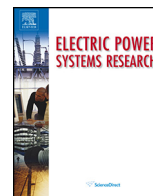




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# Impulse withstand voltage of single-phase compact distribution line structures considering bare and XPLE-covered cables

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### ABSTRACT

This paper is dedicated to investigate the impulse withstand voltage of single-phase compact distribution line structures of 15 kV class. The structures are tested in laboratory with the application of standard lightning impulse waveforms of positive polarity. Three situations are considered: (i) XLPE-covered cables with brand new insulation; (ii) XLPE-covered cables with punctured insulation; (iii) bare cables, aiming at assessing the critical case in which the insulating layer of the cable is completely deteriorated. The results indicate that the presence of an XLPE layer covering the cable leads to a significant increase in the impulse withstand voltage of the investigated structures compared to the use of bare cables. In the cases considering brand new XLPE-covered cables, insulation breakdown leads to the formation of a pinhole in the insulating layer at points up to about 200 cm from the tested structure. The presence of pinholes in the tested cable specimens has no significant effect in the breakdown voltage of the tested structures, except when the pinhole is sufficiently close to the pole. Finally, to provide elements for investigating the performance of the structures when subjected to nonstandard impulse voltages, parameters for volt-time curves and for the disruptive effect (DE) method are provided for the critical case of structures with bare cables.

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## 1. Introduction

Compact distribution lines, also known as spacer-cable lines, have emerged as a technical solution to improve the electrical performance of distribution lines [1–3]. They consist in the use of insulated cables attached to non-metallic spacers that are sustained by a steel cable. Fig. 1 illustrates three-phase and single-phase compact distribution lines. Details about their components can be found in [3–5].

The use of compact distribution lines has significantly increased in the last decades. CEMIG, one of the major power utility companies in Brazil, standardized the use of three-phase compact distribution lines in urban areas in 1998 after ten years of tests [2]. Data from 2015 indicate that out of 36,300 km of 13.8-kV medium-voltage distribution lines installed in urban areas by CEMIG, 28% already correspond to compact lines [4].

Reports have shown an improvement of power quality indicators when compact distribution lines are compared to con-

ventional overhead lines composed of bare aluminum cables, wood crossarms and porcelain insulators [2–4]. The better performance of compact lines is mainly justified by the XLPE insulating cover of the cable, which reduces the number of outages due to contact with tree branches, animals, and extraneous objects. A lower number of outages due to lightning is also expected due to a presumable increase in the impulse withstand voltage of compact lines compared to conventional lines. In addition, the presence of the steel cable that sustains the non-metallic spacers contributes to reducing the amplitude of lightning-induced voltages on compact lines [6,7]. The good performance of compact distribution lines has motivated Brazilian power utilities to expand their use also to single-phase distribution lines applied in rural areas.

Despite the improvement of power quality indicators associated with the use of compact distribution lines, there are still uncertainties regarding their lightning performance. One of the reasons is the lack of available experimental data on their impulse withstand voltage. This is an important concern because lightning is still a major cause of outages in distribution lines, being responsible for about 30% of the outages in the distribution networks of CEMIG from 2010 to 2012 [3]. Another concern associated with the use of compact lines is related to the fact that the electric arc associ-

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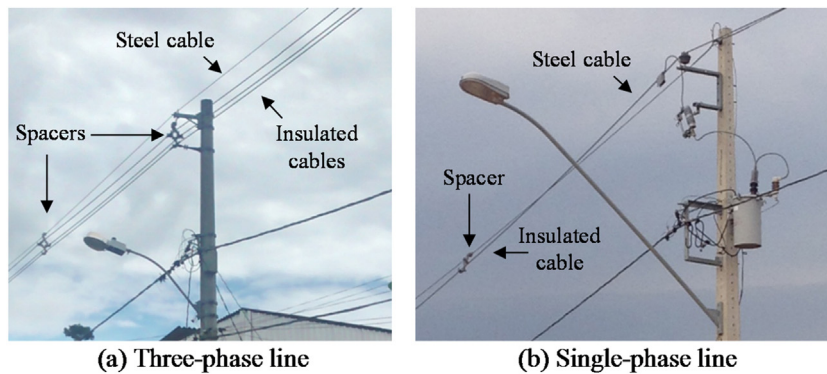


Fig. 1. Compact distribution lines. (a) Three-phase line and (b) Single-phase line.

ated with the short-circuit current following insulation breakdown caused by a lightning event tends to concentrate at a single point on the cable if it has an insulating layer, which can lead to cable burndown [8,9].

