ASSESSING THE RISK OF DAMAGES IN LOW VOLTAGE EQUIPMENT DUE TO LIGHTNING SURGES AND THEIR IMPACT ON CUSTOMER CLAIMS

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ABSTRACT

This paper deals with the development of a methodology to assess the possibility of damages in equipment of low voltage customers due to lightning surges. The main objective of the work is to include this methodology in a computation system that supports distribution companies to evaluate whether customer claims related to damaged equipment are to be approved or not.

The proposed methodology allows to assess whether a specific customer could be affected by a lightning strike according to his/her location and to the surge main parameters, by using data from a lightning detection system and from equipment surge withstand capability.

A specific study using ATP (Alternative Transients Program) was carried out to assess the propagation of lightning surges in electric power distribution systems and their impact over low voltage customers. On the other hand, the withstand capability of the main household appliances was determined by a series of tests carried out in the University's power quality laboratory.

The paper details the modeling used, the results of the simulations and how the existing uncertainties were handled. Also, some issues regarding the withstand capability of electric household appliances to lightning surges are discussed. A proposal of assessing customer claims regarding damaged equipment is presented to be incorporated in the computational system.

INTRODUCTION

The University of São Paulo, in collaboration with a group of electric power distribution companies, is developing a computer system for technical assistance and analysis regarding claiming requests of customers who have their equipment damaged by various kinds of disturbances in their supply system. This systems aims at speeding up the response of the company in a standardized way, taking into account off-line studies of phenomena in typical network configurations that consider events that might result in damages to household equipment. Furthermore the system takes into account sensitivity and tolerances tests that were carried out in the University´s power quality laboratory.

The system which is currently being used by the distribution companies [1] comprises the analysis of short and long duration events (short circuits, neutral opening, phase opening, etc.) and some other transient phenomena (capacitor switching and system re-energization).

Amongst new research activities that have been developed by the research team, one should outline the analysis of equipment damage due to lightning surges. Information regarding these occurrences are collected from the lightning detection system which is nowadays available.

This issue is fairly important since the current legislation might hold the distribution companies responsible for damaged equipment related to lightning strikes.

OVERVOLTAGES IN LOW VOLTAGE DISTRIBUTION INSTALLATIONS DUE TO LIGHTNING STRIKES

This paper shows how to consider power surges and lightning strikes in the computer system to assist the technical staff in distribution companies in analysing request claims related to damaged household equipment. This system should be able to provide diagnosis related to possible burning equipment due to lightning strikes, depending on the customer location in relation to the strike point, as well as other important lightning parameters that consider the power network and surge tolerance characteristics of the damaged equipment.

A more viable methodology for this analysis consists in evaluating, by means of computational simulations, the possible overvoltages in electric facilities due to lightning strikes in the power network. On the other hand, laboratory tests can indicate the withstand levels of the equipment with respect to surge overvoltages, i.e. an indirect justification of the damage in pieces of equipment.

However, due to uncertainties associated with many factors involving the propagation of lightning strikes along the electric power network and the burn of household equipment, it is not possible to determine in a precise way the effect that a lightning strike will cause to a given piece of equipment.

For this reason, one should assume as a principle a procedure that provides conservative results, in a reasonable way, so that the customers that have their equipment damaged are somehow favoured along the decision process. This approach demands analysis criteria that allow the classification of indemnity requests in approved or not, by means of a procedure that is certified by the Regulatory Board.

In practical terms, due to the uncertainties in locating the exact point of the lightning strike, in most situations it is not possible to determine whether the surge hit the distribution network or a neighbouring spot, mainly in urban areas. Therefore, simulations consider the most pessimistic condition, which is the direct strike, that encloses the cases in which the strike hits the primary and secondary distribution lines as well as connection laterals. It also encloses customer installations, buildings and structures that are connected to the power supplying network, since in such cases the propagation of overvoltages might occur through existing installation cables or through open paths due to disruptions caused by the strike.

