HOW TO PROTECT LED ROAD LAMPS FROM LIGHTNING STRIKES BY CHOOSING INSTALLATION METHODS

A comparing investigation on

- **Material for lamp poles: Metal or composite?**
- **Power cables: Shielded or unshielded?**
- **Grounding: The influence of different levels of resistance to ground.**

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BACKGROUND

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Background.

LEDs save energy. All over the world, for road illumination, gas discharge light sources are exchanged for light emitting diodes, LEDs. We are still in the beginning of a process of exchanging all light sources for LED-lamps, a process that also includes road illumination systems. The reason is that LED-lamps saves electric energy, without loss of illumination quality. LED-lamps are much more energy efficient than the alternatives. LED-lamps are saving energy, but are very sensitive to over-voltages, much more sensitive than gas-discharge lamps.

Many lamps destroyed at the same occasion. The experience of damages caused by lightning strikes is yet limited, but in many cases hundreds of LED have been destroyed by one single lightning strike. High energy lightning pulses are propagated from the point of impact along the power supply cables to all lamps connected to the same network. Therefore, in areas where thunderstorms are common, lightning strikes have caused great damage on LED-lamps along roads.

High voltage pulses, with short duration carries low energy, but are fatal to LEDs.

Since LED-lamps are much more sensitive to overvoltage, a LED lamp will destroyed by very short pulses exceeding the recommended voltage by only a few volts. This makes LED lamps extremely sensitive to lightning, even if the lightning hits far away from the lamps. This is a new problem not existing with gas discharge tubes, which are very resistant to over-voltages with short duration. Many manufacturers install over-voltage protection units close to the LEDs for this reason.

Power distribution systems and cables are used for many years. Installing power cables for road illumination is a long time investment. Assuming that the power distribution systems will be based on copper cables, the power supply-networks may be unchanged for many years. The lamps, on the other hand, may be gradually redesigned, and exchanged within a few years. The light sources have been exchanged over time: from light bulbs to gas discharge tubes, and now to Light Emitting Diodes, LEDs. So may be, within a few years the LED-lamps that we install today, will be replaced by new generations of lamps, even more efficient than the LED-lamps of today. So the power cables which are installed today, are expected to survive several generation of increasingly efficient lamps, equipped with gradually upgraded control systems. Whatever is within the field of development of the lamps, the cables may be unchanged. Therefore the design and installation of cables are worth investigating.

Grounding principles. It is important to investigate how to make ground connections to get maximum protection against incoming lightning pulses.

Protection units. Protection units, (transient protection- or surge protection units) designed for protection against sudden over voltages, are used to a great extent, but there is a need for investigating how to choose between different protection units, and where they should be mounted.

Other threats than lightning. Of course there are other threats to LED-lamps: Sudden breaking of strong currents may also cause high voltage peaks in the system.

Point of impact. If a strike of lightning occurs close to a lamp, at the top of the lamp pole, or at the incoming cable, how can you protect the next lamp connected to the same power line, and how can you protect lamps in a neighbouring area from being destroyed too?

The lightning strike can occur far away or very close to the lamp. Far away sources are likely to generate high energy pulses propagating along the cables. Important aspects are: choise of power cable, type of lamp poles, grounding quality, travelling time for the lightning pulse before arriving at the next lamp in the system. Pulses from distant sources will propagate along the cables until they arrive at a branch point. The branch point may be where two or more power cables are connected, at a connection between protective earth and ground, or where a lamp is connected. After the branch point, each branch will get a part of the incoming pulse, in proportion to the geometry of the cross section of the cable, and the loads at other ends of the cables.

Maintenance. To exchange LED lamps on lamp poles, along a road, often skylifts are needed. When LED-lamps are damaged it not possible just to exchange some small damaged part, but probably a whole heavy and big lamp house including transformer, over voltage protection and light source must be exchanged. Today the work of handling the removal of a damaged lamp, and mounting a new one is more expensive than the cost of the lamp itself. When a road lamp has to be replaced, the work also often includes redirecting traffic away from the service team. Replacement of a single lamp includes stopping of traffic, using skylifts, etc., a time consuming work. The calculated life span of a lamp is about 10 years, but damaged lamps need to be replaced immediately.

