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STUDY ON THE BEHAVIOR OF LOW-VOLTAGE CABLE INSULATION SUBJECTED TO THERMAL CYCLE TREATMENT

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Abstract. ***The paper presents a study on the effects of thermal aging on a low-voltage cable. Cable samples with a length of 50 cm were subjected to thermal cycling from +140 °C to -20 °C in a climate chamber with controlled temperature. This treatment compares the short-term failure or the emergency overload of some cables under real operating conditions at low temperatures. The effect of the temperature cycle is investigated through electrical measurements such as dielectric spectroscopy, voltage response measurements, and mechanical measurements such as Shore D hardness investigation. The results revealed that the thermal cycles of accelerated aging caused the plasticizer to diffuse into the jacket and then be released into the environment. At the same time, the thermal shocks produced microcracks in the cable jacket, accelerating the removal of the plasticizer.***

Keywords: low-voltage cable insulation, extended voltage response, dissipation factor, mechanical hardness.

1. INTRODUCTION

Electric cables are constitutive elements important in electricity distribution and transport networks. A major concern within electricity companies is preventing failures caused by the degradation of electric cables. In the current context, low-voltage electric cables have a decisive role in the distribution network. Thermal overloads caused by short-term faults or emergency overloads may occur during operation. In this way, the electric cable endures temperatures that change the molecular structure of the respective cable insulation and ultimately reduce its lifespan. Studies reported results regarding the behavior of low-voltage cables at constant temperatures of 110℃, 125℃, and 140℃ for a certain period [1-2], [4-5].

The present paper studies the behavior of a low-voltage cable with polyvinyl chloride (PVC) insulation subjected to thermal cycles with variable temperatures. An analogy can be drawn to a situation where a cable is exposed to high temperatures beyond its limit for a period of time and then suddenly experiences a drop in temperature to negative environmental levels.

2. MATERIALS AND METHODS

2.1. Test preparation methodology

CYYF 3×1.5 mm^2 low-voltage cables (Omnicable SRL, Romania) were tested. The different parts of the cable are illustrated in Figure 1. According to the manufacturer information, the conductors are made of copper; the insulation is manufactured from PVC mixture according to SR CEI 60502-1; the filling material contains mainly plasticized PVC granules (SDR); the cable jacket is made of PVC mixture type ST 1/ST 2 according to the standard mentioned above. The maximum temperature allowed on the conductor under normal operating conditions is about 70 °C. The investigated cable has an increased flame propagation delay, according to SR EN 60332-3-24:2010. Unfortunately, the technical sheet of the cable does not provide any information regarding its thermal aging.

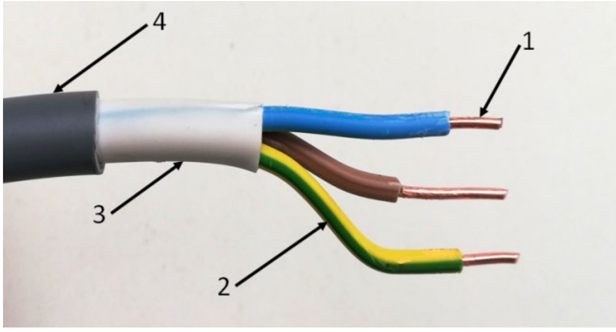


Figure 1. Cable structure: 1 - copper conductor, 2 - conductor insulation, 3 - filling material, 4 - cable jacket.

Figure 2. Test cable setup.

The cable sample used for testing can be seen in Figure 2. To create the inner electrode, the three conductors of the cable are short-circuited, and the outer electrode is made of aluminum foil wrapped over the cable jacket. A copper ring is fixed around the aluminum foil to establish the electrical connection.

The tested samples were subjected to thermal cycling in a CH 250 TVT climate chamber (Angelantoni, Italy) with the temperature curve adjustment program, measured by thermocouple sensors.

Figure 3. Arrangement of the samples in the climatic chamber CH 250 TVT.

The 50 cm long cable samples were placed in the climatic chamber in static air and uncontrolled humidity conditions.

