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INSULATION DIAGNOSIS OF HIGH VOLTAGE POWER CABLES

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ABSTRACT

In this contribution based on field application of advanced diagnostics a systematic approach for condition assessment of high voltage (HV) power cables is discussed. Based on the assumption that there is not one dominant failure process in HV cable networks in addition to partial discharges also dielectric diagnosis has be included to determine the actual condition of service aged cable insulation systems.

KEYWORDS

HV power cables, advanced diagnosis, condition assessment

INTRODUCTION

Similar to other HV components e.g. power transformers, circuit breakers and overhead lines the average service age of transmission power cable networks is between 30-45 years [1]. Moreover, no or limited knowledge exists about such future performances as:

- insulation degradation processes,
- operation reliability,
- maintenance /replacement expectations.

The transmission power cable networks (HV cable systems) are strategic assets and in contrast to medium voltage (MV) the HV networks are very reliable. In particular, failures in the HV network are not occurring as often as a result of the relative small number of components and the historical good quality and proper maintenance in the past of the network. Also, due to the high redundancy (ring networks, "N-1" criterion) and the possibility of remote switching actions from operation centers, the outage probability and time are relatively low [2].

It is known that the liberalization of the energy markets, the increase of power demand and higher flexibility towards high voltage grids, lead to a more severe exploitation of HV cable systems in the future. As a result, a system failure may lead in addition to emergency repair costs also to a loss of income or to claims. According to [3] repair costs of a failure in a HV cable link can be estimated around 500 €/kV. This means that the repair of a failure in a 150 kV link costs around 75 k€. In addition also costs of not delivered energy have to be taken in to account and these additional costs, depending on claims and penalties as contracted can be much higher.

Thus, in coming years more and more strategic decisions have to be taken about maintenance or replacement of the oldest or cables circuits [3,4], figure 1. Normally, such

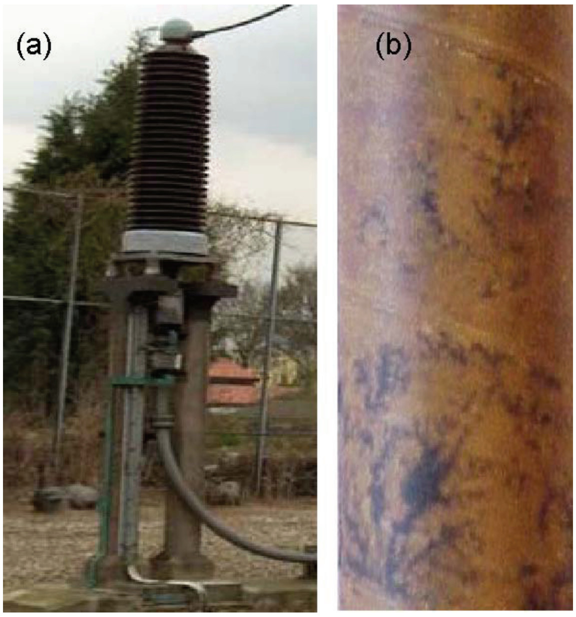

Figure 1: Insulation degradation of service aged HV power cables:
(a) example of external gas pressurized 150kV service aged power cable,
(b) example of insulation degradation by treeing activity through the different layers of impregnated paper insulation.

strategic decisions belong to the responsibilities of asset management (AM), [7]. In particular, based on information about the present and future asset performances e.g. technical condition and the knowledge of degradation processes, decisions about maintenance and replacement can be prepared. However, at present setting up such AM strategies may face three difficulties:

a) due to very low number of failures no statistical predictions are possible [5],
b) degradation processes of HV cables are more complex and the systematic knowledge about the actual aging needs further investigations and field verifications as shown in [3], (figure 2),
c) with regard to HV power cables no fixed diagnostics are available for on-site condition assessment [4,6,12,13], (figure 3).

