International Conference on Lightning Protection
33rd International Conference on Lightning Protection
25 - 30 September 2016
Estoril, Portugal

Preliminary analysis of the impulse breakdown characteristics of XLPE-covered cables used in compact distribution lines

Ronaldo E. de Souza Rafael M. Gomes Guilherme S. Lima

Fernando H. Silveira Alberto De Conti Silvério Visacro

LRC – Lightning Research Center
Graduate Program in Electrical Engineering – Federal University of Minas Gerais
Av. Antônio Carlos 6627, 31270-901, Belo Horizonte, MG, Brazil
ronaldoesf@ufmg.br

***Abstract*—This paper presents preliminary results related to the impulse breakdown characteristics of XLPE-covered cables. Tests with standard lightning impulse voltages (1.2/50 µs) applied to a typical single-phase structure employed in compact distribution lines used in Brazil were performed. Results in terms of breakdown voltage, time to breakdown and pinhole location are presented.**

Keywords-breakdown; compact distribution lines; impulse voltage; pinhole formation; XLPE-covered cables

I. INTRODUCTION

Since the mid-nineties, many electric power utilities in Brazil have been replacing conventional medium voltage overhead distribution lines (bare cables supported by ceramic insulators installed on wood cross arms) by a new standard named compact distribution lines (cables covered with cross-linked polyethylene – XLPE – sustained by polymeric insulators and spacers). Fig. 1 shows both conventional and compact distribution lines installed in the electrical system of CEMIG, which is one of the major power utilities in Brazil [1].

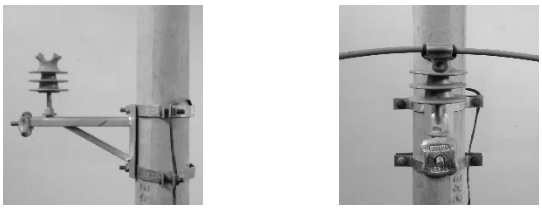
The application of compact distribution lines has several advantages such as the increase of circuit reliability; lower failure rate due to temporary contact between phases or between conductors and trees; safety improvement for people; reduction of the distance between conductors; and less tree trimming [1], [2]. Experimental investigations have also shown that covered cables increase the basic impulse insulation level of the medium voltage distribution lines compared to the use of bare conductors [3], [4].

(a) Conventional configuration with bare conductors. (b) Compact configuration with covered cables.

Figure 1. Overhead distribution lines.

The presence of the XLPE layer surrounding the cable also modifies its behavior when it is submitted to impulse voltages. Specifically in compact distribution lines, the breakdown mechanism of covered cables presents phenomena that do not occur in bare conductors such as deposition of charges on the outer surface of the insulating layer, occurrence of partial disruptive discharge, and pinhole formation [2], [3], [5].

This work aims to present a preliminary investigation of the impulse behavior of a typical single-phase structure employed in compact distribution lines (Fig. 2). The whole structure – a 15-kV pin-type polymeric insulator supporting a 15-kV XLPE-covered conductor without metallic sheath – was submitted to standard lightning impulse voltages (1.2/50 µs). A brief discussion on the main phenomena related to the breakdown process in covered cables is performed. Preliminary results contemplating the impact of the presence of XLPE-layer on breakdown voltage, including the influence of charge deposition and polarity effect on time to breakdown, are presented. Furthermore, a discussion about partial disruptive discharge occurrence and pinhole formation is also presented.



(a) Pin type polymeric insulator. (b) XLPE cable tied to the insulator.

Figure 2. Single-phase structure used in compact distribution lines.

This work has been supported by the Brazilian agency CAPES. Fernando H. Silveira would like to acknowledge the financial support provided by the National Council of Scientific and Technological Development (CNPq), under grant 309326/2015-0. Alberto De Conti would like to acknowledge the financial support provided by the National Council of Scientific and Technological Development (CNPq), under grant 306195/2013-5, and by The State of Minas Gerais Research Foundation (FAPEMIG), under grant TEC-PPM-00066-15.

