Statistical Approach in Power Cables Diagnostic Data Analysis

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ABSTRACT

This paper describes the application of statistical analysis to the on-site diagnostic data of HV power cables to set-up knowledge rules and measuring criteria for particular cable insulations and accessory (joints, terminations). Such approaches can successfully be employed later in Asset Management decision processes. In this paper based on different cable data populations of two diagnostic parameters like: partial discharges and tan δ , statistical analysis has been applied. Besides this, several practical examples also have been presented

Index Terms — Cable insulation, data analysis, partial discharges, statistical analysis.

1 INTRODUCTION

IN recent years growing interest in non-destructive and advanced diagnostic systems resulted in several modern diagnostic methods with output data suitable for statistical analysis. Analysis of diagnostic data of medium voltage (MV) and high voltage (HV) power cables especially from on-site measurements is a complex process. This is even more difficult when diagnostic input data can not be verified by the general knowledge of particular insulation types or e.g. component types. It is known that the analysis of PD processes and dielectric losses can reflect the aging condition of cable insulation and also by the evaluation of maximum values, e.g. PD amplitude or dielectric losses can be used to estimate borders between acceptance limits. Therefore diagnostic parameters like: partial discharge (PD) amplitude, PD inception voltage (PDIV) or dielectric losses represented by tan δ or Δ tan δ can be used for statistical processing [1-5]. As a result, obtaining experience norms for diagnostic data (PD or dielectric losses) including confidence boundaries will help to evaluate the insulation condition of new or service power cable systems. Having such boundary values can support asset management (AM) decision processes e.g. about the type and intervals of maintenance inspections or replacement schedule [3]. Moreover, if failure data is available, statistical failure analysis can be a powerful tool to determine whether replacement is necessary now or in the future, to obtain a certain reliability of the network [4-5].

Beside this, diagnostic data obtained on-site plays an important role because it:

- gives information about actual cable condition (on-site measurements result directly or after measurements),
- gives the possibility to estimate norm values for particular cable components,
- supports the maintenance and operation decision processes for maintenance/replacement of power cable systems,
- helps to develop knowledge rules in cable data interpretation as well as cable insulation aging processes,

With diagnostic information as obtained using on-site diagnostic methods, all combined results properly interpreted can be used for a classification of the cable systems.

One of the major goals in on-site testing of service aged MV/HV power cables in the coming years will result with more attention put to decisions which have to be taken about maintenance or replacement of the oldest serviced cables circuits. Those circuits are reaching their life limits and their reliability must be predicted based on actual diagnostics results [2]. In general, such strategic decisions are the responsibility of the asset management [6]. According to [5] the following chart of analysis procedures is presented in Figure 1. Based on information about the present and future asset performance, characteristics e.g. technical condition and the knowledge about degradation status inject additional

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criteria when decisions about maintenance or replacement have to be taken. However, at present such AM strategies may meet several difficulties due to: very low numbers of failures, no cable service history availability. In the case where no statistical predictions are possible or prediction has to be limited because of low quality data (data not complete) [3].

With regards to degradation processes HV cables are more complex than MV power cables and the systematic knowledge about the actual aging needs further investigations and field verifications. Another problem is the lack of HV power cables fixed diagnostic rules for on-site condition diagnostics. Because of these reasons for few last years in the field of on-site cable diagnostic, efforts are put to systematize measuring procedures and test criteria [7]. This mostly regards to clarification the rules and guidelines for applied voltage ratings and limitations for old and new circuits. Performing on-site diagnostics on similar types of components typical "limits" like PD amplitude, at Uo, or 1.7 Uo, or the maximum acceptable dielectric losses range can be set for a particular component e.g. insulation type in certain age or condition. This approach can help develop reference database which can be used to reflect typical practical condition situations:

Status A: New or aged: no defects or aging symptoms which means the minimal maintenance for optimal availability.

Status A/B: Aged: degradation observed, possibly harmful defects present which means: no impact on reliability, keep in status B, against minimal cost and maintain optimal availability. But it also could be that the reliability is decreased which means: refurbish to status B, or if this is not possible, stabilise to prevent quick aging, maintain optimal availability, by periodical condition assessment.

Status C/D: Significantly aged: very degraded, serious defects present which means very low reliability, instable situation, end as quick as possible. But it also could be that no operation is recommended which means: maintenance aimed to prevent environmental pollution and safe conservation, extension of life time or availability is no issue.

Developed in this way knowledge rules and measuring experience provided with large numbers of data will help to setup service criteria for different cable types as well as cable accessories.