It follows that assessment of actual condition is getting more important [8,10]. Actual knowledge of the condition of HV cable systems may support the network managers

- to evaluate overall condition of the power network condition,

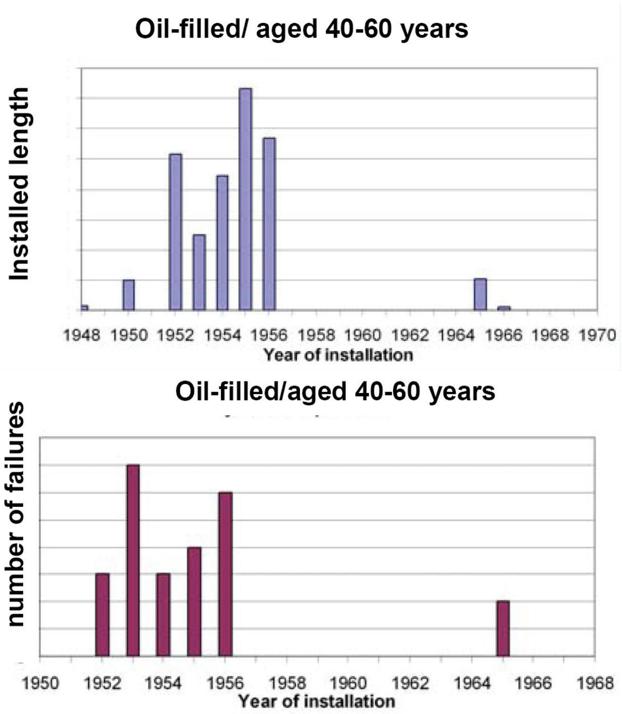

Figure 2: Failure statistics of two types of oil-filled power cables. It follows from these examples that the service age of the whole cable system is not sufficient to be used as indicator for replacement decisions.

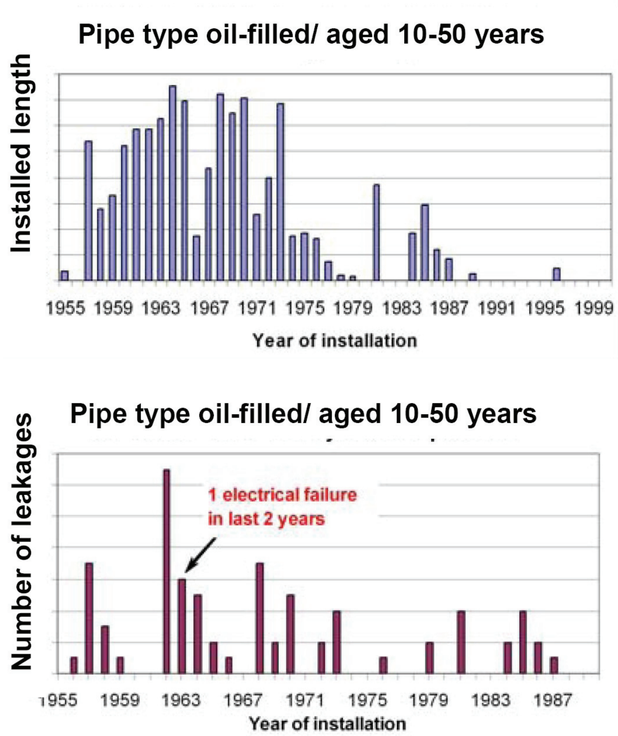

Figure 3: Failure statistics of two types of oil-filled power cables. It follows from these examples that the service age of the whole cable system is not direct related to the failure statistics of a subsystem.

- to be able to estimate the reliability of the power network,
- to set up maintenance/replacement schedule, diagnostic data may provide important information for conditions assessment.

It is known, that HV power cable failure can occur as a result of the normally applied operational voltage or during a transient voltage lightning or switching surges. The failure can occur if localized electrical stresses are greater than the dielectric strength of dielectric materials in the area of the localized stress or the bulk dielectric material degrades to the point where it cannot withstand the applied voltage.
Therefore performing non-destructive diagnostics on-site could be an important issue to determine the actual condition of the cable systems and to determine the future performances [9]. In particular there is need to develop programmes consisting of

- diagnostic tools,
- implementation/application support,
- knowledge rules,

to support the asset management of HV power cable circuits.
Therefore in this contribution based on field application of advanced diagnostics a systematic approach for condition assessment of HV power cables is discussed.