The testing methodology by thermal cycling was carried out in accordance with JEDEC Standard Temperature cycling JESD22-A104-B [3]. The maximum positive temperature level was fixed at + 140 °C, and the lower temperature was set at -20 °C, with a temperature rate change of 3 °C/min. The duration of the isothermal period at the upper temperature as well as at the lower temperature is 50 minutes. A complete temperature cycle takes 200 minutes. As shown in Figure 3, eight cable samples were placed in the climatic chamber, corresponding to the studied cycles: 3, 6, 9, 12, 15, 18, 24, and 30 cycles. Figure 4 shows the evolution of the temperature in the climatic chamber during the heat treatment.

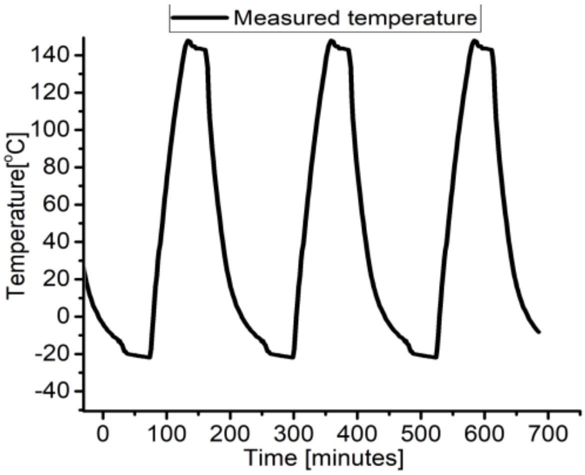


Figure 4. Temperature variation *vs.* time measured in the climatic chamber.

2.2. Characterization Methods

2.2.1. Extended Voltage Response Measurement

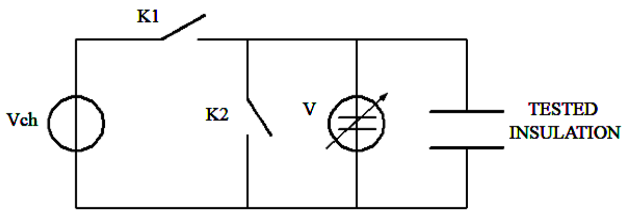
The extended voltage response (EVR) measurement method is based on the decay voltage slopes' values and the charged dielectric material return voltage.

The discharge voltage is measured after the dielectric was previously charged after a period of 100 ÷ 4000 s. The dielectric material is short-circuited for a few seconds after it has been charged, then the return voltage is measured. The initial slope of the measured discharge voltage is proportional to the specific conductivity of the material. The slope of the measured return voltage is proportional to the polarization conductivity of the material.

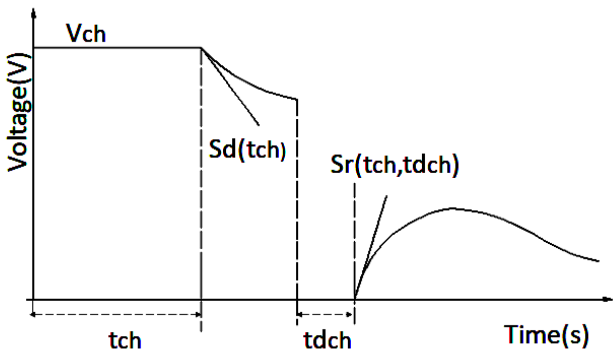
$$S_d = \frac{\sigma V}{\varepsilon}, \quad (1)$$

$$S_r = \frac{\beta V}{\varepsilon}, \quad (2)$$

where σ is the conductivity, β is the polarization conductivity, V is the measured voltage, and ε is the dielectric material permittivity. Parameters S_d and S_r represent the incipient slope of the discharge voltage and the initial slope of the return voltage, respectively. The values of S_d and S_r do not depend on the dimensional physical characteristics of the dielectric material. Figure 5(a) schematically shows the operating principle, and Figure 5(b) presents the timing diagram of the EVR method [5-8].



(a)



(b)

Figure 5. EVR method: (a) Schematic circuit. Switch K1 is turned on and switch K2 off during the charging period since, during the discharge period, the switches' states are reversed; the switches are off during the test; (b) Time diagram. $S_d(t_{ch})$ and $S_r(t_{ch}, t_{dch})$ represent the slopes of the measured values of the decay and return voltage, where the charge and discharge times were denoted by t_{ch} and t_{dch}.

