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***Abstract*— In recent years, the increasing frequency of extreme heat events, particularly in urban areas, has raised concerns about the reliability of Medium Voltage (MV) underground distribution systems. Among the components most affected by higher and higher temperatures, cable joints have emerged as particularly susceptible due to partial discharge (PD) phenomena with premature faults. This paper presents a structured test protocol to evaluate the dielectric performance of MV joints under combined thermal and electrical stress in a controlled laboratory setting. The methodology includes diagnostic measurements such as PD activity, dielectric loss angle (tanδ), and insulation resistance (IR), carried out under both ambient and high temperatures (via thermostatic chamber). The aim is to correlate joint insulation behaviour with operating temperatures, identify early degradation signs, and support the qualification of joint technologies for use in a more resilient distribution grid.**

***Keywords*— Medium Voltage cable joints, thermal stress, partial discharges, electrical resilience**

I. INTRODUCTION

The power system represents one of the most complicated (because of its number of components) and complex (due to the interactions existing among the installed equipment) systems developed so far. Its proper operation is strictly related to an accurate planning and design, which must be able to consider in advance several external factors that may affect the service quality perceived by the users. One of the factors that is arising as fundamental is the *temperature*: in fact, in recent years several regions around the world (e.g., United States [1], China [2], India [3] and Europe [4]) have faced an increasing number of days with relatively high temperatures and reduced precipitation, the so-called *compound drought and heatwaves* events [5]. In urban areas, these kinds of phenomena lead to *heat islands*, as highlighted in [6]. The increase of the temperature, especially in urban areas, led to an increasing number of failures, which in particular affected the operation of the in Medium Voltage (MV) systems. These systems are the backbone of the urban power systems in Europe and are commonly used for their reduced visual impact and the reliability level were able to guarantee in the past: it is estimated that the total lengths of MV underground cable is around 30 million km worldwide [7]. Hence, due to the extensive coverage underground cable systems have, it is important to address the problem of the increasing number of faults associated to high temperature by investigating which are the more susceptible components and, on these bases, suggesting effective procedure and approaches for mitigating the downtime of the distribution system. Recently, several researchers have been investigating these aspects (see as overview of the impact of extreme weather events, including heatwaves, the recent review [8]).

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Basically, most of the available literature indicates cable joints as the most susceptible component to the thermal stress, affecting the long-term reliability of distribution system. The extreme heat events result in elevated ground and joint temperatures, accelerating aging and triggering early-stage dielectric breakdown phenomena such as Partial Discharges (PD). Recent research highlights oldest studies on the sensitivity of PD inception to temperature, emphasizing the need for protocols that can assess dielectric stability of joints under combined thermal and electrical stresses.

The aim of this work is to define a structured measurement protocol to evaluate the dielectric performance of MV joints subjected to combined thermal and electrical stresses in a controlled laboratory environment.

This protocol focuses on identifying early degradation phenomena through: Partial Discharge (PD) measurements at multiple voltage levels; Dielectric loss angle (tanδ), and Insulation Resistance (IR).

The overarching objective is to correlate the evolution of these diagnostic parameters with operating temperature, enabling the early identification of failure risks associated with extreme environmental conditions. The methodology aims to provide a standardized framework for joint qualification and to support the development of predictive maintenance strategies for climate-resilient MV power distribution infrastructures, in line with the analytical models and experimental observations previously reported in the literature [9-12].

II. Objectives and Scope of the Test Protocol

MV cable joints are recognized as critical components within power distribution networks, particularly susceptible to combined thermal and electrical stresses. Extensive field and laboratory investigations have demonstrated that prolonged exposure to elevated operating temperatures (frequently exceeding 50 °C during summer peaks) and lack of rains, significantly accelerate insulation aging and increase the probability of PD phenomenon in MV joints [13-15]. It was also highlighted the combined effects of load current, soil thermal resistivity, and external heatwaves in creating thermal hotspots that undermine the dielectric integrity of joints over time [9].