A Faraday cage. A Faraday cage is supposed to give a perfect protection against lightning strikes. Is it possible to design Faraday-cage in practice? One idea may be that a shielded cable, with the shield connected to ground, the lamp poles are made of metal, the lamp housing made of metal, the power cables are shielded, and all parts of the metal shielding are well connected to each other, make a Faraday cage system. In theory that would be perfect, but the question is if that is a realistic solution?

Travelling time. It is well known, that lightning pulses propagate with a limited speed, but the question is if the travelling time for a lightning pulse is long enough for activating breaking units that can save lamps further down the same line.

The purpose of this project was to find efficient methods of protecting LED-lamps from the consequences of lightning strikes. When new power cables are installed, you have to choose installation methods and cable quality also after considering other aspects, such as the need for transmitted power, and long time mechanical stability.

The most important questions were considered to be:

- Choise of cable types: shielded or unshielded cables?
- Choise of lamp poles: Metal- or non-metal lamp poles?
- Design of ground connections?
- Location and types of lightning protection units?

Aim. The general aim was to find the best installation methods for protecting road lamps from lightning strikes.

Method. Lab experiments were performed, using a lab copy of a system of four road lamps covering a road stretch of 120 meters. In the lab experiments, all cables were of correct length, 43 m-cables between the poles, and 8 m-cables inside the poles. The height of the lamp poles had to be shortened from 5 m to 2 m, without changing the length of the cables inside.

- Aluminium lamp poles were compared to non-conducting composite lamp poles.
- Shielded power cables were compared to unshielded power cables.
- The influence of grounding was investigated by comparing different levels of resistance to ground.

Lightning pulses were injected at the following points:

- At the lamp-house of Lamp1
- At the shield of the power cable close to Lamp1
- At the PE-conductor close to Lamp1

The voltages were recorded at the following points, inside each lamp:

- The Line port inside the lamp house
- The Neutral port inside the lamp house
- The PE port inside the lamp house

Test criterium for comparing different installation methods:

The test criterium used for comparing different installation methods was the voltage magnitude recorded at the above mentioned points of each lamp, when a lightning pulse was injected close to Lamp1.

PART 1.

INTRODUCTION

Part 1 gives a short description of background, aim, method and results, together with a discussion.

A SHORT DESCRIPTION OF BACKGROUND, AIM, METHOD AND RESULTS

Background. In order to save energy, all over the world, LED-lamps are installed for road illumination. A drawback is that LED-lamps are much more sensitive to over-voltages, compared to gas-discharge lamps. In some locations were lightning strikes are common this is a great problem. Hundreds of neighbouring lamps may be destroyed by one single strike.

Aim. The aim of this study was to find the best installation methods for protecting road lamps from lightning strikes.

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RESULTS -PART 1.

A short summary based on possible damages on Lamp2 – the second lamp in a row, where the Lamp1 or the incoming power cable is struck by lightning.

The results showed that

- there are <u>no important advantages for aluminium lamp poles</u> compared to non-conducting composite lamp poles.
- <u>Shielded cables may be advantageous</u>, but only if the grounding is very good, and if the shield is thick enough to carry the energy of the lightning pulse without melting.
- <u>The resistance to ground showed to be important</u>. In order to protect neighbouring lamps the resistance to ground must be close to zero, otherwise the lightning pulse will propagate to next lamp, and so on, destroying a long row of lamps along the road. (In this report "resistance to ground" denotes the resistance beween PE and ground at each pole.)

