2019 International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Analysis of the Maximum Overvoltages Conducted to the Low Voltage Electric Installations

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***Abstract* — Studies indicate that approximately 100 million lightning flashes reach Brazilian soil per year, causing damages to both energy utilities and consumers. In critical periods, with great atmospheric activity, there is a significant increase in consumer complaints, due to high interruption rates and frequent fails in electrical equipment and installations. For that, data from previous researches, recent bibliographic sources, Brazilian standards and technical specifications of electric companies were used, in order to develop models that are as representative as possible in simulations in the ATPDraw. More than 1000 simulations were run out, resulting a data collection that allowed the elaboration of charts of occurrence cumulative probability of maximum overvoltages in the low voltage installations, due to direct lightning flashes in the medium and low voltage lines, in several types of lines and soil resistivity conditions. Analysis of these charts shows that the probability of high levels of overvoltage occurring at LV consumer electrical installations is low and, in the vast majority of cases, equipment malfunctions can be avoided with the proper use of surge suppression devices.**

Keywords* — *Distribution Lines, LV Installations, Overvoltages, Surges.

I. INTRODUCTION

Although it has a predominant tropical climate, Brazil is an extensive country and, in this way, presents distinct regions in climatic conditions. In the summer months in some regions and in the near periods the changes of seasons in others, the number of storms is extremely high and consequently also very large the amount of lightning flashes that reach these regions. Most distribution lines are aerial and vulnerable to the effects of lightning impacts. Overvoltages from direct lightning flashes to the lines can cause great damages, from supply interruptions to malfunctions of equipment installed in utility lines and in consumer electrical installations [1], [2].

In critical periods in terms the storms, there is a significant increase in consumer complaints, due to high interruption rates and frequent faults in electrical equipment and installations. The resolutions issued by the regulator define minimum standards of energy quality that must be maintained by the distribution companies. It is determined that any damage to an electrical installation with a voltage lower than 2.3 kV, generated by an instability from the utility distribution line, must be reimbursed to the consumer by the company [3].

Currently, there are many questions about the origin of the consumer equipment malfunction. In many situations, the equipment can be damaged by surges from direct lightning strokes on the own buildings or that reach points close to them. However, it is possible the occurrence of surges conducted from the distribution lines to the low voltage (LV) electrical installations [1]. Thus, the knowledge of the maximum levels of lightning overvoltages in distribution lines and electrical installations of consumers can subsidize the decision in processes of reimbursement of damages. Such condition is in the interest of both the consumer and the utility.

In this work, the results of a study on the maximum values of overvoltage that can occur in the electrical installations of consumers from direct lightning flashes on the medium and low voltage lines are presented. For the reliability of the results, analytical calculations, simulations in ATPDraw® and results from previous experiments are used. The modeling of the components was done considering the standards of distribution lines commonly used in the southern region of Brazil, one of the most critical regarding to the frequency of lightning occurrence.

II. METHODOLOGY

The methodology used is basically as follows:

- a typical MV/LV circuit is selected from the regions with the highest number of occurrences due to lightning;
- this circuit is modeled, as representative as possible, in components and circuits of the ATPDraw, as well as the sources of current and voltage;
- simulations are performed with the sources positioned at different points in the circuit;
- tabulation and statistical treatment of results.

To achieve the proposed objectives, typical overhead distribution lines of non-urban regions, where lightning occurrences are more frequent, are considered. It was not taken into consideration possible shielding from buildings or afforestation.

For modeling and simulation purposes, it was considered a medium voltage circuit (MV) having at the end a transformer which feeds a LV line with a typical topology [4]. The transformer is in the load center of the LV circuit with symmetrical topology. The lines are considered according to the established by the Brazilian standards [5], [6], with the transformer protected by metal oxide surge arresters [7] installed close to MV bushings. The number and location of the consumers installations were also obtained from the typical LV circuit.

The lightning parameters used in this paper are in accordance with the recommendations of IEEE Guide 1410 [8] and CIGRÉ working Group C 4.407 [9]. The simulations were performed with the current source positioned at different points for both, MV and LV lines. The ATPDraw current source used was the Heidler model with different peak values and waveform.