In this paper special efforts were put to highlight the statistical approaches in cable diagnostic analysis and to show briefly the processes of distribution data fitting, distribution selection based on data type and norm value generation for PD parameters and tan δ parameter. Further on in this paper several examples of estimated norm values based on on-site measurements will be presented.

2 ON-SITE INSULATION AND ACCESSORIES CONDITION ASSESSMENT

The insulation failures in a cable network may be caused by:

- lower dielectric strength due to aging processes,
- by internal defects in the insulation system,
- an external factors like e.g. poor workmanship installation or assembling works (missing insulation screen at the cable/joint transition or cable splice improperly prepared (cable splice not round) – especially XLPE cables.

It is known that on-site voltage testing in combination with measurements of the dielectric properties may give an indication about the actual condition of service aged cable insulation. For MV/HV power cables different on-site inspections/diagnostics are available. Thus, different diagnostic approaches to output data regarding to short and long-term condition estimations exists [1,2,4-6]. The results of non-destructive, on-site measurements may have a direct relation to the average qualitative level of the insulation at the moment of measurement and can thus be applied as a trend or fingerprint measurement during future inspections.

Based on the last 20 years of on-site experience in power cable testing it follows from [4-7] that PD diagnosis and integral dielectric diagnostics represented by tan δ may play an important role in short and long-term condition assessment. In the majority of examples the PD diagnosis may indicate weak spots in a cable connection and cable insulation itself. With XLPE installation, usually if PDs are recognized they are coming from joint or termination related problems as a result of poor workmanship, unlikely to originate in the insulation itself. The occurrence of partial discharges have physical character and it is described by such important parameters as PD inception voltage, PD pulse magnitudes, PD patterns and PD site location in a power cable. Performing onsite PD measurements at test voltages higher than Uo (normal network voltage) stresses up to 2 Uo is important to (Figure 2):

- a) inspect if there are discharging insulation defects with PD inception voltage (PDIV) > Uo. Such defects may initiate insulation failure in the case of single phase earth fault (non-earthed system) at voltages e.g. 1.7 Uo,
- b) confirm in the same way as in a successful after-laying test, that there are no PD detected up to 2 Uo and that

during the service operation the power cable insulation is free of discharging defects,

c) the on-site test has not initiated any discharging processes in the insulation which information is important to confirm the non-destructives of the diagnostic on-site test itself. PD diagnostics based on analysis of measured PD parameter like (PD magnitude, PD intensity and PDIV) results in an



Figure 2. Important diagnostic parameters and knowledge rules generation goals.

overall cable condition assessment model which can be developed.

In this case the model of condition assessment is mainly based on three correlated PD parameters mentioned above. It is common known that the PD inception voltage (PDIV) is a good indicator to monitor the degradation of the insulation of high voltage components. Experience has shown that the PDIV might decrease due to aging phenomena [3,4,5-8].

This symptom depends on several factors like e.g. type of insulation, defect, and defect volume. Also decrease of PDIV < Uo is directly related to an increase of PD intensity. Thus, the monitoring of the PDIV over an extensive period of the high voltage component and correlated PDs is important in aging phenomenon controlling. Another parameter is discharge magnitude which can be related to the defect size and the defect volume that is occupied by a discharging. The partial discharge magnitude is thus a good indication for both the energy and volume of a discharge source. On the other hand the attenuation of PD pulse magnitude depending on cable the length and insulation thickness which always should be considered. Due to aging processes (e.g. a repeated partial discharge bombardment) the volume of a discharge is expected to grow (e.g. treeing, growing cavities, etc). Therefore increasing partial discharge magnitudes is also an indicator of aging. The partial discharge intensity is called the partial discharge occurrence frequency, within a component at a particular spot in the insulation. Degradation of the insulation in high voltage equipment can be reflected by the energy content of the partial discharge bombardment. The total amount of energy dissipated is directly related to the frequency and the magnitude of the partial discharges.

Partial discharge sources need a starting electron to ignite, in aged sources a greater number of electrons may be available due to protrusions, impurities in the insulation and micro particles caused by aging (e.g. electrical or mechanical stress). Therefore the partial discharge intensity can also be an indicator for aging condition assessment

Unless the fact that all power cables have high voltage life expectancy, during the whole service life > 30 years they are subjected to thermal, mechanical and environmental stresses. All these influences raise the working temperature of the power cable. As a result higher temperature accelerates chemical reactions resulting in degradation of dielectric characteristics by e.g. polarization processes in the paper or oxidation processes in oil or in extreme case braking cellulose bonds. Such increase of degradation results in increases of loss factor and further degradation. Therefore measurement of dielectric losses at operational power frequencies is important issue to avoid failures at relatively high operating field strength of HV power cables.

