NEW GENERATION OF ON-SITE DIAGNOSIS FOR DISTRIBUTION POWER CABELS

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ABSTRACT

Nowadays the use of diagnostic tools to assess to condition of high voltage components is steadily increasing. Applying advanced, non-destructive off-line diagnostic tools, the results of the measurements are different diagnostic parameters, e.g. partial discharge (PD) inception voltage, PD magnitudes at different voltages, tangents delta, etc. It is also known that aging, degradation, and failure mechanisms are statistical in nature. Moreover, to estimate the time to failure correct statistical interpretations is needed. As a result, due to statistical behavior of these mechanisms diagnostic results need statistical features. As the amount of usable data is increasing with number of measurements conducted, this opens up the opportunity to statistically analyze this data.

GENERAL

As a one of Asset Management (AM) goals by the utilities, the lowering of the probability of failure within the medium voltage network, power utilities need to assess the condition of their cable systems [1-3]. Depending on the result of this assessment a decision can be made about the maintenance, e.g. whether or not to replace particular components of the cable system or to replace the cable system as a whole.

An important aid in AM decision processes is the categorizing the actual insulation condition e.g. by the concept of condition indexing. In particular, this concept involves the process of transferring diagnostic or failure information of a component into a condition index of the component. It is known that for most medium voltage components in particular power cables insulation and accessories failure data are unavailable, thus making it impossible to make a good prediction of expected life time of these high voltage components based on failure data.

On the contrary, with regard to PD on-site diagnostics for MV power cable networks large experiences exist.

In this study, applying advanced, non-destructive diagnostic tool for on-site condition assessment of mV power cables up to 60kV diagnostic data was used for statistical analysis, because in contrast to failure data, for most populations of HV components there is much diagnostic or inspection data available (figure 1). As a result, based on experiences and statistical analyses the diagnostic information could be used to index the actual insulation status of a MV component.

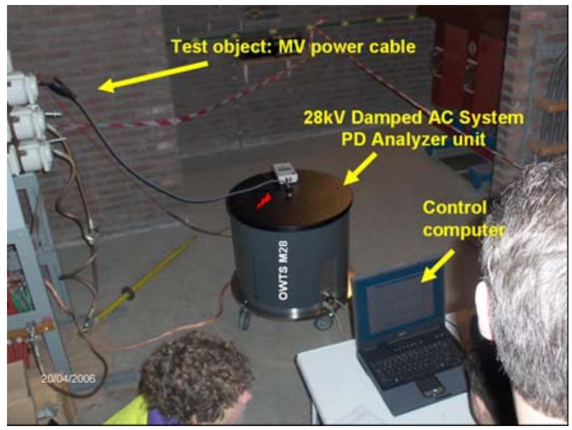


Figure 1. Advanced no-destructive diagnosis of MV power cables using OWTS M28 system. To determine the actual insulation condition of a MV power cable at damped AC voltages PD detection, localization and PD analysis including dielectric losses assessment are performed [2].

In particular the diagnostic data used for analysis was obtained from partial discharge (PD) measurements at DAC voltages are used, because this method provides most powerful information about diagnostics data as obtained from on-site inspections.

CONDITION ASSESSMENT OF MV POWER CABLES

To fulfill the utility expectations with regard to condition assessment several aspects should be taken into account by selecting diagnostics for on-site condition assessment. Based on selection of an effective diagnostic tool several issues have to be taken into account. In table 1 an overview is given of most important requirements. It follows from this table that with regard to diagnoses several parameters has to be measured in function of the applied test voltage.

TABLE 1
Characterization of on-site diagnostics parameters

Condition assessment	Type of diagnosis	Important parameters
Weak-spots	PD diagnosis	- PDIV - PD magnitudes at voltages up to 1.7xU_0 - PD location - PD patterns
Integral condition	Dielectric response	- tan δ behavior at voltages up to 1.7xU_0

