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Determination of the Discharge Current on Distribution Network Surge Arresters

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***Abstract*— This paper presents the results of a study to determine the statistical distribution of the amplitude of the short duration impulse currents discharged by surge arresters installed in medium voltage systems. This procedure considers the survey of the currents discharged by silicon carbide surge arresters taken from the field. The objective of this analysis is to define improved strategies for surge arrester acquisition and insulation coordination.**

***Index Terms*– discharge currents, surge arrester specification for medium voltage networks, silicon carbide surge arresters, etching techniques in surge arresters.**

I. Introduction

THE silicon carbide surge arresters installed along the AES Sul distribution network carry over 20 years of lightning activity history. This data can be retrieved through a technique known as "Etching Comparison". On the electrodes of this type of surge arresters, the etchings are associated to discharge currents occurred in the field. In the laboratory, etchings similar to these were made on brand new electrodes with a short current high amplitude impulse generator and current amplitudes ranging from 500 to 40.000 Amperes and wave shapes of 8x20 µs and 4x10 µs. A comparison between the field and laboratory etchings will help identify the profile of the currents discharged by the surge arresters installed throughout the AES Sul operational area. The results presented in this paper were registered during a three-year field and laboratory campaign involving the inspection of 5400 medium voltage surge arresters. Based on statistical analyses and considering the rate of failure of medium voltage distribution transformers, a set of silicon carbide surge arresters was sorted, removed from the field, replaced by new metal oxide surge arresters and sent to the High Voltage Laboratory of the Federal University of Itajubá to be tested and internally inspected. The etchings on all gap electrodes were recorded by digital cameras.

The results are statistical models relating current amplitudes to their respective probability of occurrence, throughout the utility area.

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II. State of the Art

The correct specification of surge arresters considering their discharged current and energy avoids oversizing and, consequently, extra costs. The surge protection of medium voltage distribution systems can be accomplished applying light, normal and heavy duty surges arresters The cost of heavy duty surge arrester can be as much as 125% the cost of a properly designed and manufactured light duty surge arrester. How these types of surge arresters are to be spread throughout the networks is constantly a source of discussion, and it is necessary to recognize that some situations, though not all, require a major energy handling capability.

The majority of utilities generally adopt a single standard surge arrester specification. This can result in some drawbacks on the surge protection throughout the company area. To associate these surge protection failures to the insulation coordination procedures or to the equipment protection, without the due scientific evidence, usually results in non-economic practices.

In Brazil there is a general agreement on the application of heavy duty surge arresters on distribution networks. This practice apparently results in an oversized protection considering the shielding of urban areas. Normally, the discharge current density of a light duty distribution class surge arrester can be about 4 times the current density of a heavy duty or of a station class surge arrester. At this point at least two questions arise: Is this really necessary? Considering manufacturing costs, what is the impact of using higher energy-withstanding resistors on the design of disconnectors, performance and costs?

Some utilities in Brazil also carry out non-standard tests to verify multiple energy handling capabilities, which do occur, but have no statistical significance and, therefore must not be used as arguments for purchasing and selling medium voltage surge arresters.

It is possible to access the value of the current discharged by surge arresters by using sensors spread along the network. However, this kind of device can only record the current amplitude and requires long observation periods. One

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alternative to such device techniques is the signal analysis – “etchings” on the electrodes of the spark gaps of the conventional carbide silicon surge arresters. This technique was the base for the first set of equipment built to detect the amplitude and polarity of discharge currents. The etchings, i.e., the size and the volume of the removed material, permit determining the shape and amplitude of current discharged by surge arresters as shown in Table I for samples from 3M – Kearny National, where there exists a correlation between the current amplitude and the “etching” size, as may be observed.

In the field or in the laboratory these “etchings” may be overlapped or not by other ones, related to any following current or to multiple discharges. The analyses may also take into consideration the materials of the electrodes, manufacturing (stamping) of the electrodes, short circuit level on the installation point, and type of non-linear resistors.