SIMULATIONS

The simulations were carried out by using the ATP – Alternative Transients Program. These simulations were fundamental to a better understanding of the overall propagation process originated by lightning strikes as well as the resulting currents from direct strikes along the distribution network. In a different fashion of what happens normally in high voltage transmission lines, direct strikes in distribution lines cause multiple disruptions on insulators, what makes the analysis of even the qualitative understanding of the phenomenon very difficult. This demands a detailed simulation, since voltage and current resulting waves are due to various interactions and reflections over many discontinuity points.

Simulated network

A typical distribution network considered for the simulations is presented in Fig. 1, which consists of:

- A 10km primary (medium voltage) distribution network, comprising 3x336.4MCM phase aluminium conductors and a 1x1/0 AWG neutral aluminum conductor, which is grounded every 300m.
- A distribution transformer to supply the low voltage circuit, which is located in the medium point of the primary circuit.
- A 150m 1/0 AWG low voltage circuit coupled to the primary line.. The neutral cable is common for both medium and low voltage networks.
- Secondary customers are supplied and located at every 30m along the low voltage network;
- Neutral is grounded at every customer coupling point.
- Distribution transformers are protected by surge arresters at the medium voltage side.
- Surge arresters are located along the primary voltage lines, on the three phases and at every 300m, as well as the feeder ending buses.
- Customer connecting laterals in low voltage networks are assumed 10 m long, with 10 mm^2 multiplex cables.
- Protective devices in the low voltage network are not considered..
- Disruptions are admitted in the primary and secondary insulators, but not for the connecting laterals and low voltage customer installation.

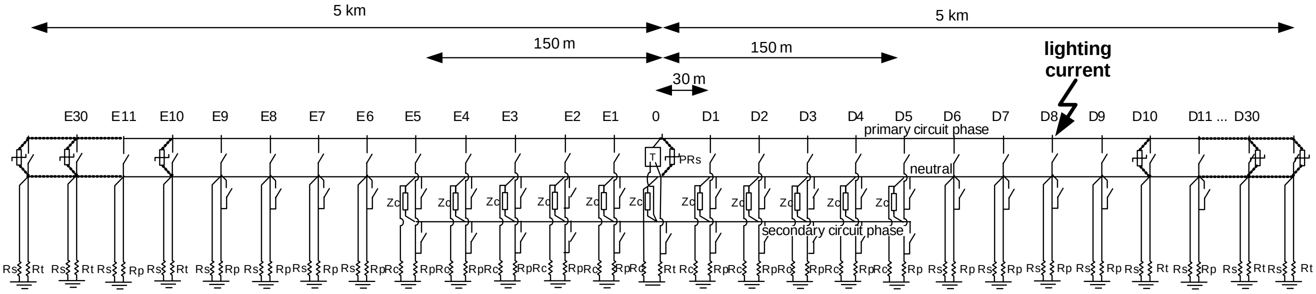
Existing networks usually comprise neutral connections amongst different primary feeders, what contributes to a more efficiency of the overall grounding system. This feature can be taken into account in order to obtain more accurate results.

Modeling the network components

Primary and secondary lines are represented through an ATP model that takes into account the variation of the network parameters with the frequency. Primary and secondary lines are represented by 30 m long branches, though this length increases for distances greater than 900m away from the distribution transformer.

Single phase and three-phase distribution transformers were considered. The Rajotte/Fortin/Cyr model [2] was adopted for single phase transformers whereas the Kanashiro model [3] was adopted for three-phase transformers.

Surge arresters are represented by a model available in ATP, by using a ZnO arrester VxI curve.



R$_T$: pole with grounding rod;
R$_S$: equivalent grounding of other customers connected to the network;
R$_C$: customer installation entrance of the secondary circuit analyzed
R$_P$: concrete pole without grounding rod.