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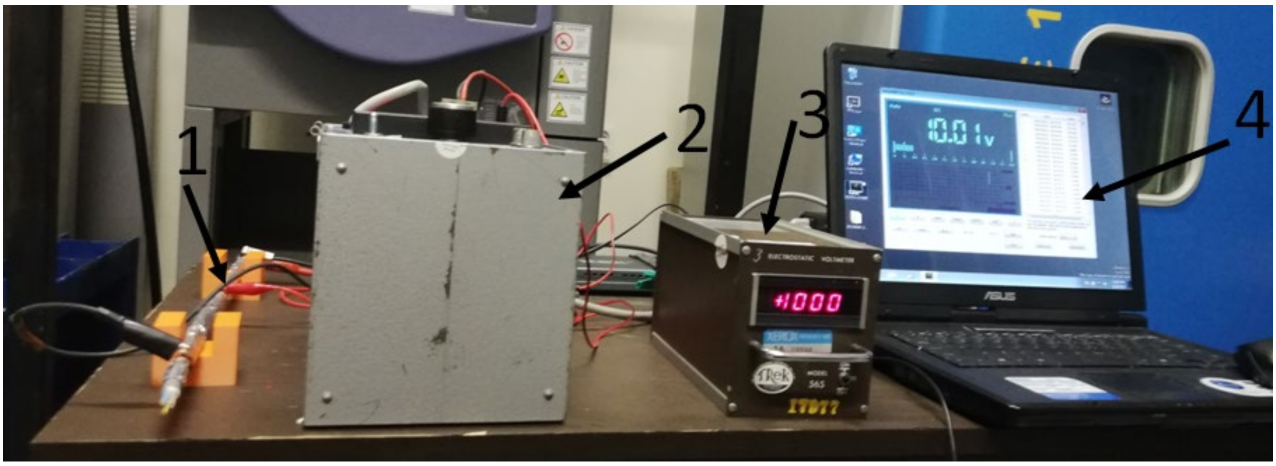


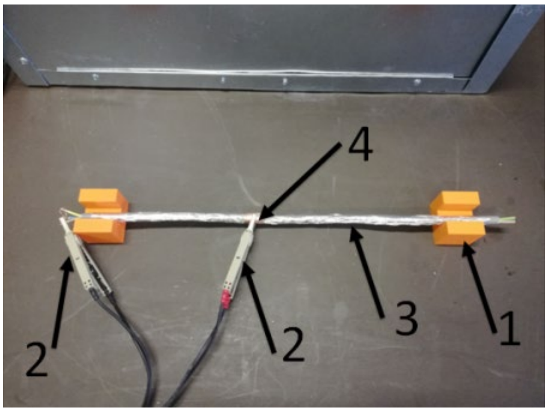
Figure 6. Component parts of the EVR method: cable under test (1), high-voltage source (2), electrostatic voltmeter (3), and computer for running the control software (4).

The variation of the decay voltage slopes is analyzed in the present work. The source voltage for the charging stage of the EVR test is set at + 1000 V, and the charging time to 2000 s. The three conductors of the cable are tied together, forming the inner electrode. The outer electrode is made of aluminum foil spread over the surface of the cable jacket with a length of 44 cm. The outer electrode is grounded to reduce electromagnetic interference. Figure 6 shows the components of the EVR setup for the investigated cables. The Trek 565 (USA) electrostatic voltmeter, having a measurement range of ±1400 V and an accuracy of 1 %, was used. The analog signal measured by the electrostatic voltmeter is transmitted to a Data Logger Hantek 365D (China), which outputs a digital signal processed by the computer program. The measurements were performed at the temperature $T = 23 \pm 0.5$ °C.

