RISK ASSESSMENT OF FIXED DEFECTS IN GIS UNDER DIFFERENT VOLTAGE WAVE SHAPES

Sander MEIJER\(^1\), Edward GULSKI\(^1\), Johan J. SMIT\(^1\), A. Jos L.M. KANTERS\(^2\)

\(^1\)Delft University of Technology - The Netherlands \quad \(^2\)TenneT B.V. – The Netherlands

S.Meijer@ewi.tudelft.nl

SUMMARY

SF\(_6\) gas has nowadays established itself as a reliable insulating medium for gas-insulated switchgear (GIS). In GIS however different kind of defects may occur, such as protrusions fixed to the conductors. Such defects locally enhance the electric field, which can result in partial discharge (PD) activity or even breakdown.

For the application of condition based maintenance (CBM) on GIS, it is important to be able to assess its insulation condition. Aspects, which have to be taken into account, are sensitive detection of partial discharge activity, identification and location of the discharging source and probability for breakdown.

In this paper, the criticality or probability for breakdown of fixed defects has been investigated. For this purpose, AC voltages have been applied to study the breakdown probabilities under pure AC condition. Secondly, the defects have been tested with standard lightning impulses (LI) and switching impulses (SI) and finally a bias-test was performed. Based on above-mentioned results, knowledge rules for risk assessment tools have been defined.

INTRODUCTION

More and more the concept of Condition Based Maintenance (CBM) is applied to HV switchgear. Based on inspections and diagnostic measurements, the condition of the insulation can be assessed. For this purpose, techniques that detect partial discharge activity can be used. Risk analysis of detected defects lead to certain maintenance actions, which are only performed when necessary. The CBM process consists mainly of five items [1]:

1) Detection of PD activity
2) Defect identification
3) Defect location
4) Risk assessment
5) Economical aspects

To detect partial discharges (PD), the ultra high frequency (UHF) technique has been used which enables sensitive online detection as well. From the measuring results, the defect has to be identified and located. Then a risk analysis is required to assess the criticality of the defect. Criticality is defined as the severity of the consequences of a failure [2]. Investigations in the criticality analysis of fixed defects are summarized in this paper. In particular, the criticality of defects depends strongly on the type of over-voltage. Figure 1 shows the maximum magnitudes that can be expected during different types of over-voltages [3]. Therefore, the breakdown of fixed defects under these different voltage-shapes has been investigated in this paper.

FIGURE 1: Possible over-voltage characteristics.

First, the AC breakdown voltage was determined. Secondly lightning impulse (LI) and switching impulse (SI) tests have been performed. Finally, bias-tests have been done in which an AC voltage of 1 p.u. was combined with LI and SI. Based on the obtained results, knowledge rules were defined.

MEASURING SET-UP

Figure 2 shows the test vessel in the test arrangement that was used for the tests. During AC testing partial discharge (PD) measurements were performed using a detection circuit according to the IEC 60270 recommendations with a 1000 pF coupling capacitor. The noise level was below 0.5 pC. Moreover, a UHF PD detection circuit was used as well, consisting of an internal disk antenna, pre-amplifier and spectrum analyser. Results have been measured up to breakdown.

To perform bias-tests, AC voltage was applied to the enclosure of the test vessel and the impulse generator was connected to the bushing of the test vessel, see figure 2. The up-and-down method [4] was used to determine the breakdown voltage under lightning and switching impulses and under combined AC and SI/LI. In each case, 20 impulses were used to determine the breakdown voltage.

Protrusions of 1-4 mm length have been tested in a plane-plane configuration, see figure 3a. Figure 3b shows a detail of the investigated protrusion, which is 1 mm thick and has a tip-radius of 70-90 µm. The distance between both electrodes is fixed to 5 mm. The gas pressure was 4.5 bar SF\(_6\).
MEASURING RESULTS

AC Testing

The AC breakdown voltage level was determined by slowly increasing the test voltage until breakdown occurred. This test was done 5 times and the average breakdown voltage was calculated. For easy comparison of the tests results, the breakdown voltage has been transferred into electric field (U/5mm) and in per unit, in which 1 p.u. is 3.74 kV/mm.

As shown in table 1 [5], only the 4 mm protrusion results in breakdown before the nominal operating field strength is reached. Although the breakdown strength depends on the protrusion length, this fact cannot be used in practice, because the length is unknown.

