THE COMBINATION OF THE DIAGNOSTICS OF PAPER-INSULATED CABLES BY THE PARTIAL DISCHARGE MAPPING WITH THE DETERMINATION OF THE MOISTURE CONTENTS IN THE CABLE INSULATION

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INTRODUCTION

Reliable operation of the network, optimisation of costs of operation, maintenance and construction of the network, as well as the correct relationships with customers and the Regulator in market economy place increased demands on the network operators with respect to the knowledge of the operated lines condition. A number of testing methods and devices able to assess the condition of the operated equipment on site have been recently developed for this purpose. One of the widespread and most reliable methods is the localization of “weak” spots in the insulation, in which discharges occur, by the localizing detection of partial discharges (PD) (local, selective). While for cross-linked polyethylene (XLPE) cables the PD detection may be assessed quite unambiguously, the situation of the paper-insulated mass impregnated cables (PILC) seems to be rather complicated. In their case, there are a large number of localities with PD of different magnitude that cannot be assessed ambiguously, and certain relatively frequent failures such as creation of a local conductive path, or armour and sheath corrosion including the subsequent penetration of moisture into the insulation cannot be discovered by this method. The report describes results of the three-year PD measurements. In 2002, PD diagnostics of PILC cables in Prague was completed by the (integral) cable condition diagnostics based on the detection of moisture contents by measuring the $\tg\delta$ in the frequency domain as a result of conclusions derived from the above measurements. Results of more than 200 measurements of the moisture content are shown and compared with the results of PD diagnostics of the same cables. The results of PD diagnostics may be evaluated with a better accuracy by combining both methods.

THE DIAGNOSTICS BY THE PARTIAL DISCHARGE MEASUREMENT

The PD diagnostics of XLPE cables

XLPE cables have a very low PD level, therefore the spots in which a higher PD level is detected may be considered “weak” and a failure may be expected to appear in such spots in a short time. The XLPE cable condition may be therefore assessed unambiguously according to the PD magnitude. In the case of new cables, detection of tens of pC is considered unacceptable, for old cables it is the level above the limit of 250 pC. Checks of newly built XLPE cables are of particular importance in order to detect and remove defects due to poor quality laying and mounting of joints and terminations. PD diagnostics has enabled us to identify 15 higher values of discharges on new joints. In all cases mounting defects were discovered during the repair works. The consistent diagnostics testing of new XLPE cables results in the increased quality of mounting work done by contractors. It is obvious from the comparison of the frequencies of detected failures in 2000, 2001 and 2002. Only one defect was detected in 2002. By replacing the classic test by increased voltage with an acceptance PD diagnostics test, and a sheath test of XLPE cables, the stress of cables will be reduced and possible failures caused in the course of assembly will be discovered at the same time.

The PD diagnostics of paper-insulated cables (PILC)

The situation is more complicated in the case of PILC cables where there are many localities having PD of low as well as very high levels in which a defect may or may not occur in a short time. We have performed assessment of cables on the basis of intensity and magnitude of PD charges. We have evaluated PD levels of PILC cables in compliance with the experience and recommendations of the diagnostic vehicle manufacturer with tolerance so that the number of repairs should not be excessive due to little experience with this diagnostics tool and a great number of measurements. Cables with the PD level lower than 10000 pC were assessed as “good”, those from 10000 pC to 50000 pC were “worse” and those above 50000 pC were “poor”. The share of dangerous PD in the category of cables designated by the PD diagnostics as “poor” is high. The success of the method and of this assessment has been verified after three and half years of measurements on the basis of the overall decrease of the cable failure rate as well as the consequent cable defects. The probability of a defect to these cables is several times higher than in the case of “good” cables (see Graph -1).
The evaluation of the categories “good” and “worse” is less reliable because in their case, at lower PD levels, a certain proportion of dangerous defective spots occur. The exact evaluation of cable condition by determining the PD critical level or PD parameters for creation of a defect is problematic. The PD level in PILC cables varies from hundreds of pC to tens of thousands of pC depending on many values as well as on the time when the measurement is performed. Some defects cannot be detected by PD diagnostics at all. The most frequent kinds of defects of PILC cables that cannot be discovered by PD diagnostics are deterioration of insulation by discharges during which the conductive failure path is created in the insulation and the PD level is consequently lowered and the armour and sheath corrosion including the consequential penetration of moisture into insulation.

A higher voltage stress may result in a breakdown in such places. The defects including the conductive failure path may be discovered destructively by high voltage tests applied. The defects of the cable armour and sheath and the estimation of the moisture contents in the insulation may be discovered by the non-destructive integral methods.

