Abstract: In industry, partial discharge technology related to switchgear has been operational for many years. Partial discharge testing has been completed on both new high voltage (HV) switchgear in the laboratory setup, as well as several older field installations, medium voltage (MV) and HV switchgear in the utility grid. The results clearly indicate that partial discharge analysis of MV and HV switchgear is an excellent online maintenance tool to access its dielectric condition. It has been found that older MV switchgear are prone to internal surface discharges over connectors and bushings. The majority of the MV switchgear are of very old design, therefore the use of online partial discharge analysis can identify parts of the installation of immediate concern. This paper reviews the application of PD monitoring to MV and HV switchgear. An actual example of pending failures, which were identified by on-line partial discharge measurements, will be presented. This application of partial discharge technology can greatly aid in the day-to-day reliability and life-extension of MV and HV switchgear components.

INTRODUCTION: CBM FOR HV SWITCHGEAR SYSTEMS

Condition Based Maintenance (CBM) is a concept already applied to HV switchgear. The principle of CBM is that the condition of equipment is assessed by inspection and diagnosis. The maintenance actions are only performed when necessary. The CBM process consists mainly of four items [1]:
1) Detection
2) Defect identification
3) Defect location
4) Risk assessment

In this paper ultra high frequency (UHF) -technique has been used to detect partial discharges (PD) activity within the equipment. To identify the origin of the measured signals, raw data such as single pulse, patterns, shape, crestfactors, etc, has to be analysed. Also physical defect models and system-knowledge is necessary for a well defined basis for the CBM process. The location of the PD source can for example be found by means of flight time measurements [2].

Defect identification and localization of the defect are components of the CBM procedure which are necessary for the risk assessment. Finally the question remains whether to open the installation. Here risk analysis is needed to obtain the criticality of the defect. Although it is applied to HV switchgear for several years, the part of risk-analysis needs more investigation. The set-up we use for HV switchgear is given in figure 1 [3].

DETECTION: UHF MEASURING TECHNIQUE

Partial Discharges (PD) in switchgear are caused by defects of the insulating system such as protrusions and particles. The discharge currents at the defects have rise-times that can be less than one hundred pico-seconds [4]. As a result of this, electromagnetic (EM) wave transients with frequency content of more than 2 GHz are emitted [5]. These signals propagate within the coaxial or rectangular bays of a switchgear system not only in the basic mode (TEM) but also in many higher order modes (TE_{mn},TM_{mn}).

MV switchgear and bus ducts usually receive less maintenance attention than the main electrical HV equipment. The design of the MV systems is frequently less complicated, but the conditions of operation can be very unfavorable. Internal inspections are limited due to the necessary outage, therefore internal bus sections are sometimes not maintained for many years. At the same time the number of switchgear bays, especially in large utility grid substations or in large industrial installations, can be very high, and the failure consequences can be very costly. For these reasons, there is a need to apply predictive technologies to switchgear systems. PD measurements were internationally recognized as an effective tool in evaluating the condition of different insulation. In this paper the applicability of UHF PD measurements in MV switchgear has been investigated during on-site and laboratory testing.
At locations where the enclosure is interrupted by a dielectric material such as: epoxy resin, glass inspection window, etc., these high frequency signals will couple out of the switchgear. These “dielectric windows” offer the possibility to pick-up the signals by means of external couplers.

The amplitude of the signals reduces due to damping but mainly due to reflections at discontinuities such as circuit-breakers and disconnectors. As consequence of UHF signal attenuation, several couplers have to be installed in an extended GIS or with external couplers more locations have to be monitored.

In case of UHF measurements with internal couplers, mostly fitted in newer type GIS, the enclosure of the installation will function as a shield for most of the external signals. When external couplers are used, e.g. for older types of GIS and MV switchgear, more background noise signals can be measured. Often noise peaks come from navigation air-traffic, TV broadcast and GSM.

The advantage of using external UHF sensors is the cost effectiveness and no invasion into the initial switchgear design. When the sensor is placed at the “dielectric window” its detection sensitivity varies widely depending on the type of out-coupling of the EM-waves and in generally to the geometries of the bay or installation-section [6]. This results in the need for an on-site sensitivity check, which can be completed during a scheduled outage. A procedure for the on-site sensitivity check of the UHF monitoring system with the use of external couplers is reported in [6].

**TYPICAL PD SOURCES**

In MV switchgear installations certain types of defects can occur, e.g.:
- internal defects in dielectrics
- protrusions on conductor or enclosure
- defects in cable terminations
- bus insulation with moist or dirty surface
- defects correlated to the surface of dielectrics
- deterioration of bus supporting structures.

In commercial MV switchgear systems, designs of bus insulation systems include several insulating components, such as small air gaps with plastic or rubber insulating covers, connected in series. Those designs are prone to developing discharges in the mentioned air gaps where the electric field concentrates. The discharges affect the adjacent insulation and create carbonized paths, surface discharges, extending gradually to grounded ends of the insulation, see figure 5b.

**LOCALIZATION**

The switchgear bay containing a PD signal with the highest value of the frequency energy content is most likely the bay containing the PD source. A measure which is used for the energy content of the frequency spectra is the AREA [7].