For each peak value, waveform and location of the current source, voltages peak values were obtained in several points of the LV line. The simulations were performed for MV lines in the conditions with and without neutral conductor and for different soil resistivities.

Finally, using MATLAB®, data is imported from ATP, which is tabulated and treated statistically in Microsoft ® Office Excel.

III. Initial Conditions, Modeling and Simulations

A. Line Characteristics

1) Typical Circuit

The typical circuit considered is a LV line powered by a 45 kVA distribution transformer (DT), which in turn is powered by an MV line with just over 1 km.

The average number of consumers is 52 and the average topology arises in a bilateral circuit with the transformer installed in the load center. Fig. 1 shows the typical LV circuit topology of one phase on one side of the distribution transformer [4].

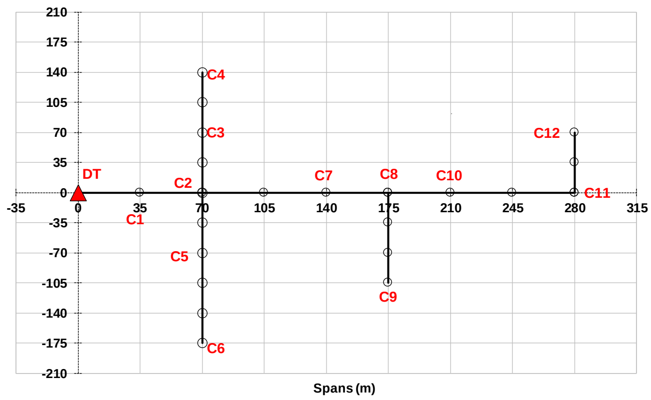

Fig. 1. Typical LV Circuit (1 Phase, one side)

C1 to C12 represent the consumers installation positions selected for verification of the maximum overvoltages.

The average span of LV lines is 35 m, while the MV lines have an average span of 70 m. The MV structure is the type P1 [5] and the secondary circuit is composed of bare conductors vertically aligned and spaced by 20 cm, with the neutral conductor positioned above the phases. In P1 type structures, the center phase conductor is higher than the others.

2) Materials and Equipment

The conductor considered for MV line is 2 AWG (ACSR) and for LV line is 2 AWG (AC). The 45kVA DT is the sampling mode in many distribution systems in southern Brazil. The TD is protected by metal oxide surge arresters installed close to the MV bushings. The rated voltage considered is 12 kV, for 13.8 kV distribution systems.

The insulator for medium voltage is the pillar type with 125 kV of insulation level and for low voltage is the pulley type insulator with insulation level of 35 kV.

MV lines are generally supported by 10 m concrete poles type double T (dT). The same type of pole is used in low voltage lines, but with 9 m in length, and in mixed lines (MV / LV) with 11 m length. Thus, the conductor's height above soil in the insulators is 7.4 m for LV lines and 8.3 m for MV lines.

3) Grounding Systems

Grounding systems are executed with vertical rods interconnected and aligned. The maximum grounding resistance admitted is 25 Ω and no point of the line can be more than 200 m from a grounding point. Despite the recent changes in Brazilian standards, these are the conditions of grounding systems of the existing lines.

In consumer electrical installations, grounding is performed with only a vertical rod of 2.4 m and 5/8 inch.

The neutral conductor groundings of the lines are executed with vertical rods interconnected in necessary quantity to obtain a maximum resistance of 25 Ω, or until the limit of 7 rods. In cases where it is not possible to obtain the normalized value of ground resistance, it must be compensated by the increase in the number of ground points [10], using factor q:

$$Rat \leq 8{,}33q \tag{1}$$

where q = grounding points number/km and Rat ≤ 100 (Ω).

B. Lightning Parameters

The wave form of the return current considered is that of the first negative downward stroke, with peak values behaving as a log-normal statistical distribution and the occurrence probability estimated by (2).

$$p(I_o) = \frac{1}{\sqrt{2\pi}\beta I_o} e^{-\left(\frac{z}{2}\right)} \tag{2}$$

where: $z = \left(\frac{\ln(I_o / M)}{\beta}\right)^2$, with M = 31.1 kA and β = 0.484.