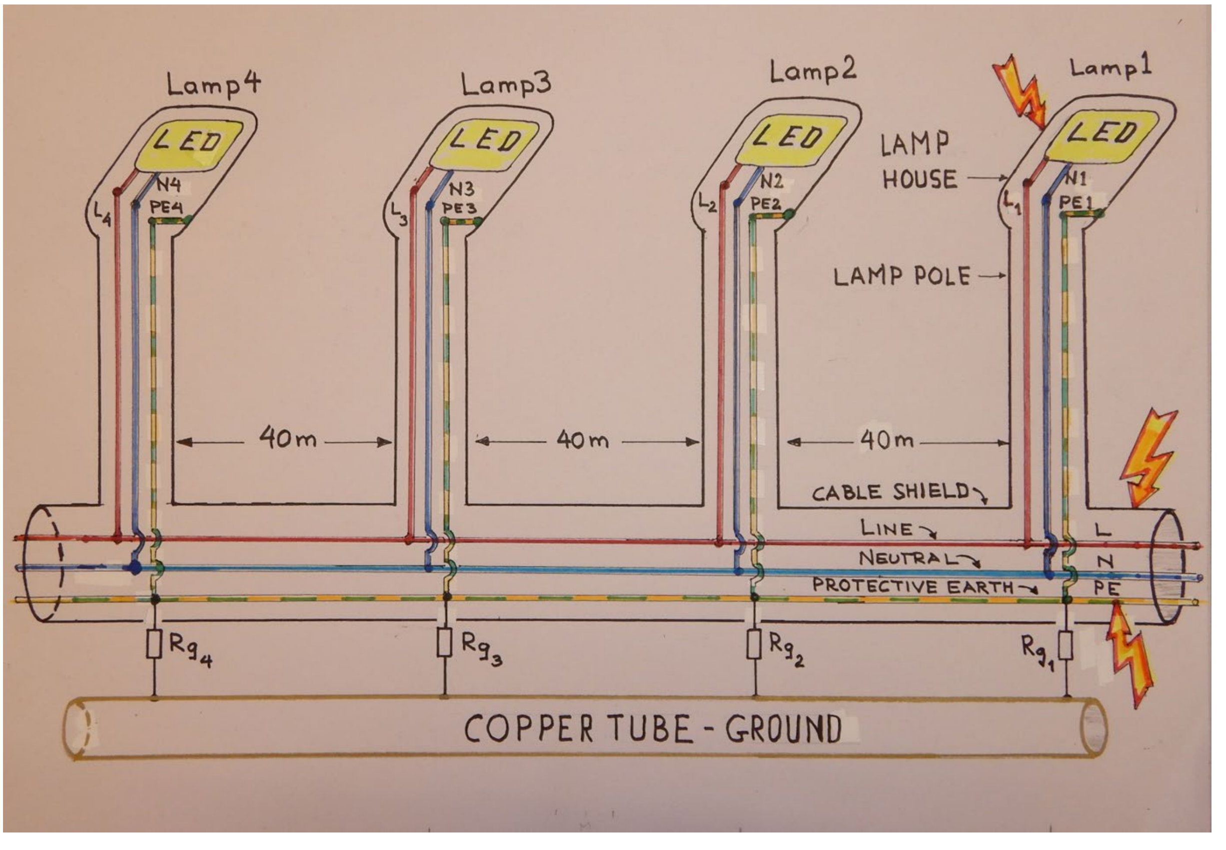

Figure 1. Lab setup with shielded power cable and aluminium lamp poles. Resistance between PE and copper tube-ground at each lamp: Rg1, Rg2, Rg3 and Rg4. Three points of injection for the lightning pulses are illustrated: <u>Injection point 1</u>: At the external surface of the lamp house of Lamp1. <u>Injection point 2</u>: At the shield of the power cable, close to Lamp1. <u>Injection point 3</u>: At the incoming PE-conductor close to Lamp1.

DISCUSSION- PART 1.

Shielded cables may perform well, but only if the shields are thick enough to carry the energy of lightning pulses, without melting. A simple way to create a shield for this purpose may be to put the cable inside an ordinary metal tube. This method can be used in old installations, where lightning strikes have caused problems. These cable shields must be well connected to the walls of all metal boxes used in the system.

Conducting metal poles or non-conducting composite poles? When choosing between conducting poles and non-conducting poles, there are no obvious advantages with metal poles, since the Faraday-cage-principle is difficult to realize in practice. The important principle is that the PE conductors must have low resistance to ground, and that the PE-conductors are properly connected to the lamp houses.

Surge protection units. Surge protection units are often installed inside the lamp houses. It may be a better idea to install the surge protection units at the bases of the lamp poles:

It is easier to examine and exchange a damaged a surge protection unit located at the base of a pole. No skylift and no stopping of traffic is needed.

It is very important that the surge protection unit has a very low resistance to ground.

A proposal. Good grounding and good shielding may be very expensive. It is not enough just to put a long metal rod deep down into ground, because the contact surface between the rod and the surrounding soil is too small. It is much better to use a large sheet of metal under ground, and connect the PE-wire to the metal sheet, creating great contact surfaces against surrounding wet soil.

