LIGHTNING PROTECTION OF TRANSFORMERS SUPPLIED BY UNDERGROUND CABLES

Brasil, D.O.C.; Brunheroto, P. A.; Ferrari, E. L.; Oliveira, J. J. S.; Tahan, C. M. V.
Escola Politécnica da Universidade de São Paulo – G.D.P.E.A.
Av. Prof. Luciano Gualberto 158, Trav. 3, São Paulo, S.P., Brasil
docb@uol.com.br

Abstract - **This paper deals with lightning protection in transformers supplied by underground cables when submitted to incoming surges from overhead distribution systems. As a result, number and location of surge arresters are suggested.**

Keywords: Lightning Protection, Surge Arresters, ATP, Modelling, Transformers, Underground Cables.

I. INTRODUCTION

Due to local physical characteristics and to the load to be supplied, overhead and underground lines generally coexist along a 13.8 kV distribution network. An underground cable, for instance, usually supplies Brazilian vertical and horizontal condominiums. Underground networks are intrinsically protected against surges. Lightning strokes to several points on the overhead network may nevertheless penetrate the underground network and affect the distribution transformers on the underground network. Lightning arresters installed both on the derivation bus on the overhead network and, occasionally, at the end of the underground cable aim at providing adequate protection to the equipment on the underground network, particularly to transformers.

This work proposes to present the main results achieved over the study of transformer protection in loop or radial underground networks connected to overhead lines for several lengths of underground cables. Eletropaulo Metropolitana, a distribution company that is concerned with reevaluating its protection system for such transformers taking into account location and minimum number of lightning arresters, supported this study.

II. NETWORK MODELING

This work was developed with the help of the ATP electromagnetic transients program. The basic modeling used is described as follows:

A) Overhead network:

The 13.8 kV overhead lines are represented by the wave propagation model (distributed parameters) with the help of the Line Constants subroutine, bearing in mind the influence arisen from whether or not to consider the correction of parameters according to the frequency, as in JMarti subroutine. A set of 4 wires regarding the 3 phases and the neutral wire was represented. Since overhead line is multi-grounded, it was necessary to model different sections on the line to represent the real grounding conditions of the network.

B) Underground network:

The set of cables herein represented is composed of 4 cables, 3 for the phases and one for the neutral, all of them with the corresponding shielding and with the same features (35mm2, 8.7/15 kV EPR insulation). The basic geometric configuration of phase cables is presented in Fig. 2.1. The neutral cable is located 0.162 m apart from the centre of phases set at a depth of 0.8 m. Preliminary simulation tests were carried out in order to validate the modeling of these cables for the phenomenon of lightning surges. Fig. 2.2a shows the circuit used for the test, where a 10 kA surge current with 1μs of time to crest was applied in the middle of an open cable 1 km long. With the help of Cable Constants Subroutine the models tested were: wave propagation model (distributed parameters) with and without correction of parameters according to the frequency through Semlyen subroutine and concentrated parameters (PI's circuits). Figs. 2.2b to 2.2d present the overvoltage profiles in the open end of the cable. As it can be seen, the results obtained with both models were similar. For matter of simplicity the underground cables were represented by PI circuits, with section lenghts varying from 15 to 100 m.

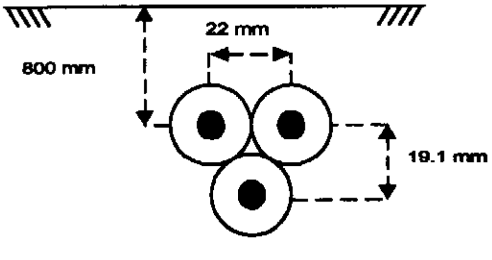

Fig. 2.1 - Geometric configuration of the phases cables

C) Transformer model:

The transformer was represented by the saturable transformer component available in ATP. It was included in this model the representation of the parasitic capacitances.

