APPLYING A FUZZY SYSTEM FOR LIGHTNING LOCATION AND PROTECTION OF DISTRIBUTION SYSTEMS AGAINST OVERVOLTAGE BY SURGE ARRESTERS

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Abstract—The protection of electric power systems against temporary overvoltages, due to switching and lightning contributes directly to the improve reliability and quality of the energy supplied to consumers. In this context, the application of metal–oxide surge arresters for lightning protection of distribution lines is of great interest to electric utilities. However, due to the high cost of purchase and installation is unfeasible for electric utilities install surge arresters in all structures of transmission lines and distribution. Thus, this paper proposes the implementation of an overvoltage protection system composed of metal-oxide surge arrester, from the application of a fuzzy system for location the point of occurrence of flashover and definition the amplitude of the lightning overvoltages. Furthermore, it is to develop a procedure for the specification of the sizing, placement and total number of surge arresters for protection of distribution lines optimized from the data provided by the fuzzy system.

Index Terms—flashover, lightning overvoltage, surge arrester, fuzzy systems.

1 INTRODUCTION

In the electric power sector, the criteria of reliability and continuity of supply are critical to the constant research and development of procedures to improve the Power Quality (PQ) and related services available to consumers. To achieve adequate operating conditions in an Electric Power System (EPS), and consequently a high level of PQ, two of the requirements are the installation of a Lightning Protection System (LPS) and a grounding system.

The LPS consists of Surge Arresters (SA), which lead the atmospheric discharge to the ground, at the same time they limit voltage on the equipment to which they provide protection. This limit voltage is composed by the sum of the voltage discharge of the SA and by the induced voltage developed by the discharge current between the SA line and ground leads (IEEE, 2011). The study of LPSs can be employed to solve various problems, some of the most important being:

- Reduction of unplanned shutdowns which result voltage sags and load shedding (Miranda et al., 2007);
- Definition of the location and number of SAs to be installed (Short and Ammon, 1999);
- Determination of influence of SA placement on phases on the level of shutdowns of the line and on the level of energy absorption of SAs (Short and Ammon, 1999; Ringler et al., 1997);
- Analysis of the use of shield wire and SAs with or without spark-gap and assessment of the performance of a line in the event of lightning, so as to include critical regions (Piantini, 2008).

In this context, the improvement of the response of distribution lines to lightning induced overvoltages by the installation of shield wire and SAs was analyzed in (Thanasaksiri, 2004). The effects of footing impedance and also shield wire size on line protection are assessed. The line performed better with the SA than with shield wire, especially if the SAs were installed on every pole of the line.

A useful and complete guide to the protection of power systems by SAs is available in (IEEE, 2009). This guide discusses the use of metal-oxide SAs to protect equipment with rated voltages above 1 kV against overvoltages. In addition, it provides information about the use of SAs for protection of substations, transmission and distribution systems and large electric machines.

In (Munukutla, 2010), a lightning protection system for a Transmission Line (TL) is described, employing a minimum number of SAs, placed on different towers with varying distances between them. The dependence of these placements on the tower footing resistance was analyzed. With the implementation of these methods of analysis, the number of unplanned shutdowns was reduced and the reliability of the services provided to the consumer improved.

At this conjuncture, from the analysis of the incidence of direct lightning in a Distribution Line (DL) rural configured with parameters provided by electric utilities, will be presented a method to locate the point of occurrence of flashover and respective overvoltage based on fuzzy logic. The following, after identification of the critical points flashover and its peaks overvoltages using the elaborated Fuzzy System (FS), will develop a procedure to achieve the best sizing, placement and quantification of SAs to be applied for the protection of DL evaluated.

Thus, the rest of the paper is organized as follows: the next section presents the main questions regarding overvoltages of atmospheric origin in EPS. The third part gives details about the selection, modeling and implementation of metal-oxide SAs. In the fourth part are shown particularities of the FS implemented. The following, are exhibit the results of computer simulations, the application of FS developed, and use the SA to protect the line evaluated. Finally, the findings of this study are presented in the last section.

2 OVERVOLTAGES OF ATMOSPHERIC ORIGIN IN ELECTRIC POWER SYSTEMS

The incidence of lightning on the conductors of TLs and DLs (direct lightning) or in the vicinity (indirect lightning) can cause overvoltages of high magnitude in the lines. If the amplitudes of these overvoltages exceed the levels of the system supportability can occur faults between one or more phases to ground, and the need to actuate protection devices against overcurrents (Visacro, 2005).