However, it was shown that the 2 mm, 3 mm and 4 mm protrusions give measurable PD activity at nominal operating stress. Only the 1 mm protrusion gives no measurable PD activity below 2.1 p.u. Analysis of the partial discharge patterns confirms the fact that three stages occur before breakdown [6]. Figure 4 shows the PD magnitude for the 4 investigated protrusions as function of the relative voltage (related to the breakdown voltage of each protrusion). From the obtained results, the following can be concluded:

<table>
<thead>
<tr>
<th>Stage</th>
<th>PD magnitude [pC]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage 1: 0.28-0.53 Ubd</td>
<td>0.40</td>
</tr>
<tr>
<td>Stage 2: 0.50-0.73 Ubd</td>
<td>0.62</td>
</tr>
<tr>
<td>Stage 3: 0.81-1.00 Ubd</td>
<td>0.89</td>
</tr>
</tbody>
</table>

It is clear that these three defined stages are independent of the protrusion geometry, and thus the detected PD pattern (i.e. PD process) can be used as an independent input parameter for further analysis. In practice, a maximum AC over voltage of 1.8 p.u. can be expected. This means that defects, which have a PD process corresponding to the 0.55Ubd-value or above, may result in breakdown. From figure 4 it can be concluded that this is the case for protrusions in stage 2 or 3.

Lightning and switching impulse testing

Table 2 shows the results from the lightning and switching impulse tests. Comparing the results with the maximum overvoltages that can occur, shows that in case of lightning, all defects can lead to a breakdown. Moreover, in case of switching overvoltage, only the 1 mm protrusion will probably not lead to a breakdown.

As shown before, protrusions of 2-4 mm give partial discharge activity at nominal operating stress. This means, that protrusions that may result in breakdown under LI and SI conditions can be detected by partial discharge activity. This offers the possibility to take proper maintenance actions before breakdown will occur.

Bias testing

To test the influence of the nominal operating stress on the lightning and switching impulse strength, a bias test has been performed for the 1 and 2 mm protrusions. An example of the applied test voltages is shown in figure 5. The gap between the electrodes is pre-stressed by a field strength of 1 p.u. In case of the 2 mm protrusion, PD activity is present during the tests. On the contrary, no PD activity is present in case of the 1 mm protrusion. Moreover, higher pre-stressing up to 3.4 p.u. was applied to investigate the influence of corona stabilization on the results. It can be expected that the breakdown strength is reduced (in the worst case) or

Figure 3: Detail of the test arrangement: a) electrode configuration with protrusion and b) protrusion.

Figure 4: PD magnitude as function of the voltage relative to the breakdown voltage.

Table 1: Comparison of AC breakdown values with maximal expectable over-voltage levels.

<table>
<thead>
<tr>
<th>Protrusion</th>
<th>AC [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>4.9</td>
</tr>
<tr>
<td>2 mm</td>
<td>2.9</td>
</tr>
<tr>
<td>3 mm</td>
<td>2.2</td>
</tr>
<tr>
<td>4 mm</td>
<td>0.9</td>
</tr>
<tr>
<td>overvoltage</td>
<td>&lt;1.8</td>
</tr>
</tbody>
</table>

Table 2: Comparison of AC breakdown values with maximal expectable over-voltage levels.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mm</td>
<td>5.6</td>
<td>5.0</td>
<td>5.9</td>
<td>5.6</td>
</tr>
<tr>
<td>2 mm</td>
<td>3.4</td>
<td>2.4</td>
<td>3.4</td>
<td>3.0</td>
</tr>
<tr>
<td>3 mm</td>
<td>2.7</td>
<td>1.9</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>4 mm</td>
<td>1.3</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>overvoltage</td>
<td>&lt;6.5</td>
<td>&lt;4.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 Example of a switching impulse superimposed on the AC voltage.
increased (in best case) by about the magnitude of the bias voltage. In table 3 the results are shown with a pre-stressing of 1 p.u. Comparing these results to the results in table 2 shows that the breakdown voltage is reduced by about 1 p.u. in case of the 1 mm defect and slightly less than 1 p.u. in case of the 2 mm defect. The differences for both defects is that due to the pre-stressing, PD activity is present in case of the 2 mm defect and not in case of the 1 mm defect. It can therefore be concluded that corona stabilization has a positive influence on the breakdown strength.

| Table 3: Comparison of AC breakdown values with maximal expectable over-voltage levels. |
|-----------------|-----------------|
|                | AC- LI+ | AC+ LI- |
| 1mm            | 4.8     | 3.5     |
| 2mm            | 3.0     | 1.7     |
| overvoltage    | <6.5    |

The results of the influence of several bias voltages are shown in figure 6: the solid line shows the measured breakdown values; the dashed line the estimated breakdown values. The estimated values have been determined by simply subtracting the bias-voltage from the LI breakdown levels. It can be concluded from figure 6, that in the measured values are slightly higher than the estimated values. Based on this it can be concluded that corona stabilization has a positive influence on the breakdown strength, as stated before.