The effective front time values were obtained considering the correlation between parameters suggested by ANDERSON and ERIKSSON, in the CIGRÉ report [9]:

$$S_{30/90} = 3.2 I_p^{\,0.25} \tag{3}$$

for $t_{fe} = T_{30/90}/0.6$ and $S_{30/90} = 0.6 I_p / T_{30/90}$

The tail times values were selected based on those suggested by IEC 62305-1 [11]. Consequently, the values of effective front time and tail time used in the simulations of direct lightning are shown in Tab. I, for the different peak current values. Also, it is included in this table are the parameters used in the Heidler source in the ATPDraw.

TABLE I. Current Impulse Wave Form for Direct Strokes

I_p (kA)	T_{fe} (μs)	T_f (μs)	T_h (μs)	Heidler Wave Form Parameters			
				$T1$	$T2$	$T_{35\%}$	n
10	1.8	5.7	50.1	3.5	70.0	69.0	10
20	3.0	9.8	100.2	5.9	140.0	138.9	10
40	5.0	15.9	100.1	10.2	135.0	135.8	10
80	8.6	27.0	199.6	17.4	272.3	272.9	10
100	9.8	26.0	199.8	16.6	271.2	271.4	10
150	13.3	41.0	350.3	25.7	480.0	481.4	10
200	16.7	53.0	349.7	33.6	474.0	475.7	10

C. Modeling

1) LV and MV Distribution Lines

For simulation purposes, single-phase lines were considered, using the central conductor of the MV line, neutral conductor and phase A of the LV line. The model chosen in ATPDraw to represent the line segments was JMARTI. The parameters, such as the conductor's characteristics, spans length, operating and surge frequency, and horizontal and vertical position of the conductors, are in accordance with section A. However, 3 soil resistivity conditions were considered: 100, 500 and 1000.

2) Concrete Poles

The concrete pole was modeled by a surge impedance Z_p (Ω), calculated according to (4) as recommended in [13], and by a ground resistance. Studies, simulations and field tests [14] show that it is possible to estimate the contribution of the conventional concrete pole to the line ground, using (5).

$$Z_p = \frac{60}{\sqrt{\varepsilon_r - {j\sigma}/{\varepsilon_0 \omega}}} ln\left(\frac{h+\sqrt{h^2+R_{avg}^2}}{R_{avg}}\right) \tag{4}$$

where h is pole height, R_{avg} is the mean pole radius, ω the angular frequency, ε_o and ε_r are the electrical permittivity for vacuum and the relative electrical permittivity of the concrete, respectively, and σ is the electrical conductivity of the concrete.

$$Rp = \frac{\rho_c}{2\pi e} ln\left(\frac{r_c}{r_{fe}}\right) + \frac{\rho_s}{2\pi e} ln\left(\frac{2e}{r_c}\right) \tag{5}$$

where R_p (Ω) is the pole ground resistance, ρ_c and ρ_s are the electrical resistivities of concrete and soil, respectively, r_c and r_{fe} are the radii of the equivalent cross-sections of the concrete and iron, respectively, and e is the depth of the base of the buried concrete.

For the buried concrete, it is considered an average resistivity of 75 Ω.m. The depth e = L/10 + 0.6, where L is the pole height (the minimum value for e is 1.5 m).

TABLE II. SURGE IMPEDANCE OF THE POLES

L (m)	Z_A [Ω]	Z_B [Ω]	Z_C [Ω]
9	15.10	13.68	-
10	15.10	13.67	12.89
11	15.23	13.71	-

TABLE III. GROUNDING RESISTANCE OF THE POLES

ρ_s (Ω.m)	*L* (m)	R_P [Ω]
100	9	58.36
	10	55.19
	11	52.36
500	9	177.7
	10	166.9
	11	157.4
1000	9	326.9
	10	306.6
	11	288.8

The surge impedances of the poles are shown in Tab. II, where ZA is the impedance of the pole part between the MV insulator and the neutral insulator; ZB the impedance of the pole part between the neutral insulator and the ground level; ZC is the impedance of the pole between the MV isolator and the ground level (line without neutral). The grounding resistances, for different resistivity conditions are shown in Tab. III. Fig. 2 shows the 3 types of ATPDraw circuits of MV lines used in the simulations.