In transmission and distribution systems with nominal voltages below 200 kV, as assessed in this article, the incidence of a direct discharge in an energized conductor line entails break its isolation, through a process called disruptive discharge in isolation, or flashover. This procedure causes in most cases dielectric failure of the system, resulting in burning equipment with probable physical and materials damage (Visacro, 2005).

Although the direct incidence of lightning on DLs is less frequent than the indirect one, the study of methods of protection against overvoltages of atmospheric origin on these lines is of great value. This is due to severity of these overvoltages for DLs and because on open field lines in rural areas, which may be the highest structures in its surroundings, and in less occupied urban areas, their occurrence is more likely.

3 MODELING OF METAL-OXIDE SURGE ARRESTER

The SAs are one of the most commonly used devices for protection and insulation coordination of various types of electrical equipment and systems, and thus were chosen to be modeled in this article. The metal-oxide SAs, currently, are the type often used on DLs and TLs by virtue of the nonlinear characteristic of their blocks of resistors in the region of low intensity current, because this property implies a lower drained leakage current. Other features that make them used the most are short response time to transients, low residual voltage, high thermal stability and high energy absorption capacity when faced with temporary and transient overvoltages (De Nigris et al., 1998; Melchior, 2003; Modrusan, 1983).

Thus, next will be presented the requirements for implementation of the Pinceti and Giannettoni model (Pinceti and Giannettoni, 1999) in ATP software, run in the graphical interface ATPDraw, as well as the electrical characteristics of the SAs needed on the line employed in this analysis.

A. Characteristics of Pinceti and Giannettoni Model

The Pinceti and Giannettoni model was validated by comparison with the conventional ATP model and with the workgroup 3.4.11 model of the IEEE (IEEE, 1992). This model was chosen because it represents adequately the dynamic characteristics of the SA, it requires only electrical parameters to build the circuit and it does not need iterative corrections during its computer simulations. These features make it a very attractive model in terms of computational effort and the ready availability of necessary data from manufacturers.

Fig. 1 illustrates the model proposed by Pinceti and Giannettoni, and (1) and (2) demonstrate the parameters necessary to determine inductances L_0 and L_1. In addition, in (1) and (2), Vn corresponds to the nominal voltage of the, varistor to $V_{R1/T2}$ the residual voltage due to a current surge of modulus 10 kA and 1.2 µs rise time, $V_{R8/T2}$ the residual voltage for a current of wavefront 8 µs and $V_{R8/20}$ the residual voltage for a current of 10 kA and waveform 8x20 µs.

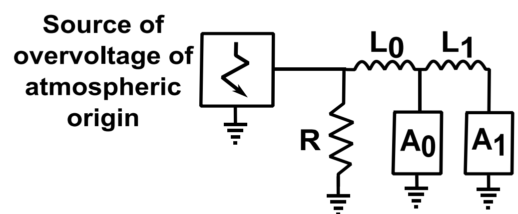

Figure 1: Model proposed by Pinceti and Giannettoni, adapted from (Pinceti and Giannettoni, 1999).

$$L_0 = \frac{1}{12} \frac{V_{R1\ T2} - V_{R8\ T2}}{V_{R8\ 20}} V_n\ [\mu H] \qquad (1)$$

$$L_1 = \frac{1}{4} \frac{V_{R1\ T2} - V_{R8\ T2}}{V_{R8\ 20}} V_n\ [\mu H] \qquad (2)$$

The characteristics of nonlinear resistors A_0 and A_1, derived from the model proposed in (IEEE, 1992), are determined by multiplying voltages A_0 and A_1 in Table I by the residual voltage due to a surge current of modulus 10 kA and 1.2 µs rise time, and will be defined in subsection B.

TABLE I: CHARACTERISTICS OF THE NONLINEAR RESISTORS ACCORDING TO (PINCETI AND GIANNETTONI, 1999).

Current (kA)	$2e^{-6}$	0.1	1	3	10	20
A_0 Voltage (pu)	0.81	0.97	1.05	1.11	1.19	1.28
A_1 Voltage (pu)	0.62	0.79	0.87	0.92	1.01	1.09

B. Electrical characteristics of the modeled line and surge arrester

The sizing of the SA chosen for the line under study was based on the line operating data, the overvoltages determined by the simulations of lightning and the data provided in a SA catalog.