The experiences have shown [2] that the observed changes in the voltage at which the PD activity starts PDIV is a good indicator to monitor the degradation by discharging defects. Moreover the increase of PD activity up to 1.7 U_0 is important indicator about the PD activity at voltages higher than the operational stress which may occur during the service life.
Due to the fact that diagnostic test e.g. dielectric loses, should have non-destructive character the maximum voltage level as used for the on-site diagnosis should not excide the 1.7 U_0 (max voltage stress as expected to a cable section during the service life).
After a survey of all relevant information about the HV components, diagnostics are carried out to assess the condition of each type of component. Interpretation is done based on criteria for each diagnostic as suitable to demonstrate or to capture the actual insulation condition. All results together are analyzed by different methods [1, 3] and used for a classification of the component into three possible condition categories, (table 2). It follows from this table that based on information which is provided during periodic or condition based inspection the actual condition of HV component can be used to schedule the necessary maintenance activities and to determine the reliability of this particular asset in the total network configuration.
Apart from information collected through diagnostic techniques, it is worthwhile to collect and share also information from stresses in service, from maintenance experience, from failures and defects detected in the population of assets and from other sources like laboratory tests and/or exit materials.

PD INSULATION DEGRADATION ANALYSIS

It is known, that degradation and aging mechanisms are statistical in nature. In particular, the degradation analysis is one of the crucial tasks in condition assessment of HV components. Due to complexity of thermal, mechanical and electrical processes this analysis is still in development for almost all HV assets. Nevertheless based on the knowledge of individual degradation processes e.g. as initiated by discharging insulation defects more detail information can be obtained about the insulation aging processes.
To obtain applicable norm values, different laboratory measurement data as obtained during aging till breakdown experiments were used. In figure 2 an example of the measurement data is shown. The trend lines are drawn;

TABLE 2
Example of relation between technical conditions, condition based maintenance index and required maintenance actions.

Condition status	Condition index	Required action
No degradation is observed	(9) New or aged	No extra attention required e.g. next inspection in 5..10y
Insulation degradation observed; no serious defects	(6) Strongly aged	Extra attention is needed e.g. inspection within 1y
Significant insulation degradation observed; serious defects	(1) Nearby end of lifetime	Maintenance is necessary; e.g. repair or replacement

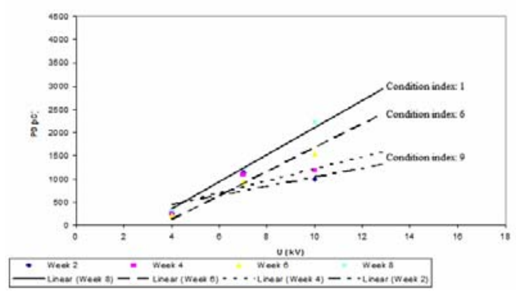


Figure 2 Cable terminations aging with condition index

these trend lines represent the maximum PD magnitude at a particular time. The figure shows that with increasing aging, and thus insulation degradation, the trend lines become steeper. In other words, severely aged high voltage object have steeper trend lines then moderately or not aged high voltage components.
Based on the knowledge about the defects present in the high voltage components, the measurement data for each object was condition indexed.

COMBINING THE STATISTICAL AND AGING ANALYSIS TO OBTAIN APPLICABLE NORM VALUES

The data of the age based condition indexing was combined with the statistical analyses. The following procedure was followed:

1. As indicated, the aging trend lines of the experimental test data were indexed in a linear way according to figure 2.
2. the partial discharge magnitudes under consideration were put in a dataset,
3. the datasets were fitted to a statistical distribution,
4. the partial discharge magnitudes that lie in between the condition index regions were estimated,
5. the boundary values at which these estimated partial discharge magnitudes are situated were calculated.

To illustrate the dataset size needed in order to do statistical analysis, diagnostic data as obtained on oil-impregnated

paper insulation was measured with the OWTS methodology (figure 1).
Naturally in this experiment all data was available from the start of the analysis, meaning that about 330 data samples were present. In real life situations one will start with few data samples and this number will steadily grow with measurements done. Therefore also this experiment will be illustrated in reverse order to reflect real life situations. Starting a small dataset and finishing with a dataset with 330 data samples. The procedure followed to obtain the various sized datasets was simple. Using a random selection procedure the full dataset was reduced to half its size. The half sized dataset in turn was then again reduced to half its size and so on. This procedure continued to the smallest dataset of 9 samples.
The suggested distribution was the Weibull distribution. Using the Weibull distribution the norm values were calculated for all the other datasets (e.g. 50%, 25%, etc.).
Also to determine the best fitting distribution per dataset for each dataset size (e.g. 50%, 25%, etc.), the suggested statistical distribution was selected. Then according to this distribution the norm values were calculated. The results of this analysis are denoted in