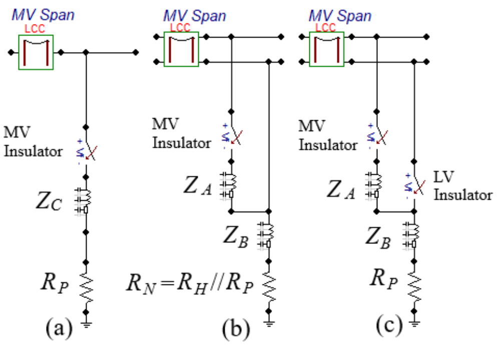

Fig. 2. ATPDraw Circuits of Span with Pole: a) Line without Neutral; b) Phase/Neutral Line: Grounding Point; c) Phase/Neutral Line

Note: Resistance of neutral conductor (R_N): grounding with aligned rods (R_H) more the grounding pole contribution (R_P).

3) Insulators

For the purpose of modeling and inserting this component into the model circuits, the insulators were modeled as voltage-controlled switches, as show Fig. 2.

Flashover voltage of 35.6 kV was obtained for the LV insulator, from laboratory tests results [15]. For the pillar insulation (MV), the flashover voltage was calculated by the DE (Disruptive Effect) method [15] which has the following equation:

$$DE = \int_{t_0}^{t_b} [v(t) - V_0]^K \cdot dt \tag{6}$$

where *DE* is the constant disruptive effect for a given interval under a specified voltage waveform, *v*(t) is the instantaneous voltage over the insulation, V_0 is the initial voltage or minimum voltage to be exceeded, t_0 is the time when V_0 is exceeded and t_b is the time at which disruption occurs. The parameters V_0 and K can be estimated using different procedures proposed by literature. For distribution line insulators, recent studies [12] suggest using (7).

$$K = \alpha \times \frac{v(t)}{V_0} \tag{7}$$

In this paper, for MV insulator, the used constants are: DE = 270 (kV.μs), Vo = 0.6 CFO (kV) and α = 0.24. The CFO (Critical Impulse Flashover Voltage) for pillar insulator is around 140 kV. This value can be different due to different materials (porcelain or polymer) and installation position.

TABLE IV. INSULATOR FLASHOVER VOLTAGES

Ip(kA)	Insulator Flashover Voltage (kV)
	Direct Strokes
10	217,80
20	176,40
40	176,40
80	147,60
100	147,60
150	131,40
200	131,4

Tab. IV shows the flashover voltages for the voltage-controlled switches, obtained from the characteristics of the insulators, current and voltage waveforms and equations (6) and (7).

4) Distribution Transformer

The transformer model used was developed in [16] for analysis of surges transferred to secondary when lightning occurs close to the MV Line. The three-phase model consists of three equal single-phase RLC circuits. In this paper, a single-phase model is used with the parameters for nominal line voltage of 13.8 kV/ 220-127 V and power of 45 kVA, according to Fig. 3.

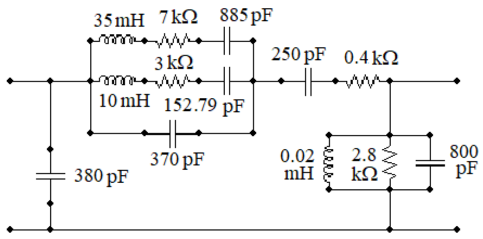

Fig. 3. Distribution Transformer ATPDraw Circuit

5) Surge Arrester

The surge arrester is modeled on the software like a variable resistor. The *I* x *V* curve was obtained from manufacturer datasheet for the 12 kV model [17].

6) Consumer Installation

The load of an electrical installation is variable, according to the installed and connected devices. In this case, an average typical single-phase load [19] was used, whose equivalent circuit is shown in Fig. 4.