To determination the SA to be implemented were required some parameters of the line and the region where it is located, as the voltage line, equal to 69 kV, the phase voltage, equal to 39.8 kV, and Keraunic Index (I_k) whence located line, approximately equal to 60, second reference (NBR 5419, 2005). By means of I_k and (3) was defined density Flash Density (FD) to the region of the line as shown below,

$$FD = 0.0024 I_k^{1.63}. \quad (3)$$

From these data and the manufacturer's information contained in (ABB, 2012), the electrical characteristics of the SA modeled in this article were defined. For each system voltage, the combined data from Tables II, III and IV, which contain the guaranteed protection characteristic of SAs, provide a range of values for the maximum system voltage (*Um*) and for the nominal voltage (*Ur*).

TABLE II: GUARANTEED PROTECTION RANGE OF SURGE ARRESTER, ADAPTED FROM (ABB, 2012).

Maximum System Voltage	Nominal Voltage	Maximum Residual Voltage for 8x20μs Wave of Current	
Um	Ur	5kA	10kA
[kVrms]	[kVrms]	[kV peak]	[kV peak]
52	42	103	109
	48	118	125

TABLE III: MINIMUM UR OF SURGE ARRESTER FOR LIGHTNING, ADAPTED FROM (ABB, 2012).

System Grounding	Fault Duration	System Voltage Um [kV]	Minimum Nominal Voltage Ur [kV]
Effective	≤1s	≤100	≥0.8xUm
Effective	≤1s	≥123	≥0.72xUm

TABLE IV: LIGHTNING PROTECTION CHARACTERISTIC OF SURGE ARRESTER, ADAPTED FROM (ABB, 2012).

Maximum System Voltage	Nominal Voltage	External Insulation		
Um	Ur	1.2/50 μs	60 Hz	250/2500 μs
		dry	humid (10s)	humid
[kVrms]	[kVrms]	[kV peak]	[kVrms]	[kV peak]
52	42-60	310	150	250
	66	370	180	300

Considering that the chosen SA must have a continuous operating voltage above the system nominal voltage, using the Table II, it was adopted one of 52 kV, a value immediately above the phase voltage of the line. To determine *Ur*, Table III was analyzed, according to which Ur≥0.8xUm, since the grounding of the line is taken as effective and thus Um≤100 kV; that is, *Ur* is 41.6 kV. Thus, in Table II the value equal to or just above that found for *Ur* should be taken; thus, the *Ur* adopted is 42 kV.

Next, the parameters of (1) and (2) were determined from the data in Tables II and IV, which gives V_n equal to 42 kV, $V_{R1/T2}$ equal to 310 kV, $V_{R8/T2}$ and $V_{R8/20}$ equal to 109 kV, L_1 equal to 19.36 μH, L_2 equal to 6.45 μH and characteristics of nonlinear resistors A_0 and A_1, as shown in Table V.

TABLE V: CHARACTERISTICS OF NONLINEAR RESISTOR IN THE SURGE ARRESTER MODELED.

Current (kA)	$2e^{-6}$	0.1	1	3	10	20
A_0 Voltage (kV)	251	302	326	343	370	396
A_1 Voltage (kV)	193	244	268	286	313	338

C. Implementation and simulation of the surge arrester model

The circuit in Fig. 1 was implemented with nonlinear resistors parameterized with data previously recorded with a 1 MΩ linear resistor, to avoid numerical instabilities during the simulation. A source was used to simulate lightning of waveform 1.2x50 μs and discharge current 10 kA. The response of the simulation, is displayed in Fig. 2, in which the consistency of the behavior of the model may be noted, because when the SA was subjected to a voltage greater than its nominal voltage, its impedance fell, allowing the atmospheric impulse current to be dissipated. Also verifies that the value of the overvoltage resulting was limited, and recovered the high impedance value of SA after the end of the request voltage.