A realistic compromise is to concentrate the grounding and shielding efforts to those places were lightning strikes are common, and the natural surroundings are favourable, and leave other places without special protection.

PART 2. DETAILED RESULTS AND ELABORATE COMMENTS ON THE RESULTS, COVERING THREE LEVELS OF RESISTANCE TO GROUND

DESCRIPTION OF LAB TEST DESIGN, LAB PERFORMANCE AND RESULTS.

The numbers, 000550 etc., refer to corresponding data files.

INTRODUCTION TO PART 2.

Part 2 gives an elaborate description of results together with graphical data and tables.

The Discussion-Part2 is also more elaborate than Discussion-Part1.

What criteria can we use for comparing different installations with respect to possible lightning damages?

Criteria for evaluation: For evaluation of the laboratory measurements the following question was used:

- How much of the incoming lightning pulses are reaching Lamp1 and Lamp2?

In practice this was made by registering the voltages at lamp1 and lamp2, when a controlled lightning pulse was injected either at the lamp house, at the incoming cable-shield, or the incoming PE-conductor close to Lamp1.

The different coupling cases were compared by looking at the percentage of the incoming lightning pulses reaching the lamps. The lamp-voltages were expressed in absolute values, and in percentage of the voltage of the injected lightning pulse. If this percentage was high, the lamp was considered broken.

Background for lab test design.

- The purpose was to compare different power cables, lamp poles and installation principles, with respect to consequences of lightning strikes.
- What are the consequences of a lightning strike on a system of road lamps, depending on the material chosen for the installation, and the impact points of the lightning strikes?
- How does the resistance to ground influence the consequences of lightning strikes?
- In theory, a completely covering metal case, a “Faraday cage” is supposed to give a good protection against lightning strikes.
- For a system of road lamps a Faraday cage would imply that the cables are well shielded, the cable shields connected to metal lamp poles, and the lamp poles connected to metal lamp houses. In addition the outside of the metal shield must be well connected to ground.

Injection points. Looking at the possible points of lightning impact, the following three points were chosen for injecting lightning pulses: [See Discussion Part2 for further explanations!]

- At the house of the first lamp. The lightning discharge is injected at the external surface of the metal lamp house.
- At the cable shield. The lightning pulse is injected at the shield of the incoming power cable close to Lamp1.
- At the PE-conductor. The lightning pulse is injected at the PE-conductor of the power cable close to Lamp1.

Test performance. Lightning pulses were applied at the above three locations:

1) The housing of Lamp1.

2) The incoming cable shield close to Lamp1.

3) The PE-conductor close to Lamp1.

The voltage recording system. The base instrument of the measuring system was a 100 MHz, 4- channel oscilloscope equipped with 15 kV-high-voltage probes. The surge pulse from the generator, was triggering the oscilloscope and always recorded by Channel 1. The remaining channels, Ch2, Ch3, Ch4, were moved around and connected to different spots of interest, repeating the same input pulse at channel 1. Since the input voltage at Ch1 always was the same, the oscilloscope performed as multi-channel, 100MHz, high voltage measuring system.

The lightning pulse generator. The standard lightning pulses, (surge-pulses), were generated by a lab generator (Transient 1000) designed for modelling lightning strikes. The duration of a standard surge pulse is 50 us (50 microseconds = 0.000050 sec). The rise time of a standard surge-pulse is about 1.2 us. The maximum peak of the surge pulse can be chosen between 500 V and 4100 V. In order to avoid sparks, the voltage peaks of the surge-pulses were often chosen in the interval 1-2 kV. The time scales are important because the time of travel for a lightning pulse propagating from one lamp to next lamp is about 200 ns (= 0.2 us= 0.2 mikroseconds = 0.0000002 sec) [43/0.2=215 ns] for the cable length of 43 meters. [The velocity of travel for a wave front inside a cable is about 0.2 m/ns. (0.2 meters per nanoseconds)] Assuming a cable length of 43 meter, a lightning pulse arrives to Lamp2 about 215 ns after arriving to Lamp1.

