Analysis of MV Cable Joints Equivalent Impedance and its Variation vs. Temperature

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Abstract – **This paper presents a mathematical study along with the first preliminary results to correlate the equivalent impedance of a medium voltage cable-joint to its Tangent Delta value (i.e. its Dissipation Factor value). The failures of cable joints are a broad and current topic which is being investigated inside the electric engineering community. In the paper the results of both the study carried out to determine correlation between the joint impedance and its Tangent Delta value and the variation of this last one vs. temperature are presented.**

Keywords – **tangent delta, cable joints, measurement system, temperature, impedance measurement, XLPE, EPR**

I. INTRODUCTION

Underground Medium Voltage (MV) cable spread among power networks is increasing every day for supplying critical areas such as crowded urban areas. Hence, their implementation results in a massive use of terminations and cable-joints either for new installation or for replacement purposes. These two accessories are the weakest in the underground cable power networks, thus they require special precautions when tackled. The terminations are much easier for maintenance as they are accessible at the end of the lines. However, they are subjected to several studies to improve their reliability [1, 2]. The cable-joints instead are critical for both fault location and maintenance as they are buried under ground. Moreover, their failure during heat waves in summer attracts attentions for cable-joint analysis to explore the effect of influence quantities which may lead to failure.

To this purpose, different monitoring systems have been developed in the literature to predict cable-joint faults and to establish their ageing level. Measured quantities varies from the environmental one (temperature, humidity, pressure, etc.) [3, 4] to the electrical ones (voltage, current, partial discharges, etc.) [5, 6]. Alternatively, in some cases both kind of measurements are implemented [7].

Monitoring systems may highlight the most critical parameters that affect the cable-joint life [8, 9]. Among them, cable-joint Tan Delta (which is known also as Tanδ and Dissipation Factor) is one of the most effective, and difficult to measure, diagnostic method for cable-joints insulation property analysis.

In literature, different studies can be found for Tanδ analysis on insulating materials (and not on the cable-joint system), such as silicon rubber which is the most used material for cable-joints manufacturing. Temperature, frequency, and voltage level are three influent quantities which are typically considered. In [10] the effect of voltage level on Tanδ of insulating materials has been studied, whereas in [11] Tanδ variation has been observed when frequency is variating. For polymeric insulating material such as silicon rubber, Tanδ versus temperature has been studied in [12].

Abovementioned studies are done on insulating materials in shape of specimen which fits between electrodes of typical measurement instrument (in cubic shape or thin layers), whereas cable-joints are completely different systems. In particular, when we consider a cable-joint it means that we are studying a complex system composed by several layers of different materials. Moreover, it is installed on portion of cables, which have their own insulating layers, resulting in a further increase of the system complexity. Most of studies on cable-joints are focused on material used in them like in [13]. In [14], Tanδ of cable joints is measured applying different frequencies without any analysis of its variation. A setup has been designed, calibrated and implemented for measuring Tanδ under 1 kV AC voltage and 50 Hz frequency in [15]. In [16] the setup has been improved to measure Tanδ in a wide temperature range (5 to 60) °C. In this paper such a setup is used for measuring Tanδ and the impedance of three cable-joint samples at temperatures of 5 °C, 24 °C and 60 °C. Moreover, equivalent resistance and capacitance of the cable-joints are calculated explicitly. Hence, by using the series (and then the parallel) model of the cable-joint under test (CUT), some conclusions about
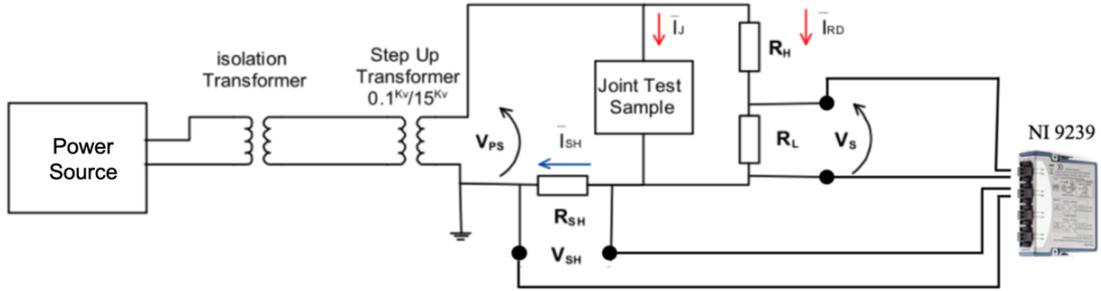
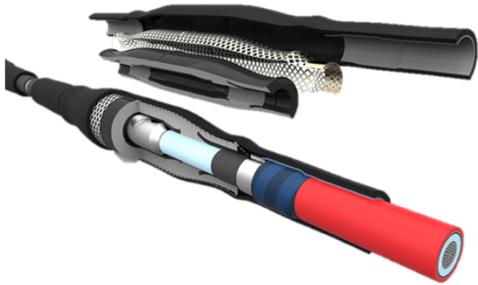*Fig. 1. Automatic measurement setup for the Tanδ Measurement*

