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Practical Experiences with On-line PD Monitoring and Interpretation for MV Cable Systems

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Abstract—PD monitoring on-line with location (PD-OL) is one of the successful diagnostic tools for MV cable networks which has been recently introduced to the main utilities in the Netherlands and also a few worldwide. Data acquired by PD-OL need to be correctly interpreted in order to identify the upcoming faults in MV cable networks and possibly forecast the remaining life of the component. Interpretation of the measured signals by means of statistical analysis of various PD patterns as well as trend watching in the patterns, which is considered as the prominent advantage of the on-line monitoring, enables us to estimate the degradation stage in insulation systems. In this paper, we present the result of such analysis applied on two life circuits. The data was obtained over a period of over two years continuous monitoring of the circuits including PILC/XLPE cables and oil-filled / grease / polymer joints. The results of analyses on several weak spots which were detected before failure are presented. Besides, results of failed accessories are discussed in relation to their prior PD behavior as diagnosed by PD-OL.

Keywords—diagnosis, monitoring, partial discharges, monitoring, power cable insulation, power cables.

I. INTRODUCTION

Demands for reliable power cause a growing tendency to apply different strategies in the form of condition-based maintenance [1], [2]. For installed medium voltage (MV) cable systems, PD measurement is often the only source of reliable information to evaluate the state of the insulation. Success stories of off-line PD measurements [3], [4] led to an increase demand for the technologies capable of performing a continuous monitoring. Several on-line monitoring systems have been introduced to the market lately. PD monitoring on-line with location (PD-OL) is one of the successful diagnostic tools for MV cable networks which has been recently installed by the main utilities in the Netherlands and also a few units are installed abroad (Fig. 1). To correctly identify upcoming faults in MV cable networks and possibly forecast the remaining life of the component, correct interpretation of the measured signals is required.

The interpretation can be done by analysis of the measured signals, the patterns created based on these signals as well as their development over time. Statistical analysis of various PD patterns created for PD related parameters including PD charge magnitude, PD charge density and PD charge repetition rate resulted [1] in robust knowledge rules used to estimate the degradation stage in insulation systems. Besides, trend watching in the patterns, which is considered as the prominent advantage of the on-line monitoring, enables us to forecast the end of life of the components.

II. PD PATTERNS

PD patterns are subjected to detailed analysis to obtain information on the insulation condition to prevent failures in cable networks. In the following a brief explanation of these patterns is presented.

A. PD Mapping

Three dimensional PD mapping diagrams are used to visualize the PD concentration along the cable length over a period of time. Each single dot in the diagram represents the magnitude (in pC) of an individual PD as a function of its location and its time of measurement.

B. PD Magnitude

PD charge magnitude depends on various factors such as conductor size, insulation thickness, type of the insulation, size and the location of the defect [5]. Different defects give rise to specific magnitudes of discharges. For instance, magnitudes of corona discharges usually are in the same range. Therefore, statistical modeling of PD charge magnitude has in principle the potential to identify the type of the PD source (e.g. internal, surface or corona discharges). Weibull statistics is an approach to classify the discharge magnitudes and their distribution. The
shape parameter of this model is used to represent the defect type [6],[7]. The Weibull cumulative function is defined as

\[ F(q; \alpha, \beta) = 1 - \exp\left(-\left(\frac{q}{\alpha}\right)^\beta\right). \]  

(1)

where \( \alpha \) and \( \beta \) denote the scale and shape parameter respectively, and \( q \) represents the discharge magnitude.

C. PD Charge Density

PD charge density patterns represent the intensity of the discharge activity at a certain location and it is defined as the summation of apparent charge magnitudes along a relative length \( (L_{\text{eff}}/L_{\text{cable}}) \) which, in our case, is taken as 1% of the full cable length during relative measuring time \( (T_{\text{eff}}/T_{\text{cycle}}) \). This parameter is given by

\[ PD_{\text{dens}}(l,t) = \sum_{j=1}^{n} q_{i,j}(l,t) \]

(2)

where \( q_{i,j} \) is discharge magnitude. The summation over indices \( i \) and \( j \) accumulates the charge over length \( L_{\text{eff}} \) and time \( T_{\text{eff}} \). This value is expressed in “nC / power cycle” [1]. Also the maximum PD charge density recorded at each location within measuring time \( T_{\text{eff}} \) [1] can be taken for further investigation of the degradation stage.

D. PD Occurrence Rate

PD occurrence rate quantity is defined as the number of measured PDs accumulated over the relative length \( (L_{\text{eff}}/L_{\text{cable}}) \) during relative measuring time \( (T_{\text{eff}}/T_{\text{cycle}}) \).

\[ PD_{\text{occ}}(l,t) = \sum_{j=1}^{n} \frac{n_{i,j}(l,t)}{T_{\text{eff}},j/T_{\text{cycle}}} \]

(3)

where \( n_{i,j} \) is the number of PDs accumulated in one record covering about one power cycle. The normalization on \( T_{\text{eff}}/T_{\text{cycle}} \) results in the unit number of PDs per power cycle [1]. Alternatively, the maximum PD occurrence rate in one of the power frequency cycles within \( T_{\text{eff}} \) [1] can be an informative index to judge the insulation state as well.

III. CASE STUDIES

In this section two circuits are studied. Both circuits are XLPE cable circuits incorporating several polymer joints. Only PD’s collected prior short before and after maintenance action is subjected to the analysis.