The dielectric losses measurement (tan δ) can be applied in the determination of the loss factor of the insulation material [7-9]. Due to the fact that this factor increases during the ageing process of the cable, the tan δ measurement should be regarded as a diagnostic and/or supporting measurement. In practice, for HV insulation it is known that in addition to absolute value of tan δ at certain test voltage also the increment of tan delta as measured at two designated voltages so called Δ tan δ or tip-up is important for condition assessment. The loss tangent can be measured as a function of voltage to check the quality of impregnation. The tan δ value of a cable is strongly influenced by the composition of the connection, the trace, and the deviations in joints and the actual measurement is only applicable as a trend measurement if composition circumstances of the trace and thermal conditions of successive measurements are virtually identical. For HV paper insulated cables the tan δ can be an important indicator of possible thermal breakdowns. In particular for paper-oil insulated power cables this is of importance to determine also the degradation ratio of the paper. Relaying on the dielectric properties, mainly polarization of the insulation, the dielectric response on interaction between macroscopic polarization and the electric field is good a representation of the time dependency of the polarization processes in the insulation.

3 STATISTICAL ANALYSIS – DIAGNOSTIC DATA PROCESSING

It is known from the praxis that the data available from the diagnostic inspections of MV/HV components can be characterized as follows:

- 1. for one particular type of the component, small populations of data can be available,
- 2. the data available for one particular type can be influenced by factors like: service life, time moment of inspection and maintenance history.

These two aspects have to be taken into account in different ways. The first method, applicable for representative population sizes involves the process of distribution fitting and norm value generation based on distribution. The second method applicable for small populations of data involves norm generation bases upon so called non-parametric calculating [10]. The statistical analysis than can be divided in two different ways. The second approach is the analysis based on non-parametric methods. With this method the data can be analysed based on histograms of the failure data. The empirical cumulative distribution function (CDF) is based on the histogram and has no underlying mathematical distribution. A disadvantage is that predictions which lay outside the range of observations are not possible. Although this method can give valuable information it is not further discussed in this paper. Another approach is based on parametric methods. With this method statistical distributions are used to fit the data and to estimate the accompanying parameters. The distributions or probability models are used to explain the behaviour of the breakdown processes or the life time data. The processes can be described as random events which result in random variables which can have a discrete or continuous character [10, 11, 12]. Life data, reliability parameters and in fact the results of the majority of measurements, are examples of continuous variables. Examples of discrete random variables are the number of faults/breakdowns following the application of a voltage of given discrete shape and duration. For the statistical evaluation of data obtained on HV components, the most popular models/distributions are:

- In the case of discrete random variables: binomial- or Poisson distributions,
- In the case of continuous random variables: e.g. Normal, Log-Normal, Exponential, Weibull and Gumbel distributions.

Diagnostic data like PD amplitude as a function of test voltage and life time data can be regarded as continuous data, for this reason, the discrete models are not further taken into account.



Figure 3. Basic steps of performing the statistical analysis on data.

The statistical analysis is performed as shown in the flowchart of Figure 3.

In the figure it can be seen that several distributions can be used to fit the continuous random data. With goodness-of-fit tests it can be seen which distribution fits the data best. When the appropriate distribution is chosen the confidence bounds of the distribution can be obtained. These bounds show the variation of a fitted distribution with a certain required reliability. In general: if more input data (more samples) are available this results in smaller confidence bounds (with respect to the same level of reliability).

3.1 DISTRIBUTION FITTING

Distribution fitting means that the data points from the diagnostic data are best fitted with an appropriate distribution. The horizontal axis represents the failure time, age or



Figure 4. Empirical density function (EDF).

diagnostic parameter of the components and the vertical axis represents the unreliability F(t) in percentages (Figure 4).

Parametric distribution fitting has to be done in a number of steps where matching a dataset to a particular statistical failure distribution is done. After that to characterize the particular distribution, using selected statistical parameters the boundaries e.g. $1-\sigma$, $2-\sigma$ or $3-\sigma$ can be calculated. In probability and stochastic process theory, a statistical distribution can be described by a number of different formulas [12-13]. Each formula is related to the other. The probability density function (PDF) and the cumulative density function (CDF) are the most basic formulas and will be used to denote the failure distributions. Usually these formulas are denoted by:

$$F(t)$$
, for the CDF (1)

$$f(t) = dF/dt \text{ for the PDF}$$
(2)

Another related term is the hazard rate, which describes the conditional probability that system or component fails within the interval (t, $t + \Delta t$]. The hazard is related to the CDF and PDF via:

$$z(t) = f(t)/R(t)$$
, with $R(t) = 1 - F(t)$ (3)

The function R(t) is also known as the reliability function. Normally the formulas describing a statistical distribution are functions of time, t. In the analysis of the diagnostic data generated by the measuring systems time is replaced by partial discharge or dielectric losses parameter (tan δ).