Fig. 1. Network configuration for the simulations

Line insulators were modeled by normally open switches that change their status to closed when some specific voltage conditions are reached, thus simulating the disruption. The model described in [4] is used, where the parameter called disruptive effect (DE) is given by the following expression:

$$DE = \int_{t_0}^{t} [U(t) - U_0]^k \, dt$$

where $U(t)$ is the applied voltage, t_0 is the time instant when $U(t) > U_0$; U_0 is the voltage value for t_0 and k is a constant.

Many different models can be considered for load representation, such as the one in [5] for resistance, in [5,6] for inductance, in [5] for capacitance and in [6,7] for composition of the basic elements. As for the basic cases in this work, 5 different load models were considered: resistance (R=30 Ω), inductance (L=3,5 μH [6]), capacitance (C=4 ηF), Hoidalen model [6] e Bassi model [7].

The connection laterals in low voltage circuits to supply customers use multiplexed cables, represented by line distributed parameters.

Grounding is represented by resistance and inductance in series. Different grounding resistance values were considered in a parametric analysis.

Lightning strikes were represented by a current source connected to the line. The triangular waveform was used (two simple ramp functions: constant growing up to the crest and constant decrease after that).

A 2.25 / 80 μs (crest time / half-value time) waveform was assumed for the base case simulations, as shown in Fig. 2.

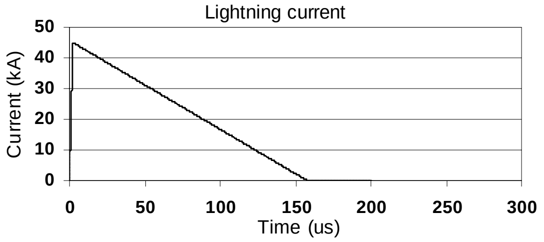


Fig. 2. Assumed lightning current.

Overvoltage at the low voltage customer coupling points – Simulation results

Fig. 3 shows examples of the obtained results in a simulation where the following grounding resistance values were assumed: $R_T = R_S = R_C = 100\ \Omega$ and $R_P = 200\ \Omega$, and striking at 600 m from the distribution transformer.

Simulations have shown that waveforms and magnitude of the overvoltages vary considerably as a function of the customer load representation. Amongst different load models utilized during the simulations, the most appropriate ones for this study were the Bassi models [7], based on laboratory tests.

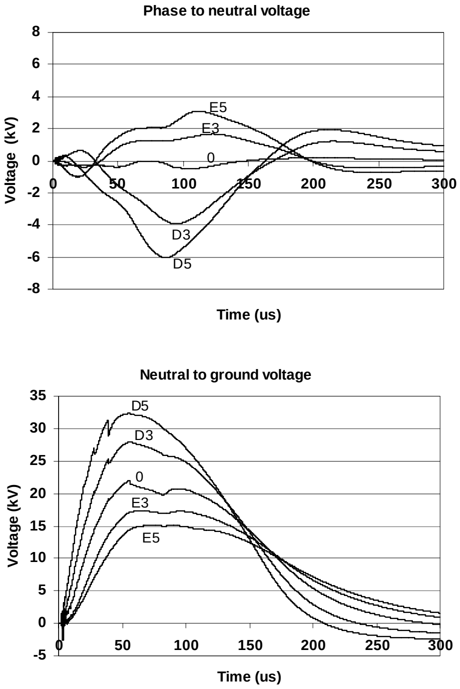


Fig. 3. Voltage waveforms at the low voltage customer coupling points

The simulations determine the voltage at the secondary customer coupling points as a function of the magnitude of the lightning current and distance between the striking point and the distribution transformer.

The crest phase-neutral and neutral-ground voltage values were obtained as a function of the distance, for different lightning current values. Fig. 4 shows the corresponding graphs, obtained for the network of Fig. 1, and grounding resistance values $R_T = R_C = R_S = 100\Omega$.

EQUIPMENT WITHSTAND CAPABILITY TO LIGHTNING SURGES

Disturbances to low voltage equipment

Overvoltages can show up in equipment by two different ways, namely common and differential modes. Differential mode overvoltages are due to the differences between the transient voltages of distinct phases or between phase and neutral. The common mode overvoltages are due to the potential raise on the phase and neutral with respect to the ground.