This travelling time is important when regarding the time of reaction needed for surge-protection-units, tested in another part of this report. The faster protection unit, the shorter pulse will reach Lamp2.

Design of lab tests

Lamps: All lamps were enclosed by a metal house, with a metal collar attached to the top of the lamp pole. The PE wire was connected to the inside of the wall of the metal lamp-house. The same PE wire was also connected to a PE-screw at the base of the pole. Both the aluminium poles and the non-conducting composite poles were equipped with screws for PE-connections.

Lamp poles: Poles for road illumination are usually about 5 meters high. The lamps, which are intended for mounting on top of the poles, are equipped with ready-made power cables, about 8 meter long, when delivered from factory. Because the lightning experiments were performed indoors, special poles shorted to 2 meters, were used for the lab experiments. The original 8-m-power-cables were used without changes, but had to be folded to get inside the 2-m-poles.

Two kinds of poles were compared:

- aluminium poles
- non conducting composite poles

Two types of cables were tested in the lab experiments:

- Shielded 3-conductors power cables (shield, Line, Neutral, PE)
- unshielded 4-conductor cables (Line1, Line2,Neutral, PE)

Power cables: The distance between poles for road illumination is 40 meters. The electric power is delivered by cables about 0.5 m below ground. The cable length for outdoor installations is a little more than 40 meters. The cables for the indoor lab experiments were cut into pieces of 43 m length each.

- 40 m winded on wooden coils:
- 8 turns
- diameter 1.59 meters
- distance between turns 0.12 m
- in total 40 meters on the wooden coils
- 1.5 m tails remaining in each end of the cables, for connections to the lamps.

Test pulses. The lightning pulses were delivered by a test generator, T1000, designed for standard test pulses, surge pulses: Rise time 1.2 us, duration 50 us. The open ended voltage was set to peak values between 1 kV and 4.2 kV. Depending on the load the resulting voltage over the loads varied in different test situations.

Ground. Lab ground was a 25 mm copper tube located in parallel with the cable coils and the row of lamps. All voltage values in the experiments are related to the copper tube ground.

Resistance to ground: In the lab experiment the resistance to ground, R_g, was the resistance between PE, (protective earth lamp connection), and the copper-tube ground. Throughout the testing all measurements were performed at three resistance-to-ground-levels:

- R_g <0.1 Ω ohms
- R_g =125 or 330 Ω
- R_g = 6 kΩ

The level 6 kΩ was chosen because this was the resistance value measured for an outdoor road lamp, after two days of dry weather.

R_g < 0.1 Ω represents the resistance in a short lab cable used for shorting PE to ground.

Recordings. 4 channel 100 MHz oscilloscope. High voltage 15 kV probes of equal length. All data saved and also presented graphically in the report.

Reference to outdoor road illumination systems.

Four lamp poles in a straight row cover a distance of 120 meters, when used for traffic illumination. Without changing important electrical properties, this system had to be reduced in size to fit into a lab area about 10 x 2.5 m. The length of all cables are important, because travelling time and attenuation are governing the behavior of lightning pulses propagating along power lines.

To solve the transformation from a straight-cables outdoor installation, to a narrow floor area, the cables were arranged on wooden circular-cylindrical frames, diameter 1.59 m. The cables were attached on the wooden frames in 8 turns, at a distance of 0.12 m between the turns. With this geometry a 40 m cable was shortened to a coil of length 0.84 m. The whole cable installation with four lamps was then occupying 10x2.5 m area of the lab floor.

The question was if this changed geometry made essential changes to the electrical properties of the whole system. Therefore an outdoor test track was built: Two lamp poles connected by 40+3 meters of power cable, and a copper tube in parallel, representing ground, exactly as with the indoor lab setup. A very fast square wave generator, making short pulses was used for generating the pulses. Pulse shapes, reflection factors, propagation velocity and attenuation were measured. The recordings showed no measurable differences between the outdoor and the indoor lab setups. The conclusion was that results from the compact indoor lab arrangement could be applied on real road illumination systems.

Extension of results to lamp3, lamp4, etc.

The voltage relations V_{L2}/V_{L1}, V_{L3}/V_{L2}, and V_{L4}/V_{L3} was checked. (L1: Line of Lamp1, L2= Line of Lamp2 etc.) If the resistance to ground was the same at each lamp, say R_g=330Ω, and the same type of cable was connected to the final lamp, the same voltage relations was valid for a chain of lamps.