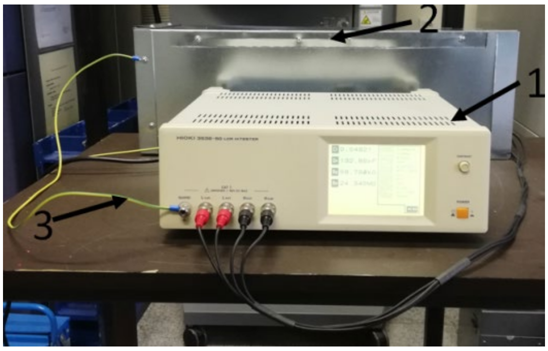
2.2.2. Dissipation factor test

The dissipation factor (tan δ) represents the tangent of the angle between the capacitive and leakage current if the insulation sample is connected to an alternating current voltage source [9-10].

The dissipation factor of the studied cable sample was measured with the LCR HiTESTER 3532-50 (Hioki, Japan) device, with an accuracy of ± 0.08 % and a response time of 5 ms. The measurements were made in a Faraday cage, made of galvanized steel sheet with dimensions 80 × 20 × 20 cm^3, not to influence the result of the measurements by the effect of environmental electromagnetic waves. The connection method of the studied cable sample can be seen in Figure 7. The measurements were made in the frequency range of 42 Hz to 200 kHz. The measurements were performed at the temperature $T = 23 \pm 0.5$ °C.



(a)



(b)

Figure 7. Experimental configuration of the dielectric measurement with LCR-meter Hioki 3532-50 in the frequency range 42 Hz to 200 kHz: (a) Sample and connection method: holder (1), crocodile clips (2), aluminum foil (3), copper ring; (b) A photo of the setup: LCR-meter (1), Faraday cage (2), and guard connection (3).

2.2.3. Shore D Hardness test

The HBD 100-0HBD 100-0 (Sauter, Germany) durometer device was used to measure the mechanical parameters. Shore D hardness is a dimensionless value that reflects the hardness of the cable's outer covering. The result is the average value of ten measurements performed on the same cable jacket [1-2], [4]. It can be noted that the selection of measurement points is made randomly. Since the geometry of the cable does not comply with the ASTM D2240 standard, which requires at least a 4 mm thickness for the material, the results of the Shore D mechanical measurements serve only for comparison reasons. The measurements were performed at $T = 23 \pm 0.5$ °C after removing the aluminum foil from the sheath of the cable sample.

3. RESULTS AND DISCUSSION

3.1. Extended voltage response results

Previous research showed that the slopes of the decay voltage are proportional to the conductivity of the studied dielectric [8]. According to the results obtained (see Figure 8), the plasticizer content in the insulation compound has a determining role. The smaller the amount of plasticizer in the material, the lower conductivity will be, like what happens in the present case. Exposing the material to a temperature higher than the maximum working temperature, but also due to the thermal shocks produced by the temperature variation, results in microcracks in the cable sheath, which facilitates the loss of the plasticizer in the external environment. According to the results obtained after three temperature cycles, a redistribution of the plasticizer, its percentage increases significantly, which causes the slope of the discharge voltage to increase beyond the initial limit. Then, as the treatment of thermal cycles progresses, the amount of plasticizer lost increases, which causes the slopes of the decay voltage to decrease gradually.

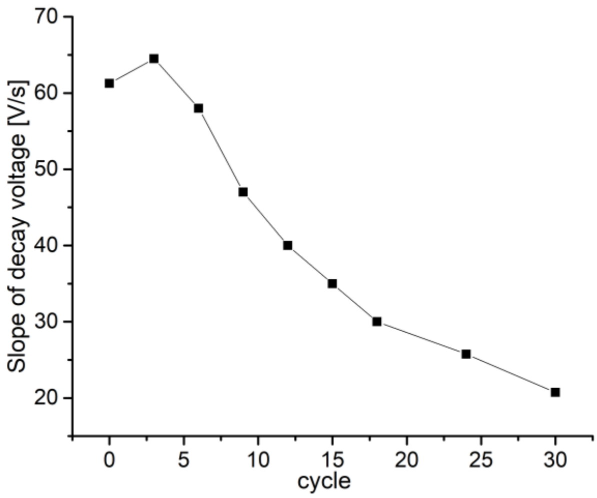


Figure 8. Slope of the decay voltages *vs*. aging cycles.

3.2. Dissipation factor measurement

Figure 9 shows the dissipation factor evolution as a function of frequency for the cable samples after a specific number of testing cycles.