One should consider that many pieces of equipment are not connected to the ground, or to the common grounded wire of the installation. This happens whenever the grounding equipment terminal is not existing or when no connection was made during the equipment installation. Thus, depending on the location where the equipment is installed, common and differential modes can occur, regardless the grounding scheme (TN or TT).

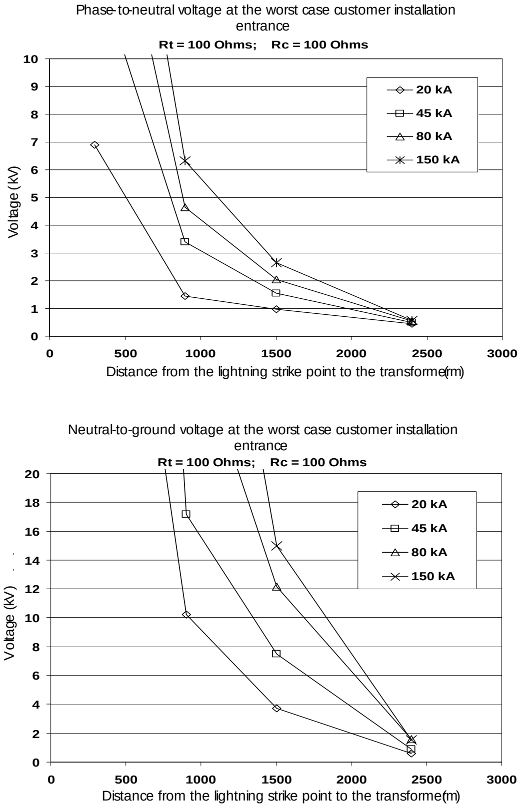


Fig. 4. Phase-neutral and Neutral-ground voltages at the customer located in the worst position (point D5)

Standards related to equipment immunity

The 61000 IEC standards series (Electromagnetic Compatibility) deal with the immunity issue in equipment seen on their functional and operative performance and are a basic reference for the research activities and objectives envisaged in this paper.

IEC 61000-6-1 specifies the following immunity levels related to surges in the supplying CA input, for residential, commercial and light industrial environments: phase to ground: ± 2 kV and phase to phase: ± 1 kV.

Although compliance with IEC 61000-6-1 is not mandatory in the Brazilian market, the immunity levels specified in this standard were taken as a reference for the definition of withstand levels to be considered during the analyses, alongside the levels obtained by laboratory tests.

Standards IEC 61000-4-5 and IEC 61000-4-12 deal with the methods to be used during the equipment immunity tests to lightning surges and served as a basis for the tests carried out in the laboratory.

Withstand capability tests

Tests were carried out in many pieces of household equipment to determine their withstand levels.

a. Applied waveforms and voltage levels

The following waveforms were used for the tests: combined waveform (1.2/50 μs voltage and 8/20 μs current) and ring wave.

That is, the combined generator (IEC 61000-4-5) presents an open-circuit voltage with crest time equal to 1.2 μs and half-value time equal to 50 μs, whereas the short-circuit current presents a 8 μs crest time and 20 μs half-value time. The ring waveform generator (IEC 61000-4-12) presents oscillatory output characteristics.

b. Waveform application

The pieces of equipment were tested with supplying terminals connected to the source in the following status: connected (operating), stand-by status (equipment connected to supply, but in OFF status, whenever this is possible, such as in TVs, DVD drivers, etc.) and disconnected (by a mechanical switch).

During the differential mode tests, the voltages were applied amongst the supplying equipment wires.

However, as for the common mode tests, voltages were applied between the supplying and grounding terminals. In appliances where there is no grounding terminal, tests were carried out by applying the voltages between the equipment supplying conductors and a conductive plaque positioned underneath and in contact with the equipment. As for desktop equipment, tests were carried out in which the grounding plan was located underneath the desk legs.