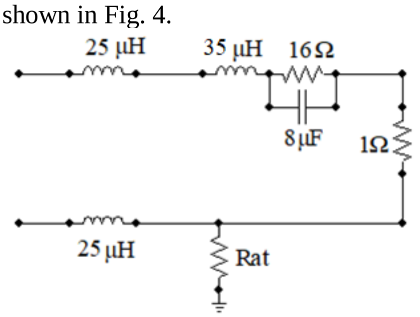

Fig. 4. Circuit of a Typical Single Phase Load

7) Grounding Systems

For simulation purposes, grounding points are modeled by a single resistance.

Resistance of consumers installation, shown in Fig. 4. is calculated by (8).

$$Rat = \frac{\rho}{2\pi L} \times ln\left(\frac{4L}{d}\right) (\Omega) \quad (8)$$

where ρ is the soil resistivity (Ω.m), L is the rod length [m] and d is the diameter [m].

The equation to calculate *Rat* for interconnected rods [20] is:

$$Rat = \frac{1}{n}\frac{\rho}{2\pi L}\left(ln\frac{4L}{a} - 1 + \frac{L}{d} ln\frac{1{,}781n}{2{,}718}\right) (\Omega) \quad (9)$$

where n is the number of interconnected rods, ρ is the soil resistivity (Ω.m), L is the rod length [m], a is the rod radius d is grounding system depth. The spacing between rods must be equal to its length.

In MV lines, with neutral conductor, the grounding resistance is calculated considering the grounding pole contribution.

8) Simulations

The simulations conditions are the following:

- 3 types of MV Line: with and without neutral conductor and with neutral conductor and number of grounding points increased;
- 2 types of LV line: with neutral and with number of grounding points increased;
- 4 points of direct impact on LV line: end of line;
- 5 points of direct impact on MV line: from 35 up to 1085 meters from DT;
- 7 different peak values of current with different wave forms;
- 3 different soil resistivities: 1000, 500 and 100 (Ω.m).

In total, in this work, more than 1300 simulations were carried out that demanded more than 110 hours.

To analyze the behavior of the surges along the lines, ATPDraw modules of ammeter and voltmeter were used.

IV. Analyzes of Results

A. Surge Attenuation along the Medium Voltage Line

The results presented below, were obtained for the case of current source located at 1085 m from the DT, on the MV conductor.

The current behavior along the MV line is shown in Fig. 5 to Fig. 7, in different conditions.

In the first case, Fig. 5 shows the current behavior along the line without neutral, from several lightning current sources, with different peak values and waveforms. In this case, the lowest current stabilizes after travelling about 300 m. This indicates that the line voltage is less than the insulator's flashover voltage. High currents tend to travel in the line for long distances causing flashover in various structures.

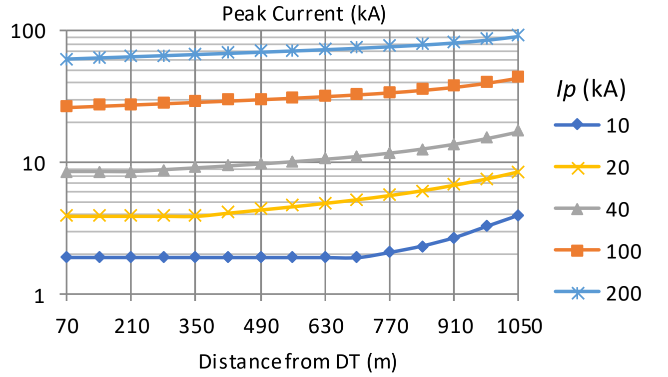

Fig. 5. Current Behavior along MV Line without Neutral – Soil Resistivity: 1000 Ω.m

Fig. 6 shows the importance of low resistivity values for line performance. When the soil resistivity is low, even at high lightning current values, the surge is attenuated quickly. Fig 7, in turn, shows the importance of the grounded neutral conductor for overvoltage attenuation. Even for a high soil resistivity, when reaches the transformer, the surge is fully attenuated.