3.2 PARAMETER ESTIMATION

When a distribution is chosen to fit the data, the accompanying parameters have to be estimated. Different parameter estimation methods can be used for this. One of them is a part of the distribution fitting as described above. The parameters can be obtained from the plot of the fitted CDF. More sophisticated methods are the least square estimation and the maximum likelihood estimation (MLE). Both methods can give different results. Based on the data one method can be preferred over another one.

3.3 GOODNESS-OF-FIT TESTS

After the parameter estimation of the distribution is done, it has to be considered how well it fits the data points. This can be done by several goodness-of-fit tests. Basically the procedure involves calculating the cumulative density functions of the distributions to be tested and then comparing these CDF's with the empirical density function (EDF) of the dataset. A picture of an EDF is shown in Figure 4. For illustrative purposes a rather small dataset is used.

The comparison between the CDF and EDF can be done based on different goodness - of - fit tests. When the least square estimation is used the correlation coefficient can be obtained. It describes the distance between the data points and the fitted distribution. Other tests which can be used for both estimation methods are e.g. the Kolmogorov-Smirnov test, the Chi-squared test and Anderson-Darling test. The results of the tests can be used to compare the fit of different distributions with each other and finally the best fitting distribution can be selected.

It is important to note that visual verification while choosing the best fitting distribution is very useful. In some instances there is so little difference between the distributions based on the calculated statistics that visual inspection is necessary to make the final decision.

Figure 5 and Figure 6 show an example of the result of the whole fitting procedure. Figure 5 shows the EDF of the measured data (blue line), also the estimated best fitting distribution, in this case a lognormal distribution, is depicted. Figure 6 shows the measured data (green bars) compared to the fitted distribution (blue line). In this figure



Figure 5. Comparison between the estimated CDF of a lognormal distribution and the EDF of measured data (example).

40% and 80% condition status boundaries with confidence bounds



confidence bounds at 50%, 75%, 90%, 95% and 99% confidence level

Figure 6. Example of PDF of the estimated lognormal distribution compared to the histogram of obtained data. Red lines represent boundary settings for particular diagnostic parameter.

the fitted distribution can be compared with the histogram of the data.

3.4 BOUNDARY ESTIMATION (DECISION SUPPORT)

The interpretation of diagnostic data can be difficult when the boundaries are not well known. For example PD measurement on a paper insulated cable gives a certain magnitude for a discharging defect and it does not necessarily has to result in a concern about the quality of the cable. To get more insight in the results of the measurements a statistical analysis on the PD values of different PD measurements on the same type of cable has to be performed. In this way a distribution can be obtained which describes the measured values obtained till so far. This can be used to classify the cable if certain boundary values are selected. This can be PD level at e.g. 40%, 80% or 95% of the distribution. When this boundary value or more is measured an advice can be given to test the cable again in a short time (to monitor if an increase can be seen) or to replace the cable section with a new cable.

Before last decision it has to be investigated if the population or a part of it can fulfil the reliability as requested by the asset manager. By means of the fitted cumulative distribution function the age of a component together with the reliability can be obtained. This is done by evaluating the B-lives. These indicate a certain level of reliability based on the age of a component. In the world of engineering the used B-life starts mostly around B10. This means that 10% of the total population will fail at a certain age (or with certain parameter value) and that 90% survives. Different values can be used as an acceptance value for unreliability/reliability depending on the criticality of a failure, cable component. When the probability of failure gets too high, components with the PD amplitude or dielectric losses higher then the chosen B-life can be maintained or replaced (Figure 6). In this case of diagnostic data it concerns measurements on non-failed components. This raises the question which boundary values (B-lives) should be chosen when considering "safe" and "dangerous" limits. In next chapter with an experimental way B-lives will be improved based on HV components tests.

3.4.1 BOUNDARY EXPERIMENTAL ESTIMATION (BASED ON TESTS OF HV COMPONENTS)

To verify the developed knowledge rules about boundary norm generation and aging processes several cable system components like termination with artificial defects were investigated in the laboratory. For aging investigation the following components were tested in the laboratory: terminations with an interface problem, e.g. internal discharges in stator and bushing insulation. Result will be shown for a cable termination which was tested in four degradation stages until breakdown. In particular, the partial discharges measured where related to a tracking mechanism. The slopes of the trend lines increase with aging. During 8 weeks of continuously applied voltage (in the range of 4 kV up to 14 kV) the reading of PD amplitude was recorded. Figure 7 shows the measurement results.

