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EMERGENCY CONDITIONS APPLIED TO TRIPLEX MEDIUM-VOLTAGE XLPE CABLES HAVING FLAT STRAP NEUTRALS

Serge PÉLISSOU, Hydro-Québec (IREQ), (Canada), Pelissou@ireq.ca
Jacques CÔTÉ, Hydro-Québec (Distribution), (Canada), Cote.Jacques.3@hydro.qc.ca
Serge ST-ANTOINE, Hydro-Québec (Distribution), (Canada), St-Antoine.Serge@hydro.qc.ca
Julien DALLAIRE, Hydro-Québec (Distribution), (Canada), Dallaire.Julien@hydro.qc.ca

ABSTRACT

The physical behavior and electrical performance of triplex medium-voltage XLPE cables with flat strap neutrals were studied during and after simulated emergency conditions. The main goal was to evaluate the influence of the direction of the neutrals and triplex cable assembly (right- or left-hand lay),as well as the neutral coverage over the insulation shield (75% and 100%). The cables were installed in underground conduits, submitted to cycling temperatures up to 130°C at the conductor, and their angular and longitudinal displacements were recorded. After the specification limit of the 1500-hours cumulative emergency overload, the cables were retrieved, examined and subjected to AC breakdown. The results indicate clearly that cables with neutrals with a left-hand direction are the less physically affected and have the greatest ACBD strength.

KEYWORDS

Temperature, cables, flat strap neutrals, performance.

INTRODUCTION

In underground distribution networks, cross-linked polyethylene (XLPE) extruded cables are rated for a maximum operating temperature of 90°C and an emergency temperature of 130°C [1,2]. Specifications also give a maximum on the emergency duration of 1500 hours cumulative during the lifetime of the cable. In practice, the operating conditions are usually below these limits, whereas several studies have shown that these cables can sustain greater temperatures without affecting their properties and even in some cases improving them [3-5]. However, concerns still remain about operating cables with flat strap neutrals at these temperatures in a duct bank. This type of cable is commonly used in downtown areas as they can fit in smaller duct diameters and also for PILC cable replacement. Kellow and al [6] have in fact demonstrated that 28-kV XLPE three single-phase cables, with an aluminum conductor and copper flat strap neutrals covering 100% of the cable's outer surface, can buckle or twist severely when submitted to conductor temperatures up to 130°C. The observed deformations were mainly explained in terms of the considerable thermal expansion differential between the insulation and the neutral straps. However, this study did not cover cables with copper conductors or the influence of the direction of neutrals, as well as the triplex assembly (right- and left-hand) on the thermo-mechanical and electrical performance of the cable at these temperatures. Currently, this type of cable has only a copper conductor to increase its loading capability, and the neutral direction is no longer specified in ICEA and CSA specifications [1,2].

The work reported here, besides investigating all the previous parameters in a duct bank configuration with actual-size cables, will also consider the coverage of two types of neutral straps and particularly temperature cycling. Furthermore, since XLPE becomes soft over ~90°C and is not totally cross-linked, the time or emergency duration parameter is also emphasized in the study. The AC (60Hz) breakdown strength (ACBD) characteristic is used to evaluate the cable's electrical performance after 1500 hours under emergency conditions.

EXPERIMENTAL

Cables

The cables are new three-phases triplex cables, rated 28 kV, tree-retardant XLPE insulated, and with a 350 kcmil (175 mm²) compact copper conductor, as shown in Fig.1.

Figure 1 – Cross-section (left) of the cable with flat strap neutrals, 100% coverage, with a left-hand direction of the lay. Example (right) of the left-hand direction of the triplex assembly for cable LL before installation with the thermocouple wires running in middle.

Four cable constructions were selected:

- **Cable RR**: with tin-coated flat strap copper neutrals (28 strips, 0,66 x 3,15 mm section), 100% coverage over the insulation shield, right-hand for the direction of the lay (R) and also for the of the triplex assembly one (R).
- **Cable RR75**: with tin-coated flat strap copper neutrals (17 strips, 0,89 x 3,81 mm section), 75% coverage over the insulation shield, right-hand (R) for the direction of the lay and also for the one of the triplex assembly (R).
- **Cable LR**: with tin-coated flat strap copper neutrals (20 strips, 0,66 x 4,57 mm section), 100% coverage over the insulation shield, left-hand (L) for the direction of the lay

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(Fig. 1) and right for the one of the triplex assembly (R).

