Laboratory Ageing Thermal Cycles of MV Cable Joints: results of different diagnostic techniques

Johnny Borghetto
T&D Technologies Dept.
Ricerca sul Sistema Energetico – RSE S.p.A.
Milan, Italy
Johnny.Borghetto@rse-web.iti

Alfredo Contin
Engineering and Architecture Dept.
University of Trieste
Trieste, Italy
contin@units.it

Andrea Morotti
Power Grid Planning
Unareti S.p.A.
Milan, Italy
andrea.morotti@unareti.it

Andrea Pegoiani
Maintenance Engineering
Unareti S.p.A.
Milan, Italy
andrea.pegoiani@unareti.it

Giovanni Pirovano
T&D Technologies Dept.
Ricerca sul Sistema Energetico – RSE S.p.A.
Milan, Italy
giovanni.pirovano@rse-web.it

Danilo Sirtori
Maintenance Engineering
Unareti S.p.A.
Milan, Italy
danilo.sirtori@unareti.it

Carlo Tornelli
T&D Technologies Dept.
Ricerca sul Sistema Energetico – RSE S.p.A.
Milan, Italy
carlo.tornelli@rse-web.it

***Abstract*— The article reports the results of a multi-year experimentation in progress at the RSE laboratories and aimed at an in-depth diagnostic analysis of the causes of failure responsible for the out-of-services which affect MV cable joints of most of the urban network in the summer periods. To this aim an experimental set-up consisting of twelve cables equipped with different types of joints were connected together to form a ring in short-circuit. The ring was energized at rated voltage and current cycles were applied by means of external coils in order to reproduce the daily load variation typical of a MV cable network. Felts were wrapped around the cables to simulate the reduced thermal conductivity of the soil during summer periods. Continuous monitoring of the degradation of the joints was carried out by Partial Discharge (PD, on-line and off-line) measurements, together with Frequency Dielectric Spectroscopy (FDS) and Dissipation Factor (DF) - measurements. Results of the experimentation are presented and discussed.**

Keywords*— *MV Cables, Cable Joints, Power Losses, Ageing Cycles, Partial Discharges, Frequency Dielectric Spectroscopy, Dissipation Factor, Diagnostics.

I. Introduction

In recent years we are assisting to an increase of out-of-services which affect underground MV distribution networks, in particular in urban areas, during the summer periods. In the great majority of the cases the observed outages are due to the failure of the connection joints between the underground cables, put in service especially for the replacement of sections of old oil/paper cables with new extruded ones,

The reasons of the increase in the failure rate in the summer periods can be ascribed to a combination of high ambient temperature and high cable load, for cooling necessities, which can cause the further drying of the soil around the cable with the consequent reduction of the relevant thermal conductivity that can lead to the overheating of the joints [3][9][11] and thus to their premature ageing.

Purpose of the paper is to describe the experimental set-up and the results of the different diagnostic techniques (PD, FDS and DF measurements) implemented to evaluate the performances of the different types of cable joints under simulated in-service condition. At this regard twelve cables equipped with different types of joints were connected together to form a ring in short-circuit. The ring was energized at rated voltage and current cycles were applied by means of external openable core transformers in order to reproduce the daily load variation typical of a MV cable network. Felts were also wrapped around the cables to simulate the reduced thermal conductivity of the soil during summer periods. The temperature was measured by thermocouples installed on the cables and joint surfaces.

PD were recorded every ten minutes h24 during the ageing cycles by means of inductive couplers installed on the ground connection of the cable shields. Periodically, the cable ring was disconnected and each cable was tested separately at different voltage levels, during cooling and at room temperature and using the mentioned different diagnostic techniques.

The experimental results shown that the formation of defects in XLPE cables where detected earlier during on-line PD monitoring while off-line PD were detected only after a significant number of thermal cycles [1][2]. FDS allowed to measure the complex permittivity and the dissipation factor as a function of frequency for each cable, putting into evidence the variation of these parameters during ageing with the temperature; variation that led, in some cases, to a further increase of the joint temperature, in addition to that caused by the current load, thus accelerating the ageing process.