II. BREAKDOWN MECHANISM OF COVERED CABLES

The characteristics of the cable used in distribution lines have an influence on the associated breakdown mechanism. In bare cables, breakdown takes place when the voltage gradient overcomes the dielectric strength of air. Due to the process of collisional ionization, electrons might be multiplied in an exponential manner leading to a disruptive discharge. Since air is a self-restoring insulation, its insulating properties are completely recovered after the flashover.

On the other hand, covered cables experience the breakdown mechanism where the disruptive discharge in the solid dielectric produces permanent loss of dielectric strength. However, a set of events occurs prior to the formation of a pinhole on the solid dielectric layer.

First, when a covered cable is submitted to impulse voltages, ionization is usually noticed around the insulator/tie region. The presence of an XLPE layer covering the aluminum conductor allows charge deposition to take place on the cable surface. The polarity of this charge is opposite to the polarity of the impinging voltage [3].

The second event is a partial disruptive discharge characterized by a luminous arc between the outer surface of the insulating layer and the grounded part of the insulator. As a result, a drop of several kV in the voltage waveform across the insulator can be observed [3].

The final step of the disruptive process consists of the formation of a pinhole in the insulating layer. Actual breakdown of the cable takes place when the XLPE cover is punctured and a highly luminous breakdown arc is formed between the pinhole and the grounded structure [3].

III. EXPERIMENTAL ANALYSIS

In order to evaluate the impulse behavior of the single-phase structure used in compact distribution lines (Fig. 2), laboratory tests with standard lightning impulse voltages (1.2/50 µs) were performed [6]. The structure is named CM2; it is composed of an L-type support arm, metallic belts, a 15-kV class pin-type polymeric insulator, a 15-kV XLPE-covered conductor, and a non-conducting tie. The whole structure is mounted on a concrete pole and all metallic structures are grounded. The conductor has seven aluminum strands covered with 3-mm thickness of XLPE without a semiconductive layer. Its cross section is equal to 50 mm².

Fig. 3 illustrates the experimental set-up. A six-stage Marx generator provided standard lightning impulse voltages that were applied to the tested structure. Each stage is able to deliver up to 100 kV. The generator output is connected to a capacitive voltage divider and to one termination of the cable.

In [4], the critical flashover overvoltage (CFO) of the CM2 structure with bare cable for positive lightning impulses was estimated. Additional test results obtained with the up-and-down method with a 3-kV voltage step are presented here to complement the results of [4] with negative impulse voltages.

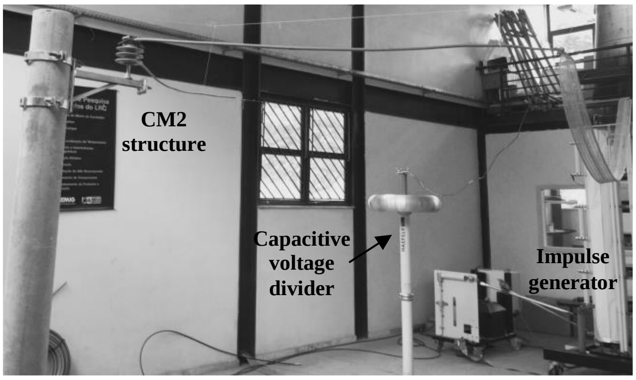


Figure 3. Experimental set-up at high voltage laboratory.

Tests with covered cables were performed for determining the breakdown voltage. The procedure involved applying five impulses per voltage level in steps of 10 kV until the formation of a pinhole.

Each sample of the cable under test was submitted to two different conditions: (i) removal of the accumulated charge, and (ii) no removal of the accumulated charge. In (i), after the application of each voltage impulse, accumulated charges on XLPE surface were removed using a grounded conductive brush. In (ii), the test began with the XLPE cover uncharged, but no charge removal was carried out until the occurrence of the disruptive discharge. Performing tests without charge removal gives a reference of the influence of the accumulated charge on the resulting breakdown voltage [5].

Tests with both polarities were performed. For positive impulse voltages, a 5-m long cable was used. For negative impulse voltages, a 12-m long cable was required to minimize the occurrence of surface discharges to the cable end. During the experiments, photographs were taken for distinguishing surface discharge (Fig. 4) from disruptive discharge with puncture of the XLPE-cover (Fig. 5).