- **Cable LL**: with tin-coated flat strap copper neutrals (20 strips, section 0,66 x 4,57 mm), 100% coverage over the insulation shield, left-hand for the direction of the lay (L) and also for the one of the triplex assembly (L), as shown in Fig. 1.

Note that the outer layer of the conductor for all the cables has a left-hand direction.

Experimental set-up

Fig. 2 shows a diagram of the underground duct bank used for the emergency testing, running from the laboratory basement to a manhole nearly 90 m away. Prior to installation, all the cables were instrumented with thermocouples in the conductor for control, and particularly at several places on the insulation shield beneath the straps. Two triplex cables were installed at a time to form a loop starting in the laboratory basement, running there and back inside 8,9 cm (3,5'') diameter 88-m-long conduits, up to a manhole where the cables are spliced. In the basement, the cable loop passes through a transformer to set the induced current for the thermal loading of the cable. No high voltage was applied to the cable. In the manhole and the basement, the cables are attached as during normal service conditions for splicing, roughly 4 m away from the conduit ends. Near the central part of the duct bank, the PVC conduits were open for 1,5 m in length, and replaced by glass conduits offering the possibility to see the movement of the cable phases during thermal cycling.

Procedure

Six series of thermal cycles were applied consecutively to the triplex cable loop in the duct bank. The first five series, each consisting of five cycles, involved applying the current 16 hours ON and 8 hours OFF to successively reach the 90°, 100°, 110°, 120° and 130°C, controlled at the cable's conductor in the conduit, roughly 8 m away from the manhole. This sequence of thermal cycling was performed to evaluate the physical behavior of the triplex cables from normal operation to emergency conditions. In the last series of thermal cycles, those at 130°C were continued until the specification's accepted limit of 1500 hours cumulative at this emergency conductor temperature [1,2]. In this way, it will be possible to verify how the cables behave during and after such extreme conditions. Note that the current intensity was optimized to rapidly reach the targeted temperature at the conductor in the conduit, in order to increase the duration under these conditions.

Diagnosis

Several diagnostic tools were used to evaluate the behavior of the triplex cables when submitted to the previous thermal treatments. During thermal cycling, the cables were continuously observed using stationary video cameras and their longitudinal and angular displacements measured. The video observation was performed at both the conduit exit and the glass section (Fig. 2). In the first case, the cable rotation was evaluated using a protractor fixed on the wall just outside the conduit. The cable observation in the glass section was essentially qualitative. However, a special device was also developed and used for more precise displacement measurements of the cable's three phases together at the conduit exit. It consisted of electronic sensors fixed via an acrylic disc on the cable and also via a reference metallic bar linked to the duct bank wall. The shrinkage or expansion of the cable leads outside the conduit to a rotation and a linear displacement of the disc, which are translated by the calibrated sensors into angles and lengths.

Furthermore, after the thermal cycles, the cables were removed from the duct bank for visual inspection, sampling and AC breakdown (ACBD) tests. Samples were taken at places where the cables appeared the most affected, for physical evaluation and ACBD tests. These tests were performed in accordance with the ICEA specification [1], using water terminations but on samples with a great active length of roughly 16,5 m. This length represents roughly 20% of the line in the duct bank, which gives a better chance of including all degrees of deformation for a better evaluation.

RESULTS AND DISCUSSION

Displacement

During thermal cycling, the current increase and decrease in the cable loop produced physical expansion and shrinkage of its components, leading to longitudinal and angular displacement of the triplex observed particularly at the conduit exit. Fig. 3 gives the maximum longitudinal displacement obtained once stabilized or just before the