With knowledge about the physical defects present in the component and the slope of the trend line condition marks were given. Combining the outcomes of the analyses mentioned in chapters 3 and tests the following procedure was applied to generate and to improve boundary values:



The aging trend lines of the experimental data were indexed according to Table 1

- 1) The partial discharge magnitudes under consideration were put in a dataset,
- 2) The datasets were fitted to a statistical distribution,
- 3) The partial discharge magnitudes that lie in between the condition index regions were estimated,
- 4) The boundary values at which these estimated partial discharge magnitudes are situated were calculated and used in on-site data analysis.

The best fitting distribution for this dataset was the lognormal distribution as in Figure 8. The partial discharge magnitudes at nominal voltage used to calculate the boundaries values were estimated at 1200 pC and 1700 pC. Using these values, the boundaries were situated at 40% and

Table 1. Condition index of the aging stages in the cable termination

Week nr	PD average amplitude [pC]	condition
2	1000	very good
4	1200	good
6	1700	moderate
8	3200	bad

80%. Again these boundaries denoted the transition between the conditions as is visible.

It has been shown in [6, 14] that aging tests of other HV components (bushings and stators) resulted also in output data which fit reliability around 40% and 80%.



Figure 8. Fitting of the measurement data of the cable termination with boundaries at 40% and 80%.

4 APPLICATION OF STATISTICAL ANALYSIS TO POWER CABLES DIAGNOSTIC DATA (EXAMPLES)

In this paragraph several examples of statistically calculated boundary values will be presented. The analysis performed on diagnostic data was used to obtain boundary values for the conditioning of 50 kV oil-paper insulated power cables, 150 kV external gas pressure HV power cables and 20 kV distribution power cables both XLPE and PILC insulation. To see when the PD amplitude is reaching a critical limit and to generate knowledge rules boundary limits were taken and from the distributions the maximum allowable PD magnitude was obtained. This makes it possible to index the condition of the cable into good, moderate or bad and to give advice for future actions.

4.1 20KV MV DISTRIBUTION CABLE

An existing database of measuring parameters consists of different types of 20 kV distribution cables and accessories. All components were installed in a 47 years period of time with the oldest installed component was in 1958 and the newest in 2005. Because of this fact, analysis of population of certain type of joint, termination and insulation types gave valuable information of PD activity in installed serviced components and their aging status during service life. Therefore emphasis was put to three main groups of cables put under investigation:

First group consist of: 30 (3-phases) paper-mass insulated cables of different length,

Second group consist of: 9 (3-phase) XLPE insulated cables of different length,

Third group consist of 42 (3-phases) mixed insulation cables of different length.

In database available parameters like:

- PD magnitude at inception voltage: PD=PDIV,
- PD magnitude at service voltage: PD=Uo,
- PD magnitude at 1.7 value of service voltage: PD=1.7 Uo

were used for the generation of boundary values of particular cable accessory type where PDs were detected and localized.

Based on the assumption that MV cable systems data are represented by three separate insulation types and for each type several different accessory types can be specified with at least 9 samples showing PD activity, boundary representing norm values could be estimated (Figure 9). For this purpose input data representing PD parameters have been fitted with best fitting distribution of e.g. Normal, Lognormal, Weibull or Exponential and 40% and 80% boundaries have been estimated by statistical tools (Table 2).

In the proposal mentioned above the 40% and 80% boundaries estimation was based on experience obtained by laboratory aging experiments as described in section 3.4.1. Combining the outcomes of the analysis based on distributions fitting and laboratory aging test till breakdown of the component, it was possible to generate and tune boundary values and set (40% and 80%) values for these components types where PDs were found. With this statistical approach it was possible to estimate the "dangerous" border values indicating ranges for three service conditions representing aging of the cable. Moreover, with known statistical boundaries obtained for MV/HV components experimental condition indexes can be used to easily mark the typical condition situation during service life.

This condition assessment approach based on diagnostic parameters gives information about how big number of components had failure and how "statistically dangerous" are measured values e.g. for the termination type 1 (mass cables) "Status A" condition range regarding PD=PDIV is specified between 364 pC-40% and 1147 pC-80% (Table 2). As a result, if investigated statistically component (termination type 1) reach = PDIV maximum PD amplitude higher than 1147 pC automatically will be marked with index – condition bad. In this way respectively all cable system components (joints, terminations, insulation parts) can be judge.



Figure 9. Example of boundary values calculation for PD- diagnostic parameter for 20 kV termination type 1

Table 2. Boundaries (40% and 80%) values calculated for all components where PD were localized and number of component is 9 or higher.

