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# DIAGNOSTIC TECHNIQUES OF MV CABLE JOINTS UNDER DIFFERENT ENVIRONMENTAL CONDITIONS

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## *ABSTRACT*

*The article reports the results and the advances of the experimentation in progress at the RSE laboratories for a diagnostic analysis of the causes of failures that affect MV cable joints, especially during the summer periods. To this purpose two different ad hoc experimental set-ups, consisting of cables equipped with different types of joints to form a ring in short-circuit, have been realized. The rings, energized at rated voltage, are loaded with current to reproduce the daily load variation typical of a MV cable network. The first set-up simulated the reduced thermal conductivity of the soil during summer periods and the second, now under test, allows to simulate, in a controlled way, the presence of rain, even of considerable intensity.*

## INTRODUCTION

Urban areas of densely inhabited cities are more and more subjected to out-of-services that interest underground MV distribution networks, in specific during the summer hot periods. In the great majority of the cases the outages are linked to the breakdown of connection joints between underground cables for the replacement of sections of old oil/paper cables with new extruded ones (in Italy the underground network is still mostly made of oil-impregnated paper insulation cables with an age that in many cases exceed the forecasted useful life of the component).

The reasons of the above-mentioned increase in the failure rate in the summer periods can be attributed to a combination of high ambient temperature and high cable load, due to cooling systems, which can cause the further drying of the ground around the cable with the decrease of thermal conductivity, that can produce an overheating of the joints [1] and their early ageing.

Purpose of the paper is to analyze the phenomenon by means of the results obtained by experimental set-ups that have been realized to reproduce the conditions that MV cables experience in the field.

Ad hoc experimental set-ups have been realized with different types of joints, new and from service, that were connected to form a ring in short-circuit. The rings have been energized at rated voltage and subjected to current cycles to reproduce the daily load summer variation typical of a MV network.

The two different set ups aimed at reproducing different environmental conditions to which the cable may be subjected: dry and hot, humid and rainy.

The first condition was reproduced by means of felts wrapped around the cables to simulate the reduced thermal conductivity and the almost absence of humidity of the soil typical of summer periods [2].

The second set up aimed at reproducing the presence of rain, even of considerable intensity and by monitoring not only the electrical and diagnostic parameters, but also environmental ones, also using IoT technologies.

Each test set-up is also replicated (with the same typology of joint) by mirror rings that allowed to measure the temperature inside the joints, thanks to the absence of voltage, by means of thermocouples installed in the internal layers of the joints.

To analyse the phenomenon different diagnostic techniques have been implemented: Partial Discharges (PD), Frequency Dielectric Spectroscopy (FDS) and Dissipation Factor (Tanδ) measurements.

The experimental results on the first set-up showed that the formation of defects was detected earlier by on-line PD monitoring (with the test circuit energized, in presence of voltage and current), while off-line PD (with the test circuit not energized and with voltage supplied only to the joint being measured) were detected only after a substantial number of thermal cycles [2] [3] [4]. FDS allowed to measure the complex permittivity and Tanδ, showing the variation of these parameters during ageing [5]; this variation led in some cases to a further increase of the joint temperature, thus accelerating the ageing process.

The ongoing experiments on the second set-up, after a certain number of thermal cycles, testify the penetration of moisture and water into some cable joints.

## EXPERIMENTAL SET-UPS

### <u>Circuit reproducing dry conditions</u>

As previously anticipated, the first experimental set-up consisted of rings with cable joints from the service (6 mixed XLPE-oil/paper) and new ones (2 XLPE-XLPE, 2 Oil/Paper, 2 mixed XLPE-oil/paper) from two different manufacturers (A and B).

All the joints were connected together to form a ring in short circuit at a rate voltage $U_0$ (23kV/√3=13.3kV) and subjected to variable current up to a load of 285A. Cycles from ambient to rated temperature, were applied to accelerate ageing because of thermo-mechanical stresses. The temperature was measured using thermocouples installed on the joints and cables surfaces.

Alongside this circuit, the so-called main ring, there was a mirror-ring, composed by new XLPE and oil/paper cables, with the same ratings. In addition to the sensors on the joint and cable surfaces, other thermocouples were put inside the joints, close to the conductor, to measure the radial temperature differences, thus allowing an estimation of the temperature of the conductors of the main ring (and estimate the effect of voltage in the ageing process).