Conclusion: It is enough to study the relations V_{L2}/V_{L1} and for the following lamps use extrapolation, in a linear way.

If $V_{L2}/V_{L1} = 0.8$, then $V_{L3}/V_{L2} = 0.8$ and

$V_{L3}/V_{L1} = 0.8*0.8 = 0.64$ etc.

OVERVIEW OF TESTED CASES

A. **00556 – 00571. Aluminium lamp houses. Shielded 3-conductors power cable. Aluminium poles. Pulse at the cable shield leading to lamp 1.**
B. **00572 – 00580. Aluminium lamp houses. Shielded 3-conductors power cable. Aluminium poles. Pulse at lamp house of lamp 1.**
C. **00581 – 00589, and 602-620. Aluminium lamp houses. Shielded 3-conductors power cable. Composite poles. Pulse at lamp house of lamp 1.**
D. **00590 – 00601. Aluminium lamp houses. Shielded 3-conductors power cable. Composite poles. Pulse at the cable shield leading to lamp 1.**
E. **00611- 00631. Aluminium lamp houses. Un-shielded 4-conductors power cable. Composite poles. Pulse at lamp house of lamp 1.**
F. **00632 – 00640. Aluminium lamp houses. Un-shielded 4-conductors power cable. Composite poles. Pulse at PE - incoming to lamp 1.**

CONSEQUENCES FOR LAMP1 – SUMMARY

Table 1. Consequenses for Lamp1 - Comparing different poles and cables.

Resistance to ground (R_g = resistance between PE and ground): $R_g = 0\ \Omega$

Pulse injection point	Case	Highest voltage percentage on L1 and N1 - ref to data file	grade
Lamp1-house	Shielded cables Aluminium poles case B	L1max: 80% - ref 578 N1max: 17% - ref 578	2
Lamp1-house	Shielded cables Composite poles Case C	L1max: 255% - ref 587 **Remark: See (*)** N1max: 263% - ref587	3
Lamp1-house	**Unshielded cables composite poles Case E**	**L1max: 55% - ref 614** **N1max: 59% - ref 629**	**1 Best for lamp house injection**
At the cable shield, S1	Shielded cables Aluminium poles Case A	L1max: 45% -ref 565 N1max: 36% - ref 557	2
At the cable shield, S1	**Shielded cables Composite poles Case D**	**L1max: 24% ref 593** **N1max: 23% ref 593**	**1 Best for cable shield injection**
At in-coming PE	Unshielded cables Composite poles Case F	L1max: 40% ref 632 N1max: 52% ref 632	2

(*) Remark: How come voltage percentages more than 100%? It looks strange that the voltage measured at Line1 and Neutral1 in Lamp1 are higher than the voltage measured for the injected pulse. The strange results can be explained by different coupling paths, and about 180 degrees phase differences inside the lamp. The results are still useful for comparing the different cases, since the injected pulses were the same in all cases.

Conclusions regarding consequences for Lamp1:
When pulses are injected at lamp1-house: Aluminium poles with shielded cables(Case A) are not better than composite poles with unshielded cables(Case E).
When pulses are injected at cable shield: Shielded cable with composite poles (Case D) are performing well
The best case is when shielded cables are combined with composite poles. (Case D).

- High impact percentage when the lightning pulse strikes outside of lamp1 is in fact not important, because in that case, when a real lightning strikes at the lamp house, the whole lamp will be destroyed anyhow.
- More important is what happens when the lightning pulse is injected at incoming PE or incoming cable shield.

Now we will proceed with a corresponding comparison for Lamp 2. Which case is the best with reference to Lamp 2?

The Lamp2-cases are very important, because they can have relevance for protecting the next lamp in a row, when lightning has struck somewhere along a line.