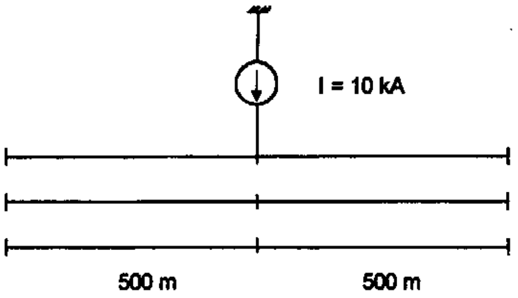

Fig. 2.2a - Cable test circuit

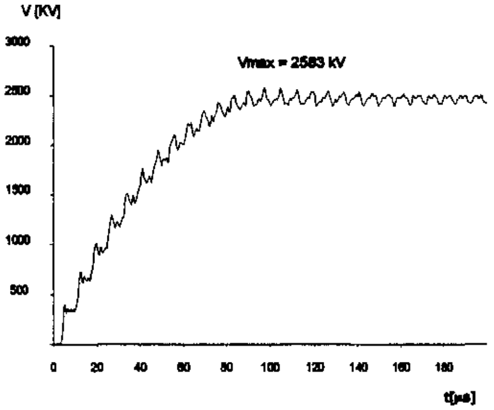

Fig. 2.2b - Cable modeled by PI's circuit (Section lenght of 50 m)

D) System representation:

Fig. 2.3 presents the basic ATP system representation, showing that 30m spans were considered for the overhead line near the derivation bus - from the overhead line to the underground cable - and 300m in more distant buses. The terminal buses in the overhead network were grounded with resistance equal to the characteristic impedance of the lines (phases and neutral) in order to avoid undesirable reflections.

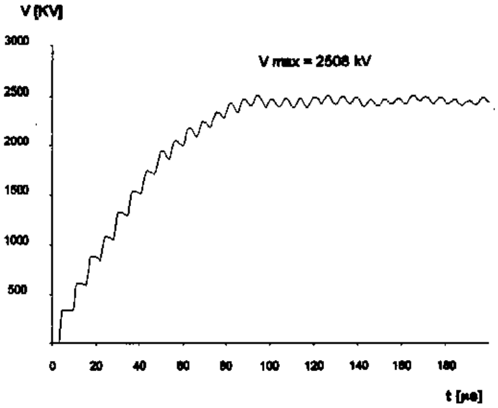

Fig. 2.2c - Cable modeled by wave propagation model (Grounded shielding represented externally NGRND=4)

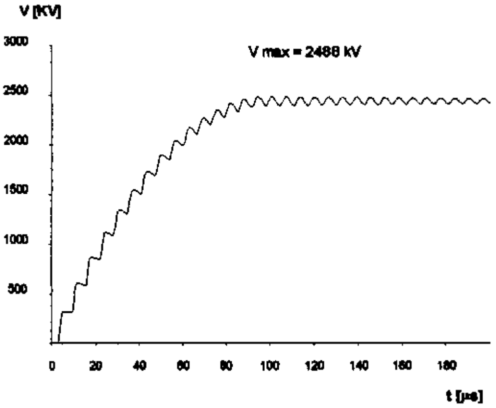

Fig. 2.2d - Cable modeled by wave propagation model (Grounded shielding represented internally NGRND=3)

As there is a great dispersion of physical configurations it was not considered the presence of other cable junctions in the vicinity in order to represent the worst condition for the phenomenon.

This work analysed the influence of:

- different locations for the lightning stroke;
- disruption of phase and neutral insulators;
- grounding resistance of the neutral;
- presence and location of lightning arresters.