Both test and mirror rings were covered with felts to simulate underground conditions during dry and hot periods, to verify the possibility of joints degradations under these conditions with very low content of humidity. Daily cycles of temperature were applied to both cable rings.

Formation of defects and relevant evolutions under the thermo-electrical stresses were monitored by means of PD measurements performed, according to [6], by HF inductive couplers (HFCT), installed in the cable-shield termination connected to the ground. The HFCT, connected with a PD monitor system, allowed the simultaneous acquisition of PD signals in twelve separated input channels, every ten minutes during the thermal cycles. PD tests were also performed at different voltage levels on each cable using capacitive couplers, to validate the results of the PD monitoring. The insulation conditions were deduced by analysing the phase resolution PD models (PRPD) assuming that the different sources of PD (different types of defects) can be associated with well-defined forms of PRPD. A time-frequency map was used to separate mixed PRPD models into sub-models, each related to a specific noise or PD (defect) source, [7]. The standard quantities defined in [6] allowed to quantify the PD activity.

Figure 1 reports an overall view of the experimental set-up, with the mirror ring on the left.

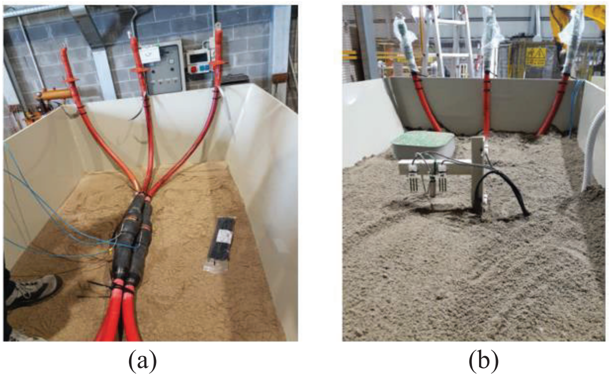
**Figure 1**. Overall view of the first experimental set-up reproducing MV cable joints during dry and hot periods.

## Circuit reproducing humid conditions

To simulate more complete environmental conditions of buried MV cables, a new set-up was realized consisting of containers filled with the same material used in the field. In these containers the joints are positioned (in trefoil disposition) together with the sensors to measure temperature and humidity of the ground close to the joints (Figure 2).

The sensors are of different typologies and some of them are connected to a specially designed IoT system of transmission (NBIoT and LoRa), which is also capable of measuring the current that flow in the cables and of harvesting the energy for its functioning from the cable current.

The new test set up consists of four containers forming to the test ring and two containers for the mirror ring: each container hold three joints, one from the previous circuit with felts and two new ones.



(a) (b)

**Figure 2**. View of the different phases of realization of the second set-up circuit with (a) joints in trefoil disposition and (b) temperature and humidity soil sensors.

Rows of nozzles were placed over each container in order to allow the simulation of rain conditions, from very light ones to real storms (Figure 3).

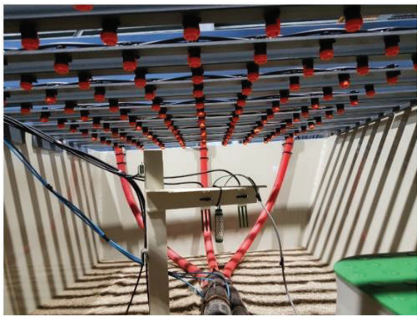


**Figure 3.** View of the nozzles to simulate the rain.

Figure 4 reports an overall view of the experimental set-up, with the mirror ring in the two containers on the left and the main ring in the four containers on the right.

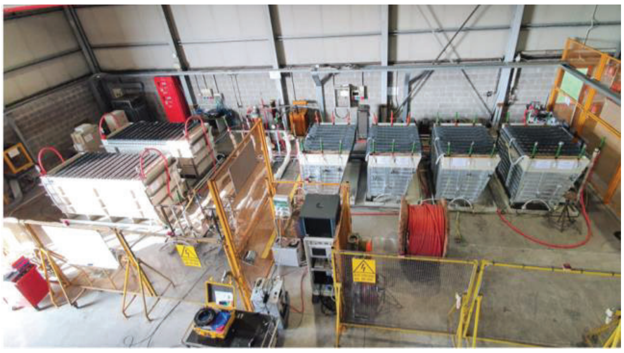


**Figure 4** – Overall view of the second experimental set-up reproducing humid and rainy periods.

PD, FDS and Tanδ measurement are carried out, as done in the set up equipped with felts, both on-line (every 10 minutes) and off-line.

