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²DIAGNOSTIC FOR PAPER CABLE CONDITION ASSESMENT

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ABSTRACT

Off line diagnostic method had been defined to detect cable links with failure risk due to presence of joint with water penetration. This method, based on tan delta measurements completed with partial discharges measurements has been applied in real conditions of replacement operations. Specific decision criteria and application results are presented. Economical aspects related to diagnostic integration in a replacement policy to prevent failures during hot summers are discussed.
EDF R&D program for cable system condition assessment is presented

KEYWORDS

MV Cable, diagnostic, PILC, joints, water penetration, underground, network.

INTRODUCTION

French MV underground network had been early and massively developed with innovative and reliable synthetic cable which represent 85 % of the MV underground network. However Paper Insulated Lead Covered (PILC) cables, mainly installed 40 years ago, are still operated, particularly in French major cities. As it could need a significant amount of investment replacement of those cables is anticipated by EDF asset management to define the adequate renewal strategy. For that, accurate condition assessments based on diagnostic tools are needed. Even if most of PILC cables are still in good condition, presence of such cable lead to fault rate increase, specifically during hot summer. This is mainly due to transition joint with water penetration, so efforts on diagnostic methods were first focused on those bad joints. Managed in a second stage cable assessment is becoming soon the central activity.
The off line diagnostic method developed and applied by EDF R&D for preventive joint replacement operations is first described. Then program in order to reach more accurate diagnostic criteria and to reduce resources involved in diagnostic are presented.

OFFLINE DIAGNOSTIC METHOD FOR TRANSITION JOINT WITH WATER INGRESS

Background

Following increasing of fault rate observed during summer 2003 heat wave, works were engaged by EDF R&D to explain degradation mechanisms involved and define preventive method in order to limit failure occurrence. Expertises hold on failed transition joints shown that water ingress in joint insulation paper was observed in most of the cases. Tan delta measurements were rapidly applied in order to characterise temperature behaviour of bad joints because this well known method is used for many years in order to appreciate insulation performance. More over, previous works performed at EDF R&D and by other research teams shown that tan delta measurement performed at very low frequency (or in a range of low frequency like dielectric spectroscopy) [1], [2] were able to detect moisture or interface phenomena. Thus such phenomena could be observed due to presence of water in the paper/oil impregnation complex.
Test carried on several joint samples removed from networks showed both :

- Dramatic decrease of insulation dielectric characteristics versus temperature increase and good correlation with water content in insulation papers after joint expertise,
- Ability of 0.1 Hz tan delta measurement performed at ambient temperature to differentiate the bad joint behaviour at higher temperature.
- Three type of behaviour were identified as shown in fig. 1:
- Type 1 : Slight increase of tan delta versus temperature and water content in paper < 1%,
- Type 2 : Moderated increase of tan delta versus temperature and water content in paper between 1 and 2 %,
- Type 3 : Dramatic increase of tan delta versus temperature and water content in paper > 2%.

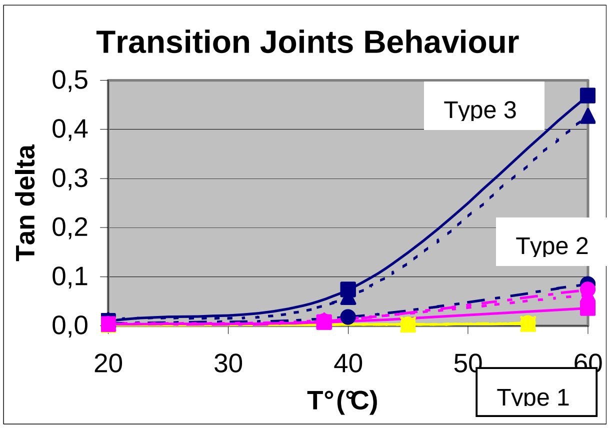

Figure 1

Reference values

On site Detection of joint with water penetration close to breakdown with tan delta measurement needs definition of reference values for :

- The healthy real cable section
- The same section with a bad joint.

Healthy section reference

Presence of transition joint implies presence of synthetic and paper cables in the same section. Tan delta classical model was used to represent (Figure 2) and calculate the tan delta value when 2 different types of cable, with different tan delta values, are associated :

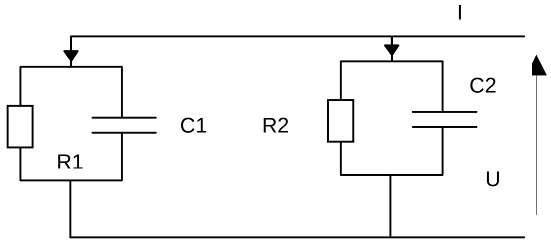

Figure 2

We assume that

$$R = \frac{1}{tg\delta \cdot C\omega}$$

Where R represent dielectric loss and conductivity phenomena.