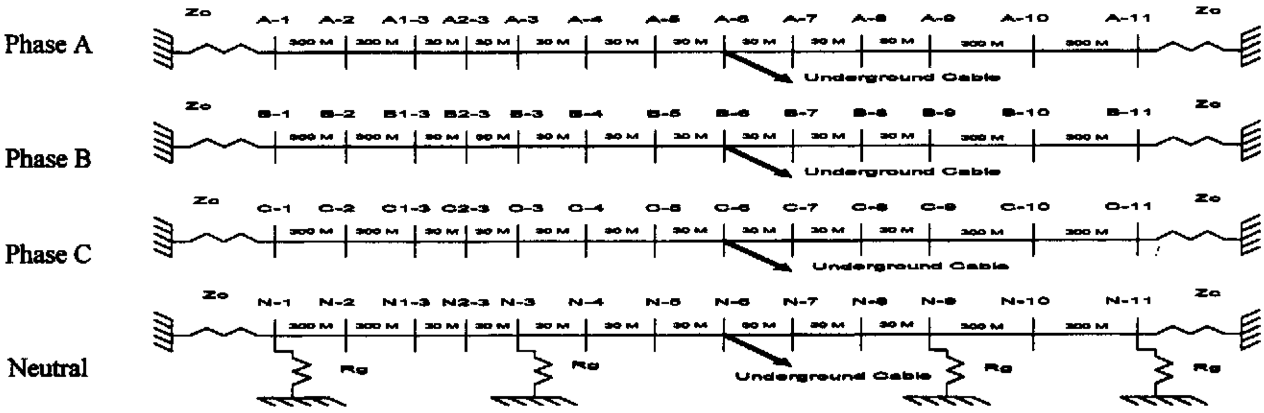

Fig. 2.3 - Overhead network for analysis

III. ANALYSIS OF LIGHTNING PROTECTION IN UNDERGROUND TRANSFORMERS

A. Description of configurations and situations studied

The majority of the cases studied basically refer to the overhead network configuration in Fig. 2.2. Concerning the configuration for underground cables, it was considered the following two conditions:

- Radial configuration. In the radial configuration transformer chamber is supplied from an underground branch cable connected to the overhead line. The underground cable counts on the protection of only one lightning arrester, located at the derivation bus. The underground cable extensions here considered were 15m, 100m and 1,000m. Two alternatives for deriving the overhead network were analyzed: in its geometrical center (bus 6 in Fig. 2.2) and at its end (bus 1 in Fig. 2.2). The underground neutral cable was grounded along with the shields, that is, at every 100m. For distances under 100m (for a full 15m extension, for instance), grounding the neutral and the shields was considered at both ends of the cable. The ZnO lightning arrester used here was rated 12 kV, 5 kA, with a typical characteristic curve with last point given by the 10.0 kA/40 kV pair.

- Loop configuration. For long cables, Eletropaulo Metropolitana utilizes loop configurations. In this configuration the transformer chamber is supplied from an undegrounded cable that may be connected in two different points of overhead line, but still operating in a radial mode. Due this configuration there are two lightning arresters in the underground cable, one in each terminal. Loop and radial configurations use the same type and rating of lightning arresters. The situation, which represents a relatively long underground 1000m cable, was studied.

The lightning stroke locations studied were the derivation bus from the overhead network (bus 6), the adjacent buses 5, 4, 3, 2-3 and a bus slightly farther from the derivation bus (bus 2). All amplitudes of lightning current (5kA-200 kA) and rising times (0.5μs-10.0 μs) were considered.

B. Data and criteria for protection in transformers

The protection level of distribution transformers in the underground network was considered 80% of the basic insulation level (BIL) to surges, i. e. a 20% safety margin between the BIL and the maximum overvoltage accepted for lightning arrester protection. First, two BILs were studied, namely 95 kVp and 110 kVp, used as protection criteria under the values of 76 kVp and 88 kVp, respectively. However in order to evaluate the failure rate only the overvoltages above the BIL were considered to lead to faults (both phase-to-ground, due to insulation of bushings and phase-to-phase, due to insulation of Delta windings). When drawing the conclusions, only the 95 kVp BIL was considered, since it represents the prevailing basic insulation level in Eletropaulo Metropolitana transformers.

C. Maximum Overvoltage Results – Deterministic Analysis

For illustration sake, table 3.1 shows all maximum phase-to-ground and phase-to-phase overvoltage levels at the transformer terminal that were found regarding lightning stroke locations on the derivation bus (bus 6) and for a 100m radial configuration of an underground cable. Special emphasis is given to the combination of currents and rising times that lead to levels greater than 95kVp, i.e. levels that would lead to transformer failures. Fig. 3.1 shows the phase-to-ground overvoltage time profile for a lightning stroke of 70 kA and 2 μs of rising time. Similar results were obtained for surge locations in other overhead network buses as well as for other underground configurations.