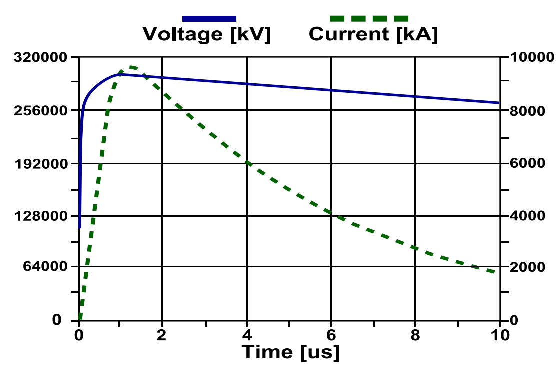

Figure 2: Response of surge arrester model to waveform 1.2x50 μs and discharge current 10 kA.

4 APPLICATION OF FUZZY SYSTEMS

To analyze the incidence of direct lightning on the line under study, initially, simulations were carried out of lightning with waveform 1.2x50 μs discharge currents 10 kA, 4.5 kA or 2.5 kA, and impedance of the air ionization channel 1 kΩ or 3 kΩ. Was simulated the applying lightning in the 9 points of the line shown in Fig. 3, with which were obtained voltages and currents for each of the three phases at each point of the line.

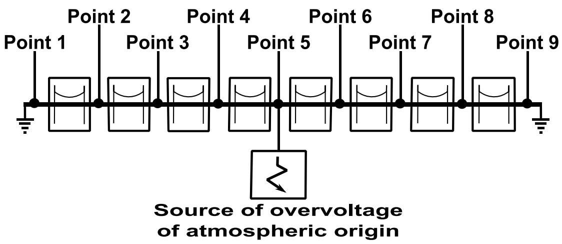

Figure 3: Simplified model of the line for simulations of lightning.

Thus, with the data from the simulations has built a multilayer fuzzy inference system, as shown in Fig. 4 and Fig. 5, from the automatic structural and parametric adjustment presented in (Flauzino and Silva, 2003, 2007). After obtaining the currents and voltages, these data were converted to the respective linguistic terms that were specified through relevance functions. Then, the linguistic terms were used in the evaluation of fuzzy rules, and finally, by the application the inference procedures, by applying the inference procedures, results were obtained which allowed identify the point of establishment flashover and the amplitude its overvoltages.

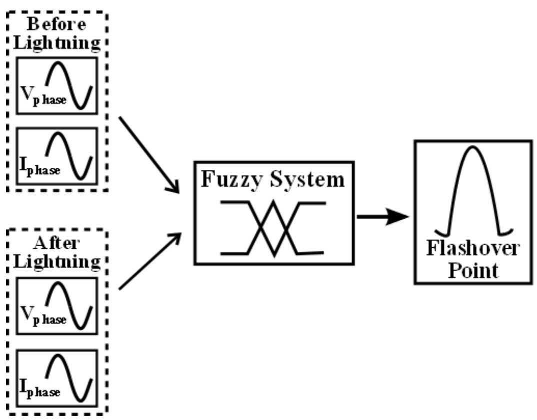

Figure 4: Fuzzy system for locating the point of occurrence of flashover and its respective overvoltage.

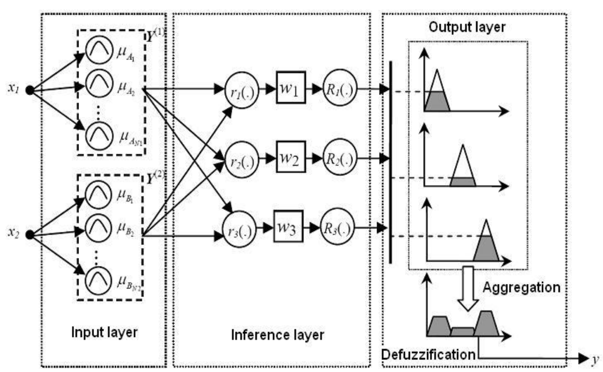

Figure 5: Multilayers fuzzy system.

For the purpose of evaluating the performance of the proposed method, a set of test samples was applied to the FS. The estimation showed average error of 0.0055%, standard deviation of 0.0143% and maximum error of 0.0437%. Fig. 6 shows the results of this test, in which each level represents a point of event flashover, and where it is possible to note the precision of the method developed. Emphasize that the point of occurrence of flashover is defined by the peak value of voltage assess and by the place where it is measured.