## RESULTS OF LABORATORY TESTS

### Circuit reproducing dry conditions

As above mentioned, current cycles were applied daily to the test circuits (main and mirror) to simulate significant load conditions to which the MV cables can be subjected during their life.

Periodically, the main ring was disconnected, and the global conditions of each single cable were tested by means of PD, FDS and Tanδ measurements using commercial instruments. Table 1 reports the reference name of the sub-set of thermal cycles after which the cables were individually tested, as well as the progressive number of the thermal cycles and the number of thermal cycles between two consecutive measurement sessions.

**Table 1.** Reference Period Name and relevant Thermal Cycles

| Period Name | Number of Thermal Cycles | Number of Thermal Cycles per Period |
|---|---|---|
| T0 | 0 | 0 |
| T1 | 42 | 42 |
| T2 | 88 | 46 |
| T3 | 144 | 56 |
| T4 | 208 | 64 |
| T5 | 301 | 93 |
| T6 | 349 | 48 |
| T7 | 435 | 86 |
| T8 | 548 | 113 |
| T9 | 644 | 96 |
| T10 | 828 | 184 |

The calibration signals were injected into different positions of the circuit to evaluate amplitude reductions and changes in resonant peaks, as a consequence to the different positions of the injection points, [3]. Also, during the application of thermal cycling, PD pulses triggered in a defect in a given cable were detected by HFCTs connected with other cables in the ring. This interference can affect the accuracy of fault identification and its location in a specific cable. By measuring the attenuation of the signal and the distortion of the signals injected into different parts of the circuit, a threshold level was determined to establish whether the detected signal was produced by a defect in a cable section other than the one measured.

In particular the attention was given to the PD tests performed on two homogeneous XLPE cable joints with aluminium conductors. The two joints, named A and B, come from two different manufacturers.

After few cycles, discharges appeared on Cable A, then several PD patterns appeared up to the maximum temperature and during the cooling phase. The analysis of the shape of the PD patterns clearly addresses the formation of a void whose typical pattern is clearly visible in Figure 5.

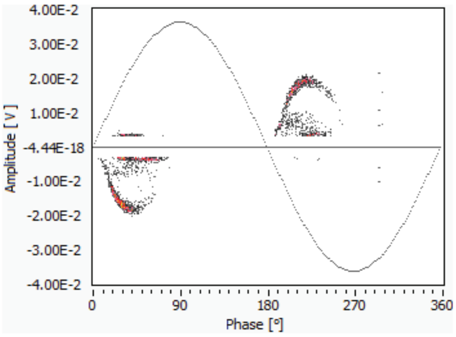


**Figure 5.** PD pattern recorded on Cable A

On cable B, the discharges appeared after about 140 thermal cycles, but their amplitude was so small that it was confused with background noise. Also in this case, the rounded and symmetrical models suggest void defects.

During the off-line PD test, discharges were noted on both cables only after some hundreds thermal cycles at nominal test voltage (U0). The PRPD model showing the highest discharges and repetition rate are shown in Figure 6,

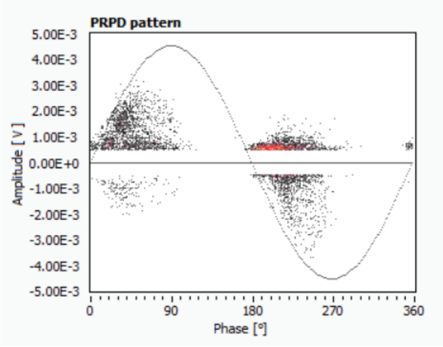


**Figure 6.** PRPD pattern recorded on Cable A at U0

Figure 7 summarizes the comparison between on-line and off-line PD measurements during the phases of inceptions of PD activities, showing a much earlier detection of signals by on-line systems (off-line measurements at U0 were possible only after 350 cycles and with a non clear identification of the defect typology).