This context has motivated the study presented in this paper, which is dedicated to estimate the impulse withstand voltage of the main single-phase structures used in compact distribution lines in Brazil. The text is organized as follows. Section 2 describes the tested structures. Section 3 describes the test procedures. Section 4 presents the obtained results, together with parameters for estimating the behavior of the tested structures when subjected to nonstandard lightning impulses for the particular case of bare cables. Section 5 presents the conclusions.

## 2. Tested structures

The main structures used in single-phase compact lines of 15 kV class in Brazil are illustrated in Fig. 2 [10]. They are referred to as CM1 [Fig. 2(a)], which uses a polymeric spacer and is applicable to tangent poles with a maximum line angle of  $6^\circ$ ; CM2 [Fig. 2(b)], which uses a polymeric pin-type insulator and is applicable to poles with a maximum line angle of  $60^\circ$ ; and, finally, CM3 [Fig. 2(c)], which uses a polymeric strain insulator and is applicable to line ends. The polymeric spacer in the CM1 structure is suspended by a metallic arm as shown in Fig. 2(a). To reduce the line swing, the lower part of the spacer is fixed to the pole by a polymeric arm. In the CM2 structure, the pin-type insulator is mounted over a metallic crossarm. Finally, in the CM3 structure a medium-voltage surge arrester is always present to reduce lightning overvoltages, as shown in Fig. 2(c). In all cases, a steel cable known as messenger is connected directly to the pole top. It has the function of sustaining spacers like the one of the CM1 structure shown in Fig. 2(a) when used in the mid spans [see Fig. 1].

The phase conductor in structures CM1, CM2, and CM3 is an aluminum cable with nominal cross-section of  $50 \text{ mm}^2$  covered by a 3 mm XLPE layer. It is attached to the CM1 and CM2 structures using an elastomeric ring made of polymeric material. Fixation of the cable to the CM3 structure is performed using a metallic clamp.

In this paper, an attempt is made to estimate the impulse withstand voltage of the structures shown in Fig. 2 in the three following conditions: (i) phase conductor with a brand new XLPE cover, (ii) phase conductor with a pinhole in the XLPE cover, and (iii) bare phase conductor. Case (iii) is useful for providing reference values to which the results obtained from cases (i) and (ii) can be compared. It can also be considered representative of extreme conditions in which the insulating layer of the phase conductor has been completely damaged. Details of the test procedures adopted in cases (i)–(iii) are given in the next section.

## 3. Procedures for determining the impulse withstand voltage of compact line structures

### 3.1. Tests considering bare cables

The critical flashover overvoltage (CFO) corresponds to the peak value of the impulse voltage that leads to 50% probability of occurrence of a flashover in a self-restoring insulation, while the volt-time curve relates the peak value of the applied impulse voltage with the time to flashover [11]. To estimate the CFOs and the volt-time curves of the structures of Fig. 2, tests were first performed considering bare cables. The CFO was determined using the traditional up-and-down method with a minimum of 20 impulses counted from the first flashover in the test sequence [11,12]. The volt-time curve was obtained by increasing the peak value of the applied impulse voltage and annotating the associated time to flashover until obtaining a significant number of points.

The tests were performed using a Haefely Marx generator of six stages (SGSA 600 kV, 30 kJ), each with a maximum voltage of 100 kV. In all cases, a standard  $1.2/50 \mu\text{s}$  voltage waveform of positive polarity was applied at the tip of the cable (aluminum,  $50 \text{ mm}^2$ ), which had a total length of either 80 cm (structures CM1 and CM2, with 40 cm extending to each side of the pole) or 40 cm (CM3 structure). The structures were attached to a concrete pole and their metallic parts were grounded. The tests were performed in laboratory temperatures between  $22^\circ\text{C}$  and  $28^\circ\text{C}$ , relative humidity varying from 55% to 82%, and atmospheric pressure of 699 mmHg. All measured values were corrected to standard environmental conditions.

The exclusive consideration of positive polarity impulses is justified by the fact that lightning-induced voltages due to nearby cloud-to-ground lightning are the most frequent source of overvoltages in distribution lines. This phenomenon is typically associated with downward negative lightning, which transports negative charges from the cloud to the ground and induces voltages predominantly of positive polarity on the closest point of the illuminated line [13–15]. Direct lightning strikes are also relevant to the lightning performance of compact distribution lines. However, estimation of the breakdown characteristics of the tested structures due to direct lightning strikes would require the application of both positive and negative polarity impulses [16], which is out of the scope of this work.

The volt-time curves associated with the tested structures were fitted using an equation of the form

$$V(t) = A + B \cdot t^n \quad (1)$$

where  $B$  and  $n$  were obtained in a least square sense for the value of  $A$  that leads to the highest coefficient of determination in a range varying from 0 to the CFO.

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