THE RESULTS OF THE THREE-YEAR PD DIAGNOSTICS IN PRAGUE

In the course of the three-year period, i.e. since the measurements started, 1,700 measurements on 1,542 cables (22 kV) of the total length of 1,301 km have been performed in Prague. Repeated measurements were carried out on 158 cables, 949 measurements were performed on PILC cables in the total length of 654 km, 359 measurements were performed on XLPE cables having the length of 299 km, and 392 measurements were performed on combined cables XLPE/PILC of the total length of 348 km. The assessments results: 65 % cables were assessed as “good”, 29 % as “worse”, 6 % as “poor” (results according to types of cables see Graph - 2).

On the basis of PD diagnostics, 58 cables or cable sections in the length of 19 km have been recommended for replacement. The savings arising from the fact that in some cables assessed as poor we recommended for replacement only the sections with high partial discharges represent 6 km of cables. In financial terms, it means the cost reduction of approximately EUR 0.5 million.
We have divided cables with defects after diagnostics into groups according to PD occurrence and behaviour at the point of defect (see Graph – 3):

A – PD were detected in the course of diagnostics and designated as a significant “weak” point, and a higher PD level appeared below or at the service voltage and it was increasing.

B – A PD level above 1000 pC appeared below or at the service voltage and it was increasing, or higher PD levels appeared at higher testing voltages. There were other places on the cable, however, that appeared more significant from the PD viewpoint.

C – No PD were detected or were negligible (hundreds of pC).

On the basis of our assessment of a number of relations in the sets of the three-year PD diagnostics, we have made the following conclusions for PILC cables (see Graph – 4):

a) We will assess cables with the maximum PD level as low as 20 kpC as “poor”.

b) We will perform the assessment also on the basis of the inception voltage and the maximum PD level at the inception voltage.

PC equal to 5 kpC at the inception voltage lower than or equal to \( U_0 \) may be considered a dangerous level. Dangerous spots are also those with the inception voltage \( U_0 \), and where PD rapidly grow with the increased voltage.

c) Identification of defective terminations is not successful, a probable cause being the fact that terminations are not disconnected from the switchboards. The presence of defects on terminations as well as on visible accessible parts of cables is sought with a thermo-visual camera, ultra-sound sensor or a contact electric sensor.

d) Any significant PD we have not detected in 33 % of all measurements, in “good” cables it is 49 % in fact. In the case of defects after diagnostics, there were 38 % of such cables. Our findings show that most of the defective cables are wet or may be wet depending on the design and age. A considerably better defect prediction can be achieved by a more accurate specification of the cable condition, namely by detecting the insulation moisture level via complementary cable diagnostics by the integral method that we have introduced.

e) Although we have a relatively high number of repeated measurements, only a few dozens of the measurements could be used for the statistical assessment because of repairs and replacements performed on the cables that changed their characteristics. No significant relations between the values obtained were discovered. Nevertheless, it seems that the higher the PD level is, the higher the probability of PD detection in the same place will be during repeated measurements. The issue will be further monitored.

f) More than a half of defects following the diagnostics in places of PD detection (groups A, B) occurred within 1 year. The period of time from diagnostics to a defect depends on the PD inception voltage (if lower than \( U_0 \), 29 % of defects occurred, if lower than \( U_0 \) or equal to \( U_0 \), 44 % of defects occurred), and on the PD level at the inception voltage (approximately the same proportion), where the discharges around 5 kpC appear to be critical. The magnitude of the maximum PD level for the investigated sample did not have any significant impact on the time of defect.

g) Unlike Western Europe, where most defects were found in joints, most defects on PILC cables in Prague occur on cable routes.

h) PD appeared in the place of future defect at least in two phases, in most cases in all three phases.

i) The database will be completed via diagnostic measurements by certain data related to PD and defects.
developed to discover such defects; these methods are called integral as they assess the overall condition of cables in contrast with the PD measurement which is in principle a localization, i.e. locally selective method. The basic methods are as follows:

a) Assessment of the condition of cable armour and sheath by measuring the zero components of the ground path;

b) Assessment of the condition of cable insulation, in particular the moisture in the insulation

b1) By spectrographic measurements in the time domain of:
   • Charging and discharging currents,
   • Back or recovery voltage,

b2) By spectrographic measurements in the frequency domain:
   • Tgδ.