These findings are consistent with foundational studies by Bartnikas and Motzinger, who established the strong temperature dependence of PD phenomena, noting that elevated temperatures reduce the inception voltage due to increased molecular activity and lowered dielectric strength [16-18]. It has been shown that thermal-electrical stress interaction promotes early-stage degradation mechanisms, particularly within joint interfaces where field inhomogeneities and material transitions occur.

Building upon these insights, this work proposes a structured laboratory protocol to assess the dielectric performance of MV cable joints under controlled thermal and electrical stress conditions. The protocol includes: a) PD measurements at multiple voltage levels, with particular attention to the variation of PD inception voltage (PDIV) as a function of joint temperature; b) tan δ analysis, providing indication about the dielectric polarization losses and thermal degradation; c) IR measurements, aiming to evaluate the moisture ingress and general aging of the insulating system.

The measurement results will be compared with the values indicated by CLC HD 629.1 S3:2019 "Test requirements for accessories for use on power cables of rated voltage from 3.6/6 (7.2) kV up to 20.8/36 (42) kV - Part 1: Accessories for cables with extruded insulation" [19]. This standard outlines the required performance criteria for type testing of cable accessories intended for use with extruded insulation power cables. The applicable voltage range spans from 3.6/6 kV up to 20.8/36 kV (included).

Unlike conventional standards, this paper presents a more detailed testing protocol in which voltage, temperature, and current are applied through controlled increments rather than fixed, discrete values. Such an approach allows for a gradual and systematic variation of the stressing parameters, enabling a more refined observation of the specimen's response under evolving conditions. Furthermore, the proposed protocol is designed not merely as a pass/fail assessment, but as a diagnostic tool aimed at evaluating the degradation trend and variation of key dielectric parameters over time. This methodology provides deeper insight into the ageing mechanisms and performance evolution of the tested components, offering a richer dataset for both predictive maintenance and design optimization.

III. Experimental Methodology and Structure

The purpose of the proposed test protocol is to assess the dielectric behaviour of MV cable joints subjected to combined thermal and electrical stress conditions. The joints under test include both heat-shrinkable and cold-shrinkable types, supplied by two major manufacturers. A further test phase may extend the investigation to products from additional suppliers.

The tests will be conducted under two different environmental conditions:

- at controlled ambient temperature (test "A");
- inside a thermostatic chamber capable of maintaining temperatures at about maximum 60 °C (Test "CT").

The cable joints will be connected in a loop (i.e., in series), allowing for simultaneous testing of joints located inside the thermostatic chamber and those kept at ambient temperature. This setup enables a direct comparison of the thermal and electrical performance of the joints under different temperature regimes.

Each test cycle will last 24 hours. After each cycle, dielectric measurements will be performed, including:

- PD measurements at increasing voltage levels, i.e., U_0; 1.25 U_0; 1.5 U_0; 1.75 U_0; 2 U_0;
- tanδ;
- IR.

The results of the PD measurements, tanδ, and IR must fall below the limits established by [19] or greater and chosen from laboratory experience.

During the tests, the temperatures of both the joints and the cables will be monitored continuously, in both the ambient environment and within the thermostatic chamber.

The current applied during each test will correspond to a defined percentage of the cable's rated current-carrying capacity (ranging from 30% to 80% depending on the test condition).

The sequence of tests includes both stepwise and constant current/temperature cycles.

A. Ambient Temperature Test Cycles

This set of tests aims to evaluate the behavior of the MV cable joints under increasing electrical load while maintaining natural ambient temperature conditions. Four different test configurations (A0 to A3) are defined, each one associated with a specific current load level and the corresponding expected joint temperature, as shown in Table I. The values reported in this table are preliminary and based on theoretical calculations [9] and will be confirmed once the testing begins and/or after the component type and cross-sectional area have been determined.

TABLE I. AMBIENT TEMPERATURE TEST MATRIX

Test Code	Current Load [%]	Expected Joint Temp [°C]
A0	30	30–40
A1	50	40–50
A2	70	50–60
A3	80	60–70

B. Thermostatic Chamber Test Cycles

To isolate and control the impact of temperature independently from electrical loading, a second group of tests will be carried out within a thermostatic chamber. These test cycles allow for the evaluation of MV cable joints performance under predefined thermal conditions, irrespective of the self-heating caused by current flow. Table II summarizes the test configurations used in this controlled-temperature environment. Also in this case, the values reported in the table are preliminary, based on theoretical calculations [9], and will be confirmed once the testing begins and/or after the component type and cross-sectional area have been determined.