CONSEQUENCES FOR LAMP2 – SUMMARY

Table 2. Test cases A, B, C, D, E, F. Consequenses for Lamp2 – Comparing different poles and cables. Resistance to ground: $R_g = 0\ \Omega$

Pulse injection point	**Case**	**Highest voltage percentage on L2 and N2 - ref to data file**	grade
Pulse at Lamp1-house	Shielded cables Aluminium poles case B	L2max: 17% ref 578 N2max: 1.5% ref 578	3
Pulse at Lamp1-house	Shielded cables Composite poles Case C	L2max: 22% ref 578 N2max: 15% ref 608	2
Pulse at Lamp1-house	Unshielded cables composite poles Case E	L2max: 13% ref 623 N2max: 0.4% ref 626	1 Best for lamp house injections
Pulse at the cable shield, S1	Shielded cables Aluminium poles Case A	L2max: 29% ref 568 N2max: --	2
Pulse at the ca-ble shield, S1	**Shielded cables Composite poles Case D**	**L2max: 8% ref 596 N2max: 8% ref 596**	**1 Best for cable-shield-injections**
Pulse at incoming PE	**Unshielded cables Composite poles Case F**	**L2max: 7% ref 638 N2max: 7% ref 638**	**1 Very good**

Conclusions regarding consequences for Lamp2:
Composite poles are very good, both with shielded cables(Case D)

and unshielded cables (Case F).

I. Faraday case: shielded cable, conducting pole, metal lamp house

Measurement cases 556-572 represent the Faraday cage, considered to give the best protection for the lamps:

The power cable was shielded, the cable shield was connected to the outer surface of the metal poles, and the poles were connected to the lamp housing. All walls were made of metal and connected to each other, and to ground. All together these arrangements made a Faraday cage.

Important conclusion from 556 – 572, lightning pulse applied on the outside of the shielded cable.[<u>**Configuration**</u>**: Shielded cable, Aluminium pole, aluminium lamp house creating a Faraday cage]:**

Note the even in this "best" case the closest lamp (Lamp1) was not saved from high voltages. The Faraday cage did not work in the near zone situation. <u>Lamp 1 was not protected by the Faraday cage, but lamp2 was saved</u>: Lamp2 was 40 meter away from the lightning impact and the lightning pulse propagated on the outer surface of the shielded cable. i.e. the Faraday cage protected Lamp2, Lamp3, lamp 4 and so on, but not Lamp1! The protection of Lamp2, 3, 4… was effective only if the resistance (R_g) between shield and ground was very low. For higher resistance to ground the Faraday cage did not give enough protection. The lightning pulses were transferred to the inside of the poles and lamps, and gave high voltages on Lamp1, Lamp2, Lamp3 etc.

<u>Important conclusion from 572 – 580 (Faraday cage) </u>.

<u>Configuration</u>: Shielded cable, Aluminium pole, aluminium lamp house creating a Faraday cage: Lightning pulse applied on the outside of the lamp housing of Lamp1;

The only case when lamp2, 3, 4… are safe, is when the resistance to ground is very low.

See 572, 575, 578!

The lightning strikes were applied very close to Lamp 1, either at the cable shield, or at the lamp house.

Lamp2, 3, 4… will be destroyed by a strike of lightning if the resistance to ground is higher than 100 ohm. See 573, 574, 576, 577, 579, 580

Lamp 1 will always always break down, even if the resistance to ground is very low ($Rg=0.1\Omega$)!

II. Non-conducting poles made of composite plastic. Shielded cables. Metal lamp houses

Conclusions from 00581 – 00580 (broken Faraday cage) . Configuration: Shielded cable, not conducting composite pole, aluminium lamp house. Lightning pulse injected on the lamp house of Lamp1.

Unexpected result: Since the poles are made of non conducting material, one would expect worse behavior compared to the metal-poles-case. On the contrary this case showed to be very similar to the case with conducting poles. Lamp 2 was saved when Rg1=Rg2=0, i.e. very low resistance to ground. See 00581, 00584, 00587.

When the resistance to ground was 125 Ω, or higher both lamp1 and lamp2 were considered broken. See 00582, 583, 585, 586, 588, 589!

Lamp 1 is always exposed to a very high voltage, independent of the impact point of the lightning strike: Three cases were tested:

For the shielded-cables case the lightning strikes were applied

- on the cable shield,
- on the lamp housing

Lamp 1 was always broken in the above cases.

Lamp2, 3, 4… can be saved if the resistance between the cable shield and ground is very low. This is the case both if the injected pulse is on the cable shield or on the lamp house.