Twenty samples were used in the tests. They were grouped according to the labels shown in Table I. It is important to highlight that only three tests without charge removal for negative voltages were successful in determining the breakdown voltage. In two samples, only surface discharges to the cable end occurred. Because of this, they were disregarded.

Figure 4. Surface discharge.

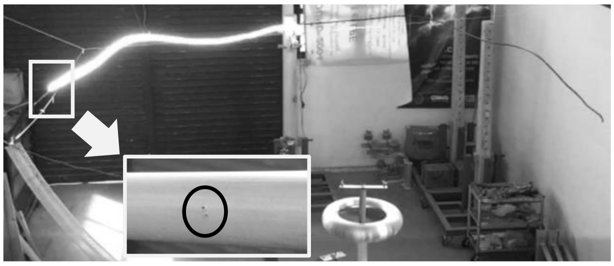


Figure 5. Disruptive discharge with pinhole formation in the XLPE-cover (or breakdown).

IV. Results and Analyses

Results are presented in terms of breakdown voltage, time to breakdown, and distance between pinhole and insulator. Preliminary analyses of polarity effect and charge influence on these three parameters are also developed.

A. *Polarity Effect*

1) *Breakdown voltage*

Table II presents the mean breakdown voltage for the CM2 structure with covered cable obtained in tests with and without charge removal. For the sake of comparison, the resulting CFO for a bare cable installed in the CM2 structure is also indicated. As can be seen, for both polarities the impulse withstand level of the structure increases if a covered cable is used instead of a bare cable. In tests with charge removal, the mean breakdown voltages obtained with covered cables were 86% and 38% higher than the corresponding CFOs obtained for bare cables for positive and negative impulses, respectively.

In addition, the results indicate that the impact of voltage polarity on the impulse withstand levels also depends on the type of cable under test. If a bare cable is considered in the CM2 the structure, the absolute value of the CFO for negative impulses is 20% higher than the one for positive impulses. On the other hand, if a covered cable is considered, the mean value of the breakdown voltage is about 11% lower for negative impulses, in absolute terms, than for positive impulses. This result is in agreement with those presented in [3].

TABLE I. Samples Division for Testing

	Charge removal	
Polarity	***Yes***	***No***
Positive	P1 (7 samples)	P2 (5 samples)
Negative	N1 (5 samples)	N2 (3 samples)

TABLE II. Disruptive Voltages: Polarity Effect.

Polarity	**CFO for bare cable (kV)**	**Breakdown voltage for covered cable (kV)**	
		Uncharged cover	***Charged cover***
Positive	130	242	310
Negative	156	216	273

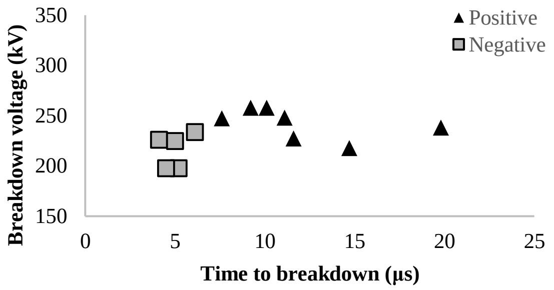
2) *Time to breakdown*

Fig. 6 illustrates the relation between the peak value of the breakdown voltage and the time to breakdown. Data are organized according to tests: (a) with and (b) without charge removal. From Fig. 6(a), it is remarkable the division among positive and negative points when the cable is uncharged before each impulse application. In this condition, the times to breakdown for positive impulses are longer than the ones for negative impulses. For negative voltages, the time to breakdown interval is 4–7 µs, whereas for positive voltages the values are in the 7–20 µs range. This effect has not been noticed in tests without charge removal. Times to breakdown for both polarities are confined to the interval between 2 µs and 7 µs.