DIAGNOSIS OF HV CABLE INSULATION

The insulation failures in a cable network may be caused by lower dielectric strength due to aging processes and by internal defects in the insulation system. It is known that unlike voltage testing, measurements of the dielectric may give an absolute indicator for the quality level of the cable insulation.

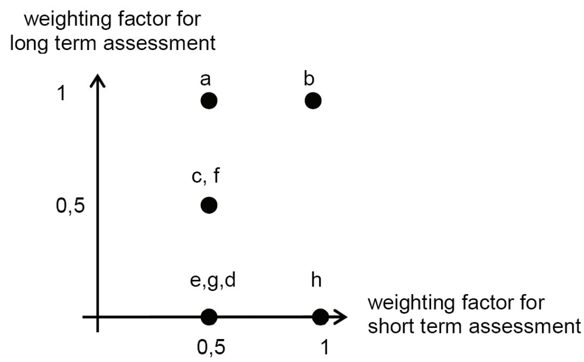

Figure 4: Contribution of different on-site diagnostics to short and/or long term condition assessment [3, 13]

a) measurement of dielectric losses / response
b) PD measurements
c) dissolved gases analysis
d) DC sheath test
e) visual inspection of accessories
f) inspection of earthing system
g) inspection of hydraulic system
h) determination of impregnation coefficient

For HV power cables different on-site inspections / diagnostics are available [1,3,12,13]. In particular with regard to information as provided, conclusions about short-and long-term condition can be made (figure 4). The results of these 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. It follows from figure 4 that partial discharge diagnosis and dielectric diagnosis may play important role in short-and long-term condition assessment, figures 5-7.

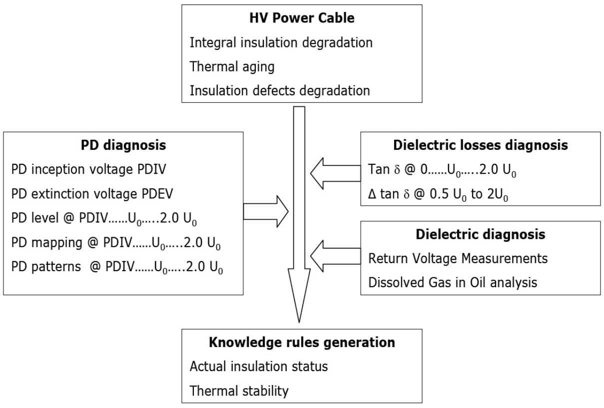

Figure 5: Example of condition aspects of HV power cable, important diagnostic parameters and knowledge rules generation goals.

The partial discharge diagnosis may indicate weak spots in a cable connection. In order to run the measurement partial discharges are ignited in the cable insulation or joints by the application of a test voltage [10-12]. 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 (figure 7). For utilities interested in applying PD diagnostics for condition assessment of its power cables all these parameters are of importance.

In particular, analyzing PD parameters for different types of cable insulation and cable accessories can results in developing experience norms [14, 15]. Such norms would be very helpful in developing knowledge rules to support AM decisions.

The tan δ measurement can be applied for the determination of the loss factor of the insulation material [3,4]. 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, in HV insulation 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 is measured as 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 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 [4].

CONDITON ASSESSMENT FILED EXAMPLES

Performing on-site testing/diagnosis of installed HV power cable circuit may have different purposes. In particular the following goals could be of interest:

a) verify that a new circuit installation or repaired circuit does not contain workmanship problems which can lead to localized PD,

b) to asses the actual condition of a cable system as a part of asset management program e.g.

- to support maintenance and replacement management or
- as a means to support the operational decisions e.g. about the load profile as acceptable for a particular cable connection.

