On-line Condition Monitoring of Tap Changers-Field Experience

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As part of previous research the authors have developed a PC-based tap changer monitor that enables the condition of tap changer contacts and associated drive system to be inferred from vibration signals. The monitoring system has been used to assess the condition of a common type of older tap changer. For this type of tap changer, it has been shown to be possible to determine not only that the tap changer is ageing, but also to identify the particular part of the tap changer that is degrading. This latter feature has been achieved by correlating induced faults on a real tap changer with changes in the vibration signatures. Monitoring systems have been applied to the on-line assessment of tap changers in a distribution network for over three years.

This paper describes the results of field studies made recently to increase confidence in the use of the monitor and to explore the application of the monitor as a maintenance tool. The approach that has been taken has been to monitor signals in a period before maintenance and to prepare an assessment of the condition of the tap changer from data supplied by the monitor. The actual condition of the tap changer, as determined from the results of maintenance inspections, are then compared with the assessments based on results from the monitor. Tap changers have also been monitored for a period after maintenance to check the effectiveness of maintenance work.

Generally the results of this exercise show that the monitor can accurately predict the state of the tap changer.

Results from long-term monitoring and subsequent plant inspection illustrate the ways in which equipment deteriorates. In some cases the deterioration is gradual, but in other there are sudden shifts in the condition. The monitoring system will accurately detect and track either types of degradation.
ON-LINE CONDITION MONITORING OF TAP CHANGERS - FIELD EXPERIENCE

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1. INTRODUCTION

It has been shown that on load tap changers (OLTC) cause the majority of transformer failures in service [1], and consequently improving the reliability of tap changers is essential in ensuring the reliability of power transformers. There is, therefore, a need for a reliable OLTC condition monitoring system, which can be readily used by maintenance engineers not only to assess the condition of the equipment, but also to check the quality of maintenance.

As part of research into failures of old OLTCs in distribution systems, a survey has been conducted among local electricity supply industries [2]. Results from the survey showed that incorrect maintenance and ageing of components are the main contributors to the failures of certain type of OLTCs. The survey also found that very few incipient faults were identified during maintenance. Instead, the majority of the faults occurred when the tap changers were in service and the transformers had to be removed from service incurring significant additional costs. Effective on-line condition monitoring systems will reduce the risk of failures in service and contribute towards considerable reductions in maintenance costs.

The dominant failure modes of tap changers were found to be contact wear, weak springs, and breakage of components in the driving mechanism. Due to the mechanical nature of tap changer failure modes, vibration monitoring has been found to be suitable for assessing the condition of OLTCs of various makes [3-6]. The authors have developed a PC-based tap changer monitoring system [2-3] that enables the condition of tap changer contacts and associated drive system to be inferred from vibration signals. The monitoring system has been used to assess the condition of a common type of older tap changer.

This paper describes the results of field studies made recently to develop confidence in the use of the monitor and to explore the application of the monitor as a maintenance tool. The approach that has been taken has been to monitor signals for a period about two months before maintenance and to prepare an assessment of the condition of the tap changer from data supplied by the monitoring system. The actual condition of the tap changer, as determined from the results of maintenance inspections, are then compared with the assessments based on results from the monitoring system. Tap changers have also been monitored for a period after maintenance to check the effectiveness of maintenance work. Generally the results of this exercise show that the monitor can accurately predict the state of the tap changer.

2. TAP CHANGER CONDITION MONITORING

2.1 OLTC Monitoring System

The condition monitoring system [2-3] was designed based on the knowledge of dominant failure modes and failure statistics of the OLTC. It consists of a transducer module, a signal pre-amplification module, a signal-conditioning/isolation module, a data acquisition module, and a PC. The system can simultaneously capture both low and high frequency signals and can be triggered automatically or manually. Automatic triggering allows on-line data acquisition, while manual triggering permits off-line data capture.

To minimise the costs involved in installing the monitoring system, non-invasive transducers are used to measure the essential parameters. The whole system can be installed while the transformer is on-line. Transducers include a 25 kHz miniature accelerometer to monitor the vibration of tap changer, a CT to monitor the drive motor current, and a pair of thermocouples to monitor the main and tap changer tank temperatures. Analog signals are isolated from the computer data acquisition system by isolation amplifiers, and digital signals are isolated by opto-isolators. A computer dial-up network is used to connect the field PC to a PC in the maintenance engineer's office sharing the data acquired by the field PC.