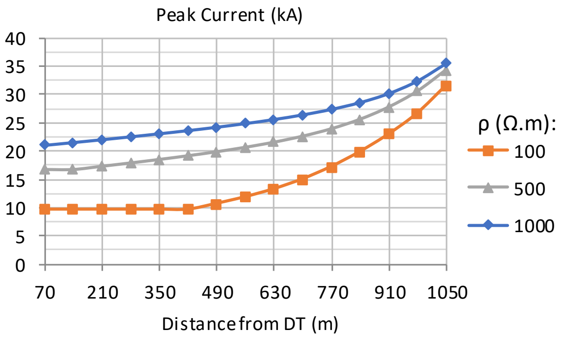

Fig. 6. Current Behavior along MV Line without Neutral – Source Current: I_p = 80 kA.

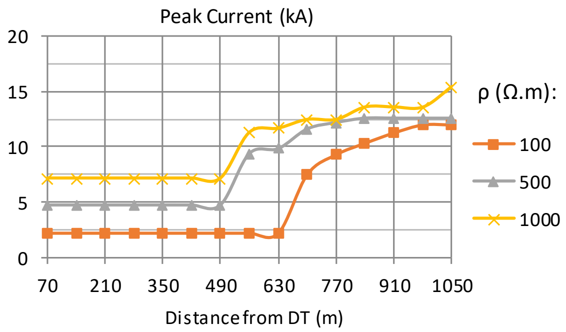

Fig. 7. Current Behavior along MV Line with Neutral – Source Current: I_p = 80 kA.

B. *Maximum Overvoltages on Consumers Installations*

1) From Direct Strokes on MV Line

Regarding the location, it was verified that there is no standard behavior for the overvoltages amplitude in the LV line conducted from the MV line. Maximum values can occur at different points in the LV circuit, regardless of the distance to the transformer or positioning in the circuit (end of line, derivation point or in middle of circuit). In this way, only the maximum overvoltages obtained were analyzed, regardless of the location of the installation. However, in all the simulated cases, a strong correlation was observed between maximum overvoltages and peak values of current sources and positioning in the MV network.

In this case, the best way to display the maximum overvoltages is using the cumulative distribution function.

The probabilities were calculated by equation (2) and attraction area was obtained from electro geometric model. It was considered the attraction area for each 70 m span and all current source peak values.

Fig. 8 and Fig. 9 show the charts of cumulative probability of occurrence of maximum overvoltages in consumers installations due to direct lightning flashes on MV line with and without neutral conductor. The values are in percentage for each 1000 transformers per year and ground flash density (Ng) equal to 1 flash/km^2/year. The letter “c” indicates that in these cases, it was compensated the high values of ground resistance of the neutral conductor by the increase of the grounding points number.

2) From Direct Strokes on LV Line

As presented in the last section, the probabilities were calculated by equation (2), but the attraction area was obtained from electro geometric model applied on the topology of LV line. For the simulations with the current sources applied in the LV line, the cumulative probability curve is unique, since the differences in the results obtained between the various conditions is small.

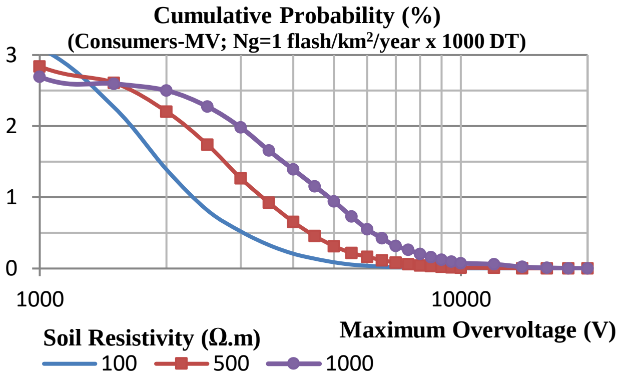

Fig. 8. Cumulative Probability for Maximum Overvoltages on Consumer Installations due to Direct Strokes on MV Lines, without Neutral Conductor. Letter “*c*” indicates grounding resistance compensated by the number of grounding points, using the *Q* factor.