II. Experimental set-up

A main ring consisting of twelve cables (of two different manufacturers A and B, six new and six from the service) of about ten meters length, equipped with different types of joints in their middle (2 XLPE-XLPE, 2 Oil/Paper, 8 mixed

XLPE-oil/paper), connected together to form a ring in short circuit was set up. All the cables have the same ratings of voltage U_0 (23kV/$\sqrt{3}$=13.3kV) and current (275A).

Cycles of temperature from the ambient to the rated temperature, have been applied to induce accelerated ageing (and possibly defects) due to thermo-mechanical stresses, inducing current in the ring by means of heating toroidal transformers. The temperature was measured using thermocouples installed on the joint and cable surfaces, Figure 1a. A mirror-ring, composed by new XLPE and oil/paper cables, also equipped with new joints and with the same ratings, has been prepared. In this mirror-ring, the same current of the main ring was induced, but in the absence of the voltage supply. In the mirror-ring, temperature sensors were also installed on the joint and cable surfaces, but inside the joint Figure 1b, close to the conductor, to measure the radial temperature differences, thus allowing a more accurate estimation of the real temperature of the conductors of the main ring (and the effect of voltage in the ageing process).

a)

b)

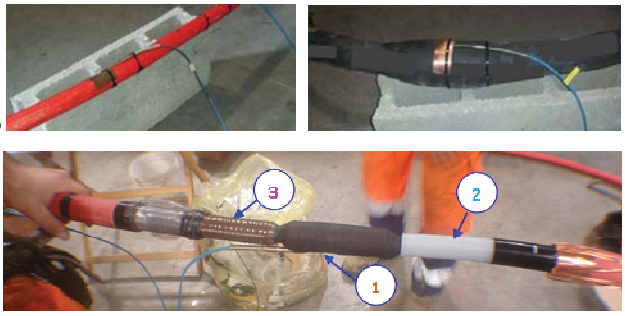


Figure 1 - View of the points of installation of the thermocouples outside the cable and the joints (mirror and main rings) a), and inside the joints (mirror ring) b).

Both rings were covered with felts to simulate the underground conditions during dry and hot periods, Figure 2. At this regard it should be noted that no humidity were simulated and that the six new joints were realized under the controlled laboratory environment (thus they should be free from assembling defects), in order to check if degradations were also possible under these conditions [12].

Cycles of temperature of the duration of one day were applied to both cable rings (about 11 hours of heating and 13 hours cooling)

Figure 2 - Experimental set-up: view of the mirror ring and the part of the main ring with the six new joints (the other six from service are on the right part of the circuit and not visible in the picture).

The formation of defects and their evolution under the thermo-electrical stresses has been monitored by means of PD measurements performed according to [4] HF inductive couplers (HFCT) with a flat response up to 80 MHz, have been installed in the cable-shield termination connected to the ground. The twelve HFCT have been connected with a PDmonitor system that allows the simultaneous acquisition of PDsignals in twelve separated input channels, every ten minutes during the thermal cycles. PD tests were also performed at different voltage levels on each separated cable by using a capacitive coupler of 2nF, before and after the application of the cycles of temperature to evaluate separately the insulation conditions of each cable of the ring and validate the PD-monitoring results. The insulation conditions were inferred analyzing the Phase Resolved PD (PRPD) patterns on the basis of the assumption that the different PD sources (different defects typologies) can be associated to well-defined PRPD shapes. A Time-Frequency map has been used to separate mixed PRPD patterns in sub-patterns each one relevant to a specific noise or PD source (defect), [5]. Standard quantities defined in [6], were used to quantify the PD activity.