Fig.1 shows a vibration signature measured using the monitoring system from a distribution type tap changer. This vibration signature consists of 4 distinctive vibration bursts, each of which is produced by a specific contact movement of the tap changer.
2.2 Condition Indicator

From field monitoring experiences, it has been found out that there is a significant degree of inherent variability among the signatures of normal condition. There are two major causes of the variability. Firstly, the signature variability is affected by the operating condition. A tap changer operates under variable load conditions, and this produces random variations in the burst amplitudes and shifts in time between individual vibration transient events produced by similar physical events. Secondly, there exist variable shifts in time between signatures, which are caused by the delay changes in the computer data acquisition system, if software triggering is used. To reduce the effect of the variable shifts in time on fault detection, the envelope signatures are aligned together. Alignment of the envelope signatures is achieved through the use of normalised auto-correlation functions of the envelopes [8, 10]. The remaining variability of the signatures is further handled using self-organising map (SOM).

Normalised auto-correlation functions of the envelopes of normal equipment condition are used as feature patterns to train a SOM [7]. The trained SOM is then formulated as a fault detector. The detection statistic (condition indicator) is defined as the minimum quantisation error (MQE) derived from the difference between normal and recently recorded signatures. The schematic diagram for the fault detection technique is shown in Fig. 2. It has been shown in [8, 10] that the mean change of MQE is a monotonically increasing process, and an on-line algorithm for the SOM fault detector has been developed and its detection properties demonstrated to be robust in [8, 10].

Detecting abrupt degradation. An effective detection technique has been designed to deal with the failure modes of OLTCs. The technique exploits the advantage of the traditional change detection technique - the cumulative sum procedure (CUSUM) [9]. The detection statistic of the CUSUM procedure is defined as for sample number \( i \) [8, 10]:

\[
c(i) = \max\{0, x(i) - \mu_c + c(i - 1)\}
\]

where \( x(i) = \ln[\text{MQE}(i)] \), which converts the log-normally distributed MQE into a normally distributed variable \( x \) [10]. This procedure is effective in detecting small shifts of the mean above the critical mean value \( \mu_c \). As soon as the mean of \( x \) exceeds the critical mean value, the detection statistic \( c(i) \) quickly accumulates to a larger value. Once the value of \( c(i) \) exceeds the CUSUM alarming threshold, \( \gamma \), the procedure stops and an alarm is given.

Detecting gradual degradation. It is possible that sudden large changes in the values of \( x \) may sometimes occur, which are caused by unpredictable faults such as cracked components. The detection statistic should give an immediate indication. The CUSUM procedure described above has, therefore, been extended to include the simple Schewhart procedure [9] for detection of large abrupt changes in \( x \). The Schewhart procedure uses the instantaneous value of \( x \) as the detection statistic. This procedure stops and raises an alarm, when \( x(i) \geq \gamma \), where \( \gamma \) is the Shewhart alarming threshold given by

\[
\gamma = \mu_c + k\sigma
\]

where \( k \) is a tuning parameter, and \( \sigma \) is the standard deviation of \( x \).
The Shewhart procedure is also used to detect and reject outliers in the data samples, as outliers tend to increase the false alarming rate. As the probability of the occurrence of outlier data is normally low, a simple two-in-a-row rule is used to reduce the effect of outliers on the false alarming. This means that a single sample above \( \gamma \) does not enter the detection scheme, but two consecutive outliers in a row are considered to be caused by abruptly occurring faults, and an alarm is raised.

**Threshold selection.** The threshold for the CUSUM detection procedure is selected to ensure that the rate of false alarming will not exceed a desired value. The false alarming rate is dependent upon the path taken by \( x \) during equipment condition deterioration. The path may however be different even for a similar OLTC as there is a statistical variability in both the lengths of the horizontal and vertical sections of the mean path. To select the values of \( \gamma \), it is necessary to estimate the range of possible mean paths of \( x \). The method, proposed to facilitate the estimation, is to obtain a statistical model for the mean path during the deterioration of a typical OLTC. Using the statistical model a range of mean path may be simulated and the values of the thresholds can be estimated for different values of false alarming probability [8, 10].

### 3. FIELD APPLICATIONS

#### 3.1 Faults Detected

**Abruptly occurring faults.** A monitoring system has been installed on an OLTC of a transformer in a 33/11kV distribution network since mid 1999. The tap changer was maintained on 14/09/1999. In the beginning of October 2000, the monitoring system gave warning that a fault had suddenly occurred in the equipment. The envelope signature of tap operation from tap 7 to 8 related to this fault is given in Fig. 3. Fig. 3(b) shows a typical vibration signal measured immediately after the maintenance. This is a typical signature obtained for the tap changer operating from tap 7 to 8, and is considered to be the signature of the tap changer in normal condition.