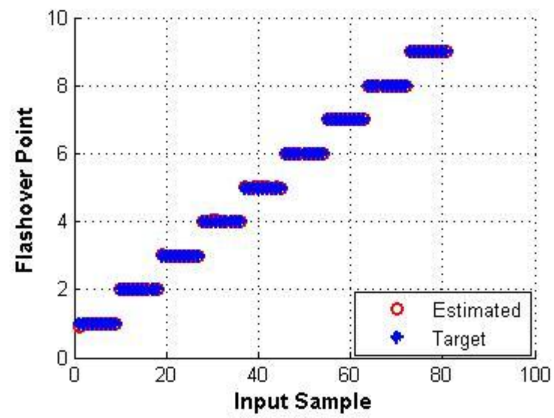

Figure 6: Test of the locating the point of flashover happening.

Already Fig. 7 contains the histogram of errors, from which it can be seen that the vast majority of the errors occur when its percentage value is very low, again showing the accuracy of the procedure implemented.

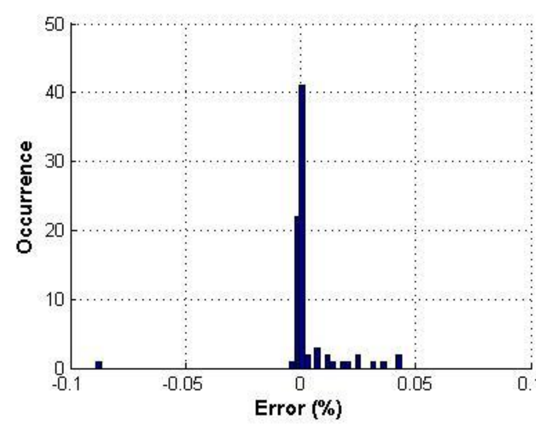

Figure 7: Histogram of the error of point location of the event flashovers.

5 RESULTS

By applying the developed FS and simulations performed with the software ATP ascertained that the most critical condition, i.e., higher overvoltage, occurs when there is an incidence lightning in point 5 of the line, as seen in Fig. 8, and that there is establishing flashovers or not as shown in Table V. The peak value overvoltage in the critical condition reaches 2,542 kV, and the Fig. 8 shows the amplitude of the overvoltages measured by meters allocated to each of the points of the line, when considers 1, 5 e 9 points of incidence of lightning (PIL).

TABLE V: OCCURRENCE OF FLASHOVER IN LINE AND THEIR INCIDENCE LIGHTNING IN EACH OF ITS POINTS.

Point incidence lightning	Measuring point of the line								
	1	2	3	4	5	6	7	8	9
1	S	S	S	N	N	N	N	N	N
2	N	S	S	N	N	N	N	N	N
3	N	N	S	S	N	N	N	N	N
4	N	N	N	S	S	N	N	N	N
5	N	N	N	S	S	S	S	N	N
6	N	N	N	N	S	S	S	N	N
7	N	N	N	N	N	S	S	S	N
8	N	N	N	N	N	N	S	S	S
9	N	N	N	N	N	N	S	S	S

S Flashover occurs   N No flashover occurs

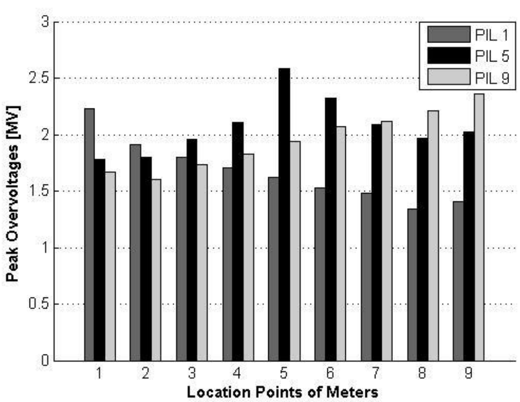

Figure 8: Range of voltages measured at all points of the line for the application of lightning in points 1, 5 and 9.

From the most critical situation, new simulations of lightning were carried out, with the addition of 1 to 5 sets of SAs. It should be noted that a set of SAs consists of 3 SAs, one per phase, and that the overvoltages on the line were acquired by meters located at points 2, 5 and 8, in all situations.

The addition of 2 sets of SAs at the ends of the line, i.e., at points 1 and 9, was not sufficient to protect the line, since the maximum overvoltage measured at point 5 is 2,586 kV.