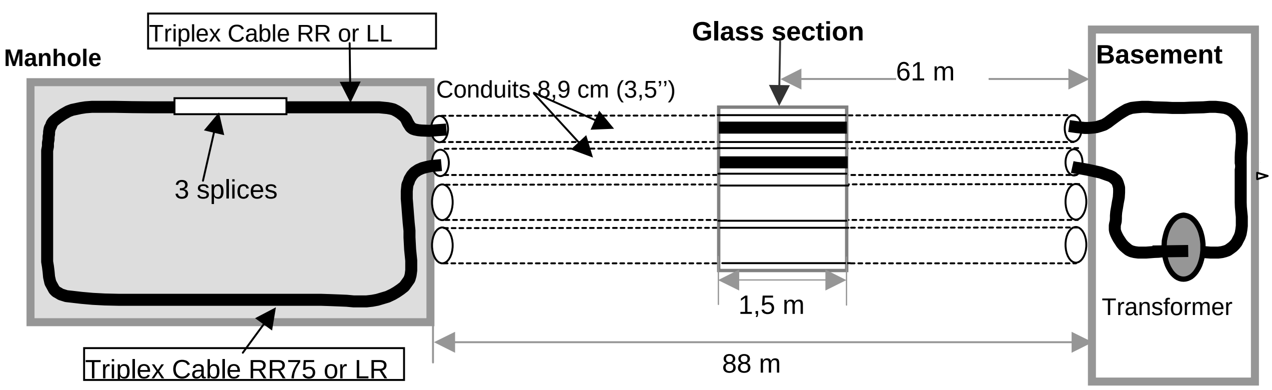

Figure 2 – Diagram of the experimental set-up: underground duct bank extending from a manhole to the laboratory basement

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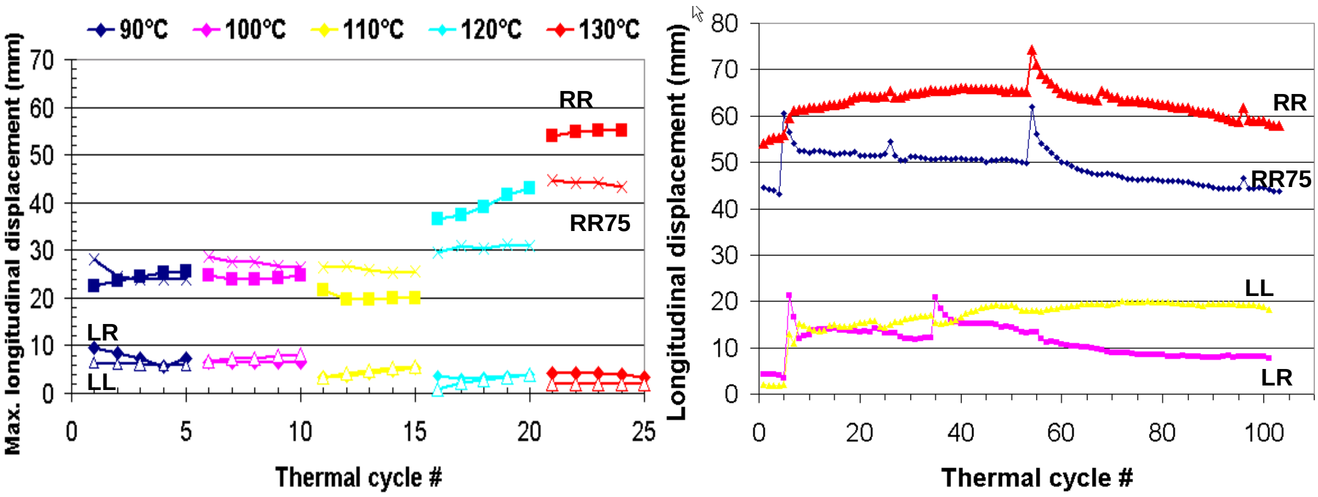

Figure 3 – Longitudinal displacement of the cables at the exit of the conduit in the basement during the first five series of thermal cycles at five temperatures (left) and during all the cycles at 130°C (right).