The signature associated with the warning is shown in Fig. 3(a). This type of abnormal signature appeared sporadically between signatures of normal condition. In Fig. 3, one of the four bursts appearing in the normal signature (Fig. 3(b)) is missing in the abnormal signature (Fig. 3(a)). This missing burst phenomenon occurs in abnormal signatures at all tap positions.

One of the bursts that corresponds to a specific contact movement is missing. This indicates that a set of contacts is not making or contacting properly causing improper contact positioning. This can be either caused by a missing contact or problems in the driving mechanism. As this faulty signature appeared only on occasions, the missing contacts hypothesis was excluded. A possible cause could be the slipping of the drive shaft. There was a concern that the abnormal contact sequence could cause deterioration to the tap changer and might lead to early catastrophic failure. It was recommended that the tap changer be inspected at the earliest opportunity.

**In a subsequent inspection, after the driving mechanism was disassembled, a slippage in the shaft was identified in the keyway of the Geneva wheel. There was about 1-2mm of play within the keyway, which, when taken at the extremities of the moving contacts, equated to approximately 40mm of play. Considering that the distance between the fixed contact is about 50mm if this condition was left unchecked, then a catastrophic failure would have been inevitable.**

**Worn contacts.** A mobile OLTC monitor has been used to record signatures before and after OLTCs were maintained. Using this approach it has been possible to correlate the change of contact wear with the magnitude of the condition indicator. This has enabled limits to be set in the detection algorithm for one type of OLTC.

In a recent maintenance carried out on another transformer, the tap changer was monitored before maintenance, and the monitoring system did not give warning regarding the condition of the tap changer. Since the value of the condition indicator was well below the threshold value, this tap changer was considered to be still in a healthy state. This was confirmed by...
maintenance crew who found no obvious deterioration in the condition of contacts.

3.2 Long Term Continuous Monitoring

In another case a monitoring system has been monitoring the condition of a tap changer since the previous maintenance. The change of condition indicator for tap operation from tap 6 to 7, corresponding to 2290 operations, is shown in Fig. 4. It was estimated that the degree of contact wear of this equipment was around 45 percent. Recently the equipment was maintained, and the technicians found the degree of contact wear similar to the estimation made by the monitoring system.

![Graph showing the change in the mean value of the condition indicator after 2400 tap change operations.](image)

Fig. 4 The change in the mean value of the condition indicator after 2400 tap change operations.

3.3 Condition Feature Map

For this type of tap changer, it has been shown that it is possible to determine not only that the tap changer is ageing, but also to identify the particular part of the tap changer that is degrading. This latter feature has been achieved by correlating induced faults on a real tap changer with changes in the vibration signatures [10].

A SOM based OLTC condition feature map is shown in Fig. 5. The map indicates that different conditions of equipment produce well-defined clusters. Each hexagon in the map display represents a distance between two adjacent map units. The bright colour shading indicates the cluster boundaries. The darker regions correspond to lower values of the distance between the map units, indicating data clusters of different equipment conditions. The moderate change in colour shading within the same cluster indicates the variability of the signatures within this cluster. The boundaries of the cluster areas, and the cluster identities corresponding to the conditions of equipment were marked and labelled using the known signatures of different conditions.

Condition diagnosis was performed by projecting newly acquired signatures onto the labelled map. The corresponding location of the signature on the map gives indication of actual condition of the equipment. By applying a series of signatures corresponding to both healthy and faulty conditions to the trained map, the trajectories showing the transition of equipment condition from healthy to unhealthy can be visualised as shown in Fig. 5. The arrows in Fig. 5 show three typical transitions from normal condition to degraded condition.

![OLTC condition feature map.](image)

Fig. 5 OLTC condition feature map.

A: area of normal operation.
B: area of weak springs.
C: area of worn fixed and moving contacts.
D: area of worn moving contacts.
Axes refer to number of SOM map units.

4. CONCLUSIONS

In this paper we have described the field applications of a low-cost tap changer condition monitor to a type of old distribution tap changers. Monitoring systems have been applied to the on-line assessment of tap changers in a distribution network for over three years. From the results from long-term monitoring and subsequent plant inspection, we illustrate the ways in which the condition of a tap changer deteriorates. In some cases the deterioration is gradual, but in other there are sudden shifts in the condition. The monitoring system presented in this paper can accurately detect and track either types of degradation.

The on-line condition monitoring can be applied to the optimisation of tap changer maintenance programs. Probabilities of rate of degradation, determined from
long-term monitoring and results of short-term tests, can be used to establish a monitoring program that will minimise maintenance costs and maximise reliability.

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6. REFERENCES