R1, C1 are describing the first type of cable (paper one) and R2, C2 the second type (synthetic).

$$tg\delta_T = \frac{1}{\frac{R1R2}{R1+R2}(C1+C2)\omega}$$

$$tg\delta_T = \frac{tg\delta_1 C_1 + tg\delta_2 C_2}{C_1 + C_2}$$

Then tan delta value for the total cable section can be approached by :

$$tg\delta_T = \frac{tg\delta pLp + tg\delta sLs}{Lp + Ls}$$

considering that capacitance per unit of length is the same for an synthetic cable and a paper cable.

- Lp and Ls are respectively the total length of paper and synthetic cable,
- tgδp and tgδs are respectively the tan delta value for healthy paper and synthetic cable.

Obviously this relation give an approximation of the value expected for an healthy section. However this approximation is compatible with the level of information generally available for the components of the cable section in on site conditions.

Measurement performed on mixed cable sections (different paper and synthetic lengths associated from 150 to 1300 m), re-created in laboratory in order to reproduce real configuration, allow us to appreciate the approximation accuracy (Table 1).
If capacitance of cables is taken in account, the difference between calculated value and measured value is about 10%. This difference rise up to 50 % if same value of capacitance is taken for the two type of cable.

Tested section	Paper length (m)	Synt length (m)	Tan delta at 12 kV (10^{-3})	Tan delta precise calc. (10^{-3})	Dif.	Tan delta simp. calc. (10^{-3})	Dif.
PILC	144	0	3,4	3,40	0%	3,00	12%
Synt N°1	0	43	0,29	0,29	0%	0,20	31%
Synt N°2	0	500	0,23	0,23	0%	0,20	13%
Mix N°1	144	500	1,42	1,26	11%	0,83	42%
Mix N°2	144	1000	0,9	0,84	6%	0,55	39%
Mixt N°3	285	500	1,94	1,77	9%	1,22	37%
Mixt N°4	285	300	2,2	2,17	1%	1,56	29%

Table 1

We will see later that this difference is acceptable because values are dramatically higher when there is a bad joint on the section.

Bad joint reference

Presence of a weak joint on an healthy section can be described by the simplified model presented above. When paper and synthetic cable lengths are associated with a joint, relation become :

$$tg\delta m = \frac{tg\delta jLj + tg\delta_T LT}{LT + Lj}$$

and

$$tg\delta_T = \frac{tg\delta pLp + tg\delta sLs}{Lp + Ls}$$

where :

- tgδm : tan delta measured with presence of a joint with water ingress on the cable section,
- tgδj : tan delta value of the joint,
- Lj : length of the joint (about 1 m).
- tgδT : calculated tan delta value of the healthy cable section with the length and reference tan delta values for each type of cable.

Considering that the length of the joint can be neglected in front of cable length the following simplified relation can be used :

$$tg\delta m = \frac{tg\delta j + tg\delta pLp + tg\delta sLs}{Lp + Ls}$$

then tan delta value for the joint can be approached by :

$$tg\delta j = tg\delta m \cdot (Lp + Ls) - tg\delta pLp - tg\delta sLs$$

In order to reach the tan delta value for a critical joint, measurements had been performed with joint removed from network associated to different lengths of cable. Joints used were failed ones or healthy joints coupled to failed ones. The measurement were performed on healthy phases after verification they were not damaged by the breakdown. 19 phases were tested in 47 configurations.
Joints with the higher measured tan delta values were selected to determine the reference value for a critical joint (Table 2).

Created section	Tangente delta (10^{-3})				Variation
	6 KV	12 KV	18 KV	24 KV	(%/kV)
43 m Synt. +Joint N°54	489.6	601.9	727.6		4.1
143 m Pilc + Joint N°54	119.8	136.9	158.3		2.7
285 m Pilc + Joint N°54	52.3	63.2	75.7		3.7
43 m. Synt. + N°55 Ph 3	685.4	847.1	1004.8		3.9
143 m Pilc + N°55 Ph 3	133.2	163.1	192.2		3.7
285 m Pilc + N°55 Ph 3	72.7	87.8	102.7		3.4
43 m. Synt.+ N°48	206.4	247.6	283.2	322.0	3.1
43 m. Synt.+ N°55 Ph 1	512.8	630.2	742.6		3.7
43 m. Synt.+ N°56	1012.3				

Table 2

Joint N° 54 (Table 3)) was selected as the critical joint (close to breakdown) reference for the calculation of tan delta value regarding cable length associated. Then the critical threshold was fixed at 6000 10^{-3} for the accurate calculation (cable capacitance taken in account). When information is not available (most of the on site measurement cases) the chosen value for a bad joint is 12000 10^{-3} (minimising approximate value).

Section	Cable length (m)	Cable tan delta (10^{-3})	Measured tan delta (10^{-3})	tgdj*Lj approx. (10^{-3}m)	tgdj*Lj accurate (10^{-3}m)
CIS + N°54	43	0,2	490	21044	5050
PILC N°1 + N°54	143,6	3,3	120	16729	6709
PILC N°1 + N°54 + PILC N°2	285	3,3	52	13965	5620

Table 3

In order to appreciate the variation of tan delta versus applied voltage representative of presence of a critical joint, a criteria had also been defined. Although tan delta increase versus voltage for healthy paper cables, increase with a critical joint is much more important.