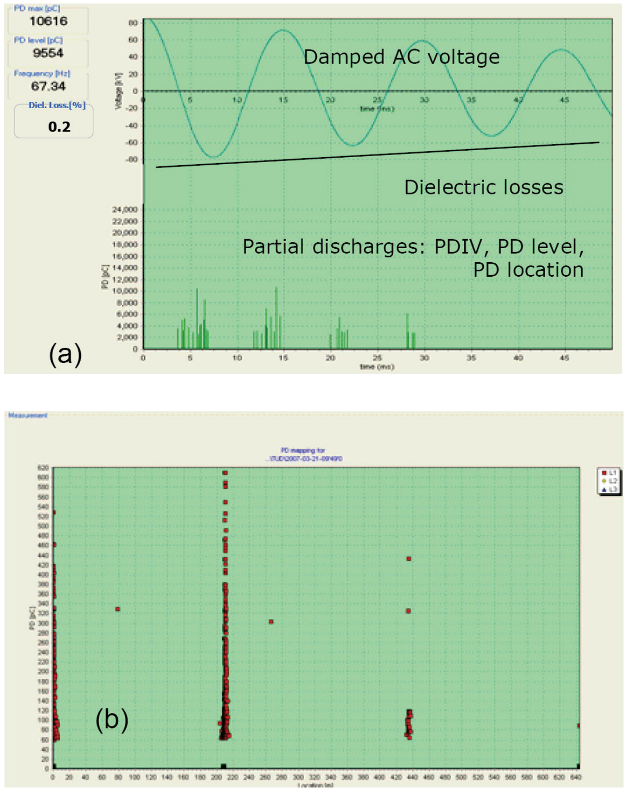

Figure 6: Non-destructive PD and dielectric losses diagnostics using damped AC voltages up to 250kV [15]: a) basic parameters b) PD mapping of PD site locations in HV power cables and accessories

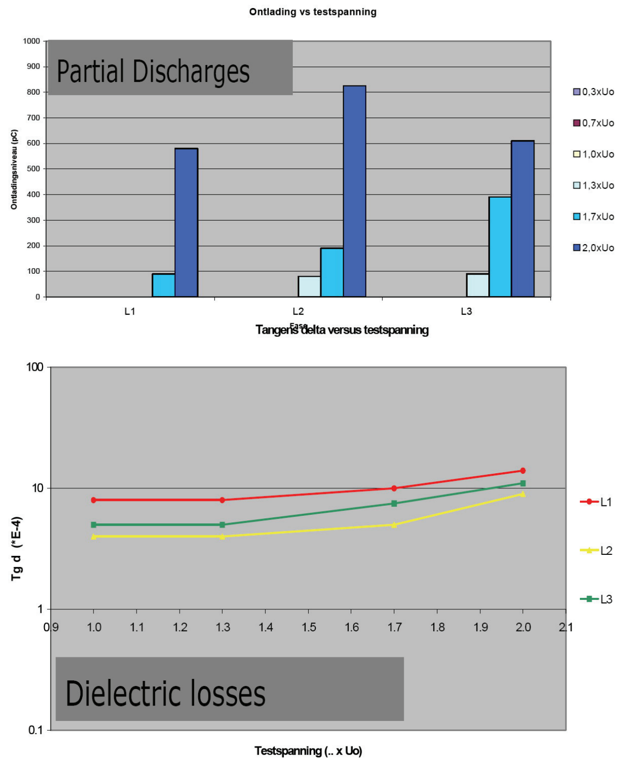

Figure 7: PD and dielectric losses evaluation of a 2 km long, oil-filled 150 kV power cable. PD analysis shows at all phases PD inception voltage PDIV > U_o; the dielectric losses analysis at voltages U_o up to 2 U_o shows low values and no significant increase of the tan δ value.

In the following figures several examples of measuring

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results as obtained from such diagnostic tests are shown. In figure 8 PD measurements as made during after-laying test of 6.4 km long, 50 kV XLPE insulated cable section are shown. Based on the PD detection and localization it could be concluded that up to 2.0 x U_0 phases L1 and L2 are PD-free and that at 1.4 x U_0 in the phase L3 PD activity of 180 pC (corona) has been observed in the cable termination.