current cut-off for each cycle. For the first five series of thermal cycles, 90 to 130°C, this displacement is greater and increases over 110°C for cables RR and RR75, going from roughly 22 to 44 and 55 mm, respectively. However, cables LR and LL show very little longitudinal displacement outside the conduit and decrease as the temperature increases, from 9-10 mm to 1-3 mm. Note that all these apparent longitudinal displacements are reversible, i.e. after cooling the cables come back to roughly their original position. The longitudinal displacement of cables with left-hand neutrals is thus between 3 to 30 times less outside the conduit compared to those with right-hand neutrals. Such differences between cables can be explained by how each of them is able to occupy the empty space or free volume in the conduit, which has a clearance of ~12,5 mm with these cables. During heating, it was observed through the glass conduits that the triplex cables rotate helicoidally and each phase separates more or less from the other, and vice versa during cooling. Cables with right-hand lay neutrals have a harder time at higher temperatures to fully occupy the conduit, particularly the cable with 100% neutral coverage (RR). That is why greater longitudinal displacement of the cable is observed outside the conduit, while the other cable types demonstrate that having neutrals in the left-hand direction gives more flexibility to occupy the conduit free volume, leading to very little movement outside, even up to 130°C. The similar results obtained for both cables LR and LL also indicate that the direction of the triplex assembly does not have much influence on cable displacement. Regarding the thermal cycles at 130°C to reach the 1500 hours cumulative limit, shown in Figure 3 (right), the results are relatively the same, except for a slight increase in the outside displacement of cable LL after the 40th cycle. The peaks observed on the previous curves are due to interruptions in the thermal cycling (up to 7 days) for maintenance, which led to much greater cooling of the duct bank, over 10°C, thus causing apparent larger displacement outside due to a greater temperature differential. However, with each cycle the duct bank gets warmer and the displacement decreases to relative stability, with always the same difference between the various cables. The slight increase of the outside displacement of cable LL may be attributed to the different direction of its triplex assembly, the only one that is left-hand. Over time, this would have forced the thermal expansion much more outside the conduit.

The angular displacement results are given in Figure 4 for the two groups of thermal cycles. In the 90-130°C series of cycles, the maximum rotation observed outside the conduits increases more or less after each cycle and also with the temperature, especially for cables RR and RR75, that have neutrals in the right-hand direction. In fact, this increase is principally attributed to some irreversibility in the rotation after cooling, i.e. after a cycle the cables do not fully return to their original angular position, which causes an angular accumulation with each cycle. This is why at the first cycle at 90°C, cable RR rotates up to 97° and at the last cycle at 130°C it reaches 300°, almost a complete revolution. For the other cables, the maximum rotation lies in the same order between 60 to 230° for cable RR75, 50 to 75° for LR and 30 to 65° for LL. These rotations of the cables, occurring in the same direction of the triplex assembly, are due of course to the ones already taking place in the conduit by the thermal expansion and also somewhat related to the direction of the outer layer of the conductor. But, their irreversibility likely stems from the friction forces between phases and the conduit, and also to some plastic deformation, which impedes the regress of the cables. In other words, over time and with increases in temperature, the individual phases occupy on an increasingly permanent basis the empty space in the conduits, thus changing the length of lay of the assembled phases. This is particularly the case for cables LR and LL: their neutrals in the left-hand direction, as the outer layer of the conductor, make them more flexible to occupy the conduit free space, leading to a much smaller rotation outside, compared to cables RR and RR75 with right-hand lay neutrals, which rotate 4 times more on average. With regard to the long-term cycles at 130°C for reaching the 1500-hours limit, as shown in Fig. 4 (right), the irreversibility tends to saturate and the difference between cables is somewhat comparable. Note that the angular reference was reset for these measurements and the down-peaks correspond to maintenance interruptions