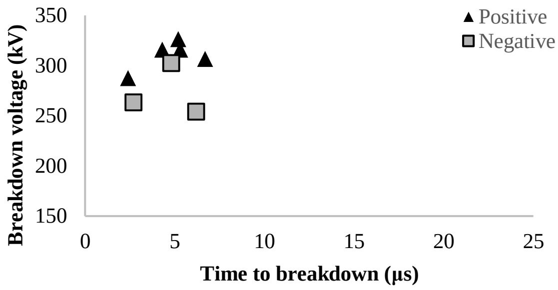
3) *Pinhole location*

Fig. 7 exhibits the distances measured between the pinholes in the cable insulating layer and the insulator for both tests conditions: (a) with and (b) without charge removal. Considering charge removal, a set of pinholes located around 50 cm from insulator for positive impulses is noted. For negative voltages, pinholes are concentrated in a 50–155 cm range.

When the charge removal was not performed, for positive impulses, two pinholes were identified within 4 cm from the insulator and the maximum distance where a pinhole was identified was 87 cm far from the insulator. For negative voltages, two pinholes were formed around 20 cm from the insulator and one pinhole was observed 312 cm far from insulator.

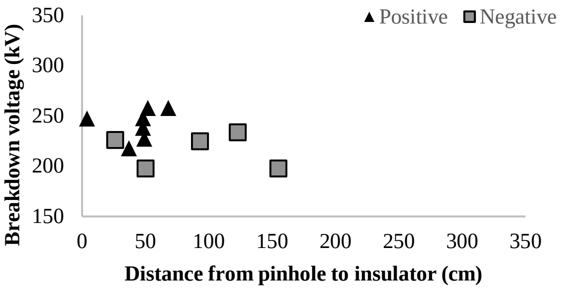


(a) Test with charge removal.

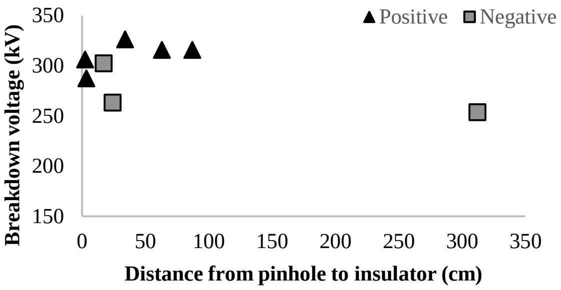


(b) Test without charge removal.

Figure 6. Polarity effect on time to breakdown.



(a) Test with charge removal.



(b) Test without charge removal.

Figure 7. Polarity effect on pinhole location.

B. *Influence of Charge Removal*

1) *Breakdown voltage*

Table III indicates the absolute mean values of the breakdown voltage associated with the CM2 structure considering an XLPE covered cable and different polarities. For positive impulses, tests without charge removal resulted in a mean breakdown voltage 28% higher than the value obtained in tests with charge removal. For negative impulses, the increase of the mean breakdown voltage considering charge deposition was of 27%, approximately.

Assuming an electrostatic condition, the charge accumulated on the XLPE cover creates an electric field in the air that opposes the applied field [5]. When the charge is not removed, the field in opposition is enhanced after the application of each voltage impulse. Thus, the charge deposition contributes to increase the mean breakdown voltage.

TABLE III. BREAKDOWN VOLTAGES FOR CM2 STRUCTURE: INFLUENCE OF CHARGE REMOVAL.

Charge Removal	**Breakdown voltage (kV)**	
	Positive Impulses	***Negative Impulses***
Yes	242	216
No	310	273

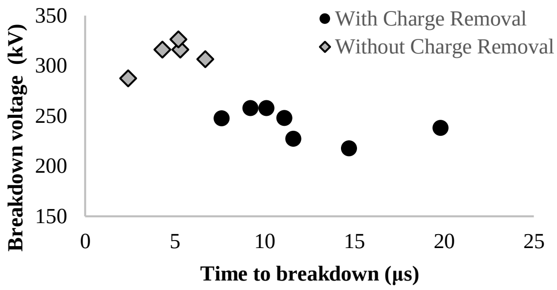
2) *Time to breakdown*

Concerning the influence of charge removal on the time to breakdown, Fig. 8 illustrates the peak value of the applied voltage and the corresponding time to breakdown. For positive impulses, times to breakdown from tests without charge removal are shorter than the ones from tests with charge removal. For negative impulses, the influence of charge removal on the time to breakdown is inconclusive. The values for both test conditions (i) with and (ii) without charge removal are confined in the same 2–7 µs range.