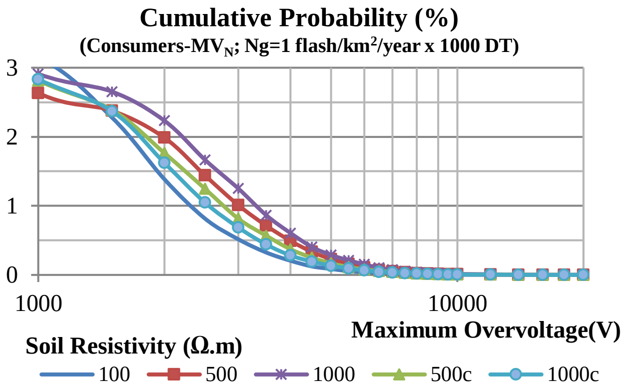

Fig. 9. Cumulative Probability for Maximum Overvoltages on Consumer Installations due to Direct Strokes on MV Lines, with Neutral Conductor. Letter “*c*” indicates grounding resistance compensated by the number of grounding points, using the *Q* factor.

Fig. 10 shows the chart of cumulative probability for maximum overvoltages in consumers installations due to direct lightning flashes on LV line. As in previous case, the values are in percentage for each 1000 transformers per year and ground flash density (Ng) equal to 1 flash/km^2/year.

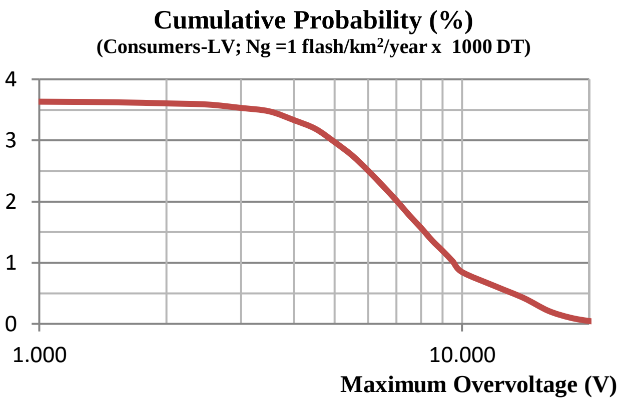

Fig. 10. Cumulative Probability for Maximum Overvoltages on Consumer Installations due to Direct Strokes on LV Lines.

V. Discussions and Conclusions

The development of this paper required a great research work, such as the data collection of the distribution systems, search of previous researches, and bibliographic survey on the subject and simulation tool. In addition, a large number of simulations were performed in order to obtain the reliability required for the results.

In the analysis of the current behavior in MV Lines with concrete poles, it is noticed that the attenuation occurs even in lines without neutral conductor. However, the use of the grounded neutral conductor contributes significantly to the overvoltages attenuation that can be reduced to values below the withstand insulator voltage in less than 1 km. It was also concluded that the use of the high resistance values compensation method with the number increase of earthing points in high resistivity sites is efficient.

The accumulated probabilities of occurrence of high overvoltage values are shown relatively low. However, considering regions with high discharge densities and high resistivity soils, the numbers can become significant. For example, in a region with ground flash density equal to 10, MV line without neutral conductor and soil with 1000 Ω.m, at each year, are expected overvoltages exceeding 3000 V in 2 of 10,000 transformers LV circuits. Despite that, the quantity of consumers from this circuit hit at the same time can be high, and considering the universe of BT circuits of large utilities, the amount of damaged equipment can be significant if the electric installations won't be adequately protected by DPS.

The overvoltages verified in the electrical installations due to direct strokes in the LV line show values of high magnitude, which was expected. However, this study does not consider the shielding factor that contributes to the reduction of the probability of direct lightning flashes on the conductors of the LV line.

At the end, it is concluded that the objectives of this work have been achieved. In addition, the results presented here may support several studies or serve as a model for others:

- The LV model circuit may present significant changes from region to region. The analysis of other circuits should be checked.
- The results of this work can also support studies of failures rate estimates of surge arresters, transformers and DPS.
- The results of this work can also support studies of failure rate estimates of surge arresters, distribution transformers and DPS.

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