BREAKDOWN PROBABILITY

In the previous section, the breakdown voltage of fixed defects of different length in case of different voltage shapes was determined. Next is the assessment of the risk for a failure in practice. To summarize the previous results, it can be concluded that the following types of phase-resolved PD patterns can be detected:

1) No detectable PD activity ($U_i > U_0$)
2) Pattern type 1: $U_i < U_0 < 0.52 \ U_{AC, BD}$
3) Pattern type 2: $U_i < U_0 < 0.74 \ U_{AC, BD}$
4) Pattern type 3: $U_i < U_0 \lor U_0 > 0.74 \ U_{AC, BD}$

in which $U_i$ is the PD inception voltage, $U_0$ the nominal voltage and $U_{AC, BD}$ the AC breakdown voltage level.

Depending on the detected pattern at B nominal voltage a different breakdown characteristic has to be taken into account:

1) No PD activity: characteristic of the 1 mm protrusion
2) Pattern type 1: characteristic of the 2 mm protrusion
3) Pattern type 2: characteristic of the 3 mm protrusion
4) Pattern type 3: characteristic of the 4 mm protrusion

Besides above knowledge rules, the risk of a failure of a gas-insulated substation mainly depends on the probability of over-voltage. Examples of such risk analysis are given in the following sections.

AC over-voltage

As stated before, a maximum over voltage of 1.8 p.u. can be expected in case of AC voltage. This means that defects which have a PD activity corresponding to a level of more than 60% of the AC breakdown voltage (so pattern type 2 and 3), may result in a breakdown. Further information regarding the probability of the occurrence of such over voltages is required as well.

Lightning impulse over-voltage

A procedure to estimate the risk for breakdown in case of lightning over-voltage consists of several steps. In this example, the following three parameters are taken into account: the probability of breakdown due to the defect, the probability distribution of lightning current and the strike probability. In particular, only a direct strike in the GIS is investigated.

The probability distribution for over-voltages due to lightning is usually expressed by the following equation [7]:

$$P(I_l \geq I_0) = \frac{1}{1 + \left(\frac{I_l}{I_0}\right)^{2p}}$$

in which $I_0$ represents the lightning current and $I_{av}$ is the average value of the lightning current. Depending on the literature, this average current is between 19.4 kA and 33.3 kA [8]. In figure 7, equation 1 was used to represent the maximum and minimum over voltage distribution.

The next step is to combine these graphs with the probability of breakdown as described in the previous section. For instance, assume that PD activity is detected and the pattern shows resemblance with pattern type 2. Then the probability distributions displayed in figure 7 have to be combined with the breakdown probability distribution that belongs to the 3 mm protrusion. The result is shown in figure 8.

The last parameter that has to be taken into account is the number of lightning strikes in the substation per year. For the investigated area, this number is about 0.0035, so once every 285 years. Combining this with the maximum probability of
breakdown of 88%, as can be seen in figure 8, this results in 0.003 failures per year and the mean-time-between-failure (MTBF) is 327 years. Table 4 summarizes the MTBF’s for the four investigated PD processes.

![Figure 8](image)

Figure 8 Combining the risk for breakdown and the over voltage probability to determine the risk for flashover.

It should be kept in mind that the figures shown in table 4 are only valid in case of a direct lightning impact on the GIS. Of course, the probability that the towers are hit by lightning is larger and should be taken into account as well. Future investigations will focus on the influence of towers as well as the probability of switching transients on the risk for breakdown.

Furthermore, the final decision in the condition based maintenance process strongly depends on economical and societal aspects as well.

CONCLUSIONS

Based on the investigations described in this paper, the following conclusions can be drawn:

1. Depending on the type of defect, e.g. length of the protrusion, different PD processes can be active during nominal operating conditions;

2. The different PD processes can be discriminated by means of the detected phase-resolved pattern;

3. Corona stabilization has a positive influence on the breakdown strength;

4. For each detected PD pattern (or PD process), a breakdown curve has been obtained experimentally;

5. To estimate the risk for a breakdown, the breakdown curve of each PD process has to be combined with the probability of expected over voltage and the number of direct impacts per year as well;

6. Especially the low number of impacts strongly reduces the mean-time-between-failure for GIS.

REFERENCES