This criteria $\Delta tg\delta/\Delta U$ (%/kV)is calculated with the following relation :

$$\Delta tg\delta\% / U = \frac{tg\delta(18kV) - tg\delta(6kV)}{tg\delta(6kV)} \times \frac{100}{12}$$

The alert level is reached when this value is over 3%/kV.

On site application

Use of reference values
Characteristics of the measured cable section are needed to determine paper and synthetic cable lengths.
Then the healthy tan delta value waited S_H and the critical threshold S_C are calculated for comparison purpose.

Table 4 give a synthetic presentation on measurements results use for recommendation.

	Tg δ < Sc/2	Sc/2 <Tg δ < Sc	Tg δ > Sc
$\Delta\delta/\Delta U$%<3%	Healthy	Follow evolution	Critical
$\Delta\delta/\Delta U$%>3%	Follow evolution	Follow evolution	Very critical

Table 4

The diagnostic method used on site combine tan delta and partial discharges measurements. The last one is useful to discriminate large scale cable alterations. In such cases joint replacement is not a mater and replacement of cable section has to be considered. Usual PD rules adapted to the French PILC cables network specificity are used for measurement interpretation and recommendation.

Limitations
Clear and accurate recommendations are given for cable sections shorter than 1 km which is the range of application advised. This is not a real restriction because most of French urban networks are without derivation. For this type of network, 90% of cable sections are shorter than 500 m. Nevertheless, influence of bad joint on tan delta is more difficult to put in evidence for longer sections (S_H and S_C are too close). Attenuation of pd pulses with long paper cable sections is also taken in consideration.

Another limitation is due to the fact that tan delta gives an evaluation of the whole cable section and doesn't allow altered joint location. Unfortunately PD measurement cannot be used for that. Most of the joint tested don't generate critical partial discharges features.

On site results
Investigations were performed in 2004 and 2005 in order to confirm range of application and criteria but the first pilot deployment of the method was managed during spring 2006 in Nantes and Marseille. Confrontation to operators requests for 26 selected cable sections was very positive on a technical point of view :

- o 16 of them were found in good condition whereas replacement were initially considered,
- o for 10 of them, high level of risk due to presence of joint with water penetration was identified.

Since the beginning of the investigations, about 50 cable sections have been tested. Relevance of recommendations was proven in all the cases for which verification was possible. Different verification method applied :

- o test after replacement with return to normal values,
- o breakdown after voltage excursion for identified critical section,
- o laboratory measurements and expertise on removed joints,
- o summer failure on an identified critical joint not removed

An example of verification is given Table 5:

Section Identification	N°7089 Lycée Technique N°0892 Soubzmain		
Length (m)	137		
% PILC	9%		
Threshold	88		
Tan delta before replacement (10^{-3})			
6 KV	277	62	323
12 KV	346	72	396
18 KV		83	
Tan delta after replacement (10^{-3})			
6 KV	12	5	13
12 KV	13	5	13
18 KV	13	5	14
Lab measurements of removed joint			
Length (m)	43		
% PILC	0%		
Threshold	279		
6 KV	1369	234	
12 KV	1630	274	
18 KV	2194	317	

Table 5

Economical aspects
Even if the integration of the method in a network replacement procedure has not yet been defined, deployment will be continued for local applications with measurement system equipment of dedicated team.
Economical interest for diagnostic method integration in a replacement procedure was calculated by comparing excavation costs avoided and diagnostic costs. Pay off depends on the reliability and accuracy of network information available for operators to determine intervention.

CONCLUSION AND PERSPECTIVES

The diagnostic method developed for detection of cable sections with failure risk due to presence of joints with water penetration has to be considered validated. Confrontation in real replacement operations gives confidence on method ability to :

- o Avoid non pertinent excavations,
- o Delay non critical intervention,
- o Identify section with failure risk,
- o Classify the different selected sections versus joint risk and cable condition,
- o Guarantee efficiency of replacement intervention.

Method is available for large deployment with objectives selected for asset management strategy optimisation. Data collection of performed measurements will contribute to improve accuracy of recommendation.
However off line diagnostic method is resources consuming. So on line methods based on partial discharges measurements will be experimented in order to define range of applicability and knowledge rules. For that, installation of several on line devices are planed during the beginning of

this year.

As electrical networks are ageing and capital intensive, reaching materials remaining life time of components is a mater of concern for EDF like other utilities in the world. A large scale program of cable sample removal has been engaged by EDF R&D. Expertise, physico-chemical analysis, electrical tests and accelerated ageing are planed. This program aim to define the actual assessment of paper cable and to approach residual life time versus operating conditions and materials environment. Long section of cable will also be removed in order to perform partial discharges measurement to reach more accurate criteria for PILC condition assessment.

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