

## AN INNOVATIVE APPROACH TOWARDS AN ALGORITHM FOR AUTOMATED DEFECT RECOGNITION FOR ON-LOAD TAP CHANGERS

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### ABSTRACT

Power transformers are valuable assets in the power network, with the primary function to regulate the transmission and distribution voltage. The regulating device is the tap changer which sets the turn-ratio. Tap changer failure is one of the leading causes of HV power transformer failure. Most tap changer failures are caused by degrading contacts. Contact degradation may be the result of contact wear or of arcing-induced carbon deposition during on-load tap changes. Contact degradation increases contact resistance, causing increased heating and arcing, eventually leading to possible failure of the power transformer. Proper maintenance therefore requires a diagnostic system which can assess the condition of the contacts. The research presented is aiming at automated defect recognition and localization from measured Dynamic Resistance Measurement (DRM) patterns, for two types of tap changers, the “Diverter Switch” type and the “Selector Switch” type On-Load-Tap-Changer (OLTC).

### INTRODUCTION

Power transformers are among the most valuable assets of the power network system. A large amount of capital is required to manufacture, transport, install and maintain them. Power transformers are used to transform the voltage levels for transmission and distribution, and are vital for the power system. As the load in the network changes, the voltage is affected and needs to be regulated. Voltage regulation is performed by on-load tap changers. Maintaining a proper voltage level is important for several reasons:

- To limit the losses;
- To maintain synchronization within the network.

The only moveable part present in the power transformer is the tap changer. The placement of tap changer is illustrated in Figure 1 [1]. The purpose of the tap changer is to change the turns ratio. Tap changer failure is one of the leading causes of failure of power transformers. Per [2] and [3] more than 40% of the failures of HV power transformers are caused by the on-load tap changer. The switching of current from one tap position to other tap position can result in heating and arcing. This can cause contact degradation and may ultimately lead to failure of the power transformer. The general life time of a power transformer ranges from 40 to 50 years, and a diagnostic

system (the dynamic resistance measurement) is used to judge the condition of the contacts during its life. The goal of the work presented is to arrive at an automatic interpretation system that can identify and locate the faulty contact based on the information received from the dynamic resistance measurement.

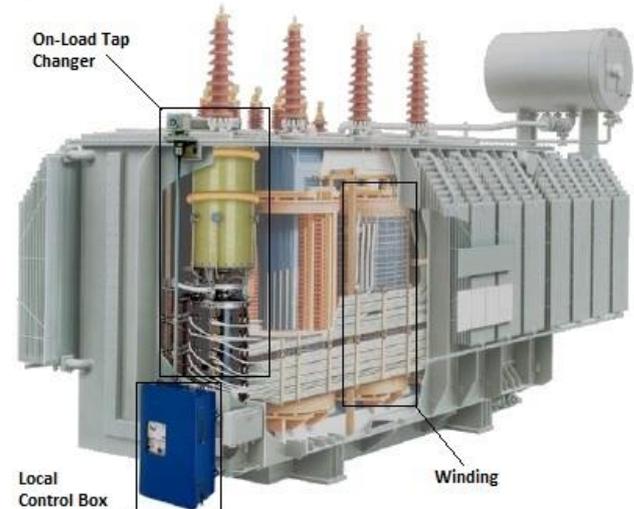


Figure 1: Artistic image showing internal section of high voltage power transformer with tap changer location.

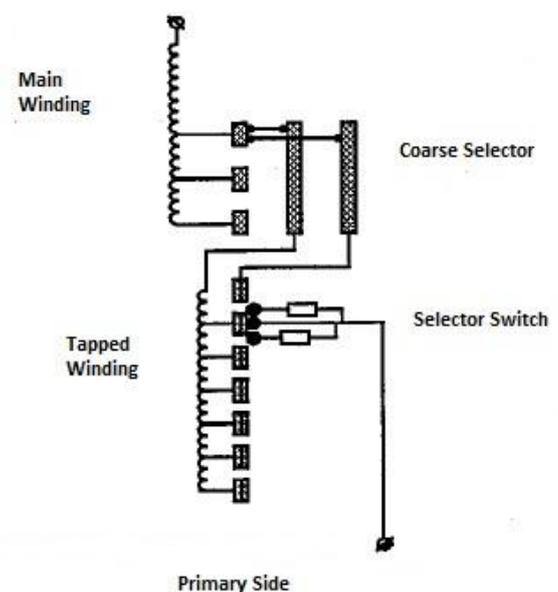


Figure 2: Simplified depiction of selector switch type tap changing mechanism.