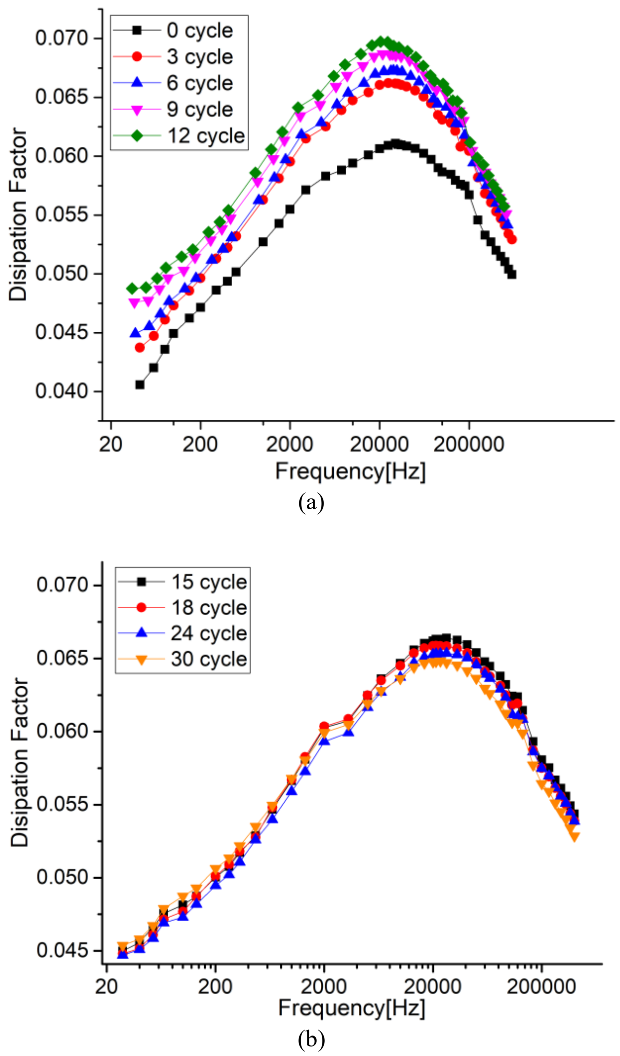


Figure 9. Variation of the dissipation factor measured on the studied frequency range, according to aging parameter: (a) 1 ÷ 12 cycles, (b) 15 ÷ 30 cycles.

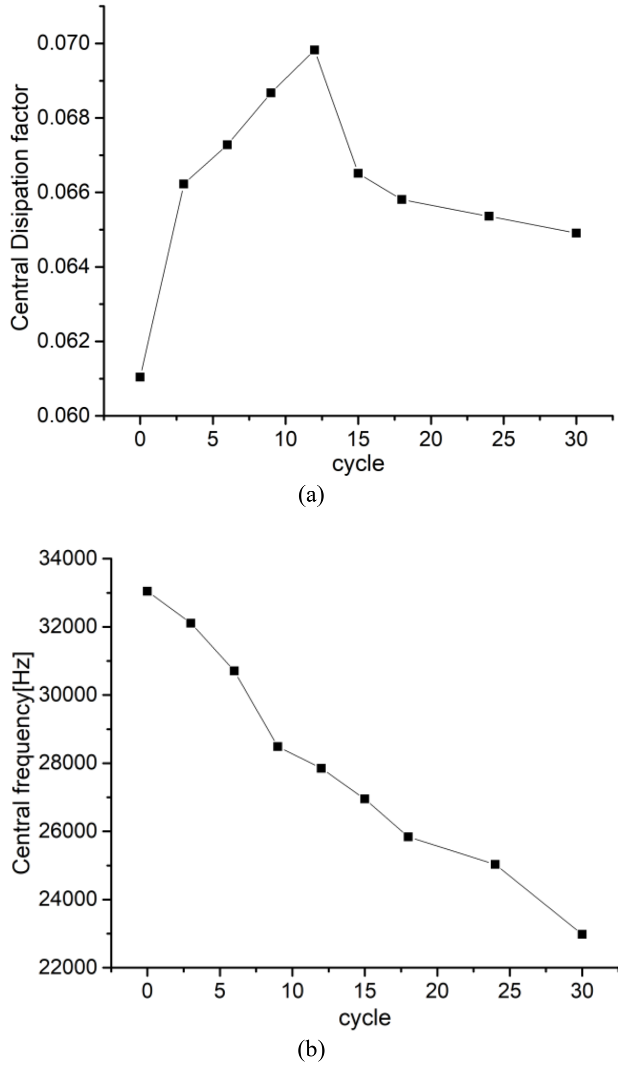


Figure 10. Measured values of the central dissipation factor (a) and the central frequency of the loss factor (b) as a function of the studied thermal cycles.