Tests were carried out by gradually increasing surge severity until the withstand level was reached. The severity was increased until the equipment was damaged.

c. Test results

Table I presents the test results which were carried out in the power quality laboratory.

Table I - Surge withstand voltage of some appliances according to tests

Appliance	Surge withstand voltage (kV)	
	Common Mode	Differential Mode
VCR (1)	2 (4)	1
DVD player (2)	≥6 (4)	2
Television (2)	≥6 (4)	2
PC (1)	2	3.5
Multifunctional Printer (2)	≥6	2
Microwave oven (1)	4	
Audio micro system (1)	≥6 (4)	2
Fax machine (1)	2	4
Air conditioner (1)	≥6	2
Refrigerator (3)	≥6	≥6
UPS (1)	2	≥6

(1) fixed voltage input
(2) automatically regulated voltage input
(3) refrigerator without electronic control
(4) equipment without grounding terminal (voltage applied from active conductors to a metallic plate under the equipment)

Tests in the selected household equipment have shown, in a general way, that the combined waveform is more severe than the ring waveform, both bearing the same magnitude. Thus, the withstand capacity obtained during the tests were assumed by using the combined waveform.

As for the withstand capabilities obtained during the tests, one notices that these values are generally greater than the immunity values specified by Standard IEC-61000-6-1 (phase-ground: ±2 kV, e phase-phase: ±1kV).

Analysis procedure

In order to analyze indemnity request due to damaged equipment related to lightning strokes, some specific procedures were established so that one could assess overvoltage conditions as a function of the distance between the striking point and the given customer, as well as the withstand capability level of a given piece of equipment. For a given withstand level, a critical distance is determined for a specific lightning current.

As a matter of fact, in a rigorous perspective, the overvoltage magnitude can only be compared with the withstand capacity of a given piece of equipment when the corresponding waveforms are exactly the same. However, having in mind that several different waveforms might occur, here is proposed the crest overvoltage values obtained by simulations to be compared with the withstand levels obtained during the tests.

a. Determination of the critical distances as a function of the equipment withstand level

The proposed procedure aims at determining the minimum distance, namely the critical distance, from the striking point up to the distribution transformer that supply the complaining customer. For lower distances, the equipment might present damages. Such critical distance is obtained as a function of the lightning current (magnitude) and the withstand voltage of the specific appliance.

b. Confidence ellipse

In the lightning detection system, the location of a single stroke is determined by a confidence ellipse that rounds the region, centered at the computed position, in which a probability of occurrence is provided. Normally, the ellipse is given for a 50% probability, but other ellipses bearing different probability values might be given.

c. Diagnosis criterion to establish equipment damage

Taking as input the critical distance and the confidence ellipse for a specific case, the diagnosis is obtained as a function of the transformer location with respect to the ellipse considered and the obtained critical distance. If the probability of the lightning stroke occurrence in the critical distance is high, one should consider that the specific piece of equipment might be damaged as a consequence of the lightning stroke.

During the application of this method, one can measure the distance by the electrical path (lines). However, when a more conservative approach is taken, one could measure the geographical distance. In this case, the area located in the circumference bearing its center at the transformer site and radius equal to the critical distance can be called the vulnerability area.

The proposed criterion leads to the possibility of damaged equipment whenever there is intersection between the confidence ellipse and the critical distance circumference. If one uses the 50% probability ellipse, the condition of not having intersection with the critical distance circumference infers a low probability that the lightning might have occurred in the vulnerability area.

FINAL CONSIDERATIONS

This paper has shown procedures to determine whether lightning strokes can damage equipment in low voltage customers. These procedures are in the process to be incorporated in a computer system that assists technical staff of distribution companies to assess customer claims due to damaged equipment.

Further developments are underway, namely: (i) measurement of surge events in distribution systems, (ii) actions to reduce customer claims by changes in protection schemes, and (iii) new laboratory tests related to equipment withstand capability.

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