Later, with the addition of 3 sets of SAs at points 1, 5 and 9, as illustrated in Fig. 9, the results in Table VII were obtained, where it is seen that the line is protected, since the maximum overvoltage measured in this situation was found at point 2 and was 244 kV, and where PM is the Point of Measurement. Moreover, the residual voltage and the current in the SAs did not exceed the limits established by the manufacturer, because they were 162 kV and 9.4 kA, respectively.

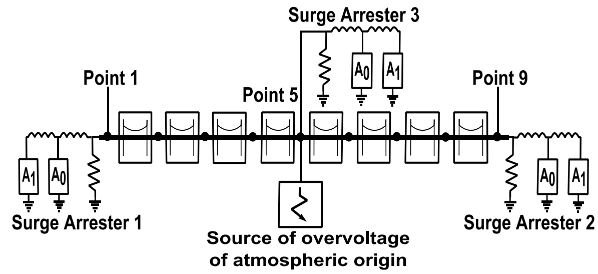

Figure 9: Simplified model of line with surge arresters at points 1, 5 and 9.

TABLE VII: MAXIMUM VOLTAGE AND CURRENT ON LINE WITH 3 SETS OF SURGE ARRESTERS.

Line with 3 sets of surge arresters					
Equipments		PM	Phase A	Phase B	Phase C
SA - 1	Current [A]	1	-322	-289	-454
	Voltage [kV]	1	-114	-133	142
SA - 2	Current [A]	5	0.94	1.61	9,480
	Voltage [kV]	5	148	132	162
SA - 3	Current [A]	9	-141	-97	364
	Voltage [kV]	9	-112	-106	125
Meter of voltage [kV]		2	-136	-111	244
Meter of voltage [kV]		5	155	132	161
Meter of voltage [kV]		8	-118	-103	133

Finally, adding 5 sets of SAs at points 1, 3, 5, 7 and 9, the data in Table VIII were obtained, where it is found that the line is also protected with this configuration, because the maximum overvoltage was measured at point 2 and is 237 kV. Also, the residual voltage and the current in the SAs did not exceed the limits established by the manufacturer, reaching 179 kV and 9.2 kA, respectively.

TABLE VIII: MAXIMUM VOLTAGE AND CURRENT ON LINE WITH 5 SETS OF SURGE ARRESTERS.

Line with 5 sets of surge arresters					
Equipments		PM	Phase A	Phase B	Phase C
SA - 1	Current [A]	1	-122	-157	263
	Voltage [kV]	1	-78	-118	124
SA - 2	Current [A]	3	-157	-164	578
	Voltage [kV]	3	-134	-128	179
SA - 3	Current [A]	5	1.83	2.49	9,247
	Voltage [kV]	5	84	97	110
SA - 4	Current [A]	7	-178	-122	7,154
	Voltage [kV]	7	-138	-124	177
SA - 5	Current [A]	9	58	32	197
	Voltage [kV]	9	-92	-91	112
Meter of voltage [kV]		2	-124	-102	237
Meter of voltage [kV]		5	138	113	146
Meter of voltage [kV]		8	-97	-91	136

6 Conclusions

With the results obtained it is concluded that the implemented FS system for to identify the point of occurrence of flashovers was efficient and robust, as exposed by the responses to the test performed and found by the measured errors. Furthermore, it is observed that the FS allows greater agility for analysis of lightning overvoltages under the DL analyzed since it determines the location of Flashovers and the amplitude their voltages at these points, contributing determination the most critical point that must be protected in line.

The overvoltages resulting from discharges on the line, with 3 and 5 sets of SAs, feature very few differences between one another. Therefore, considering the technical/economic viability of the line protection scheme, the best solution is to use only 3 sets of SAs arranged at points 1, 5 and 9, balancing the protection offered against the high cost of buying and installing these devices. It was also concluded that the use of only one set of SAs at any point on the line, including in section 5, which the highest overvoltage occurs, is not sufficient for its protection and for this reason these results were not presented.

Finally, it should be noted that this article fulfills its objective of contributing with methods and information about the project of a protection system against overvoltages of atmospheric origin based on sizing and specification of SAs. We point out that the procedures carried out on the line in question could be applied to other electrical systems, provided that be their electrical characteristics for sizing, allocation and quantification of SAs to be installed.

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