		Ν	lass insula	ated cal	bels (20)kV)			
		Nr of samples		PD at	PDIV	PD a	nt Uo	PD at	1,7Uo
	PDIV=<0,3Uo	0,3< PDIV <1,2Uo	PDIV>=1,2Uo	40%	80%	40%	80%	40%	80%
Termination									
Type 1	x	7	2	364pC	1147pC	х	х	442pC	1393pC
Type 6	6	29	15	358pC	910pC	х	х	439pC	1062pC
Joints									
Type 1	×	9	2	1394pC	4263pC	х	х	1407pC	4305pC
Type 3	×	10	4	389pC	1055pC	х	х	458pC	1288pC
Type 5	х	60	47	464pC	1122pC	262pC	601pC	560pC	1290pC
Insulation									
NA2XS(F)2Y	x	12	4	457pC	763pC	х	х	482pC	1113pC
NAEKBA	х	67	19	389pC	978p	341pC	715pC	543pC	1363pC
			Mix-insula	ted cab	les (20k	(V)			
		Nr of samples		PD at	PDIV	Í PD a	t Uo	PD at	1,7Uo
	PDIV=<0,3Uo	0,3 <pdiv<1,2uo< td=""><td>PDIV>=1,2Uo</td><td>40%</td><td>80%</td><td>40%</td><td>80%</td><td>40%</td><td>80%</td></pdiv<1,2uo<>	PDIV>=1,2Uo	40%	80%	40%	80%	40%	80%
Termination									
Type 1	x	9	14	425pC	1624pC	х	х	716pC	2387pC
Type 4	x	11	3	574pc	2356pC	х	х	1179pC	3573pC
Type 2	х	10	18	650pC	3499pC	Х	Х	1052pC	4792pC
Joints		20	25	405-0	4500-0			677.0	0.150-0
Type 1	x	30	30	485pC	1066pC	x	x	6//pC	2152pC
Type 3	Ŷ	34	10	426nC	933nC	Ŷ	Ŷ	783pC	1668nC
Type 5	x	35	5	304pC	758pC	x	x	414pC	1016pC
Insulation									
NA2XS(F)2Y	x	78	60	384pC	1050pC	х	х	534pC	1689pC
NAEKBA	x	92	50	390pC	1320pC	232pC	612pC	702pC	2100pC
			XLPE insu	lated ca	abels (2	20kV)			
		Nr of samples		PD at	PDIV	PD a	t Uo	PD at	1,7Uo
	PDIV=<0,3Uo	0,3< PDIV <1,2Uo	PDIV>=1,2Uo	40%	80%	40%	80%	40%	80%
Termination	x	x	x	x	x	х	x	х	х
Joints									
Type 1	х	7	4	1274pC	3896pC	х	х	1349pC	4130pC
Type 5	х	10	7	456pC	1212pC	х	х	417pC	1321pC
Insulation		10	0	,		174nc	721pC	20760	971nC

(x – boundary estimation not possible or no samples).

4.2 50 KV OIL-FILLED HV POWER TRANSMISSION CABLE

Input data representing oil-filled power cables consist of eleven (3 phase) 50 kV oil-filled power cables circuits. All circuits were installed in Holland between 1950 and 1993. Discussion regarding the variation of two diagnostic parameters tan δ and Δ tan δ has been done (Table 3).

Based on the fact that all single cable sections (phases) are representing the same type of insulation (with exception of circuit 3 the presence of XLPE and PILC mixed insulation is not significant) for dielectric losses measurements $\Delta \tan \delta$ and $\tan \delta$ statistical boundary have been estimated (including confidence bounds) as described in paragraph 3.4. Table 4 presents diagnostic parameters values such as estimated confidence bounds and 40% and 80% boundary values for tan δ and $\Delta \tan \delta$. From this, it follows that there is no overlap between calculated confidence bounds ranges at each confidence level (as it is visible with small data population of 150 kV cables, described later). This is a result of a larger amount of input data used for statistic estimation. With larger amount of input data boundary values for tan δ values can be estimated with higher accuracy. Figure 10 presents example of

of boundary values calculation for Tan δ = Uo (A) and 1.7xUo (B).

Based on estimated boundary values for tan δ and Δ tan δ and obtained circuit data (Table 3) it can be derived:

- that phase L1, L2 (circuit 1) and phase L2, L3 (circuit 8) are classified as most deviating (condition "bad" for Δ tan δ and condition "moderate" for tan δ condition aged),
- phase L1, L2 (circuit 2) and L1, L2, L3 (circuit 9) classified as most deviating (condition "bad"), Explanation of relatively high tan δ (circuit 9) not possible yet, circuit 10 shows the lowest aging condition "good" for all phases.150 KV external gas pressure HV power transmission cable

Input data representing oil-filled power cables consist of three external gas pressure HV power cables (3-phases) 150

Table 3. Numeric values of diagnostic parameters.