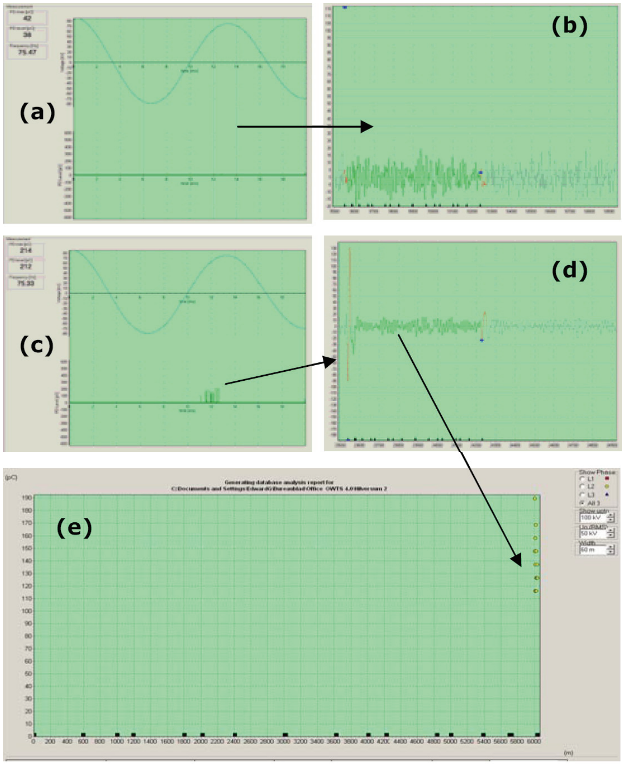


Figure 8: Example of PD measurements on new 6.4km long 50kV XLPE cable as observed using DAC voltages up to 2x Uo:
a) IEC 60270 PD pattern in phase L1, L2
b) VHF pattern in phase L1, L2
c) IEC 60270 PD pattern in phase L3
d) VHF pattern in phase L3
e) PD mapping (PD site location) of phase L3

In figure 9 PD diagnosis of 6 km long, 50 kV a paper-mass-insulated cable section. Due to the fact that this type of insulation is not PD-free the goal of this test was to estimate the actual PD levels in this service aged cable. The Measuring values are shown below:

It follows from these values that with regard to PD activity in function of the test voltage up to 1.7 x U_0 phase L3 shows increased PD activity in the cable termination. Having experience norms for this type of cable termination could be used to support the decision about maintenance/replacement of this particular component.

Phase	PDIV [xUo]	PD@1 Uo	PD@1,7Uo
L1	0.7	2500 pC	2600 pC
L2	0.7	1780 pC	4800 pC
L3	0.7	2300 pC	7500 pC

Measurement of *tan* δ provides information whether a component will perform well under service conditions.
The measured value determines the dielectric losses which might influence the power rating of a component in service.

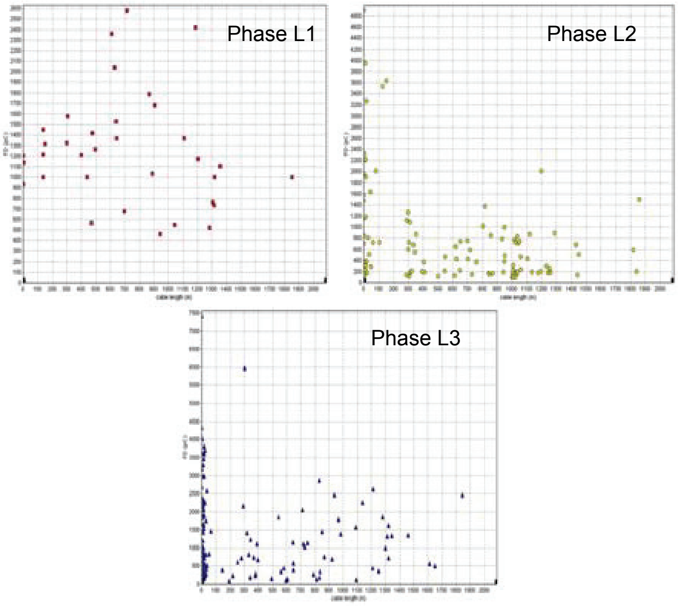


Figure 9: PD mapping of 50 kV, 6 km long service aged power cable. From the PD analysis phase blue shows high PD activity as compared to other phases. Using PD mapping analysis of the phase blue the PD source has been located in the near cable termination.