TABLE I
CURRENT ETCHINGS OF SPARK-GAPS 3M – KEARNY NATIONAL

Amplitude (kA)	Etching (mm^2)
5	3
10	5
20	20
40	45
65	77
100	114

At AES Sul there are about 108.000 surge arresters installed, which in average represents 2.160.000 surge arrester years of history. Therefore, the substitution of surge arresters without inspecting the “etchings” of their electrodes beforehand means losing a long period of lightning activity history. The data obtained during this process can be used, for instance, to check the consistency of simulation models. It is necessary to consider that these models and calculations do not have the full capacity of replacing field procedures. However, when field results can be traced to laboratory practices and calculations it is possible to maintain a direct correlation with the industry procedures.

III. DEVELOPMENT

The discharge current profile in a given region was determined based on surge arresters taken from the field in the AES Sul Network area. Photographic records of each unit, of each one of the spark gap electrodes and of the non-linear resistors were taken and stored to populate a data base. Based on the comparison of etchings found on the spark gaps against standard etchings obtained in laboratory, the number of surge arrester operations is estimated as well as the amplitude of the discharged current. For this, the following steps were observed:

- Random searching for surge arresters installed in the field;
- Determination of “Field Etchings”;
- Determination of “Standard Etchings”;
- Comparison of “Field & Standard” Etchings;
- Statistical analyses through performance figures.

The parameter to determine the number of surge arresters to be inspected in a research and development project such as the present one can be any linked to the lightning performance of the networks, such as the number or frequency of the system shutdowns or of surge arresters presenting actuated automatic disconnections. The non-satisfactory performance of distribution transformers during lightning impulse tests does not explain the differences in failure rates observed throughout the company operational area. Therefore, considering the importance of this equipment for system performance, the number of failed transformers per year was chosen as the criterion for defining the number of surge arresters during the development of this project. The transformer failure rates were grouped per region, per team and per batch group, according to Table II.

TABLE II
TRANSFORMER FAILURE GROUPING

Failure Rates [%]	Severity
0 to 2.50	Low
2.51 to 5.00	Average
5.01 to 7.50	Severe
> 7.50	Unacceptable

The sets that presented transformer failure rates higher than 7.5% were considered separately, since such deviations are unacceptable. The proposal, shown in Table III considered the possibility of adopting three surge arrester types for the company area, i.e., Light Duty – Urban, Normal Duty – either Rural or Urban and Heavy Duty – areas with high intensity of lightning activity. It is important to highlight that the observed deviations can be associated to factors such as grounding resistance, or even to a group of factors that include the quality of medium voltage transformers manufactured in Brazil.

TABLE III
SURGE ARRESTER DISTRIBUTION PER AES SUL REGION

Region	Team	Number of Surge Arresters	Region Totals
Central	Caçapava do Sul	451	1868
	Cachoeria do Sul	311	
	Santa Maria	558	
	Santiago	548	
Fronteira	Alegrete	257	1202
	Santa do Livramento	240	
	São Borja	468	
	Uruguaiana	237	
Metropolitana	Canoas	266	1314
	Montenegro	316	
	Novo Hamburgo	407	
	São Leopoldo	325	
Vales	Lajeado	341	946
	Santa Cruz do Sul	340	
	Venâncio Aires	265	
Total Number			5330

A. *Field Etchings*

All surge arresters removed from the field are opened in the laboratory – after leakage current and RIV tests – for internal inspection of their elements, observation of the status of their spark gap electrodes and calculation of the areas related to the discharge currents. In order to compute the etching area, the electrodes were visually analyzed and the most evident discharge etching was selected. The area of this “representative” etching area was computed by the AUTOCAD® software. This means to oversize the amplitude current discharged by the surge arrester. Fig. 1 illustrates the smallest and largest area left in a given surge arrester taken from the field due to a lightning discharge.

Area =1,33 mm^2 Area =42,17 mm^2

Fig. 1. Field etchings - Smallest and largest areas of a surge arrester removed from the field.