		Circuit 1			Circuit 2			Circuit 3			Circuit 4			Circuit 5	
Condition parameter	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3
Tan δ @ Uo [%]	0.28	0.28	0.27	0.37	0.36	0.30	0.24	0.25	0.24	0.10	0.10	0.10	0.12	0.12	0.11
Tan δ @ 1.7Uo [%]	0.38	0.37	0.34	0.42	0.42	0.37	0.30	0.30	0.27	0.16	0.18	0.16	0.20	0.20	0.19
Δ Tan δ [%]	0.10	0.094	0.071	0.054	0.055	0.075	0.064	0.049	0.039	0.06	0.075	0.06	0.076	0.075	0.076
PD @ Uo [pC]	24	5	15	50	340	230	750	1000	880	11000	12000	12000	5000	5000	6000
PD @ 1.7Uo [pC]	26	6	18	300	450	500	X	1800	1800	30000	35000	36000	24000	26000	30000

		Circuit 6			Circuit 7			Circuit 8			Circuit 9	
Condition parameter	L1	L2	L3									
Γan δ @ Uo [%]	0.14	0.14	0.14	0.15	0.15	0.16	0.29	0.29	0.28	0.86	0.72	0.59
Γan δ @ 1.7Uo [%]	0.21	0.21	0.21	0.22	0.22	0.22	0.36	0.37	0.37	0.82	0.65	0.55
\ Tan δ [%]	0.077	0.072	0.076	0.070	0.069	0.059	0.076	0.083	0.088	0.043	0.068	0.046
PD @ Uo [pC]	20	34	24	9	8	4	30	30	35	20	40	42
PD @ 1.7Uo [pC]	30	36	37	10	9	5	31	32	35	38	42	43



Table 4. Numeric values of confidence bounds for 40% and 80% boundary = 50%, 75%, 90% 95% 99% confidence level.

		99	1%	95	%	90)%	75	5%	50)%			
	Value	LB	UB											
Boundary:40%	0.196%	0.152%	0.253%	0.161%	0.238%	0.166%	0.230%	0.175%	0.219%	0.183%	0.209%			
Boundary: 80% 0.361% 0.269% 0.485% 0.289% 0.452% 0.299% 0.436% 0.317% 0.412% 0.335% 0.39											0.390%			
	tan δ @ 1.7Uo													
		99	1%	95	%	90)%	75	5%	50)%			
	Value	LB	UB											
Boundany:40%	0.263%	0.210%	0 316%	0 220%	0 302%	0 234%	0 206%	0 2/3%	0.286%	0.251%	0.276%			

Boundary:40%	0.263%	0.219% 0.316	% 0.229%	0.302%	0.234%	0.296%	0.243%	0.286%	0.251%	0.276%
Boundary: 80%	0.408%	0.330% 0.503	% 0.347%	0.479%	0.356%	0.466%	0.371%	0.448%	0.386%	0.431%
				∆ tan δ						
		99%	95	5%	90	1%	75	5%	50	%

		99	70	95	70	90	J%	/ 5%		50%	
	Value	LB	UB								
Boundary:40%	0.056%	0.045%	0.667%	0.048%	0.064%	0.049%	0.063%	0.051%	0.060%	0.053%	0.059%
Boundary: 80%	0.080%	0.068%	0.092%	0.071%	0.089%	0.072%	0.088%	0.075%	0.085%	0.077%	0.083%

kV and one (3-pahses) section of 110 kV. All circuits have been installed between 1950 and 1990. No maintenance history was available for the particular circuit.

PD measurements were performed at 0.4 Uo up to Uo PD, numeric values are presented in Table 5.

Next measuring result regards to dielectric losses diagnostics and indicates overall insulation condition. By increasing the test voltage and comparing losses of measured phases it was observed that measured tan δ was in range of <0.30% -0.49%> ($30x10^{-4}$ – $49x10^{-4}$). The highest values were observed in phase L1 (circuit 1) at every increment of testing voltage.

By comparing values of tan δ at consecutive test voltage levels Δ tan δ in function of test voltage, has been derived. It follows that phase L1 represents the highest values of this parameter (Table 5). For this purpose both statistical distributions have been fitted and 40% and 80% boundaries have been calculated (Figure 11) including the confidence bounds at 50%, 75%, 90%, 95% and 99% confidence level (Table 6).