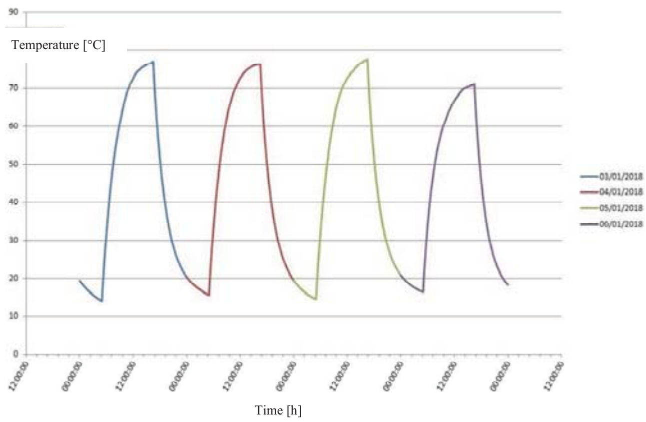


Figure 3 - View of four 24 hours cycles test.

III. RESULTS OF LABORATORY PD TESTS

Problems related to calibration of the system in [pC] and signal interference between different cables in the ring, were preliminary examined to obtain more accurate PD test results [1].

Calibration signals were injected in different positions of the circuit, and amplitude reductions and modifications of the resonant peaks, due to the different location of the injection points, were assessed, thus demonstrating that the use of the discharge amplitude threshold levels (in [pC] or [mV]) to analyze PD-test results, may induce significant errors. In order to overcome the problem the shape analysis of the PRPD patterns, as suggested in [4], were adopted in this work.

Moreover during the application of thermal cycles, PD pulses incepted in a defect of a given cable can be detected by HFCT connected with other cables of the ring. This type of interference can modify in an unpredictable way the shape of PRPD patterns thus affecting the accuracy of the defect identification and its location in a specific cable. By the measurement of the signal attenuation Figure 4 and distortion of injected signals in different part of the circuit, due to the different dynamic characteristics of the cables (mainly related to impedance mismatching at the cable terminals and joints), a threshold level was determined in order to establish if the detected signal was produce by a defect in a cable section different from the one under measurement.

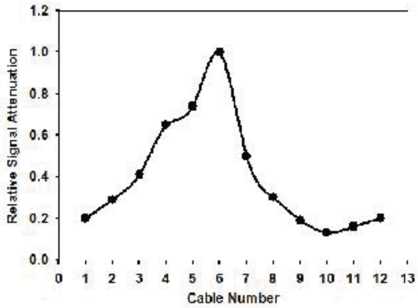


Figure 4 - Behaviour of the relative attenuation of the calibrated signal as a function of the cable position within the ring when a calibrated signal is injected at the terminal of Cable N.6.

The attention is in particular was given to the PD tests performed on two homogeneous XLPE cables having stranded aluminum conductors with a cross section of 185 mm^2. The two joints, named A and B, come from two different providers.

After 20 cycles, the first discharges appeared at 78°C on Cable A, then different PD patterns were recorded up to the maximum temperature of 84°C and during the cooling period Figure 5. The shape analysis of the PD patterns clearly addresses to the formation of a void whose typical pattern is clearly visible particularly in Figure 6A (82°C). This PD pattern was rapidly modified as the temperature increased Figure 6B, 84°C, as an indication of the recent formation of the defect.

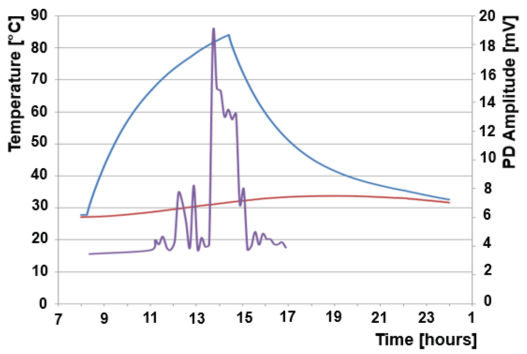
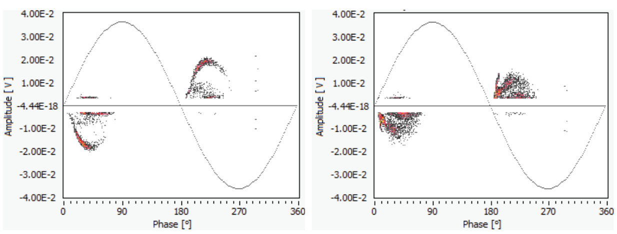


Figure 5 - Behaviour of room (red line) and conductor (blu line) temperature with the Vmax (purple line) recorded on Cable A during the 21th thermal cycle.