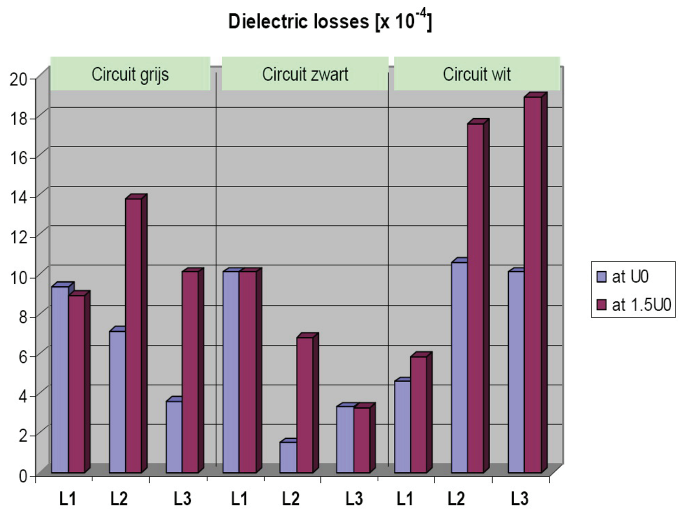
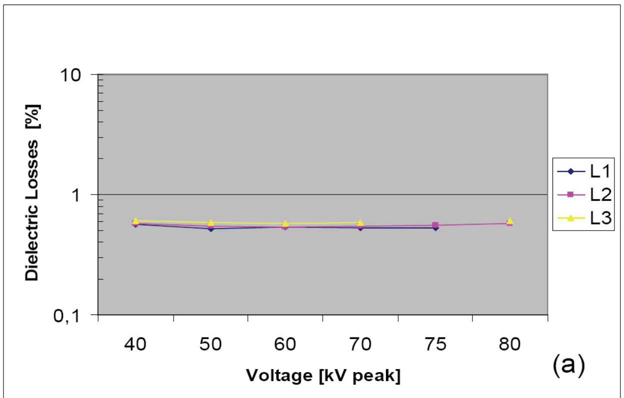


Figure 10: Example integral diagnosis of a gas-pressurized, mass insulated 150kV by dielectric losses as measured using OWTS HV250 at U_o and 1.5U_o on three 150 kV power cable circuits (external gas-pressurized); (installed 1960) length 6.2 km.

In practice, in HV insulation 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. In figure 10 an example is shown of dielectric losses diagnostic as applied to 3 cable systems of the same type. It follows from these results that analyzing the dielectric losses at different voltages e.g. at U_o and 1.5 U_o may provide for condition assessment valuable information.
In figure 11 two examples are shown of dielectric losses diagnosis as applied to service aged HV power cables. With regard to oil-filled power cable up to 1.5 x U_o no regular PD activity has been observed. As a result during normal operation at U_o no PD activity is present in the cable insulation and referring to PDIV > 1.2 x U_o this cable can be judged as PD-free. Taking into account the service age of this cable and based on tan δ the measured values between 35 x 10^{-4} and 62 x 10^{-4} with regard to overall insulation degradation no indication of advanced aging has been observed (figure 11a).



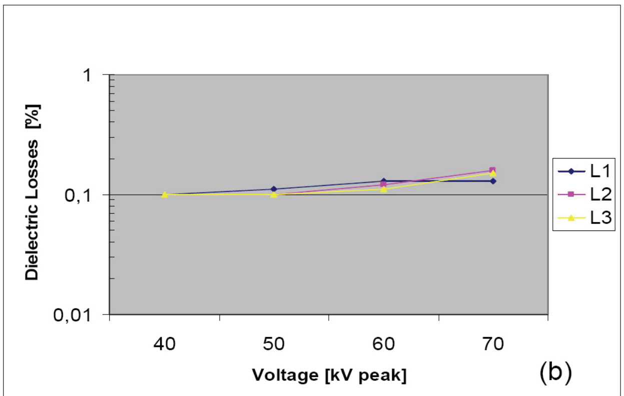


Figure 10: Examples of dielectric losses diagnosis of two service aged power cables:
a) dielectric losses (tan ∂) as measured on a 40years old oil filled power cable length 12.4 km using damped AC voltages (23 Hz)
b)dielectric losses (tan ∂) as measured on a 29 years old XLPE power cable length 14.9 km using damped AC voltages (30 Hz)

With regard to XLPE power cable up to 1.3 x U_o no regular PD activity has been observed. As a result during normal operation at U_o no PD activity is present in the cable insulation and referring to PDIV > 1.2 x U_o this cable can be judged as PD-free. Taking into account the service age of this cable and based on *tan* δ the measured values are lower than 15 x 10^{-4} with regard to overall insulation degradation no indication of advanced aging has been observed (figure 11b).