## Types of OLTC

There are several on-load tap changing mechanisms. The focus of this research is on two of the tap changing mechanisms.

### Selector Switch Type

The simplified configuration of this type of tap changer is shown in Figure 2 [4]. This type of OLTC makes fine tap selection and switches the load current at the same time while the coarse tap selector switches to the next contact without current flowing through it.

### Diverter Switch Type

The simplified configuration of this type of tap changer is shown in Figure 3 [4]. This type of OLTC first selects the next fine tap position and then switches the load current to it. The coarse tap selector always switches to the next contact without current flowing through it.

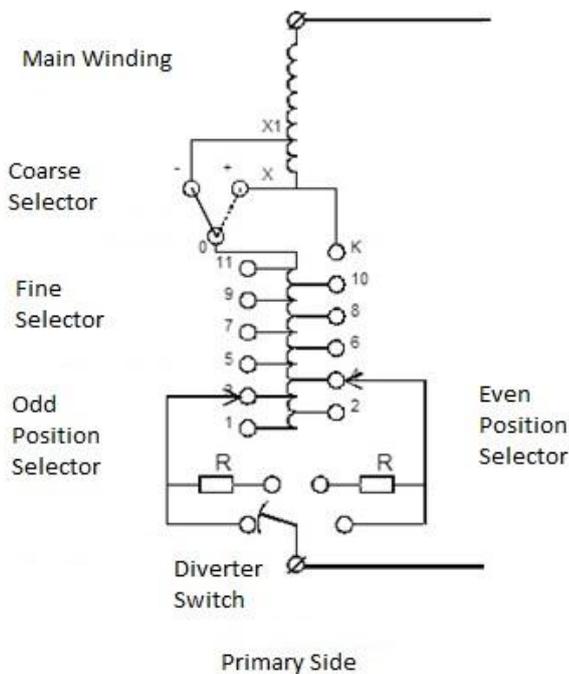


Figure 3: Simplified depiction of diverter switch type tap changing mechanism.

## DYNAMIC RESISTANCE MEASUREMENT

Dynamic resistance measurement is an off-line technique to examine the condition of the contacts of the on-load tap changer. The technique is not as accurate as static resistance measurement but provides more relevant information and takes far less time. Temperature adjustment is applied when comparing the data with previous records. Figure 4 [4] shows the circuit and terminal connections for performing DRM.

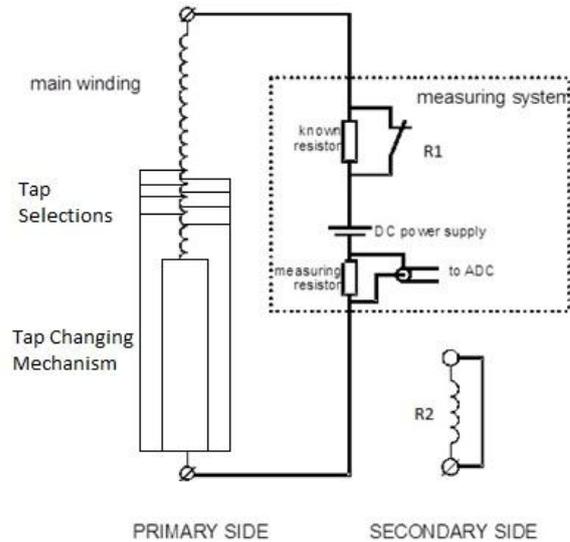


Figure 4: Measuring set-up.