A B

Figure 6 - PD pattern recorded on Cable A (XLPE joint) during the 21th thermal Cycle at different temperatures: A) 82°C, B) 84°**C.**

After 30 thermal cycles, the cable ring was disconnected and each cable has been tested separately at different voltage levels. The shape analysis of the recorded PD patterns confirmed the presence of void defect on the cable.

On Cable B, discharges appeared probably around the 138th thermal cycle, but their amplitude was so small to be confused with the background noise. Again, the rounded and symmetrical patterns address to a void defect.

Once discharges were incepted in both cables, the PD activity continued during a significant number of thermal cycles showing a very low signal amplitude (below 1-3 mV) and a rounded and symmetrical PRPD patterns.

Always with an apparent random behaviour, bursts of pulses having higher PD, incepted and disappeared during the thermal cycles. Sometime these bursts incept during the cooling period and continued until a new heating period started. Figure 7 shows the profile of temperatures and the PD activities recorded during the 28th thermal cycle as an example.

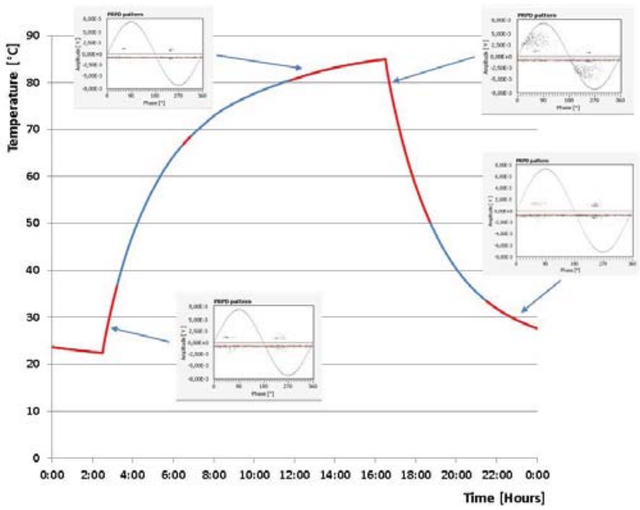
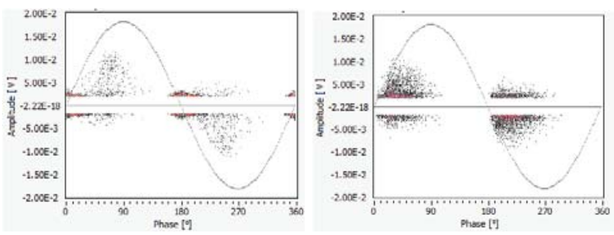


Figure 7 - Behaviour of conductor (blue line) temperature with the PD activity (purple line) recorded on Cable A during the 28th thermal cycle.

Examples of PRPD patterns recorded during the 28th cycle are reported in Figure 8. Sometime, bursts of higher discharges appear during the heating and disappear during the cooling of the cable.
A possible explanation of this behaviour could come from the different dilatation/retirement of the different materials within the cable joint.



A B

Figure 8 **-** PD patterns recorded on Cable A during the 28th thermal Cycle at different temperatures: A) 33°C, B) 56°C.

Continuing with the cycles it is noted that the PD activity with greater amplitude occurs during the cooling phases while during the heating phase its activity is of amplitude slightly higher than the background noise, Figure 9.