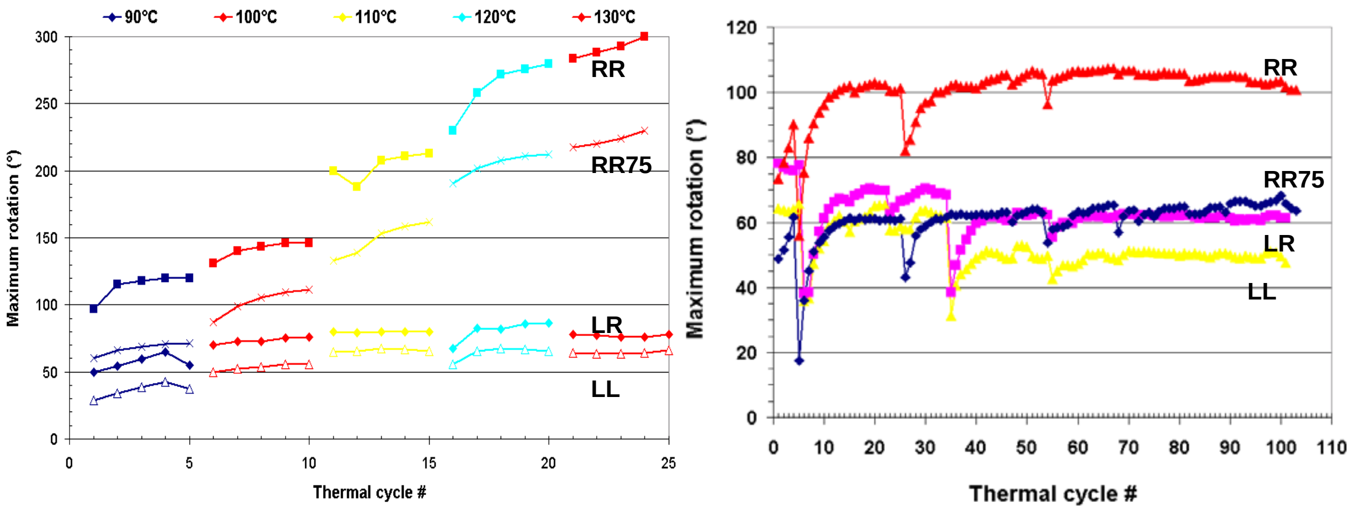

Figure 4 – Angular displacement of the cables at the exit of the conduit in the basement during the first five series of thermal cycles at five temperatures (left) and during all the cycles at 130°C (right)

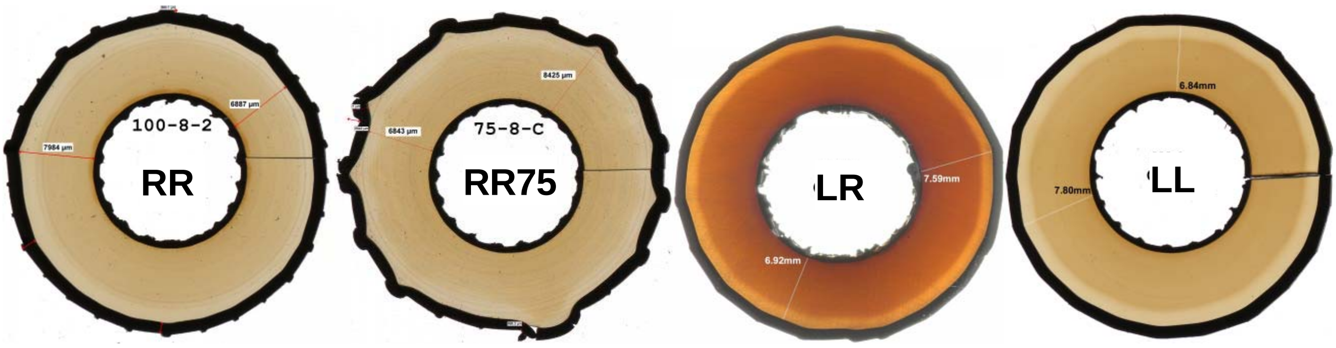

Figure 5 – Slices of the four cables taken after retrieval in the worst portion, as revealed by the visual inspection

as explained previously. Once again the cables with left-hand lay neutrals, particularly LL, have an easier time occupying the free space in the conduit, thus showing less rotation outside. Furthermore, not much Influence was also observed by the direction of the triplex assembly.

After all these series of thermal cycles, the net balance of rotation is 65°, 75°, 245° and 345° respectively for cables LL, LR, RR75 and RR. Although these rotations are quite significant for cables with right-hand lay neutrals -more than four times compared to cables with neutrals in the opposite direction- they could apparently be absorbed easily by the cable length available in the manhole, leaving low mechanical stress on the splices.

Visual examination

Once the thermal cycling was completed, the cables were removed by pulling at one end for a visual inspection. All the cables appeared to be in relatively good condition, with no buckling or twisting being observed. In addition, they were easily retrieved. However, the inspection of the wafers taken from the worst parts shows some neutral indentation on the cable's insulation shield, as revealed by the examples in Fig. 5. Thermal cycling in excess of the XLPE melting temperature indeed caused some neutral penetration, particularly for cable RR75, which was found to be the most affected with a neutral indent up to 1,2 mm, as shown in Fig. 6, and even breaking the insulation shield in some places. Cable LR also shows some neutral indent up to 0,52 mm, but the least penetration were found with cables RR and LL under the specification limit of 0,38 mm for concentric neutral cables. The reason of these differences may be attributed to the lower neutral coverage of cable RR75, which allows radial thermal expansion of the extruded layers between the neutral straps, while the other cables with 100% coverage contains it and makes it more uniform. These local visual inspections show that cable RR75 is the worst affected and cables RR and LL the least. Consequently, the reduction of flat strap neutral coverage is not recommended for XLPE cables when submitted to emergency conditions.