## Method

The measuring technique uses a DC power supply to introduce a current in the tap changer circuit as shown in Figure 4. After disconnecting the transformer, the secondary side of the transformer is short-circuited. The primary side is series connected to a “known” resistor (R1), a measuring resistor and a DC power supply. The known resistor has a bypass switch which is usually closed. After each transition the bypass switch is opened during a certain period (manually selected, usually around 1 second) and thereby the known resistor becomes part of the circuit. This sequence is performed for each of the tap changer contacts, and repeated until for each phase a total of four series is performed. For each series, the current is recorded providing a record as shown in Figure 5 [4] (for one tap position) and Figure 6 [5] (for all tap positions). From the DRM record the resistance at each tap position is calculated, yielding a resistance graph as shown in Figure 7 [5]. Four measurements series are performed:

- Measurement 1: current setting 1, from 1st to last tap
- Measurement 2: current setting 1, from last to 1st tap
- Measurement 3: current setting 2, from 1st to last tap
- Measurement 4: current setting 2, from last to 1st tap

The reason for varying the current is because of the thickness of the oil layer that develops on the contacts after some time of operation. The reason for performing two measurements at the same test current in opposite directions is to account for the mechanical positioning of the contact at which it rests after its transition. Once all measurements are performed the resistance at each tap position is calculated. This results in 4 DRM records and 4 resistance graphs for each phase, hence a total of 12 DRM records and 12 resistance graphs.

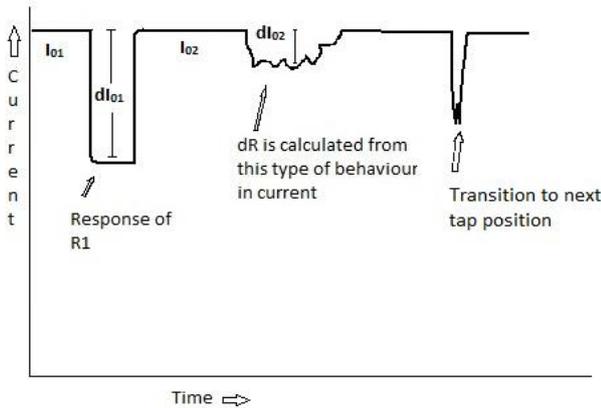


Figure 5: Schematic current record of one tap position.

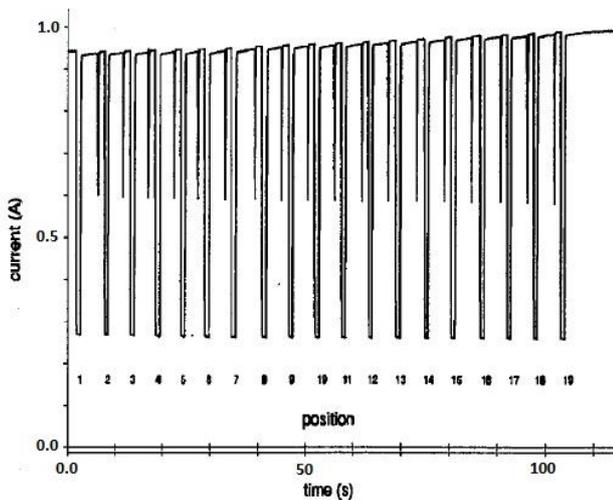


Figure 6: Recorded current during measurement (DRM record).

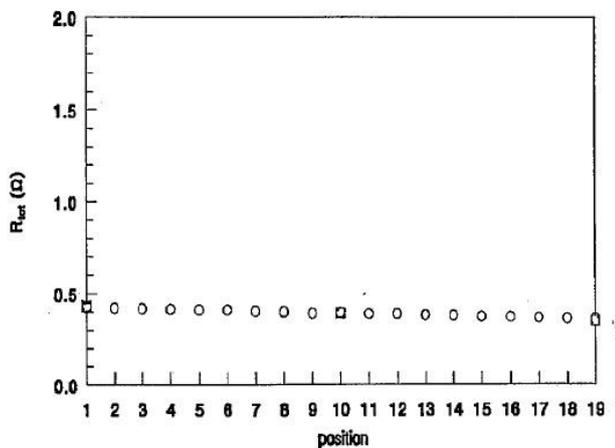


Figure 7: Calculated resistance at each tap position obtained from DRM records (resistance graph).