B. *Standard Etchings (in the Laboratory)*

The standard etchings are obtained from the application of pre-knowledge impulse currents to new electrodes, aiming at determining the area of each discharge current level by means of the etching size. Based on standards IEC 60099-1 and ANSI C62.1, the current levels of 0.5, 1.0, 2.0, 5.0, 10.0, 20.0 and 40.0 kA positive and the negative polarities, one shot of each polarity per sample, were applied to surge arresters pro rated sections. Each sample is represented by a section of a full surge arrester. Fig. 2 shows the wave shape of a short duration current impulse, positive polarity applied to new electrodes of Manufacturer I. The sensibility of channel 1 is 200A/V which results in a discharge current of 5,22 kA.

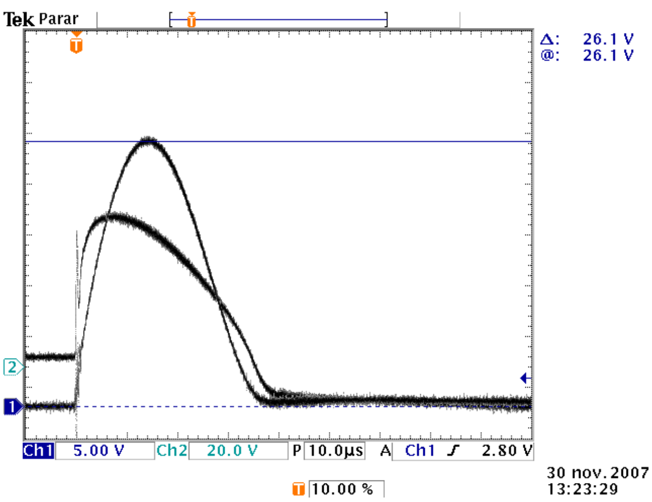


Fig. 2. Current impulse applied to a new electrode

Fig. 3 shows the smallest and largest areas obtained during laboratory tests with 5 kA current impulses in a pro rated section with seven new electrodes of Manufacturer I. Considering each individual electrode etching it is possible to observe some dispersion in the computed area. This was also statistically analyzed using the MINITAB® software. Table IV shows the correlation between discharged current and area for Manufacturer I. The same data is shown on Fig.4 and Table V for Manufacturer II.

5,2 kA →Area = 7,99 mm^2 5,2 kA → Area = 12,72 mm^2

Fig. 3. Standard etchings - Smallest and largest areas on gap electrodes of Manufacturer I surge arresters

TABLE IV

CURRENT X AREA CORRELATION FOR MANUFACTURER – I

Negative Amplitude		Positive Amplitude	
(kA)	Average Area (mm^2)	(kA)	Average Area (mm^2)
0.50	1.81	0.51	2.15
1.00	4.23	1.01	3.53
2.10	6.58	2.08	7.51
4.80	10.2	5.22	10.6
9.40	17.1	10.0	16.2
20.4	40.9	19.9	38.4
42.4	63.1	40.0	53.9

9.76 kA →Area = 15.30 mm^2 9.76 kA →Area = 24.66 mm^2

Fig. 4. Standard etchings - Smallest and largest areas on gap electrodes of Manufacturer II surge arresters

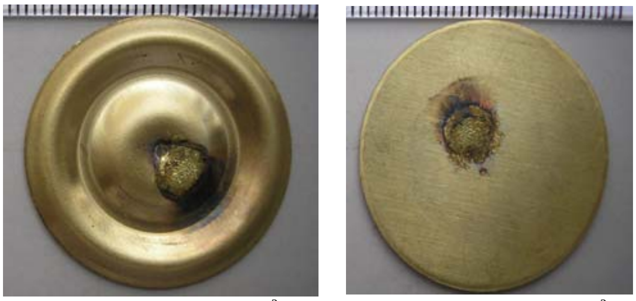
TABLE V

CURRENT X AREA CORRELATION FOR MANUFACTURER – II.

Negative Amplitude		Positive Amplitude	
(kA)	Average Area (mm^2)	(kA)	Average Area (mm^2)
0.506	1.67	0.55	2.42
1.06	3.55	1.05	5.01
1.94	5.94	2.08	7.33
4.72	11.4	4.84	10.8
9.70	21.2	9.76	19.9
19.8	36.9	19.9	36.0

39.4	49.7	38.6	50.9

Fig. 5 illustrates the 20.2 kA standard etchings through the surge arrester electrodes of "Manufacturer III". Table VI shows the correlation of the discharged current and area. This information for Manufacturer IV is shown on Fig. 6 and Table VII, respectively, for a 9.8 kA discharged current.



