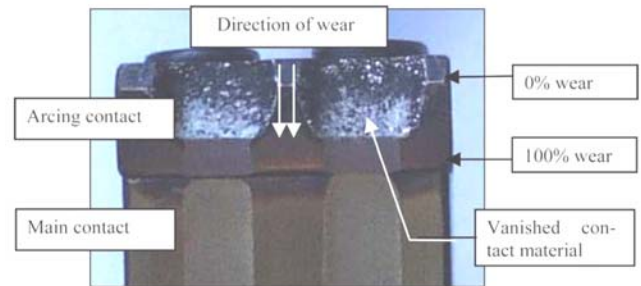In Figure 6 a contact is shown that is about 75% worn at the arcing contact during operation.

Figure 6. Worn arcing contacts taken from a service/aged OLTC. These contacts are approximately 75% worn.

VI. Conclusions

The typical aging mechanisms that can act on on-load tap changers are discussed. To diagnose the condition of service aged high-speed resistor type on-load tap changers dynamic resistance measurement are used. The interpretation of DRM is dependant on the OLTC type and working principle. Taken this into account upcoming defects can be localized and the cause for the deviation of the resistances can be determined, as presented in examples.

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