### Resistance Measurement Principles

The resistance values are calculated from the DRM

records. The circuit that results provides the DRM records is connected on the primary side while the secondary side of the transformer is short circuited. The resistance value measured at the primary side is influenced by the secondary resistance [5]. Therefore, the value of the secondary resistance should be known. Directly after switching on the current on the primary side the measured resistance equals:

$$R_{tot} = \frac{U_o}{I_o(0)} - N^2 R_2$$

After the current, has stabilized, the resistance equals:

$$R_{tot} = \frac{U_o}{I_o(\infty)}$$

$$R_2 = \frac{1}{N^2} \left( \frac{U_o}{I_o(0)} - R_{tot} \right)$$

Once the secondary resistance is derived, the known resistor can be used to derive the total resistance  $R_{tot}$ . The basic purpose of the known resistor is to help in calculating the total resistance, without having to wait for the current to stabilize [5]. The known resistance is switched in series after the tap changer has established a contact at a given tap position. With the known resistance inserted, the circuit time constant decreases and the current quickly stabilizes. The total resistance value is calculated using the below formula. The current values used in these formulas are also indicated in Figure 5.

$$R_{tot} = - \frac{R_1(I_{01} + dI_{01}) + dI_{01}N^2R_2}{dI_{01}}$$

Here:

- $R_{tot}$  is the total resistance at the primary side at a specific tap position
- $R_2$  is the resistance of the secondary winding
- $N$  is the turns ratio
- $U_o$  and  $I_o$  are the primary voltage and current
- $R_1$  is the known resistance usually chosen such that the current drops by about 50%
- $I_{01}$  is the value of the current before the known resistance was brought into series
- $dI_{01}$  is the change of current (a negative value)

### Contact Resistance

The total resistance at the primary side consists of the summation of:

- the value of the measuring resistor
- the secondary resistance as seen from the primary side
- the resistance of the connecting cables
- the winding resistance, and
- the contact resistance

$$R_{tot} = R_{measure} + N^2 R_2 + R_{cable} + R_w + R_{contact}$$

As  $R_{measure}$ ,  $N$ ,  $R_2$  and  $R_{cable}$  are known, the total resistance allows to derive the sum of  $R_w$  and  $R_{contact}$ . In case the contact resistance is virtually zero (which is the case for healthy contacts [4]) we may derive the winding

resistance from the measured total resistance.

### Dynamic Contact Resistance (dR)

The contacts of the tap changers are originally clean and smooth, so when they move against one another there is no increase in contact resistance. After many operations, carbon is deposited on the contacts, resulting in an increase in contact resistance as shown in Figure 5. Thus, the measured resistance will deviate from the overall resistance previously termed as  $R_{tot}$ . Per [5] the value of increased resistance due to carbon deposits and unsmooth contacts is derived from

$$dR = \frac{dI_{02}(R_{tot} + N^2R_2)}{I_{02} + dI_{02}}$$

### Transition Time

The time taken by the contacts of the tap changer to completely transfer the current to the next tap position [4] is shown in Figure 8.

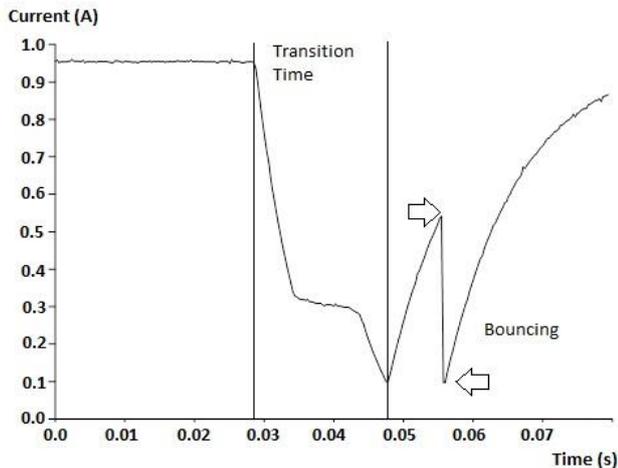


Figure 8: Behavior of current during the transition.

## FAULT INDICATORS

The fault indicators are derived from the DRM records. These indicators shall provide the basis to identify the faulty contacts.

### Contact Resistance

If the contact resistance is increased it is important to know the location of the OLTC contacts with increased contact resistance.

### Fine or Coarse Tap Position

If the contact resistance is increased on a fine tap selection contact, the deviation is only seen at that specific position. If it is increased on a coarse tap selector contact, the deviation is observed on all fine tap positions connected to that coarse tap selector.