**FIELD EXPERIENCE**

As an example, a 10 kV switchgear has been investigated. The busbar system is air insulated and the circuit breaker existing of a vacuum chamber is further insulated by epoxy resins and rubber. The construction of the front-side and the back-side of a circuit breaker, which can be moved on wheels in and out the bay, is given in figure 2.
This separating wall was originally made out of asbestos, but because of new regulations in the use of asbestos, it has been changed into a metallic wall.

At one bay the frequency spectrum as shown in figure 4a has been measured at one of the inspection windows. In this figure differences between the signal and the background noise frequency spectrum can be seen. At the frequency peak of 786,25 [MHz], a phase resolved PD pattern was measured, see figure 4b. For this purpose the spectrum analyser was used in zero span mode, and tuned to above mentioned centre frequency.

The pattern was classified as a surface discharge [6]. This was confirmed by visual inspection of the component. It was found that the insulating rubber was affected by the discharges, see figure 5a. This rubber “socket” was deteriorated in an early stage. Another rubber “Socket”, figure 5b, which was positioned at the same location some time before was heavily affected by partial discharges. So this was already the second time since the removal of the asbestos plate, that problems occurred.

LABORATORY MODELLING

To understand the origin of this problem, a simulating set-up has been made. With this set-up different configurations with two separating walls have been investigated: one with a metallic disk and one with an insulating material (PVC), see figure 6. The metallic disk is given a round edge to reduce the chance of corona generated by this edge. Furthermore this edge is earthed, just like the metallic wall inside the original installation.

Looking at the configuration shown in figure 3, high electric fields can be expected in the system at point B, due to the metallic wall. Because of the rather sharp edge of the metal wall at the place near the insulating rubber, corona will occur. After some time the material will deteriorate. Three cases have been investigated:
- a metal separating wall with the more affected connector
- a metal separating wall with the less affected connector
- a PVC separating wall with the more affected connector.

To reproduce the PD pattern originating from surface discharges, the more affected circuit breaker connector was investigated, see fig. 5b, using the earthed metallic disk. At an applied voltage of 12 kV, a frequency spectrum as shown in figure 7a was measured. It can be seen that the frequency spectrum has a high energy content. The energy content was calculated by the following key-value AREA:

\[
AREA = \sum_{i=1}^{400} S_i + \frac{S_{i+1}}{2}
\]

The phase resolved pattern is taken at a frequency of 346,3 MHz, shown in figure 7b. This phase resolved pattern shows the surface discharge pattern of the more deteriorated insulation rubber. Pd magnitudes are given in table 1. As expected, the phase resolved pattern was classified as a surface discharge.
Case 2
The simulate the actual situation in the 10kV AIS distribution installation the circuit-breaker connector, which was less affected by the partial discharges was investigated. In this way the PD pattern of a connector, which was relatively short affected (compared to the first case) by PD activity was obtained. At an applied voltage of again 12 kV, a frequency spectrum was measured. It can be seen in table 1 that the energy content of the frequency spectrum, AREA, is less than in the first case. A signal of early stage PD activity can still be detected by the external UHF couplers. Also a phase resolved pattern is measured at a center-frequency of 411,8 MHz. This phase resolved pattern has the same shape as the one detected in the field, see figure 4b. For PD magnitudes see table 1. The diagnosis and classification of the PD pattern concluded that it was again a surface discharge.

Case 3
Finally the metallic disk was replaced by a dielectric disk made of PVC, to investigate whether a dielectric wall could improve the construction with the rubber insulation as used in case 1. In contrast to cases 1 and 2, no PD activity could be detected at a voltage level of 12 kV. Moreover to measure any PD activity the applied voltage had to be raised to 23 kV (=2,3*U nominal). In this case also a frequency spectrum was measured. Again the key value AREA was calculated and the frequency spectrum had less energy content than in the first and second case, see table 1. The phase resolved pattern was taken at a center-frequency of 338,9 [MHz]. The diagnosis and classification of the PD pattern concluded that it was corona. The corona was due to the metallic strip made on the PVC disk to simulate that the PVC disk is fixed to the earthed enclosure.

Table 1: PD magnitudes of the three cases

<table>
<thead>
<tr>
<th>Defect</th>
<th>Disk</th>
<th>pC</th>
<th>uV</th>
<th>AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td>More affected</td>
<td>Metal</td>
<td>437</td>
<td>129.6</td>
<td>3104.34</td>
</tr>
<tr>
<td>Less affected</td>
<td>Metal</td>
<td>190</td>
<td>21.9</td>
<td>405.21</td>
</tr>
<tr>
<td>More affected</td>
<td>PVC</td>
<td>35</td>
<td>10.2</td>
<td>50.80</td>
</tr>
</tbody>
</table>

CONCLUSIONS
From the measurement results in this paper, the following conclusions can be drawn:
1) Measurements with the external UHF coupler are applicable to medium voltage switchgear installations, e.g. air insulated switchgear, as well as to HV switchgear systems.
2) Using advanced PD analysis techniques distinction can be made between the different patterns detected by the external UHF coupler.
3) UHF PD measurements can contribute to CBM procedures.
4) With UHF PD measurements one can also determine the position of system design errors, which then can be corrected.

REFERENCES