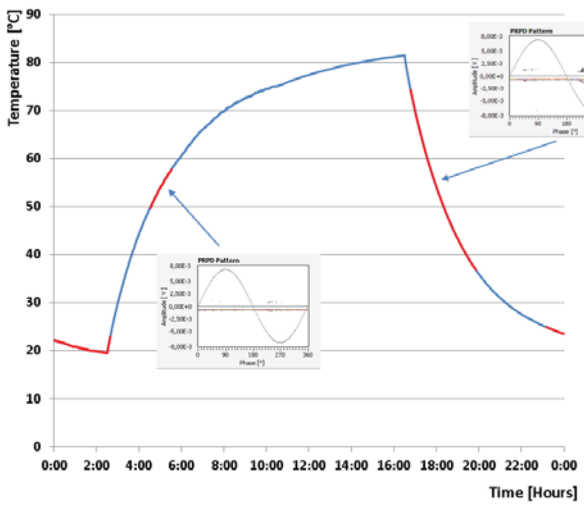


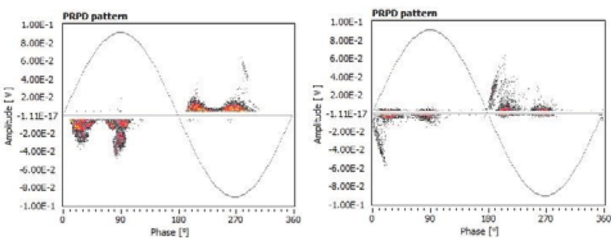
Figure 9 - Behaviour of conductor (blue line) temperature with the PD activity (purple line) recorded on Cable A after the 28th thermal cycle.

Progressively, both the bursts of higher discharges and the continuous smaller PD, tend to decrease both in amplitude and repetition rate.

During the 298th cycle, PD were recorded on Cable A only in the range of temperatures of 46°C and 51°C. Before and after this range, the PD monitoring system detected only background noise. On Cable B, no PD were recorded during the whole cycle.

After other 51 cycles, the extinction in both cables is almost completed. PD profiles recorded in both cables during the whole 349th cycle, show only few spots of discharges. PRPD patterns recorded during these spots are still rounded and symmetric in polarity. The experiment is still running and discharge activity is continuing with these characteristics.

During off-line PD test discharges were recorded on both cables only after the 208th thermal cycle at the highest test voltage (2U0). The PRPD patterns showing the higher discharges and repetition rate are reported in Figure 10 as examples. In particular, Figure 10A is relevant to test performed on Cable A at 2U0, after 349 thermal cycles while Figure 10B shows the PRPD pattern recorded on Cable B at 1.5 U0 after 301 cycles. The irregular shapes of these two patterns, similar to those recorded at different voltage levels, do not allow a clear identification of the defect typology that affect the two cables.



A B

Figure 10 - PRPD patterns recorded on: A) Cable A after 349 thermal cycles at 2 U0; B) Cable B after 301 thermal cycles, at 1.5 U0.

IV. Results of Laboratory FDS and DF Tests

In addition to PD measurements, FDS and DF measurements were carried out off-line (on line measurements are not allowed with these techniques); TABLE 1 reports the measurement periods from T0 to T9 with Number of Thermal Cycles per Period.

In particular FDS measurements were carried out by DIRANA® system (by Omicron GmbH) in the range from 0.001Hz to 5kHz, and DF measurements at 50 Hz with a voltage from 0.5 to 2.0 the nominal voltage, using an OMICRON MI600 (also by Omicron GmbH).

TABLE 1
Reference of 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**

After about 280 cycles, significant variation were registered during the heating phase of XLPE homogenous joint A: the steepness of the curve increased thus reaching higher temperatures at the end of the heating period, Figure 11. Comparisons were also made between the same joint type in the test ring and in the mirror ring (without voltage), differences up to 15°C were observed in presence of the same current of 285A, thus confirming the importance of voltage losses to the temperature variation; in particular it was assessed that the phenomenon was increased in presence of temperature above about 55°C.

In order to avoid exceeding too much the maximum temperature allowed for the joints, it was decided to shorten the heating time. This at the aim to avoid a probable discharge due to too high temperatures (a condition not allowed for laboratory requirements).

In order to investigate this sudden change in the temperature behavior, FDS measurements were also carried out at high temperature during the cooling phase of the cycle (without the presence of current).