TABLE 3
Calculated boundary values using the suggested distribution

	100%	50%	25%	13%	6%	3%
Distribution	Weibull	Expo	Expo	Logn	Logn	Logn
UB (80%)	2872	2825	2749	2458	2581	2757
LB (40%)	943	897	873	752	665	966

Starting with a dataset consisting of 19 data samples statistical analyses can be performed and the result does not deviate significantly from those as obtained for data set populations of more. Looking at real life situations, it is impossible to know the best fitting statistical distributions in advance. Therefore the recommended approach is to collect the available data, and then determine the best fitting distribution. With this distribution the norm values can be calculated.

ACTUAL IMPLEMENTATION OF THE DERIVED KNOWLEGDE ON DIAGNOSTIC DATA

It is known that multiple PD parameters are important in relation to condition assessment of high voltage components. The most important parameters include:

- PD level at U0: PDU0
- PD inception voltage: PDIV
- PD level at 1.7U0 or 2U0: PD2U0

Based on these parameters the so-called 'condition index generator' was constructed. The flowchart is divided into two columns. The left column describes the general steps to assess a high voltage component. The right column describes the actual phenomena and processes related the partial discharges and aging.
First from a database containing PD measurements all the available parameters were assessed for usefulness. Form these parameters: PDU0, PDIV and PD2U0 were selected.
The second step is to relate the PDU0, PDIV and PD2U0 parameters to insulation degradation. In the flowchart this is shown in the right column; decreasing PDIV in time, increase in PD magnitude with increasing test voltage and increase in PD magnitude with increasing aging stadium.
Thirdly regarding the PDU0 and PD2U0 parameters boundary values were determined and the associated norm values calculated for several high voltage components.
The fourth step is related to a new measurement. Based on the PDU0, PDIV and PD2U0 parameters available from a measurement report of a particular inspection on a HV component, condition indices for these parameters are determined. These condition indices are weighted and combined to produce an 'overall condition index'.
Based on this 'overall condition index' a proposal on future actions for this particular HV component has been developed and the figure 3 shows graphically the decision process.
Furthermore to perform the condition indexing a procedure is proposed and translated into an easy-to-work-with tool, the 'Condition index generator' (CIG).
The CIG allows an engineer to easily evaluate the condition of a high voltage component. The CIG is divided into five stages. Each stage evaluates a different aspect of the condition indexing procedure.
Stage 1: Stage 1 allows the selection of a high voltage component. Thereafter the applicable norm values are loaded into the CIG (PDU0, PDIV and PD2U0).
Stage 2: In stage 2 the PDU0 magnitude has to be entered into the CIG. After filling in this value, a condition index is determined regarding this parameter. The condition indexing is done using derived norm values.
Stage 3: In stage 3 the PDIV has to be entered into the CIG. In the CIF the PDIV is related to the nominal voltage of the high voltage component. Thus if an engineer wants to set a PDIV of 3kV belonging to a component rated for 10kV, the engineer would fill in 0.3 in the PDIV-field.
For PDIV the following condition indexing scheme is used:
$\mathrm{PDIV} \le 0.3U_0$, condition index: 1,
$0.3U_0 < \mathrm{PDIV} \le 1U_0$, condition index: 6,
$1U_0 < \mathrm{PDIV}$, condition index: 9.
This condition indexing scheme is used, a low PDIV results in extensive insulation degradation as well as it is an indicator for aging of the insulation. A PDIV above nominal voltage means that in normal operation of the high voltage component no partial discharge activity is present; therefore this situation is given condition index 9.
Stage 4: In stage 4 the parameter to add is the PD2U0 magnitude. After filling in this value, a condition index is determined regarding this parameter. Again the condition indexing is done using the norm values derived in from the available data.
Stage 5: In the final stage, stage 5, the condition indices

related to PDU0, PDIV and PD2U0 are multiplied by weight factors. The weight factors are:
After the multiplication of condition index (CI) with its weight, the results are added to each other. All the weight factors of the same order but due to direct relation to insulation degradation, as reflected by W_{PD2U0}, this weight factor is given slightly more weight.