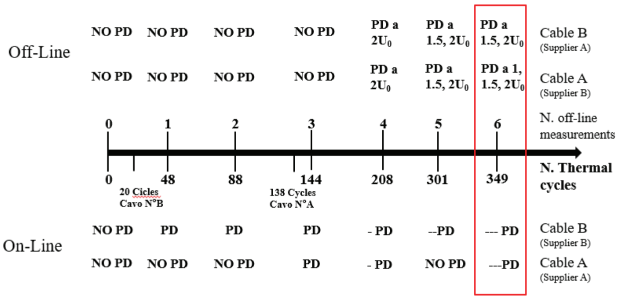


**Figure 7.** Comparison between on-line and off-line PD measurements.

FDS measurements were carried in the range from 0.001Hz to 5kHz, and Tanδ measurements at 50Hz with a voltage from 0.5 to 2.0 the nominal voltage.

The measurements were carried out according to the Periods reported in Table 1. All the joints were initially characterized at T0 (see Figure 8).

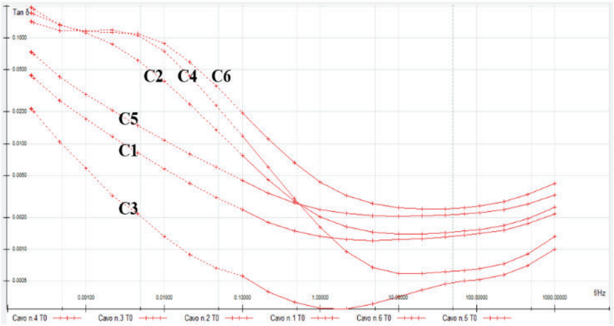


**Figure 8.** Initial FDS characterization at T0.

The U-shaped curves are from manufacturer A and the S shaped curves are from manufacturer B; shapes that will be maintained during all the measuring periods as shown in Figure 9.

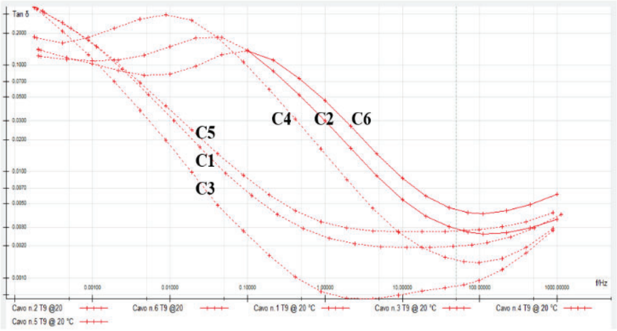


**Figure 9.** FDS characterization after 9 periods

By comparing Figures 8 and 9, FDS curves shift in the right direction, indicating a progressive ageing. Always from Figure 9, joints coming from manufacturer B show more power losses than those from manufacturer A.

After about 280 cycles, significant variations were recorded during the heating phase of the homogeneous joint in XLPE A: the slope of the curve increased reaching higher temperatures at the end of the heating period. Comparisons were also made between the same type of joint in the test ring and mirror ring (without voltage): temperature differences up to 15°C were detected in the presence of the same current, thus confirming the importance of voltage losses; in particular the phenomenon increased in the presence of temperatures above about 55°C.

To examine this sudden change in temperature behavior, FDS measurements were carried out at high temperature during the cooling phase of the cycle (without current) putting in evidence an increase of Tanδ values by an order of magnitude at all frequencies (same measurements were carried out on the samples from manufacturer B showing much lower values).

## Circuit reproducing wet conditions

After setting up the new circuit, initial characterization of the joints in dry and wet conditions were carried out.

The dry measurements confirmed the presence of PD activities on those joints coming from the circuit with felts, and some activities were registered also on the new ones assembled (Figure 10).

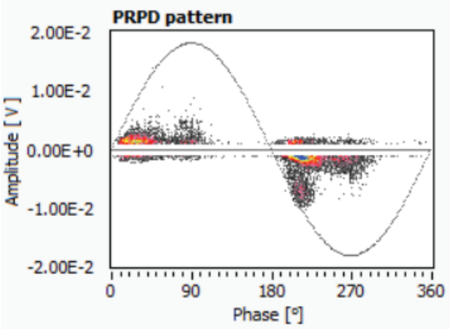


**Figure 10.** PRPD pattern recorded on Cable 10 at 1.5 U0: (initial characterization) in dry conditions.

FDS measurements were also carried out. From Figure 11, for Cable 2 (one from previous ageing), the initial measurements (at T0) in dry and wet conditions are perfectly superimposable, but after some cycles (T1) the Tanδ curve increases its values. This deviation is probably the consequence of the fact that the soil has been humidified and the barriers to water penetration have degraded because of the thermal and mechanical stresses introduced with the previous ageing period.