AC breakdown

Fig. 7 gives the results of the ACBD voltages obtained for the three samples (one per phase) for each of the four cables. These results obviously show that cables RR75 and particularly RR have the lowest mean ACBD voltage with 162 and only 110 kV respectively, while cables LR and LL reach 196 and even 215 kV. Note that all the breakdowns were obtained in the active length of the samples, i.e. no termination failure, thus showing actual ACBD values. For comparison these ACBD values obtained for cables RR and RR75 are at the limit of the required ACBD minimum withstand values in the new ICEA specification [7], which

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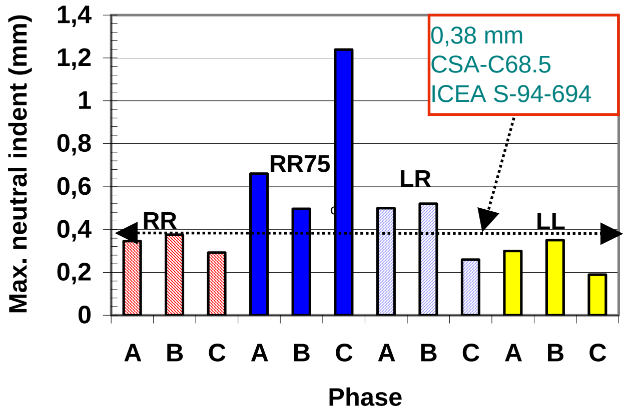

Figure 6 – Maximum neutral indent for the four cables

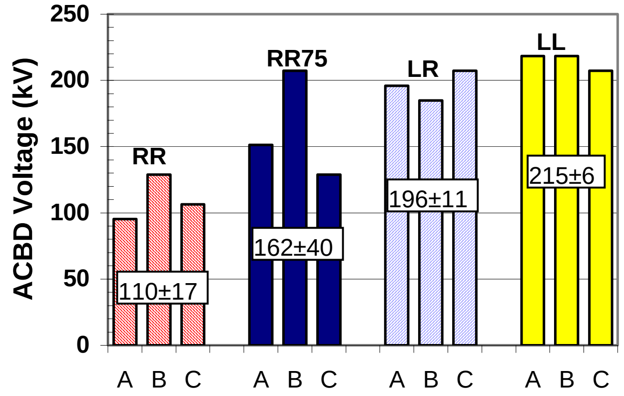

Figure 7 – ACBD voltage of the four cables after thermal cycling with mean value ± standard deviation