Table 3.1 - Maximum Overvoltage Levels for a 100 m Radial Configuration and Lightning Strokes in A6

	Ts (μS)					
Ir (kAp)	0.5	1	2	4	6	10
200	70.9	101.9	152.3	192.7	182.9	176.9
150	113.4	103.4	169.1	196	149.5	193.2
140	76.4	117.9	172.4	189.3	142.5	163.2
130	79.5	122.9	175.9	178.8	149.4	161.3
120	81.9	129	178.9	166.4	196.7	161.7
110	85.2	135.8	[illegible]	136.1	[illegible]	202.7
100	90.0	143.6	135.9	[illegible]	200.5	178.1
90	99.2	150.7	199.0	139.1	191.9	150.5
80	225.9	210.7	167.4	172.8	163.1	141.3
70	208.8	190.9	190.9	165.5	158.4	132.3
60	186.7	171.2	197.8	156.7	147.8	123.8
50	165.3	151.7	[illegible]	167.2	137.4	118.6
40	150.3	143.7	129.9	[illegible]	122.7	111.4
30	139.5	134.7	121.4	121.4	108.4	105.9
20	124.9	120.8	109.1	100.1	94.1	93.1
10	93.5	90.1	82.6	76.4	75.9	70.9
5	74.1	71.9	67.3	61.5	55.4	47.4

Phase-to-Phase Overvoltages at the Transformer Terminal

	Ts (μS)					
Ir (kAp)	0.5	1	2	4	6	10
200	111.9	107.2	138.3	184.7	158.5	131.3
150	118.4	118.4	158.6	179	107.9	154.6
140	95.6	122.3	162.3	168.8	194.1	128.2
130	92.6	126.4	167.3	152.9	181.7	122.9
120	89.6	131.6	173.1	131.9	191.5	126.1
110	87.5	137.2	178.7	119.6	189.2	163.7
100	92.1	140.7	[illegible]	152.2	[illegible]	182.9
90	96.8	149.1	[illegible]	107.2	134.5	116.6
80	203.9	187.7	[illegible]	190.5	[illegible]	109.9
70	187.8	170.1	151.9	[illegible]	116.9	103.4
60	170.4	155.2	119.2	147.3	109.5	96.9
50	152.9	139.4	107.9	108.5	102	90.4
40	135.7	123.9	97.4	99.6	94.5	83.5
30	118.4	108.9	89.3	90.6	86.7	76.3
20	101.3	94.5	81.5	81.3	78.1	69.9
10	84.3	80.5	72.6	70.2	67.3	59.5
5	74.5	71.9	66.4	60.6	55.9	47.1

Phase-to-Ground Overvoltages at the Transformer Terminal

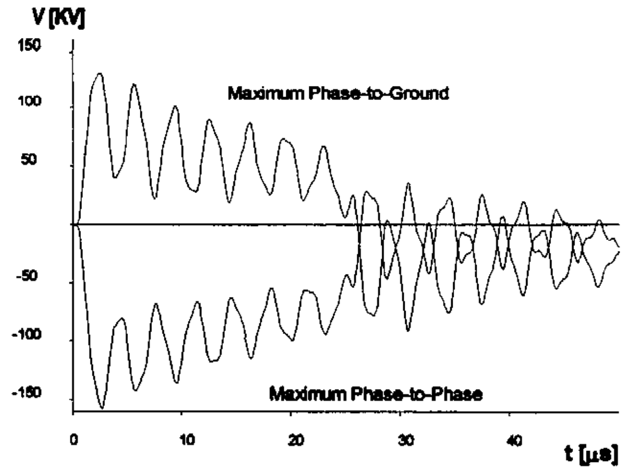

Fig. 3.1 - Overvoltage Profile illustration

D. Statistical Modelling

- Ceramic level and strike distance. A sensitivity analysis for ceramic levels of 100, 80 and 60 was carried out, although the conclusions were drawn by using the typical ceraunic level of 60, corresponding to the region under study. The evaluation of the density of lightning strokes to the ground was based on the following expression:

  $$DR=0.14x(NC)^{1.03} \quad (1)$$

  where:
  DR: density of lightning strokes to ground, in km^2/yr.
  NC: ceraunic level.
  For example, a ceraunic level equal to 60 will result in 9.5 strokes/km^2.yr.

  The strike distance (SD), based on the electrogeometrical model proposed by Whitehead [3], was determined by the following expression:

  $$SD = 9xI^{0.65} \quad (2)$$

- Distribution of lightning stroke currents and rising times. The distribution of lightning stroke currents was considered as a log-normal with a mean value equal to 20 kA and standard deviation equal to 0.92. Rising time values were obtained based on a distribution of di/dt rates, with mean value equal to 22 kA/μs and standard deviation equal to 0.69 [4].