Fig. 2. Schematic description of the layers of a cable-joint

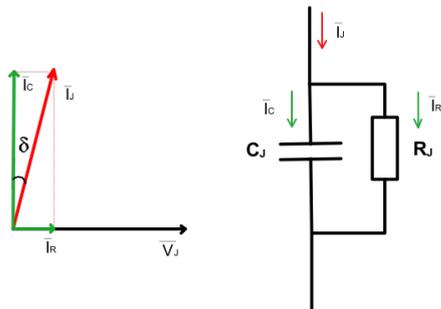*Fig. 3. Parallel equivalent model of the cable joint and correlation with Tanδ*

the mechanical structure of the cable-joints and Tanδ vs. temperature relationship can be drawn.

The paper consists of the following Sections. In Section II the Tanδ measurement setup is briefly recalled and described. Experimental tests are described in Section III, while the mathematic computation of the CUTs impedance is presented in Section IV. Experimental results are listed and commented in Section V, whereas some conclusions are drawn in Section VI.

II.   TAN DELTA MEASUREMENT SETUP

To measure Tanδ, the setup presented in [16] has been used and recalled in Fig. 1. It includes a programmable

power source Agilent 6813B, an isolation transformer, a step-up voltage transformer (0.1 kV/15 kV), a resistive voltage divider, a shunt resistor, a Data Acquisition Board NI9239 (DAq) and a personal computer. The setup allows to measure Tanδ with an accuracy up to 10^{-5} starting from the voltage and current measurements on the CUT.

Three cable-joints, referred as *A*, *B* and *C* for the sake of privacy, insulated with silicone rubber, connect two pieces of 0.5 m cables. A picture detailing a typical cable-joint structure is shown in Fig. 2. *A* is made from a manufacturer and it was installed in-field before its removal for performing tests. This in-field cable-joint has been chosen to perform test on an actual cable-joint. It connects two portions of cables insulated by EPR. As for *B* and *C*, they are made from another manufacturer and installed on XLPE insulated cables. The installation of these two cable-joints has been done in a laboratory environment.

III.   EXPERIMENTAL TESTS

A. Temperature Tests

A thermal chamber is used for measuring Tanδ and impedance of the CUT at 5 °C, 24 °C and 60 °C. When the temperature is set, the samples are placed in the chamber for 24 hours to ensure a thermal stability. Once steady-state conditions have been reached, 1000 measurements of Tanδ and impedance have been performed. Such a procedure has been replicated for the 3 temperature of interest.

B. Impedance Computation

In this subsection is detailed how the impedance has been computed by starting from the acquired measurements.

In [16] Tanδ was computed by knowing the voltage and the current of the CUT, $\bar{V}_J$ and $\bar{I}_J$, respectively. In this work instead, the Tanδ is used as a known parameter to compute the impedance of the CUT.

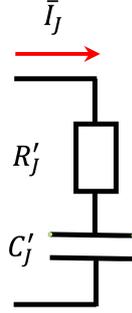First of all, Tanδ can be defined from the well-known parallel model of a cable-joint [17], as shown in Fig. 3:

$$\bar{I}_J$$

$$R'_J$$

$$C'_J$$

Fig. 4. Series equivalent model of the cable joint

TABLE I. *TanδvsTemperature Measurement Results*

CUT	5 °C		24 °C		60 °C	
	$Tanδ$ [-]	$\sigma_{Tanδ}$ [-]	$Tanδ$ [-]	$\sigma_{Tanδ}$ [-]	$Tanδ$ [-]	$\sigma_{Tanδ}$ [-]
A	0.03563	$5 \cdot 10^{-5}$	0.01853	$1 \cdot 10^{-5}$	0.01370	$1 \cdot 10^{-5}$
B	0.05420	$6 \cdot 10^{-5}$	0.043009	$6 \cdot 10^{-6}$	0.003068	$8 \cdot 10^{-6}$
C	0.04663	$6 \cdot 10^{-5}$	0.02043	$1 \cdot 10^{-5}$	0.00520	$1 \cdot 10^{-5}$