20.2kA →Area = 27.77mm^2 20.2 kA → Area = 43.0mm^2

Fig. 5. Standard etchings - Smallest and largest areas on gap electrodes of Manufacturer III surge arresters

TABLE VI
Current X Area Correlation for Manufacturer - III

Negative Amplitude		Positive Amplitude	
(kA)	Average Area (mm^2)	(kA)	Average Area (mm^2)
0.538	3.54	0.50	2.62
1.056	3.91	1.02	4.34
1.96	4.86	2.16	6.88
4.76	9.15	4.72	8.95
9.76	18.0	9.34	17.0
18.1	26.7	20.2	33.5
39.6	51.5	40.0	49.7

9.8 kA →Area = 25.89mm^2 9.8 kA → Area = 38.70mm^2

Fig. 6. Standard etchings - Smallest and largest areas on gap electrodes of Manufacturer IV surge arresters

Table VII – Current X Area Correlation for Manufacturer – IV.

Negative Amplitude		Positive Amplitude	
(kA)	Average Area (mm^2)	(kA)	Average Area (mm^2)
0.44	6.55	0.438	7.07
0.912	11.0	1.10	12.3
2.10	16.5	2.08	20.1
5.62	26.2	4.80	25.2
10.4	32.3	9.80	34.8
20.0	44.1	20.2	46.9
39.6	53.7	40.2	61.8

IV. FIELD ETCHINGS X STANDARD ETCHINGS

The correlation between the discharged current and the laboratory etchings is obtained by a standard curve fitting process. Fig. 7 shows the curve fitting result, given by (1) of the data on Table I and positive amplitude.

$$current^{-1} = 0{,}18579304 + \frac{0{,}84157534}{ln(area)} \qquad (1)$$

Similar plots and fittings were developed for each manufacturer. Assuming that there is a straight correlation between the field and standard etchings, i.e. that the laboratory tests are designed to reproduce the field stresses, it is possible to evaluate the amplitude of the discharged current through the surge arresters removed from the field. Applying MINTAB® Statistical Software it is possible to develop statistical models for the discharge current amplitude for each manufacturer and region.

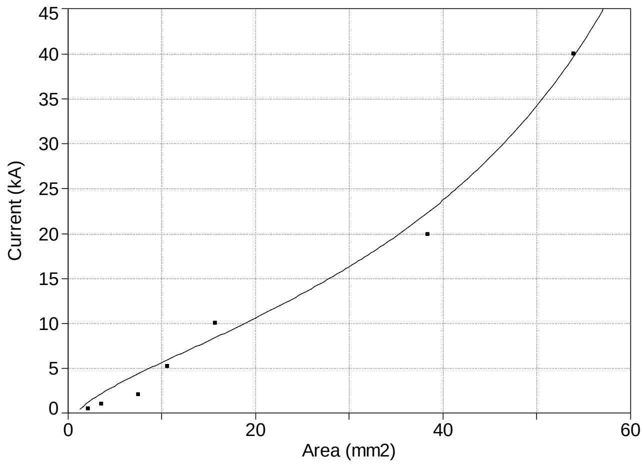


Fig. 7. Correlation between discharged current and etching area for Manufacturer I – Positive impulse

Fig. 8 shows the statistical model for the discharged currents of Santa Maria, urban area, positive and negative impulses. This model shows that about 93% of the discharged currents in this urban area are lower than 10 kA. The lower and upper probability limits for this current amplitude are 92.5% and 94.4%, respectively. This analysis can be extended for currents lower than 5 kA, which results in 82% for the lower limit, with the most probable value of 85% and 87%, for the upper limit.

Fig. 9 shows the statistical model for the rural area of Santa Maria. These results show that 71% of the surge arresters installed in the region discharged short duration currents with amplitudes lower than 5 kA. The lower and upper probability limits for this current amplitude are 65% and 77%, respectively. For currents lower than 10 kA, this analysis results in 81% for the lower limit, with the most probable value of 86% and 91%, for the upper limit.