### Dynamic Contact Resistance

The dynamic contact resistance is observed while the contacts are moving or if insufficient pressure on the

contacts causes them to vibrate.

### Fine or Coarse Tap Position

If a dynamic contact resistance is observed during contact movement, it is important to know whether this involves the coarse tap selector or the fine tap selector. If a dynamic resistance is caused by insufficient pressure it appears on all tap positions and possibly even when the contacts are at a steady position.

### Transitioning Spring

The motor winds the spring to accumulate the energy which is then released during the transition to next fine tap position [6]. The time taken by spring to release the energy is an indicator which can be compared with the information provided by the manufacturer. In some cases the contacts involved in transition, bounce as shown in Figure 8. If the current drops to zero during more than 5 ms during bouncing, then it is termed undesirable.

## ALGORITHM

The algorithm uses the fault indicators presented to identify the type and location of fault. The transition times and markers when known resistor is switched in is provided to the algorithm as input.

### Condition Indicator & Levels

In this paragraph, we propose a common indicator that provides information about the condition of the on-load tap changer. The condition indicator involves the following three factors:

- the maximum resistance difference between the phases as derived from measurement 3 & 4 ( $R_{w\_max}$ )
- the maximum dynamic contact resistance as derived from measurement 3 & 4 ( $dR_{max}$ )
- the degradation factor obtained from the dynamic contact resistance ( $dR_{factor}$ ). The dynamic resistance is calculated for each tap position. We select the value with the highest degradation factor and use it to derive the condition indicator. The degradation factor can be calculated at each tap position by using formula

$$dR_{factor} = \frac{(dR_{max}^2)}{dR_{min}}$$

Here:

- $dR_{max}$  is the maximum value of dR obtained from measurement 3 or 4
- $dR_{min}$  is the minimum value of dR obtained from measurement 1 or 2

Finally, the condition indicator is derived from:

$$Condition\ indicator = R_{w\_max} + dR_{max} + dR_{factor}$$

Table 1 shows the proposed condition indicator criteria.

Table 1: Levels defined for proposed condition indicator.

Condition	Condition Indicator (mΩ)	
	Diverter Switch	Selector Switch
Good	0 to 20	0 to 100
Suspicious	20 to 400	100 to 250
Bad	>400	>250

### Three Phase Resistance Match

The transformers are manufactured such that each tap position has an equal number of turns and thereby an equal resistance. If all the tap positions have equal resistance, the OLTC is in healthy condition from this perspective.

### Reference Resistance

The algorithm uses the value of the resistance and calculates the percental increase with respect to a reference value.

1. At any tap position where the resistance values of three phases match, this value is used as reference value.
2. If no position is found where  $R_w$  matches for all three phases the following method is used as an approximation: at each tap position the maximum difference of resistance between phases is derived. We select the pair of phases with the highest resistance difference, and choose the lower resistance value as the reference.

The proposed criteria for judging the relative and absolute contact resistance changes are presented in Tables 2 and 3.

Table 2: Relative levels proposed for contact resistance change.

Percental Change	Termed Aging
0 – 5%	Healthy
5 – 10%	Light
10 – 20%	Medium
+20%	Advance

Table 3: Absolute levels proposed for contact resistance change.

dR Value (mΩ)	Termed Aging
0 – 5	Healthy
5 – 10	Light
10 – 15	Medium
+20	Advance

### Transitioning Spring

The transition times are compared with previous records or with details provided by the manufacturer. They are also checked for bouncing duration.

### Interpretation Steps

- The value of the condition indicator answers the question whether the transformer is suitable for service.
- The amount of contact resistance change as derived from Tables 2 and 3 are used to locate the fault. It shows whether the fault is at the coarse tap selector or at the fine tap selector, and identifies the faulty contact.
- If bouncing is detected it is notified in the algorithm output.

### CONCLUSION & FUTURE WORK

As a proof-of-principle, the algorithm output of DRM interpretation of about 10 transformers is compared to the result of expert judgement. It is concluded that it is very well possible to perform an automated analysis on dynamic resistance measurement data. As a next step, the algorithm will be applied to many more measured patterns and improve the statistical significance of the results. Based on the results a specific set of instructions and criteria will be coded that can serve as a fully automated defect recognition algorithm.

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