To analyze the movement of the polarization spectrum, the graphs shown in Figure 10 were constructed, namely the measured loss factor in Figure 10(a) and the measured central frequency depending on the number of cycles in Figure 10(b).

According to the graphs in Figure 10, the measured central frequency has a decreasing trend during the aging process of the cable. The central frequency of the loss factor moves to the left because the slower polarization processes become more significant.

The measured values of the dissipation factor that describe the intensity of the polarizations increase up to cycle 12, then have a decreasing trend with the advancement of the aging process. This phenomenon can be explained by the migration of the plasticizer from the insulation of the conductors and from the filler material outside to the jacket. Until the 12th cycle, there is an agglomeration of the plasticizer migrated from the inside to the jacket area, increasing the loss factor values. Because the number of polarizable molecules increases, after the 12th cycle, the loss of the plasticizer through the jacket accelerates, a fact that leads to a decrease in the value of the loss factor.

3.3. Shore D test results

The dimensionless Shore D values are between 0 and 100 (soft and hard). In Figure 11, the results of the measurements are given after each aging cycle. It can be noticed that after the first three heat treatment cycles, the measurements show a sudden softening of the cable jacket. This phenomenon can be explained by the migration of the plasticizer contained in the conductors' insulation and the filling material towards the jacket, causing a sudden softening of the material. Then, as the thermal cycles progress, due to the thermal shocks, microcracks appear within the jacket, increasing the amount of plasticizer released to the outside, while the migrating plasticizer from the inside begins to run out, thus increasing the jacket's hardness.

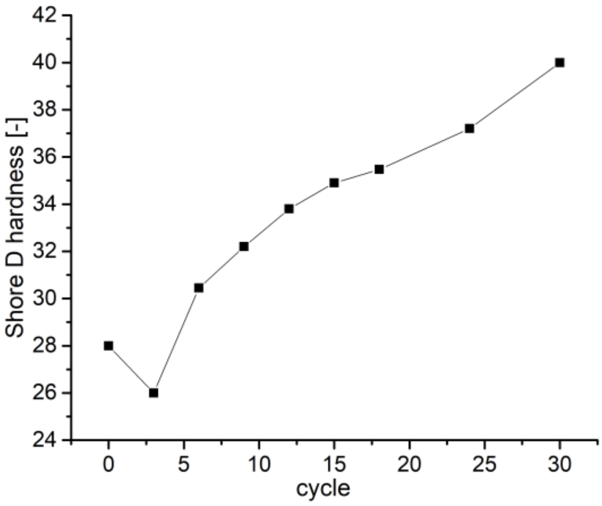


Figure 11. Changes in the hardness of the PVC cable samples according to each thermal cycle.

4. CONCLUSIONS

In this paper, the overall behavior of the polymeric substances based on the PVC component of a low-voltage cable was studied: core insulation, filling material, and outer sheath. The test cable is thermally accelerated, aging over a period of 30 cycles, with temperatures varying from + 140 °C to − 20 °C. The aging period of the cable was relatively short, such that no dechlorination was found, but the main factor in the aging process was the migration and the loss of the plasticizer from the polymeric materials. The results of the measurements describe the overall behavior of the polymeric materials in the cable composition and their mode of interaction. The thermal stressed cycles determine thermal shocks that have the effect of mechanical changes, i.e., microcracks in the cable sheath, which lead to the acceleration of the evaporation of the plasticizing material. The measured center loss factor and the measured center loss frequency were shown to be good indicators in assessing the aging condition of the respective cable.

5. ACKNOWLEDGEMENTS

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