TABLE II. THERMOSTATIC CHAMBER TEST MATRIX

Test Code	Chamber Temp [°C]	Expected Load Current [%]
CT0	30	25
CT1	40	35
CT2	50	45
CT3	60	55

The experimental test procedure and dielectric measurements are illustrated in the block diagram shown in Fig. 1. In the flowchart the test cycle counter is initialized (c = 0), followed by setting the desired current and temperature, running a 24-hour cycle, and monitoring temperatures. electrical diagnostics are then performed, including the measurement of dielectric losses (tan δ) and insulation resistance. PDIV is measured at the test voltage Ui, and results are compared with a reference PDIV value. If PDIV(Ui) falls below the reference, the test fails. Otherwise, the cycle proceeds with incremental voltage adjustments (Ui=Ui+ΔV) until either the iteration counter (i) reaches 5 or the cycle counter (c) exceeds 4. The test concludes successfully if all cycles are passed without failure.

The iteration counter (iii) was fixed at 5, representing a trade-off between achieving sufficient measurement resolution and maintaining an acceptable overall test duration.

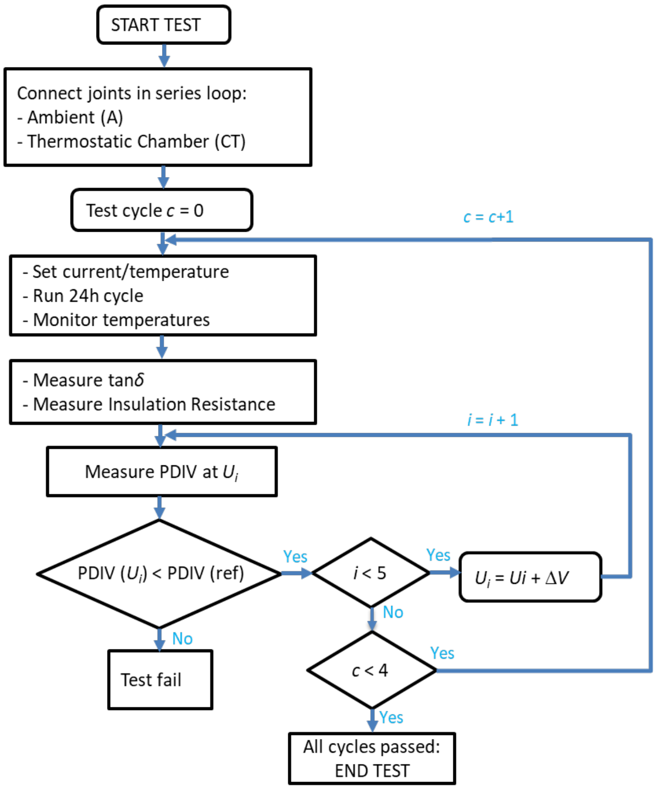

Fig. 1. Block diagram of the test procedure and dielectric measurements. Legend: AV = 0.25 kV; PDIV (ref) is the Partial Discharge Inception Voltage that will be fixed as reference at the beginning of the test and following the CLC HD 629.1 S3.

IV. Measurement Strategy and Diagnostic Targets

Following standards such as CLC HD 629.1 S3 [9], IEC 60270 [20] and IEC 60502-4 [21] and the proposed protocol employs classical diagnostic quantities, with even unconventional testing protocols, to assess the condition of MV cable joints under thermal and electrical stress. Among these, the PDIV is particularly interest, as it directly reflects the insulation's susceptibility to localized dielectric breakdown.

As shown in Figure 2 - carried out in a completely arbitrary and indicative way, the actual trend and values of which will be validated at the end of the experimental results - PDIV significantly decreases with increasing temperature, confirming the strong thermal sensitivity of cable joint insulation systems.

The graph compares three joint technologies: heat-shrink, cold-shrink, and a high-resilience design.