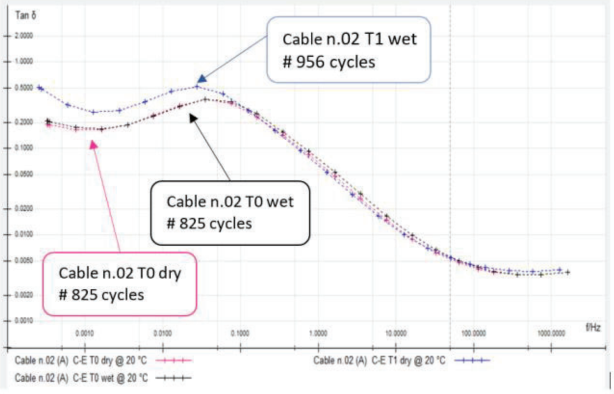


**Figure 11.** FDS measurements carried out on Cable N2 (old one), at T0 dry & wet and T1 wet.

Similar phenomena occurred also to the two new cable joints (9 & 10) of the same type of Cable 2 (mixed XLPE-oil/paper). Figure 12 reports, for example, the measurements on Cable 10. In these two cases the ingress of water was not due to ageing from high temperatures (in the new setup the temperature never exceeded 50°C), but to a probably bad assembly of the joints, after the initial settling period. This problem eventually led to discharges in both the new joints (9 & 10) after about 240 and 250 cycles respectively (Figure 13).

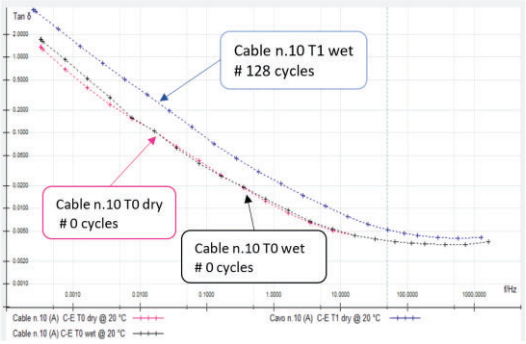


**Figure 12.** FDS measurements carried out in wet conditions on joints N°10 at T0 dry, T0 wet e T1 wet.

a) b)

**Figure 13.** a) Discharge that has "wrapped" on the cable starting from the conductor and arriving at the screen; b) signs of discharge inside the main insulating body.

## DISCUSSION AND CONCLUSION

On the set-up reproducing dry conditions, PD were detected starting after the 20th and 140th cycles for manufacturer A and B respectively, while off-line PD were recorded respectively only after about 200 and 300 cycles and at voltages higher than U0. After 280 cycles, PD showed a progressive attenuation, differently from off-line PD tests that showed an increasing of activity proving that the defects on both cables were still active.

A possible explanation could concern the expansion / shrinkage of the different materials mainly inside the cable joint. During the initial period, voids are formed during the thermal expansion of materials and disappear due to the shrinkage of the material. When the defects are well formed, thermal expansion tends to reduce their size thus reducing the spaces where PD can occur. Therefore, the presence of the defect can only be assessed with off-line tests (also performed at higher voltages).

As regards the FDS measurements, it was possible to establish a correlation between the sensitive variation of this parameter during aging with the temperature variation, which led, in some cases to a further joint temperature increase, in addition to that caused by the current load.

Based on the above results, the aging mechanism associated with temperature in dry conditions can be connected to PD phenomena due to voids and delamination induced by thermal stresses; this phenomenon is also enhanced by the increase in dissipation factor, which gives rise to a further temperature increase, accelerating the aging process.

When considering wet conditions, FDS measurements allowed to put into evidence the degradation of the water barriers of the old joints due to ageing cycles at increasing temperatures and of the new ones, due to a bad assembly of the joints. The cycle tests are continuing, and the two joints will be replaced with others of a similar type.

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