THE ESTIMATION OF THE MOISTURE CONTENTS BY MEASUREMENTS OF TG DELTA IN THE FREQUENCY DOMAIN

The introduction of the tg delta measurement in Prague

Dielectric spectroscopy performed on the basis of frequency dependence of the polarisation quantities of insulation is one of the methods for assessment of the insulation condition. The values of capacity, permittivity and loss tangent (tgδ) are analysed in the large frequency range from 0.001 to 1,000 Hz.

The response of tgδ in the frequency domain can be used for the determination of the percentage of moisture contents in the cable insulation via the method of the detection of the minimum value. A low voltage (140 V) can be applied for the measurement in the case of PILC cables, a high voltage ranging from 0.5 to 2x U0 must be used for XLPE cables. The exclusion of a strong temperature dependence, which is typical for tgδ measurements, is the advantage of measurement of tgδ in the frequency domain.

In 2001, a possibility of completing diagnostics of partial discharges (PD) with the integral diagnostics of the cable condition based on the contents of moisture in the insulation was verified in PRAGUE - first, by the measurement of the recovery voltage course, later by the measurement of tgδ at different frequencies. After the evaluation of both methods, the method of tgδ measurement, which is simpler with respect to the measurement itself as well as to the evaluation, was introduced in 2002. This method is also very fast. Measurements are performed simultaneously with the PD diagnostics, and the connection of the device, the measurement itself and the basic assessment take 30 minutes for one three-core cable.

The first experience with tg delta measurements

By the end of 2002 we performed measurements on 232 cables (22 kV). We also carried out comparative measurements of tgδ with our colleagues from other utilities using different methods of measurements. The comparison has shown that the tgδ delta method gives similar results at the frequency of 0.1 Hz (indeed, only at the frequency equal to 0.1 Hz). The method of tgδ measurement of the amplitude attenuation shows deviations probably caused by the different measurement method that was used.

Having assessed the measurements performed so far we have determined 3 basic types of characteristics of the tgδ course. These characteristics are included in the following graph (Graph 5) where the black curve describes the tgδ response for a “wet” PILC cable, the red curve shows the tgδ response of a slightly wet PILC cable and the blue curve describes the tgδ response for a dry combined cable.

GRAPH 5 - Tgδ responses, basic characteristics

The next graph (Graph 6) illustrates the dispersion of tgδ responses for cables of the same moisture level. The tgδ curves shown here refer to 7 cables that are in good condition without any significant moisture contents ranging from 0.5 to 0.55 %.

GRAPH 6 - Tgδ responses for cables with the same moisture level

Graph 7 depicts tgδ responses at repeated measurements performed on the same cable. The first measurement was carried out in April 2002 and the second in August 2002. The difference of outside temperatures was considerable and there was also a considerable difference between the temperatures of the ground. The differences in the responses of the measured tgδ values are obvious. Nevertheless, the stability of the measurement results and their independence from the temperature was confirmed for the purpose of the evaluation of measurements by the method of the detection of the minimum tgδ value at any frequency. Despite the difference
between the curves, the minimum $\tan\delta$ values remained nearly the same and, therefore, the cable moisture remained at the same level as well.

![Graph](image.png)

**GRAPH 7 – $\tan\delta$ responses of the same cable measured under different temperature conditions**

The $\tan\delta$ measurements results for paper insulated cables (PILC)

141 PILC cables have been subject to measurement since the beginning of 2002. According to the manufacturer’s methodology, minimum $\tan\delta$ values were detected, regardless of the frequency at which these minimum values were obtained. The moisture in the cable was calculated from these data and the results were divided into three basic categories. For our needs, we have further divided the category of moist cables into sub-categories V1 to V3. The results measured are shown in the following table.

<table>
<thead>
<tr>
<th>Cable assessment</th>
<th>Moisture contents in %</th>
<th>% of measured cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>S (Dry cable)</td>
<td>Humidity &lt; 0.5 %</td>
<td>9</td>
</tr>
<tr>
<td>V (Moist cable)</td>
<td>0.5 % ≤ Humidity &lt; 2 %</td>
<td>86</td>
</tr>
<tr>
<td>of which V1</td>
<td>0.5 % ≤ Humidity &lt; 1 %</td>
<td>37</td>
</tr>
<tr>
<td>of which V2</td>
<td>1 % ≤ Humidity &lt; 1.5 %</td>
<td>37</td>
</tr>
<tr>
<td>of which V3</td>
<td>1.5 % ≤ Humidity &lt; 2 %</td>
<td>7</td>
</tr>
<tr>
<td>M (Wet cable)</td>
<td>Humidity ≥ 2 %</td>
<td>5</td>
</tr>
</tbody>
</table>

The $\tan\delta$ measurement results for combined XLPE/PILC cables

In the case of these cables, the situation concerning the moisture assessment has been more complicated. Generally, due to great differences between the parameters of paper insulation and XLPE insulation the values of the cable with XLPE insulation may be neglected, and the $\tan\delta$ values measured can be converted in a simplified way to a paper-insulated cable.