- Cold-shrink joints exhibit the steepest decline in PD inception voltage, dropping from approximately 19.7 kV at 30 °C to just over 16 kV at 60 °C, indicating a rapid degradation of dielectric strength with temperature.
- Heat-shrink joints follow a similar trend but with slightly better thermal performance.
- In contrast, the high-resilience design demonstrates the most stable behavior, maintaining V_i above 19.5 kV even at 60 °C, underscoring its enhanced thermal robustness.

This temperature-dependent behavior, namely PDIV(T), is central to understanding the thermal aging mechanisms and predicting the onset of insulation failure. By characterizing PDIV across a range of temperature and voltage conditions, the protocol enables the identification of the most thermally vulnerable joint types. When integrated with complementary measurements such as tanδ—which tracks polarization losses—and IR—sensitive to moisture ingress and insulation deterioration—the methodology provides a comprehensive framework for condition assessment and technology benchmarking.

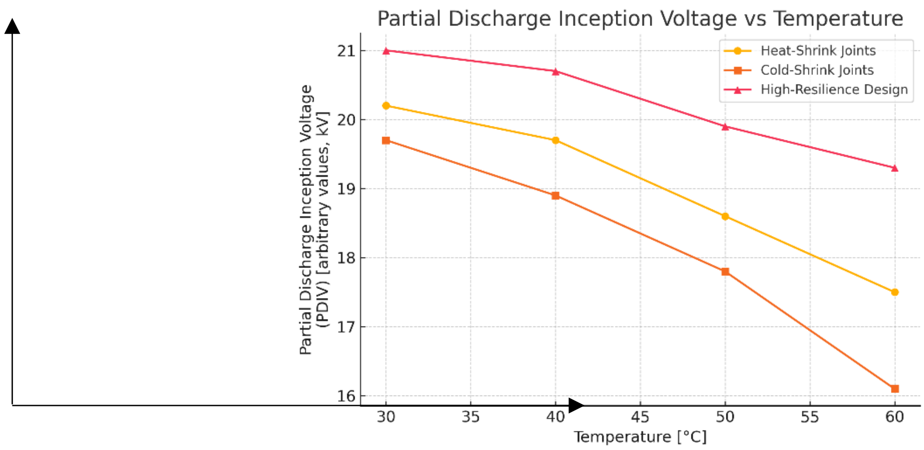

Fig. 2. Trend of PD Inception Voltage vs Temperature for Different Joint Technologies.

V. Applicability and Future Use

The proposed dielectric measurement protocol suggests a structured and replicable method for evaluating the thermal and electrical performance of MV cable joints. Developed in response to the growing impact of extreme heat events, this protocol is designed to support both laboratory benchmarking and real-world qualification of joint technologies.

By analyzing temperature-dependent variations in PDIV, tanδ, and IR, the protocol enables early detection of insulation degradation. This makes it particularly suitable for urban distribution networks, where underground joints are frequently exposed to thermal stress and where faults can lead to significant service disruptions.

The modular structure of the test cycles allows for application across different joint types, cable sizes, and installation conditions. It also enables comparative testing between manufacturers, offering a standardized framework for assessing resilience under identical stress scenarios.

In addition, the protocol supports the development of predictive maintenance models by providing diagnostic trends that can be integrated in the future into asset management strategies. As such, it contributes to improving operational reliability and aligning grid components with future climate resilience requirements.

Conclusion

This paper outlines a comprehensive dielectric testing protocol to evaluate the performance of MV cable joints under controlled thermal and electrical stress conditions. The proposed methodology includes ambient and thermostatic chamber cycles with measurements of partial discharges, dielectric loss angle, and insulation resistance.

The protocol aims to support the development of resilient joint technologies by providing repeatable and standardized test sequences. Once experimental tests are completed, the results will help define qualification criteria for joint technologies suitable for extreme temperature conditions, contributing to more reliable and climate-resilient distribution networks.