To decide on the surge arrester duty cycle that must be applied to this region it is necessary to consider that light duty surge arresters are capable of performing some duty cycles of normal duty surge arresters, the number of units installed in each region and the need to maintain an inventory and substitution policy compatible with the company's needs.

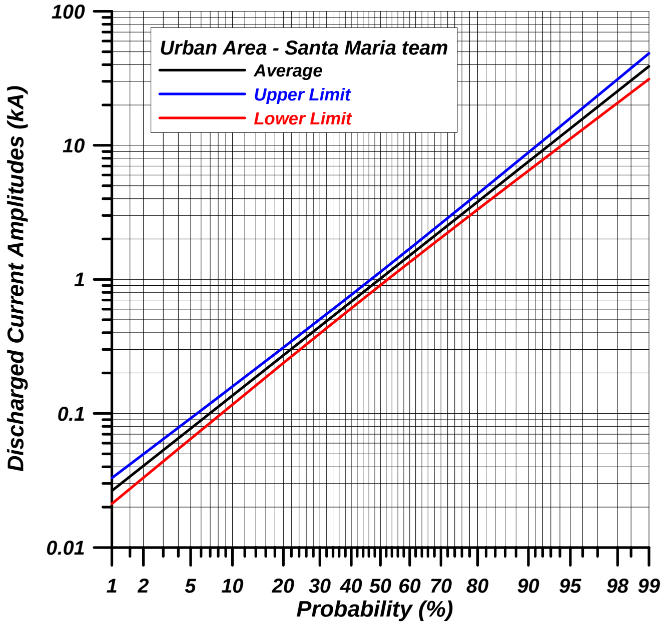


Fig. 8. Statistical Model of Santa Maria Region - Urban area

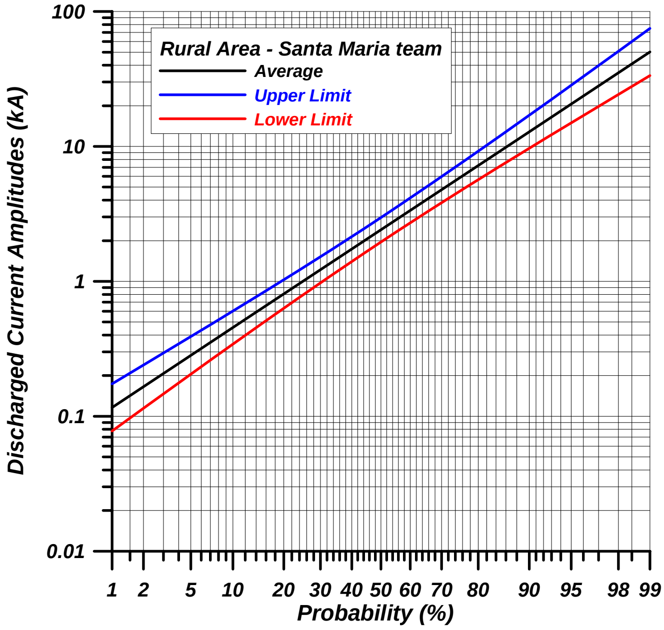


Fig. 9. Statistical Model of Santa Maria Region - Rural area

Fig. 10 and 11 show the statistical model for AES Sul rural and urban areas. It is possible to observe that there is no statistical difference between negative and positive impulse polarities. In urban areas and for impulse currents with positive polarity, 92.5% of the discharged currents are lower than 10 kA, against 83% in the rural area. For current amplitudes of 5 kA, urban and rural, the probabilities are 84% and 67%, respectively.

V. Comments

The data presented in this paper approaches the main existing recommendations in national and international normalization supported by insulation coordination studies. According to the presented data, it is apparently possible to operate at AES Sul with two levels of rated discharge current, i.e., 5 kA and 10 kA; enabling the joint application of light and normal duty surge arresters. The first is recommended for urban areas and the latter for rural areas.