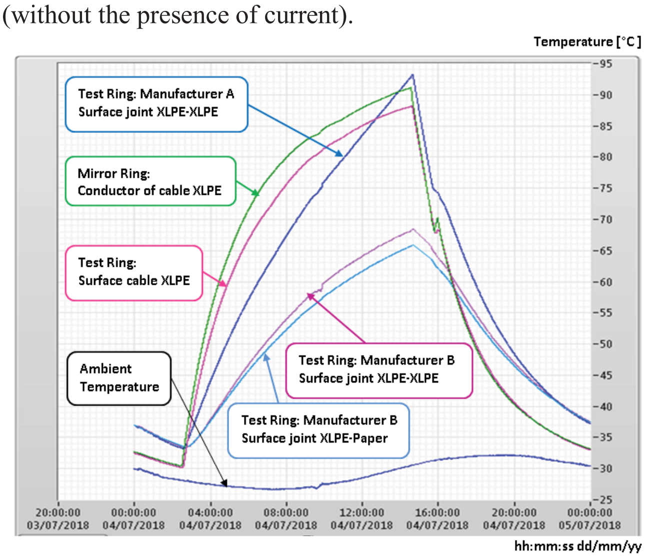
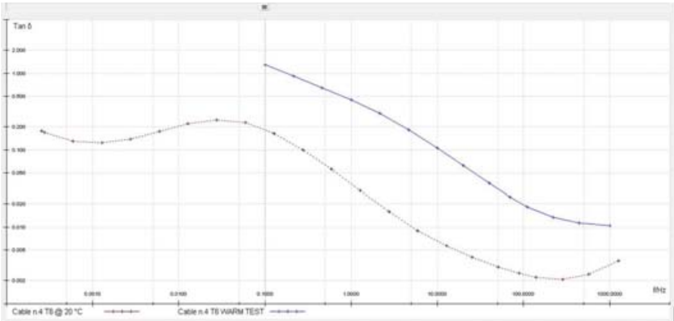


Figure 11 – Increase of the steepness of the temperature curve of XLPE homogenous joint A.

Figure 12 reports the Tanδ behaviour of the joint at 20°C and at 70°C; as it is possible to see the dissipation factor increased by an order of magnitude at all frequencies (similar measurements were carried out on the same joint type, but from manufacturer B, and Tanδ behaviour showed much lower values).



Measurement	Frequency	Tan δ	Capacitance (C)	Resistance (R)	Impedance (Z)	Power Factor
Cable n.4 T6 @ 20 °C	100 mHz	0.181926	2.3591 nF	3.708 GΩ	663.76 MΩ	0.178989
Cable n.4 T6 WARM TEST	100 mHz	1.295628	4.0759 nF	301.384 MΩ	238.584 MΩ	0.791630

Figure 12 – Tanδ behaviour of the XLPE joint at 20°C and at 70°C.

Figure 13 shows the daily aging cycle applied to the reel after the deterioration has started. The cycle provides to simulate a variable daily load by applying a constant voltage of $1.2U_0$.

The deterioration phenomenon occurred mainly on the kits of manufacturer A and involved at first the homogeneous joints in extrusion, then the mixed ones and finally in the homogeneous joints with paper insulation (Figure 14).