TABLE II. *Impedance Measurement results*

CUT	5 °C		24 °C		60 °C	
	$|\bar{Z}|$ [MΩ]	$\sigma_{|\bar{Z}|}$ [MΩ]	$|\bar{Z}|$ [MΩ]	$\sigma_{|\bar{Z}|}$ [MΩ]	$|\bar{Z}|$ [MΩ]	$\sigma_{|\bar{Z}|}$ [MΩ]
A	15.0175	$6 \cdot 10^{-4}$	15.3392	$2 \cdot 10^{-4}$	15.8612	$3 \cdot 10^{-4}$
B	9.2752	$2 \cdot 10^{-4}$	9.6064	$1 \cdot 10^{-4}$	10.3574	$2 \cdot 10^{-4}$
C	9.7353	$2 \cdot 10^{-4}$	9.86523	$6 \cdot 10^{-5}$	10.2561	$2 \cdot 10^{-4}$

$$Tanδ = \frac{|\bar{I}_R|}{|\bar{I}_C|} = \frac{X_c}{R_J} \quad (1)$$

Where $\bar{I}_R$ and $\bar{I}_C$ are the resistive and reactive current components, respectively, which theoretically flows in the equivalent resistance R_J and reactance X_c of the CUT model, respectively.

The purpose of this work is to measure the variation of X_c and R_J vs. temperature to get information on the physical phenomena related to Tanδ vs. temperature changes. As a matter of fact, as it was already shown in [16] Tanδ decreases when temperature increases. Thus, from (1) there are three plausible options:

- Both X_c and R_J increase but R_J increases more than X_c.
- X_c decreases and R_J increases.
- Both R_J and X_c decrease but the latter more than the former.

To understand which parameter influences Tanδ, a series model of the CUT has been adopted. The adoption of such a model can be explained by the performed measurements: by knowing $\bar{V}_J$ and $\bar{I}_J$ the

impedance of the CUT is computed as:

$$\bar{Z} = \frac{\bar{V}_J}{\bar{I}_J} = R'_J + jX_c' \quad (2)$$

where R'_J and X_c' are the series equivalent resistance and reactance of the cable-joint, as depicted in Fig. 4. Therefore, it is not possible to approach the cable-joint modelling directly with a parallel equivalent model. Hence, given that the CUT is a complex system composed by different layers of different materials, the direct measurement of R_J and X_c would have been difficult. Therefore, to obtain the relations between the series and the parallel model of the CUT the following system must be solved:

$$R'_J = X_c' * Tanδ \quad (3)$$

$$|\bar{Z}| = \sqrt{R_J'^2 + X_c'^2} \quad (4)$$

After some manipulation, not reported for the sake of brevity, it results:

$$R_J = \frac{(X_c')^2 + (R'_J)^2}{R'_J} \quad (5)$$

$$X_C = \frac{(X_c')^2 + (R'_J)^2}{X_c'} \quad (6)$$

From (5) and (6) it is finally possible to correlate the performed measurements results with the actual CUT parameters. In particular, the two expressions allow to determine the CUT model parameters by starting from the knowledge of Tanδ and $\bar{Z}$.

IV. EXPERIMENTAL RESULTS

Before applying (5) and (6) Tanδ and $\bar{Z}$ have to be measured. In Table I the former is listed along with its standard deviation of the mean (1000 measurements). Two comments arise from the Table. Firstly, the measurement accuracy is very high for the purpose (between 10^{-5} and 10^{-6}), hence little variation of Tanδ can be detected. Secondly, as previously mentioned, Tanδ is decreasing with the temperature.

Impedance measurement results are presented in Table II in terms of mean value of the module and its standard deviation of the mean. At a glance, it is not clear from the impedance module what is happening to the CUT model when temperature changes. However, from it, X_c and R_J can be computed.

To this purpose, Table III contains their values (along with the capacitance of the CUT C_J) computed for each temperature value. By using some graphs, it is possible to understand at a glance the data in Table III.