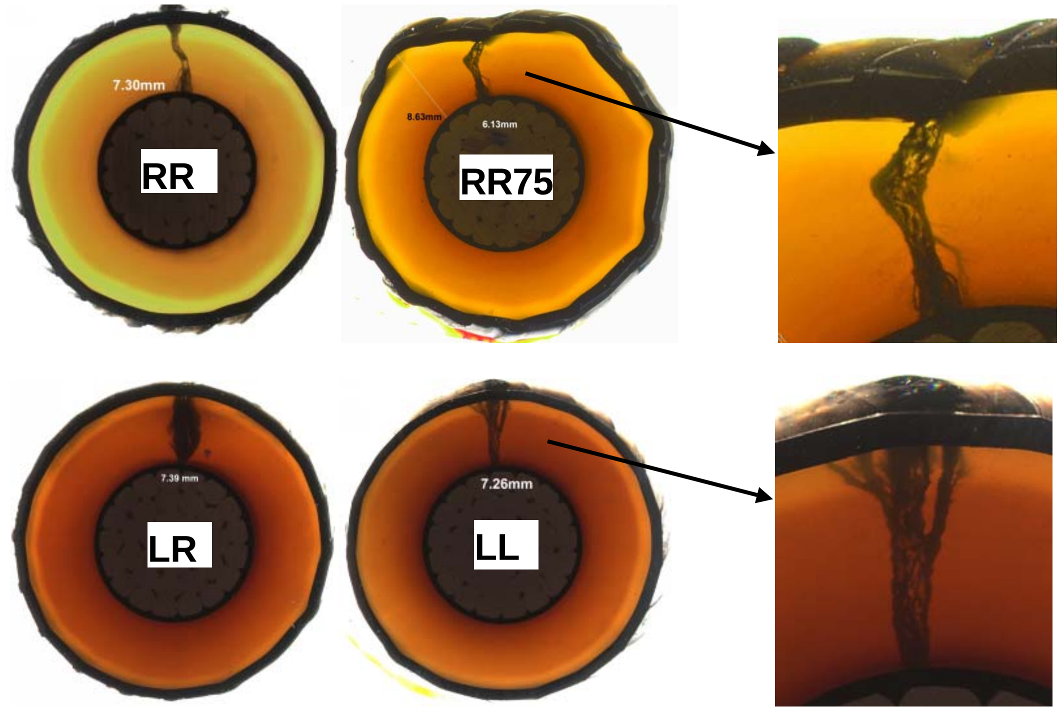

Figure 8 – Slices of each cable showing typical breakdown path after the ACBD test. The insulation thickness is indicated at the breakdown

are 26 and 15 kV/mm after respectively 120 and 360 days of aging, corresponding to roughly 185 and 106 kV for a 28 kV class cable, without considering the volume effect. Furthermore, it was found that breakdowns of cables RR and RR75 all originated from or related to a strong neutral indent in the insulation shield, even in some cases corresponding to "open" insulation, when for cables LR and LL five out of six of the breakdowns originated from the conductor shield; one could not be defined as it has to be burned for localization. Note that such observations for cable RR did not result from the visual inspection, most likely due to interference from the full coverage of the straps. This demonstrates the necessity of the ACBD test to evaluate globally a piece of cable. Fig. 8 gives examples of the breakdown path starting from the insulation shield and developing in electrical branches towards the inner conductor for cables RR and RR75, while for the other two cables the breakdowns originated from the insulation or the conductor shield since the electrical branches are directed towards the outside or the insulation shield. In the first case, the neutral penetration in the insulation shield was such that it generated cracks, which exposed the cable insulation to air, resulting in a local electric field enhancement, which at lower voltages certainly triggered the failure in the form of a breakdown tree with electrical branches developing in the direction of the conductor shield. For cables LR and LL the reverse situation is observed: the breakdown tree appears to start from the conductor shield, develops towards the outside and is not related to the indentation on the insulation shield, which is less marked, as evidenced also by the much greater ACBD voltages. These results demonstrate clearly that cables with flat strap neutrals in the right-hand direction may suffer damaging neutral indentation when submitted to long-term emergency conditions, along with a decrease in electrical performance. Conversely, cables with their flat strap neutrals in the left-hand direction were not so much affected after the same conditions and gave the greatest ACBD voltages. In other words, for a XLPE cable intended to be used “normally” up to emergency conditions, just changing the direction of the flat strap neutrals from right to left results in no damageable neutral indentation and a preservation of its electrical performance.

CONCLUSIONS

Thermal cycling performed up to emergency conditions on XLPE distribution triplex cables with flat strap neutrals installed in a duct bank led to the following conclusions:

- The longitudinal displacement of the cables just outside the conduit is reversible and their thermal expansion takes place helicoidally in the conduit free space. The longitudinal displacement of cables with left-hand neutrals is between 3 to 30 times less outside the conduit compared to those with right-hand neutrals, indicating that the former have the capability to expand much more inside the conduit.
- The cables’ thermal expansion in the conduits also leads to an irreversible rotation of the cables outside, up to ~70° for cables with the lay neutrals in the same direction as the outer layer of the conductor lay, and 245-345°, almost a complete turnaround, for cables with lay neutrals in the opposite direction. Cables with left-hand neutrals rotate thus roughly 4 times less outside the conduit compared to those with right-hand neutrals. These rotations could apparently be absorbed easily by the cable length available in the manhole, leaving low mechanical stress on the splices.
- The direction of the triplex assembly, same or opposite of neutrals lay, does not have much influence on the longitudinal and angular displacements outside the conduit.
- After the 1500-hours cumulative emergency overload, cables with left-hand lay neutrals are much less physically affected and give the greatest ACBD voltages, while cables with right-hand lay neutrals show severe neutral indentation on the insulation shield with some cracks exposing the insulation, and consequently, lowering their electrical performance. It is believed that a cable, in triplex assembly, having its flat strap neutrals in the same direction as the one of the outer layer of the conductor offers a better thermo-mechanical and electrical behavior, particularly under emergency conditions.

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