- Shielding provided by buildings near the overhead transmission line. Transmission towers were assumed 9m height and 1.8m line width. Three basic assumptions concerning shielding near the overhead lines were considered, as follows:

  1. No shielding provided by neighboring buildings. This case considers the distribution line only all over a plane ground. This can be the case of rural distribution lines or the supply of new building blocks.
  2. Supply of a building. The derivation bus is assumed to be near some isolated building protected against lightning strokes (one lightning rod at 15m to 25m from the ground). Such protection provides shielding for lightning strokes over the lines. This is shown in Fig. 3.2.

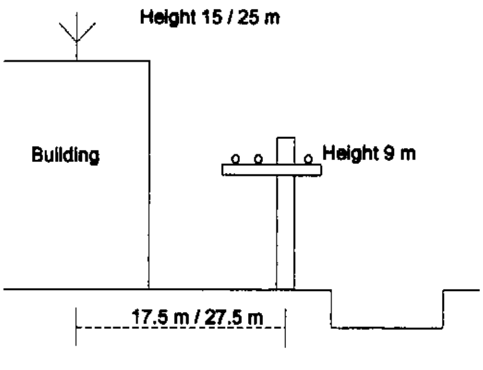

Fig. 3.2 – Shielding with one rod only

  3. Supply of a large area, having a high density of buildings. An additional shielding was assumed to be provided by a group of buildings uniformly distributed along each sidewalk. Each building is equipped with a lightning rod, having the same characteristics as in the previous case.

- Description of network branches. The basic network for all simulations - from which all results concerning the transformer protection were obtained - is represented in Fig.ure 2.2. For statistical evaluation, the typical overhead feeder was assumed to be 10000m long. Different shielding characteristics were simulated by the generation of random numbers. This led to results that provide the incidence of lightning strokes per year in each branch in the basic network .

- Evaluation of failure rates of transformers. As aforementioned, failures were assumed to occur when a phase-to-phase or a phase-to-ground overvoltage exceeds the 95 kVp maximum BIL. The evaluation of the risk associated with these two types of overvoltage (failure risk) can be carried out by the following expression:

$$R=\sum_{i=1}^{nr} Nr_i \times \sum_{j=1}^{nc} Pc_j \times \sum_{k=1}^{nt} Pt_k \times P_{j,k} \quad (3)$$

where:

R: failure risk (number of times per year) of phase-to-phase or phase-to-ground overvoltage exceeding the maximum value.

Nri: Number of strokes per year in the overhead network branch i.

Pc_j: Probability of occurrence of a lightning stroke current j. The statistical distribution of lightning stroke current was divided into intervals. The current j was assumed to be the maximum value of such interval.

Pt_k: Probability of occurrence of a rising time k. Such times were grouped into intervals, where rising time k represents the maximum value of the interval. This probability, for a given stroke current j, was determined by the adopted di/dt growth rate distribution.

Pj,k: Probability of a lightning stroke j and a rising time k leading to an overvoltage level greater than the maximum limit. This value is considered null when the overvoltage value is less than the limit or 1 otherwise.

The time period between failures was then evaluated as the inverse of the failure risk.

- Failure probability. Each lightning overvoltage was marked with 0 or 1. "0" indicates no failures whereas "1" indicates that the overvoltage exceeded 95 kVp, thus leading to failure. Combinations of currents ranging from 5kA to 200kA with rising times from 0.5μs to 10.0 μs were used for the simulations. The results were included in tables covering 15m and 100m radial configurations as well as a loop configuration supplying a 1000m underground cable.

IV. RESULTS OF THE STATISTICAL ANALYSIS

For ilustration sake, Table 3.2 regarding a ceraunic level equal to 60 shows a comparison of failure rate for underground cable lenghts of 15 m, 100m and 1500 m.

The results regarding transformer failure rates obtained from the statistical analysis are very sensitive to the underground cable length, the shielding near the overhead network and the number and location of lightning arresters.

In order to set up an acceptable level of failure risk and then propose appropriate solutions for the protection of transformers, the following procedure was adopted:

- Failure rate criterion: set up an average failure rate for the entire group of transformers equal to 1/100, i.e. one failure for every 100 transformers per year. Set up a maximum failure rate of 1/50 for any three subsets of transformers formed as a function of the underground cable length (up to 15m, up to 100m and over 150m).
- Shielding offered by buildings near overhead lines: at least one building near the overhead line was assumed for underground cables up to 100m long. For this situation a 15 m height rod shielding was supposed to be installed on the top of the building, ensuring additional shielding for underground cables derived from the overhead line. For longer underground cables (e.g. cables in private building blocks in suburban areas), it was not considered additional shielding offered by nearby buildings.