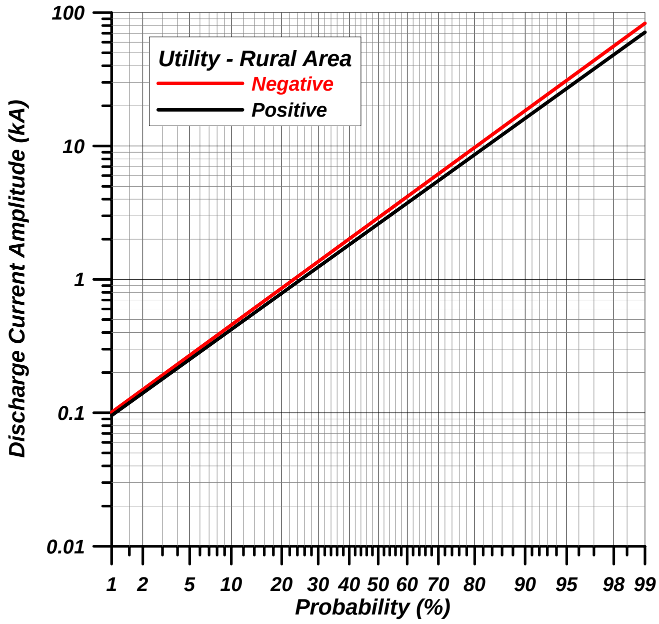


Fig. 10. Statistical Model for AES Sul - Rural area

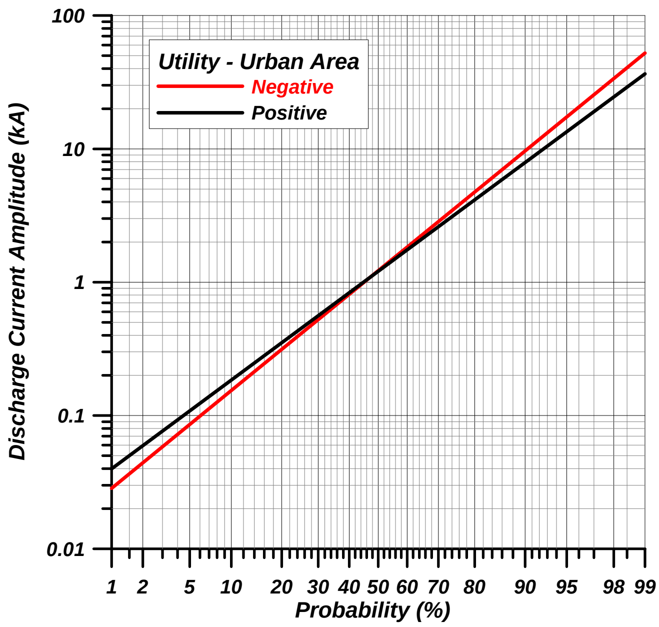


Fig. 11. Cumulative Probability Function for utility urban area

The need for application of heavy duty surge arresters must be carefully considered. Observing Fig. 10 and Fig. 11, which is specifically related to a region in South Brazil, it is possible to verify that the percent difference in considering heavy duty surge arresters – 100 kA and normal duty surge arresters – 65 kA is lower than 0,5%. Therefore, some points must be highlighted:

- Is this really necessary? Considering this percent value as a base, for AES Sul, this means 140 extra failed surge arresters in a period of 20 years.
- What is the additional cost impact for the utility relative to this “extra protection”?
- It is interesting to observe that worldwide only few manufacturers can supply this kind of surge arrester. Is it of best interest to reduce the utility purchasing options?
- Assuming that heavy duty surge arresters can adequately manage high current short duration impulses of 100 kA amplitude, what is the value of the associated residual voltage? Is this lower or higher than the rated basic levels of standard distribution transformers?

The estimated savings in this case is of approximately 20%, considering adequate surge arrester design. Unfortunately, this is not currently the case in the Brazilian market. The expected cost reduction considers not only the savings in materials for the manufacturing of non linear resistors , but also the savings in materials for manufacturing surge arrester housings, such as glass fiber reinforcements, high cost housing polymers, metal fittings and others. In general, proper design will result in higher scale savings.

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II. Biographies

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