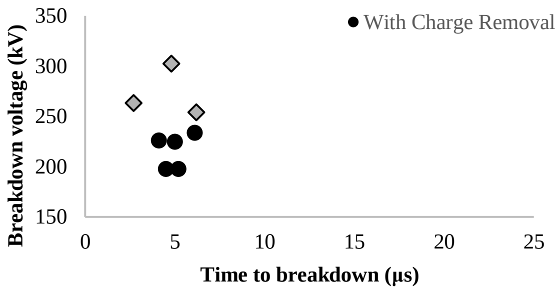
3) *Pinhole location*

Fig. 9 presents the pinhole dispersion along the cable for both impulse polarities. For positive ones, it seems that pinholes from tests with charge removal occur more often at a distance around 50 cm from insulator. From a total of seven samples, six cables were punctured in the 37–68 cm range. Pinholes obtained from tests without charge removal were measured in a wider range of 2–87 cm.

For negative impulses, tests with charge removal provided pinhole formation in the 50–155 cm range. Pinholes from tests without charge removal were observed at distances from 17 to 312 cm.

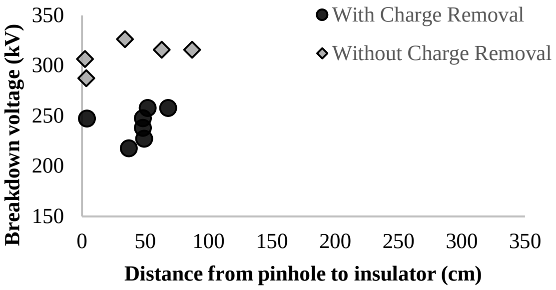


(a) Positive impulses.

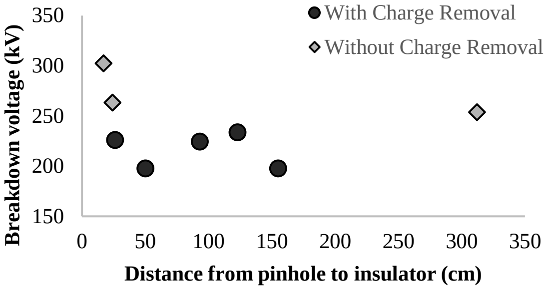


(b) Negative impulses.

Figure 8. Influence of charge removal on time to breakdown.



(a) Positive impulses.



(b) Negative impulses.

Figure 9. Charge removal influence on pinhole location.

C. *Partial Disruptive Discharge*

All the results and analyses presented in sections A and B are related to the occurrence of complete breakdown. However, in some tests partial disruptive discharges were observed, as shown in Fig. 10. This phenomenon occurs when the voltage gradient in the region near the insulator/tie overcomes the breakdown strength of air without leading to damage on the XLPE cover. As indicated in Fig. 11, the voltage measured for this event is characterized by a sudden drop of several kV with prompt amplitude recovery after the extinction of the electric arc.

Table IV indicates the absolute peak value of the impulse voltages measured when partial disruptive discharges were first observed. In tests with positive voltage, partial disruptive discharge was observed only once among 670 applied impulses. It occurred in the test with charge removal at the 198-kV level.

Figure 10. Partial disruptive discharge.

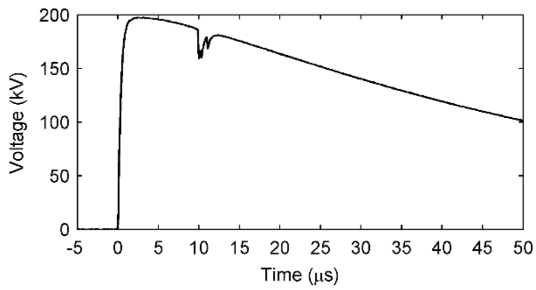


Figure 11. Voltage drop on the waveform measured during the occurence of a partial disruptive discharge.

TABLE IV. PARTIAL DISRUPTIVE DISCHARGE VOLTAGES FOR CM2 STRUCTURE.