Table 3.2 - Comparison of Failure Rates and Times between Failures

****** **Underground Cable - 100 m** ******* **Results for ceraunic Level 60**

	No Shielding	1 rod - 15m	1 rod - 25 m	Several Rods 15 m	Several Rods 25 m
Failures/year (PG)	0.01023	0.00536	0.00200	0.00536	0.00187
Time Between Failures	97.79147	186.42641	500.76182	186.49032	534.57545
Failures/year (PP)	0.02788	0.01816	0.01046	0.01459	0.00538
Time Between Failures	35.86561	55.07571	95.63549	68.56348	185.72136

****** **Underground Cable - 15 m** ******* **Results for ceraunic Level 60**

	No Shielding	1 Rod - 15 m	1 Rod - 25 m	Several Rods 15 m	Several Rods 25 m
Failures/year (PG)	0.00509	0.00267	0.00099	0.00267	0.00093
Time Between Failures	196.59856	374.90888	1007.56761	374.90888	1074.73878
Failures/year (PP)	0.01378	0.00749	0.00294	0.00720	0.00253
Time Between Failures	72.59299	133.55123	339.88523	138.80901	395.30746

****** **Underground Cable - 1000 m (Loop)** ******* **Results for Ceraunic Level 60**

	No Shielding	1 Rod - 15 m	1 Rod - 25 m	Several Rods 15 m	Several Rods 25 m
Failures/year (PG)	0.00092	0.00048	0.00018	0.00048	0.00017
Time Between Failures	1082.68852	2064.66182	5548.77865	2064.66182	5918.69722
Failures/year (PP)	0.00482	0.00253	0.00094	0.00253	0.00088
Time Between Failures	207.67386	396.02922	1064.32853	396.02922	1135.28377

Note: PG: Phase-To-Ground PP: Phase-To-Phase

- Estimated number of transformers supplied: around 1500 transformers, for which 90% are supplied by 15m underground cables, 9% by 50m cables (adopted 100m for safety) and only 1% by cables with extension longer than 150m (adopted 1000m).

V. CONCLUSIONS AND RECOMMENDATIONS

By using the methodology presented in the previous sections (criterion for failure rates, ceraunic level, shielding, etc.), Table 3.3 illustrates a proposal of protection recommendade related to the underground cable length.

This table shows a maximum failure rate equal to 1/55 years, corresponding to the 100m underground cable. The average total failure rate can be determined by the relation between the total number of failures (12.63) and the total number of transformers (1500), which results in an average failure rate equal to 1/119 years. Therefore both the average and maximum failure rates meet the criteria adopted. The protection of transformers should then follow the scheme proposed in Table 3.3, which can be summarized as follows:

- 1 lightning arrester, installed in the sending extreme of the cable, is appropriate to protect underground cables up to 100m long. The lightning arrester characteristic is described in section III.
- 2 lightning arresters should be installed, one in each end of the underground cable, to protect underground cables with extension longer than 100m.

Two comments should be outlined:

- The influence of the protection offered by lightning arresters located in adjacent poles to the derivation bus was evaluated for some configurations. This analysis shows that such adjacent arresters do not bring sensitive improvement for phase-to-phase overvoltage levels in the transformers.
- The analysis of phase-to-ground and phase-to-phase overvoltage in the transformers shows that:
  - Phase-to-ground overvoltages are less constraining than phase-to-phase overvoltages.
  - Lightning arresters in the overhead network significantly reduce phase-to-ground overvoltages, but they can increase phase-to-phase overvoltages.
  - Insulation rupture in more than a single phase in the overhead network reduces phase-to-phase overvoltages. Lightning arresters can therefore worsen phase-to-phase overvoltage levels, since they avoid insulation rupture of other phases which are not affected by the stroke.

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Table 3.3 - Total Failures by year

Underground Cable (m)	Existing Transformers	Considered Protection	Failure Rates	Failures by year
15 m	1350	1 ligtning arrester	0.0074870	10.110
100 m	135	1 ligtning arrester	0.0181568	2.450
1500 m	15	2 ligtning arresters	0.0048152	0.072
Total Failures by year				**12.630**