This confidence interval represents the maximum error expected at this calculated boundaries norm. The lower the confidence level the lower maximum error is. From the Table 6 follows that there is an overlap between 40% boundary and the 80% boundary for tan $\delta = 0.4$ Uo and Uo as well as for $\Delta \tan \delta$. The overlap between boundary 40% and 80% is present only at 99% and 95% confidence level. This overlap is

due to small number of data as used for 110 kV and 150 kV gas pressurized cables.

It follows from this evaluation that based on both parameters tan δ and Δ tan δ :

- phase L1 (section 1) is classified as most deviating (condition moderate for Δ tan δ and condition "bad" for tan δ, condition aged),
- phase L1, L2, L2 (section 3) are deviating (condition "moderate"),
- all phases (section 2) show no deviation (condition "good' condition no aging),
- two phases (section 4) show no deviation (condition "good" no aging), phase L1 (index 6, condition "moderate").

5 CONCLUSIONS

Based on the research results as discussed in this contribution the following can be concluded:

- 1. Service aged power cables are important assets and there is an increasing need to obtain information about actual condition by applying integral and defect related on-site diagnostics.
- 2. Partial discharges, dielectric losses diagnosis can be used for non-destructive on-site testing and diagnosis of new and service aged power cables

Tuble 0. Humeric Values of diagnostic parameter	Table 5.	Numeric	values	of diagr	nostic	parameter
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	;	Section 1			Section 2	2	Section 3			Section 4		
Diagnostic parameter	L1	L2	L3	L1	L2	L3	L1	L2	L3	L1	L2	L3
Tan δ @ 0.4Uo [%]	0.37	0.32	0.30	0.39	0.37	0.35	0.35	0.35	0.36	0.37	0.37	0.34
Tan δ @ Uo [%]	0.50	0.41	0.42	0.44	0.45	0.43	0.48	0.47	0.47	0.47	0.46	0.45
PD level @ 0.4Uo [pC]	13	2	3	112	145	138	40	13	28	21	18	42
PD level @ Uo [pC]	51	74	44	113	166	250	160	106	72	106	86	101
∆ Tan δ [%]	0.125	0.09	0.12	0.051	0.074	0.089	0.132	0.121	0.108	0.105	0.098	0.103



Figure 11. Example of boundary values calculation for Tan δ =0.4 Uo (A) and Uo (B)

Table 6. Numeric values of confidence bounds for 40% and 80% boundary = 50%, 75%, 90% 95% 99% confidence level.

	tan o @ 0.400													
		99%		95	5%	90)%	75	5%	50)%			
	Value	LB	UB											
Boundary:40%	0.345%	0.326%	0.364%	0.330%	0.359%	0.333%	0.357%	0.336%	0.353%	0.340%	0.350%			
Boundary: 80%	0.372%	0.350%	0.394%	0.355%	0.389%	0.358%	0.386%	0.362%	0.382%	0.366%	0.378%			
				tan δ	@ Uo									

		99%		95	5%	90	1%	75	5%	50	%
	Value	LB	UB								
Boundary:40%	0.456%	0.439%	0.473%	0.443%	0.469%	0.445%	0.467%	0.448%	0.464%	0.451%	0.461%
Boundary: 80%	0.481%	0.460%	0.502%	0.465%	0.497%	0.468%	0.494%	0.472%	0.490%	0.476%	0.486%

				Δ tan δ							
		99%		95	5%	90)%	75	5%	50)%
	Value	LB	UB	LB	UB	LB	UB	LB	UB	LB	UB
Boundary:40%	0.104%	0.082%	0.125%	0.087%	0.120%	0.089%	0.117%	0.094%	0.113%	0.098%	0.109%
Boundary: 80%	0.135%	0.109%	0.160%	0.115%	0.154%	0.118%	0.151%	0.123%	0.146%	0.128%	0.141%

P. Cichecki et al.: Statistical Approach in Power Cables Diagnostic Data Analysis

- 3. Statistical analysis can be a useful tool for analysing different types of diagnostic data and life time data.
- 4. Estimation of boundary values for particular cable system components can result in reference values, so called borders between "good", "moderate" and "bad" condition status.
- 5. Tracing the boundary values ranges it is possible to reduce un-expected cable failure by taking decisions: replace, maintain, refurbish or measure (check) again.
- 6. With statistical approach to diagnostic data and boundary estimation on-site measuring criteria can be setup and reference developed.
- Knowledge rules about aging processes and physical PD background knowledge is necessary to estimate B-lives values.
- 8. To support AM decision processes, based on field experiences and by using sufficient amount of diagnostic data for different types of insulation and accessories statistical analysis can be used.

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1568



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