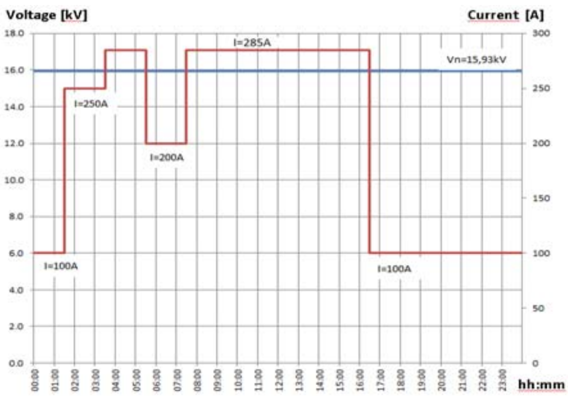


Figure 13 – Daily aging cycle applied

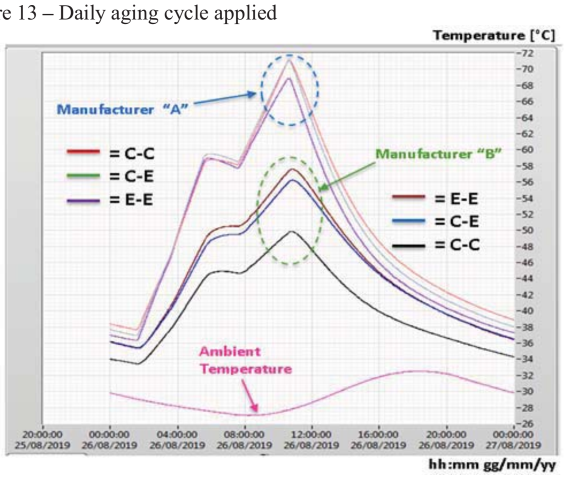


Figure 14 – Joints temperatures after more than 280 cycles

This situation was also reflected by the FDS measurements carried out all along the period on all joints at ambient temperature. In particular with reference to one joint under examination an extracted of the curves is reported in Figure 15. Here it is evident that another important phenomenon occurred in addition to what occurred from T0 to T1. Then from T6 to T9 the behaviour of Tanδ with frequencies stabilized.

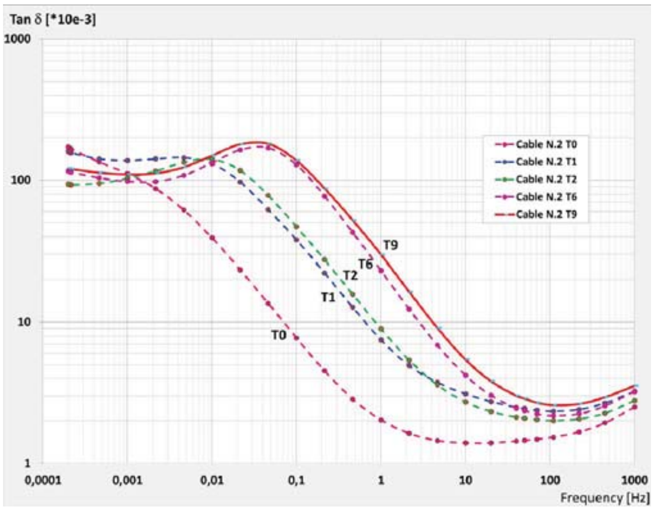


Figure 15 – FDS behaviour of the joint from 0 to 644 cycles .

On the contrary the only Tanδ measurements carried out at 50 Hz throughout the testing period at ambient temperature didn't show any particular variation for all the type and for both the manufacturers, Figure 16.

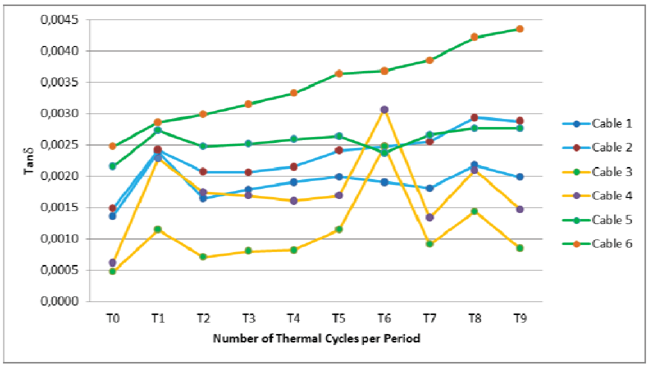


Figure 16 - Tanδ measurements at 50Hz for the six new joints.

Also Tanδ measurements carried out at different voltages didn't show any particular evidence of ageing phenomena, showing a non-regular behaviour especially on XLPE cables.

V. Discussion and Conclusions

In simulated on-line conditions, PD were recorded with a clear pattern on Cable A and Cable B after 21 and 138 thermal cycles while off-line PD were detected only after the 208th and 301st cycles (Cables A and B, respectively) with a delay of 187 and 163 cycles. Starting from the 280th cycle, PD monitoring shows a progressive attenuation of both the smaller and the higher discharges. On the contrary, the last two off-line PD tests show a significant activity of the discharges thus indicating that the defects on both cables are still active.