First of all, X_c behaviour vs. temperature is plotted in

TABLE III.   *ACTIVE AND REACTIVE IMPEDANCE COMPONENT OF THE CUT*

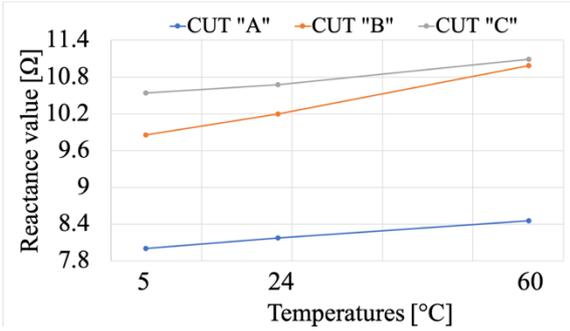| CUT	5 °C			24 °C			60 °C		
	R_J [MΩ]	X_C [MΩ]	C_J [pF]	R_J [MΩ]	X_C [MΩ]	C_J [pF]	R_J [MΩ]	X_C [MΩ]	C_J [pF]
A	421.6100	15.0233	211.8785	827.9448	15.3410	207.4898	1157.9774	15.8632	200.6602
B	171.3883	9.2883	342.6973	223.5510	9.6147	331.0657	3375.9225	10.3574	307.3281
C	208.9942	9.7452	326.6327	483.0588	9.8674	322.5859	1973.0488	10.2559	310.3673

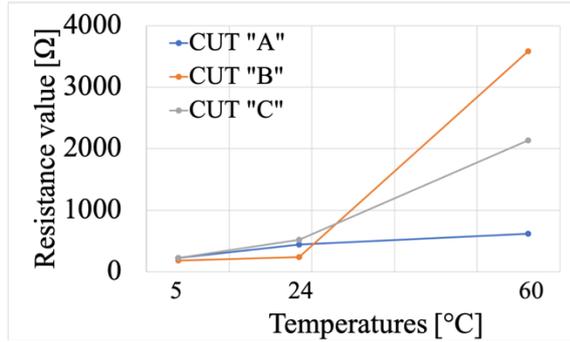*Fig. 5. Reactance values for the three CUT measured at three different temperature*

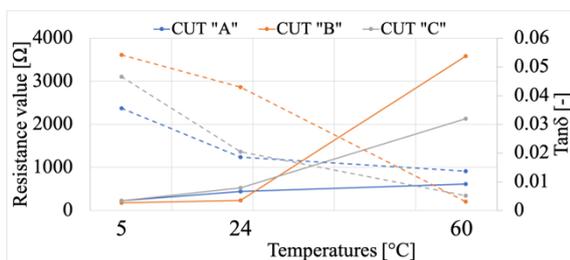*Fig. 6. Resistance values for the three CUT measured at three different temperature*

Fig. 7. Resistance (solid line) vs Tanδ (dotted line) values comparisonfor the three CUT measured at three different temperature

Fig. 5. For all the 3 tested CUTs, a slight increase of the reactance can be seen when the temperature increases. Another comment can be stated focusing on the manufacturer: the absolute value of X_c is almost equal for the CUTs B and C, while A is almost two times greater. This can be explained by both the shorter length of the cables connected to the CUT A (20 % shorter) and the different manufacturer who produced it.

Conversely, in Fig. 6 a significant increase of R_J is showed. In particular, their absolute values at 5 °C and 24 °C are very similar whereas at 60 °C a huge discrepancy is found. CUTs B and C resistance values increase more than 10 times the value at 5 °C, while the cable-joint A just triplicate its absolute value. This might be explained by the different manufacturers, which can build the joint according to their knowledge without referring to any standards.

From this two sets of results, it can be concluded that the equivalent resistance of a cable-joint is the parameter which affected by the temperature and hence affects the Tanδ. To better clarify this point, in Fig. 7 the computed R_J are plotted along with the Tanδ measured at the three different temperatures. In the picture it can be seen the strong correlation between the two quantities.

As for the mechanical structure of the cable-joints, an increase of their resistance results in the diminution of the resistive leakage current between the cable insulation and the CUT insulation (XLPE and silicone rubber). Hence, a lower Tanδ value which may lead to an extension of the overall life of the cable-joint.

As a final comment, the mathematic expressions of the cable-joint model provided in (5) and (6) allow to correlate the Tanδ with the CUT impedance. Hence, one can be computed starting from the knowledge of the other.

V.   CONCLUSIONS

In this paper the equivalent impedance of a cable-joint has been correlated to the Tangent Delta and to its variation vs. temperature. This has the aim to improve the knowledge of the cable-joint failures causes, which is a broad and current topic tackled in the recent literature. Hence, one of the key parameters to determine the ageing of a cable-joint, the Tangent Delta, has been correlated to the impedance equivalent model of a cable-joint. In particular, by starting from its measurement, the parameters which contribute to the Tangent Delta variation have been found. From the presented results it is confirmed that the proposed model is suitable to describe this phenomenon and that the main critical parameter of a

cable-joint is the active part of its impedance.

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