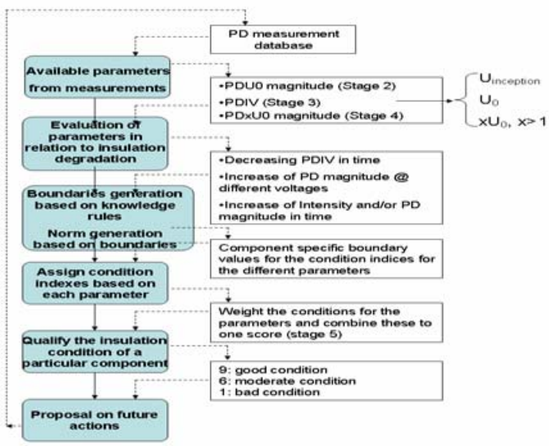
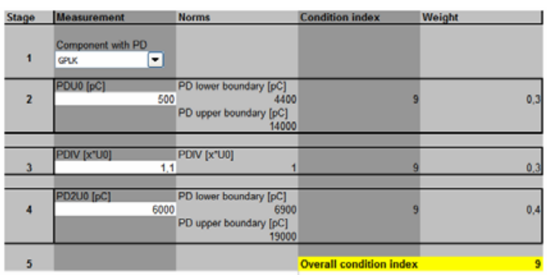


Figure 3 Flowchart to support the condition index selection process



Stage	Measurement	Norms	Condition index	Weight
1	Component with PD GPLK			
2	PDU0 [pC] 500	PD lower boundary [pC] 4400 PD upper boundary [pC] 14000	9	0,3
3	PDIV [x*U0] 1,1	PDIV [x*U0] 1	9	0,3
4	PD2U0 [pC] 6000	PD lower boundary [pC] 6900 PD upper boundary [pC] 19000	9	0,4
5			Overall condition index	9

Figure 4 Condition index generator (CIG). Based on parameters selected and experience norms as developed for particular MV power cables components like joints, terminations or insulation type condition index can be calculated to support the AM decision processes.

Determining the 'overall condition index' is done by translating the calculated value in a condition index (9 or green, 6 or yellow, 1 or red).
To evaluate the correct outcome of the proposed condition indexing concept, actual measurement reports generated by experienced engineers were compared to the 'overall condition index' generated by the CIG.
The evaluated measurement reports involve PILC cable insulation. From the currently available data, PILC norm values were obtained. Filling in the PD parameters: PDU0, PDIV and PD2U0 into the CIG and evaluating the results, it was concluded that the generated 'overall condition index' is in line with the condition index given by experienced engineers. Therefore it is concluded that this approach results in correctly generated 'overall condition indices'.

CONCLUSIONS

Evaluating the failure data from utilities, it is important to assess to condition of high voltage components based on non-destructive diagnostic data. Because very little failure data is available this in contrast to the vast amount of diagnostic data available, condition assessment based on diagnostic data is possible and thus necessary.
Previous studies done on partial discharge diagnostic data show that a number of PD parameters are important. These parameters include PDU0, PDIV and PD2U0, which are regarded the most important.
Applying statistical and aging analyses to partial discharge measurements resulted in the PDU0 and PD2U0 boundary values of about 40% and 80%. Independent measurements concerning e.g. cable termination insulation resulted into these boundary values. The conclusion that can be drawn is thus that these boundary values are generally applicable to diagnostic data of high voltage components. Also comparison between statistically determined norm values based on these boundary values and actual experience norms used nowadays shows the applicability of this approach.
Concluding can be said that this approach results in workable norm values which can be used in future condition assessment methodologies.
Setting up knowledge rules is essential in the final condition assessment of high voltage equipment. Weight factoring the important PD parameters is essential to include all diagnostic information from measurement reports. Weighing the PD parameters also takes care of the problem that no PD parameter has a decisive influence on the final judgment of a high voltage component.
The proposal regarding knowledge rule setup and implementation made in this thesis results in condition indices for cable systems, which coincide well with condition indices derived by expert engineers. Concluding can said that the implementation as shown is ready to use.

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