A. Circuit I

The first circuit includes a 4258 m of XLPE cable, 12 polymer joints and two terminations. The joint located at 1678 m shows intensive discharges which can be observed in mapping diagram given in Fig. 2. Such level of discharges can be extremely harmful for polymer material and may result in breakdown in a short time. Some random discharges are also observed along the XLPE cable. Since this activity is not continuous and randomly distributed both along the cable length as in time, this is considered as noise, due to the sensitive settings of the PD-OL detection level. They will be averaged out in the charge density and charge occurrence rate patterns.

Figure 2. Circuit I: 3-D PD mapping - intense PD activity at about 1600 m

Figure 3. Circuit I: a) PD average b) PD maximum charge density

Figure 4. Circuit I: a) PD average b) PD maximum occurrence rate
The circuit is investigated by means of PD charge density and PD occurrence rate. Fig. 3 shows the mean and maximum PD charge density pattern respectively. As can be observed in Fig. 3a the discharge concentration at the location of the defective joint is clearly noticeable, while the background from other parts of the cable has disappeared. The growing discharge density at the location of the defect observed in the pattern could point to a crucial stage of the defect in the component.

The same behavior is observed in the maximum charge density pattern. The maximum charge density occurring in one hour is clearly standing out as compared to the other cable sections and also tends to grow during the period of diagnosis. Study of the patterns for the PD occurrence rate, shown in Fig. 4, reveals similar behavior. At the location of the joint in both mean and maximum value patterns, the growth in discharge activity is clearly visible.

The discharge magnitude obtained during the period of measurement is subjected to statistical modeling by means of Weibull analysis. Fig. 5 shows the shape factor of Weibull distribution for the entire cable length. The modeling is done only if the number of PDs at a specific location and time block meets a requirement set to be at least 25. As observed in Fig. 5, the shape factor varies between $2.5 < \beta < 3$ at the preliminary stage, which is an indication of an internal discharge source [6], [7]. However, this value dropped during the last days before breakdown to $1.5 < \beta < 2$, possibly an indication of the existence of multiple discharge source. After inspection it appeared that the joint was almost burned. Possibly, both internal discharges and surface discharges contribute to the discharge activity. Fig. 6 shows the $\beta$ value estimated for the location of the defect at preliminary degradation stage. The 95% confidence interval was also calculated for this parameter. The estimated value is $\beta = 2.97\pm0.15$ which is an indication of an internal discharge source.

Based on the analysis, the network owner was advised to replace the joint. However, due to late remedial action, the joint failed in service. On the other hand, it provided the possibility for the authors to follow the PD activity from initiation to breakdown of a real defect aged under service condition. The visual inspection of the joint revealed that the joint suffered from the damage due to a hot connector.

**B. Circuit II**

The second circuit incorporates 6246 m of XLPE cable, 15 polymer joints, 6 polymer terminations and 2 RMUs. Fig. 7 depicts the 2-D mapping diagram for this circuit. As it can be seen in this diagram a joint located at about 3300 m is showing a distinctive discharge line. The 2-D diagram is preferred to 3-D here to illustrate this discharge activity. The circuit is subjected to further analysis in form of PD charge magnitude obtained during the period of measurement is subjected to statistical modeling by means of Weibull analysis. Fig. 5 shows the shape factor of Weibull distribution for the entire cable length. The modeling is done only if the number of PDs at a specific location and time block meets a requirement set to be at least 25. As observed in Fig. 5, the shape factor varies between $2.5 < \beta < 3$ at the preliminary stage, which is an indication of an internal discharge source [6], [7]. However, this value dropped during the last days before breakdown to $1.5 < \beta < 2$, possibly an indication of the existence of multiple discharge source. After inspection it appeared that the joint was almost burned. Possibly, both internal discharges and surface discharges contribute to the discharge activity. Fig. 6 shows the $\beta$ value estimated for the location of the defect at preliminary degradation stage. The 95% confidence interval was also calculated for this parameter. The estimated value is $\beta = 2.97\pm0.15$ which is an indication of an internal discharge source.

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density and occurrence rate patterns as shown in Fig. 8 and Fig. 9. Fig. 8 illustrates the mean and the maximum charge density pattern for PD monitoring over a month time. Due to the maintenance there were no measurement conducted after August 10, 2008 (ceased activity in all graphs for circuit II). As shown in Fig. 8, both average and maximum density at the location of the defect are far above those measured in the other cable section and tend to increase over the time. The mean and maximum occurrence rate patterns in Fig. 9 show similar behavior.

The circuit is further studied by means of Weibull analysis. Fig. 10 depicts the shape factor created for the complete period of measurement. The variation of this parameter, $2 < \beta < 6$, indicates the existence of an internal discharge source. The Weibull modeling was also done over the location of the defect during one single day and the 95% confidence bounds for the model parameter were estimated. This is presented in the graph of Fig. 11. The shape parameter is estimated as $\beta = 6.56 \pm 0.40$.

The joint was identified as being in a critical state replacement was advised. The replaced joint was subjected to visual inspection: it suffered from damages caused by a hot joint connector. Here, by in time warning an outage was prevented.

IV. CONCLUSION

As shown in this work, the prominent advantage of the online monitoring as compared to off line techniques is its capability of revealing the condition as it is under operational conditions. Also temporal or sudden increased PD activity is detected. Consequently it gives the network owner the opportunity for in time maintenance.

Different PD identifiers, charge density and occurrence rate and their statistical parameters, are studied in this paper. The trend over time is a main indicator to identify the condition of the components and to study the risk of failure.

The value of Weibull statistics as a potential tool in identifying the type of the discharging source, however, needs still to be verified by further study. From its absolute value it is hard to draw final conclusions. In its trend, as shown for Circuit I, a decrease in its value was observed prior to failure.

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