KNOWLEDGE RULES GENERATIONN

As shown in previous paragraphs performing on-site diagnostics can provide valuable information about the actual insulation degradation e.g. by the presence of insulation weak-spots (partial discharges) and increase of dielectric losses of the insulation, see figure 4. As a result to support the maintenance and replacement decision process these diagnostic data have to be transformed into condition categories [8]:

Condition	Definition
Normal	- *No maintenance necessary*
	- *No problems*
Degradation initiation	- *Short term: No impact on network reliability*
	- *Long term: without any maintenance possible life time reduction*
Degradation in progress	- *Short term: cable can still be operated but the network reliability is decreased Maintenance is necessary*
Failure	- *Cable can not be operated and maintenance is necessary*
	- *Based on economics repair or replacement*

Based on field experiences as obtained on PD and tan δ on-site diagnosis of oil-filled HV power cables, to support the decision process of Asset Management the knowledge rules can be developed, see an example in table 1. It follows from this example that for cables in Cat A, B, C and D where over-all degradation is evaluated Asset Management information about availability in service **=**
1- [Unplanned maintenance/ (365 x 24hrs) - CBM/year] can be determined, (see table 2).
For a cable in category D, due to the presence of local insulation defect as detected by PD diagnosis it is not possible generate any information about the availability.

Table 1: Oil-filled HV power cables Condition Assessment Knowledge Rules for on-site Partial Discharges (PD) and dielectric losses (*tan* δ) diagnosis

Condition Category	PD [pC]	tan δ @ U_o [$x10^{-4}$]	Advise
A	≤ 250	≤ 30	Condition o.k.
B	≤ 1000	≤ 50	Condition o.k.
C	≤ 1000 or ≤ 5000 and no PD concentrations	≥ 50 and ≤ 80	Follow trend by inspections
D	≤ 1000 and PD concentrations	≥ 80	Follow trend by inspections Repair on PD location
E	≥ 5000 and no PD concentrations	>> 80	Cable replacement

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Table 2: Oil-filled HV power cables AM rules for on-site Partial Discharges (PD) and dielectric losses (tan δ) diagnosis			
Condition Category	Availability in Service [%]	Planned maintenance / year [hrs]	Unplanned maintenance / year [hrs]
A	>99.9	<24	<8,7
B	>99	<48	<87,7
C	>95	<72	<434
D	<50	-	Due to presence of local degradation not possible
E	<95	-	>434

Moreover to develop decision boundaries for diagnostic parameters e.g. PD values and tan δ values at different voltage levels PDIV, 1 x U_o, 1.7 x U_o or 2.0 x U_o, according to [14] statistical analyses of diagnostic data of particular types of cable insulation and cable accessories have to be applied.

CONCLUSIONS

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

1 in coming years more and more strategic decisions have to be taken about maintenance or replacement of the oldest or cables circuits.

2 Failure statistics of service age HV power cables is not always sufficient to be used as indicator for replacement decisions and is not always direct related to the failure statistics of a sub-system, e.g. failure in accessories.

3 Actual knowledge of the condition of HV cable systems may support the network managers

a) to evaluate overall condition of the power network condition,

b) to be able to estimate the reliability of the power network,

c) to set up maintenance/replacement schedule, diagnostic data may provide important information for conditions assessment.

4 New and service aged HV power cables are important assets and have to be tested on-site. In particular, PD and dielectric losses diagnosis e.g. using damped AC voltages can be used for non-destructive on-site testing of new and service aged power cables [15];

5 Based on field experiences and using diagnostic data (PD, dielectric losses) for different types of insulation and accessories experience norms can be estimated;

6 Such experience norms for PD and dielectric losses can be used to support the Asset Management decision processes of HV power cable networks.

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