References

[1] S. Mukherjee and A. K. Mishra, "Increase in compound drought and heatwaves in a warming world," *Geophysical Research Letters*, vol. 48, 2021

[2] L. Ye, K. Shi, Z. Xin, C. Wang, and C. Zhang, "Compound droughts and heat waves in China," Sustainability, vol. 11, no. 12, p. 3270, 2019

[3] S. Sharma and P. Mujumdar, "Increasing frequency and spatial extent of concurrent meteorological droughts and heatwaves in India," *Scientific Reports*, vol. 7, p. 15582, 2017.

[4] European Environment Agency (EEA), *Extreme weather: floods, droughts and heatwaves*, EEA, 2024.

[5] K. P. Tripathy and A. K. Mishra, "How unusual is the 2022 European compound drought and heatwave event?", *Geophysical Research Letters*, vol. 50, 2023

[6] S. Iodice, L. C. Arbau, A. Maistrali, F. Marando, M. Melchiorri, P. Proietti, P. Sulis, O. Tainguy, and I. Vandecasteele, *EU cities and heat extremes*, European Commission, JRC Technical Report, Ispra, 2024

[7] R. Gerstner, M. Bawart, and P. L'Eplattenier, "New enhancements for cable fault location in complex medium voltage distribution networks," presented at the *CIRED 22nd Int. Conf. on Electricity Distribution*, Stockholm, Sweden, June 2013

[8] A. C. R. Gonçalves, X. Costoya, R. Nieto, et al., "Extreme weather events on energy systems: a comprehensive review on impacts, mitigation, and adaptation measures," *Sustainable Energy Research*, vol. 11, no. 4, 2024. DOI: 10.1186/s40807-023-00097-6.

[9] L. Calcara, M. Pompili, and B. A. Cauzillo, "Ampacity of MV underground cables: The influence of soil thermal resistivity," in *Proc. 2015 5th Int. Youth Conf. on Energy (IYCE)*, 2015.

[10] A. Sturchio, G. Fioriti, V. Salusest, L. Calcara, and M. Pompili, "Thermal behavior of distribution MV underground cables," in *Proc. 2015 AEIT Int. Annu. Conf.*, AEIT, 2015.

[11] L. Calcara, L. D'Orazio, M. Della Corte, G. Di Filippo, A. Pastore, D. Ricci, and M. Pompili, "Faults evaluation of MV underground cable joints," in *Proc. 2019 111st AEIT Int. Annu. Conf.*, AEIT, 2019

[12] M. Pompili, L. Calcara, D. Ricci, "Joints defectiveness of MV underground cable and the effects on the distribution system," Electr. Power Syst. Res., vol. 192, 2021.

[13] L. Calcara, M. Pompili, and S. Sangiovanni, "Heatwaves and underground MV cable joints failures," in *Proc. IEEE AEIT Int. Annu. Conf.*, 2021

[14] M. Pompili and L. Calcara, "Qualification of MV cable joints: Partial discharges innovative tests," in *Proc. 24th Int. Conf. on Environment and Electrical Engineering (EEEIC)*, 2024.

[15] R. Schifani et al., "On PD mechanisms at high temperature in voids included in an epoxy resin," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 8, pp. 589–597, 2001.

[16] R. Bartnikas and E. J. McMahon, *Engineering Dielectrics, Volume I: Corona and Partial Discharge Testing*, ASTM International, 1979.

[17] R. Bartnikas, "Partial Discharges—Their Mechanism, Detection and Measurement," *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 9, no. 5, pp. 763–808, Oct. 2002.

[18] E.O. Forster et al., "Effect of the electrode gap on breakdown in liquid dielectrics," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 1, pp. 440–446, 1994.

[19] CLC HD 629.1 S3:2019, *Test requirements for accessories for use on power cables of rated voltage from 3.6/6 (7.2) kV up to 20.8/36 (42) kV – Part 1: Accessories for cables with extruded insulation*, Comité Européen de Normalisation, 2019.

[20] IEC 60270, *High-voltage test techniques – Charge-based measurement of partial discharges*, International Electrotechnical Commission, 2025.

[21] IEC 60502-4, *Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) up to 30 kV (Um = 36 kV) - Part 4: Test requirements on accessories for cables with rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)*, International Electrotechnical Commission, 2023.