Charge Removal	**Partial disruptive discharge voltage (kV)**	
	Positive Impulses	***Negative Impulses***
Yes	198	168
No	–	179

When negative impulses were applied, partial disruptive discharges often occurred in tests with charge removal. For this condition, partial disruptive discharges first occurred at 168-kV level. After this, twelve other events were observed until the occurrence of a breakdown with consequent pinhole formation at the 216-kV level. In tests without charge removal, only three partial disruptive discharges occurred and the first one took place at the 179-kV level.

V. CONCLUSIONS

This work presents a preliminary analysis of the impulse breakdown behavior of a typical single-phase structure used in compact distribution lines in Brazil. This structure is composed by an XLPE-covered cable tied to a pin type polymeric insulator.

Tests with standard lightning impulse voltages (1.2/50 μs) were performed to determine breakdown voltage values, times to breakdown, and pinhole location on the XLPE cover. Twenty samples of covered cables were used. Positive and negative impulses were applied and two test conditions were evaluated: (i) with and (ii) without charge removal from the XLPE surface.

Preliminary results have shown a better lightning impulse performance of the structure if covered cables are used instead of bare cables. For negative impulses, the absolute value of the CFO associated with the use of a bare conductor is 156 kV. In tests with charge removal, partial disruptive discharges have been first observed at the 168-kV level. Complete breakdown occurred only at 216 kV. For positive impulses, the performance was even better, since the breakdown voltage of the structure considering a covered cable was 86% higher than the CFO of the same structure obtained considering a bare cable. In addition, only one partial disruptive discharge has been observed for positive impulses. It occurred at the 198-kV level in the test with charge removal.

Preliminary analyses have also indicated the influence of charge deposition on the breakdown voltage. When the charge accumulated on XLPE-cover was not removed, the mean breakdown voltage was 27% higher than the value obtained in tests with charge removal.

The obtained results were not conclusive concerning the polarity effect and the influence of charge deposition on pinhole location in terms of the impulse breakdown voltage. Apparently, there is no correlation between the distance of the pinhole formed on the XLPE cover and those factors.

Additional tests are under development by the authors in order to provide a greater number of samples to guarantee a more consistent assessment of the presented evaluations. Also, since the extension of the obtained results for a three-phase structure is not straightforward due to the introduction of new parameters that are capable to influence the resulting breakdown voltage, additional evaluations considering this type of structure are also under development.

REFERENCES

[1] R. C. C. Rocha, R. C. Berrêdo, R. A. O. Bernis, E. M. Gomes, F. Nishimura, L. D. Cicarelli, and M. R. Soares, "New technologies, standards, and maintenance methods in spacer cable systems," *IEEE Trans. Power Deliv.*, vol. 17, no. 2, pp. 562–568, 2002.

[2] J. He, S. Gu, S. Chen, R. Zeng, and W. Chen, "Discussion on measures against lightning breakage of covered conductors on distribution lines," *IEEE Trans. Power Deliv.*, vol. 23, no. 2, pp. 693–702, 2008.

[3] K. Nakamura, P. J. McKenny, M. S. A. A. Hammam, G. Adams, R. Fernandes, and F. Rushden, "Impulse Breakdown Characteristics of 13.2 kV Covered Conductor Insulator/Tie Configurations ," *IEEE Trans. Power Deliv.* , vol. PWRD-1, no. 4, pp. 250–258, 1986.

[4] G. S. Lima, R. M. Gomes, R. E. Souza, A. De Conti, F. H. Silveira, S. Visacro, and W. A. Souza, "Influence of XLPE-covered cables on the impulse withstand voltage of a single-phase structure used in compact distribution lines," in *2015 International Symposium on Lightning Protection (XIII SIPDA)*, 2015, pp. 260–263.

[5] M. Darveniza, "Electrical breakdown of air between insulated conductors," in *Proceedings of the 6th International Conference on Properties and Applications of Dielectric Materials*, 2000, vol. 2, pp. 615–620.

[6] IEC, "IEC 60060-1 Ed. 3.0: High-voltage test techniques Part 1: General definitions and test requirements," 2008.