One possible explanation could concern the dilatation/retirement of the different materials mainly within the cable joint. During the initial period, voids are formed during the thermal dilatation of the materials and disappear due to material retirement. When the defects are well formed, the thermal dilatation tends to reduce their sizes thus reducing the spaces where PD can occur. Thus, the presence of the defect can be detected only with off-line tests (carried out also at higher voltages).

As regard Tanδ measurements, it was possible to put into direct correlation the sensible variation of some joints of this parameter during ageing with the temperature variation, that led, in some cases and after about 280 cycles, to a further increase of the joint temperature, in addition to that caused by the current load.

These results clearly suggest that the systematic use of FDS in condition assessment of underground cables can provide more information on the ageing progression with respect of the traditional DF measurements.

On the base of the above results the ageing mechanism of joints with temperature can be linked to PD phenomena due to voids and delamination induced by thermal stresses (even in presence of correct in field assembling), enhanced by dissipation factor increases, that in turn augmented the joint temperature, thus accelerating the ageing process.

ACKNOWLEDGMENT

The Authors wish to thanks the personnel of Unareti for their support in preparation of the cables joints and M. Airoldi, S. Chiarello, M. Garotta and D. Ionata, of RSE for their technical support.

This work has been financed by the Research Fund for the Italian Electrical System in compliance with the Decree of Minister of Economic Development April 16, 2018.

REFERENCES

[1] J. Borghetto, G. Pirovano, C. Tornelli, A. Contin, "Test Set-Up and Preliminary Results of PD Measurements Performed During Thermal Cycles Applied to Different Types of MV Cable Joints", Proc.IEEE 2018 Electrical Insulation Conference, pp.558-561, San Antonio (USA), 2018.

[2] J. Borghetto, G. Pirovano, C. Tornelli, A. Contin, "Off-line and Simulated On-line PD Tests on Thermally Aged MV Cable Joints ", Proc.IEEE 2019 Electrical Insulation Conference, Calgary, Alberta, Canada, 2019

[3] R. Bonanno, M. Lacavalla, "Feasibility analysis aimed at defining an alert system for Distribution MV Underground Cables", AEIT 2020, International Annual Conference, 1st Virtual Edition - 23-25 September 2020.

[4] IEEE Guide for Partial Discharge Testing of Shielded Power Cable System in a Field Environment, IEEE Std.400.3-2006.

[5] A.Contin, G.C.Montanari, A.Cavallini, F.Puletti, "A New Approach to the Diagnosis of Solid Insulation Systems Based on PD Signal Inference", IEEE Electrical Insulation Magazine, Vol.19, N.2, pp.23-30, March/April 2003.

[6] IEC 60270, Partial Discharge Measurements, March 2001.

[7] J. Borghetto, M. Garotta, S. Chiarello, «Diagnostica dei cavi interrati di media tensione: risultati della prima parte della sperimentazione e nuovo setup di prova» *Ricerca di Sistema, RSE,* n. 19012954, Milano, 2019

[8] J. Borghetto, M. Garotta, S. Chiarello, « Valutazione in laboratorio di effetti di invecchiamento di linee in cavo MT» *Ricerca di Sistema, RSE,* n. 18007580, Milano, 2018

[9] S. Meregalli, S. Belvedere e S. Chiarello, «Capacità di carico di cavi interrati in funzione delle condizioni ambientali e di posa: risultati da installazione sperimentale,» *Ricerca di Sistema, ERSE,* n. 09004920, Milano, 2009.

[10] M. Rebolini, M. Sforna, A. Freddo, G. Pirovano, M. Lacavalla, P. Marcacci, «Influenza dei Cambiamenti Climatici nella gestione del sistema elettrico – La mitigazione degli Effetti» - *AEIT n.6 - Energia Elettrica e Clima*, June 2015.

[11] G. Pirovano, "Le nuove tecniche di monitoraggio della rete elettrica interrata possono ridurre i cantieri su strada", *Il Giornale dell´Ingegnere* n. 1 - January 2014.

[12] L. Calcara, L. D'orazio, M. Della Corte, G. Di Filippo, A. Pastore, D. Ricci, M. Pompili, "Faults Evaluation of MV Underground Cable Joints", Intenational Annual Conference AEIT, Firenze (Italy), 2019.