The conversion that is based on the ratio of lengths of XLPE and PILC cables is, according to our experience, limited by the value of the ratio, and it is possible only for a small proportion of XLPE cables. However, this restriction has not been very limiting so far as the greatest number of combined cables is created when networks are made denser, stations are rejoined or the technology of MV parts of stations is changed. The XLPE parts of cables therefore represent only a small proportion of the total cable length with respect to the whole cable.

The following table shows the distribution of $\tan\delta$ diagnostics results for 91 combined cables.

<table>
<thead>
<tr>
<th>Basic division of $\tan\delta$ diagnostics results for combined cables</th>
<th>% of measured cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable assessment</td>
<td>Moisture contents in %</td>
</tr>
<tr>
<td>------------------</td>
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<td>S (Dry cable)</td>
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</tr>
<tr>
<td>of which V2</td>
<td>1 % ≤ Humidity &lt; 1.5 %</td>
</tr>
<tr>
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</tr>
<tr>
<td>M (Wet cable)</td>
<td>Humidity ≥ 2 %</td>
</tr>
</tbody>
</table>

**THE COMBINATION OF THE LOCALIZATION AND INTEGRAL DIAGNOSTICS IN PRAGUE**

Measurements of $\tan\delta$ in the frequency domain are always performed in PRAGUE in combination with the diagnostics of partial discharges. Our goal is to increase the informative value and reliability of the performed diagnostics of 22 kV cables. For PILC cables, we have performed a comparison of the $\tan\delta$ diagnostics and PD diagnostics results. For the results see Graph 8.

![Graph](image.png)

**GRAPH 8 – Comparison of PD diagnostics and $\tan\delta$ diagnostics results on 141 PILC cables measured in 2002.**

The results of PD diagnostics of PILC cables concerning the “poor-quality” cables, i.e. cables with high PD are quite convincing. The number of such cables is not very high and their gradual replacement does not pose an enormous problem. Nevertheless, cables assessed as “good” or “worse” by PD diagnostics can sometimes suffer a failure. Paragraph 2.3 provides an explanation that if a cable defect is caused by moisture, PD diagnostics has no possibility of detecting it and the PD levels are reduced due to moisture in such cases. In the case of PILC cables of the ANKTOYPVS type (with corrosion protection) that are the most common in PRAGUE, the parallel use of PD and $\tan\delta$ diagnostics enables us to focus...
attention on cable segments with very high contents of moisture and to increase the effectiveness of diagnostics. We monitor, in particular, the wet (M) and very moist (V3) cables, which, however, appear to be “good” according to PD diagnostics. These cables are shown in the right bottom corner of Graph No. 8.

THE CONCLUSION

The results of 232 combined diagnostic $\tan \delta$ and PD measurements on PILC and PILC/XLPE cables performed so far meet our expectations. The assessment of cable condition according to the contents of moisture in the insulation nearly copies evaluation by PD diagnostics (Graph No.8). However, it allows for a more precise specification of “good” and “worse” results implied by PD diagnostics. The outcomes of three years’ experience of PD measurements and their analyses enabled us to re-evaluate estimations of dangerousness of the discharge level. New criteria for the assessment of cable condition include the assessment of $\tan \delta$ measurement results, and they will be introduced from the beginning of 2003. Our evaluation of diagnostics results is based on the assessment of PD diagnostics, and the result is subsequently corrected by the results of $\tan \delta$ diagnostics. “Wet cables” are assessed as “poor” regardless of PD diagnostics. In the final assessment, cables with the V3 moisture level are placed to a lower category than that corresponding to the PD diagnostics results.

Analyses and experience gained from the large number of routine PD measurements (circa 1,800) on 22 kV cables in Prague of different ages and designs, relations between the age and the type of cables and the actual failure rate of the cable network operated by Prazska energetika, a.s., together with the discovered connections of the locally selective (PD mapping) and integral diagnostics (determination of moisture in the cable by measuring loss tangent), along with other supporting means (measurements with sensors, PD, and thermo-visual measurements) allow for a more reliable assessment of cable condition. Funds for maintenance and defect prevention can be allocated very precisely on the basis of analyses and diagnostic measurements, and the failure rate of 22 kV cable network can be naturally reduced at minimum costs.

REFERENCES