Metal poles and composite poles behave exactly the same way:

There is no indication that metal poles are better than composite poles! Lamp 1 is always broken, and lamp 2 can be saved if the resistance to ground is low. This is a bit surprising. One might expect that metal poles should behave better, but this is not the case.

See data: (00565 = 565 etc.)

For injections on the cable shield: 565, 568, 571, 590, 593, 596, 599,

For injections on the lamp house: 572, 575, 578, 578, 581, 584, 587, 602,

<u>Remark on ground resistors.</u>

"Rg = 0 ohm", in the lab situation is the resistance of about 1 meter of lab cable including connections. Using a lab meter, the resistance value is maximum 0.1 ohm, and depends of the connections.

Approximation: In the following presentation of different lab cases, "Rg=0", implies Rg<0.1 ohm.

Results:

There are some important conclusions that can be made from the lab experiments.

<u>Conclusion 1.</u>

For a shielded cable, the shield does not protect the closest lamp, but offers a good protection to lamp2. The reason is supposed to be that the lightning pulse travels along the 40 meter cable like a 2 dim very short pulse wave, and the skin effect makes the high energy pulse go on the outside of the cable shield. For the closest lamp, denoted Lamp1, the impact is not considered to be a travelling wave, but behaves like an ordinary electric circuit: Inside the pole and the lamp: PE and Shield are electrically the same point at the base of the lamp post

Check graphs for measurements no: 00556-00571. Note the cases Rg=0, and Rg = 125 ohms.

Resistance to ground

For each of these cases, A, B, C, D, E, F, three levels of resistance to ground, R_g , were tested:

Resistance to ground, Level 1: $R_g < 0.2$ ohm

Resistance to ground, Level 2: $R_g = 125\text{-}330\ \Omega$

Resistance to ground, Level 3: $R_g = 6\ \text{k}\ \Omega$

Table 3. Description of test cases A, B, C, D, E, F.

List of data files and graphs for test cases. Resistance to ground: $0\ \Omega < R_g < 6\ \text{k}\Omega$

Test case	Power cable	Pole character	Pulse-injection point	Data file id-number
A	Shielded cable with three Conductors: L,N,PE	Aluminium-type good conductor	At the cable shield before lamp 1	556 - 571
B	Shielded cable with three Conductors: L,N,PE	Aluminium-type good conductor	At the lamp housing of lamp 1	572-580
C	Shielded cable with three Conductors: L,N,PE	Non conducting Composite material	At the lamp housing of lamp 1	581 – 589, and 602-610
D	Shielded cable with three Conductors: L,N,PE	Non conducting Composite material	At the cable shield before lamp 1	590 – 601
E	Un-shielded, four conductor cable: (L, L, N, PE)	Non conducting Composite material	At the lamp housing of lamp 1	611 -631
F	Un-shielded, four conductors cable:(L, L, N, PE)	Non conducting Composite material	At PE before lamp 1	632 - 640

Table 4. Aluminium poles - shielded cables. Composite poles- unshielded cables/shielded cables. R_g= 0 Ω in all cases: A, B, C, D, E, F. Resistanse to ground very low: R_g= 0 Ω in all cases. Consequenses for L1, N1, L2,N2, S2, and for the open ended, not used conductor denoted B2 at Lamp2.

Number	TYPE	Record-ing with Rg=0	Est C case	C2	C3	C4	Comment
1	**A**	556	Sin/ 1280 V	100V	L1/ 400 V	N1/ 440 V	
2	**A**	557	**Sin** 1380V	L2/ 100 V	L1/ 100V 7.2%	**N1 500 V 36%**	
3	**A**	565	SIN/ **352V**	**S2/ 32V** 9%	**L1/ 160 V** 45%	**N1/ 120V** 34%	
4	**A**	**568**	**SIN/ 332 V**	**L2/ 96 V 29%**	**L1 16V 4.88%**	**N1/ 8 V 2.4%**	**Best A-case**
5	B	572	SIN/ 144V	S2/ 16 V **11%**	L1/ 104 V **72%**	N1/ 8 V **5.6%**	**Best B-case**
6	B	575	SIN/ 128 V	L2/ 20 V **16%**	L1/ 104 V **81%**	N1/ 8 V **6.3%**	
7	B	578	SIN/ 132 V	L1/ 106 V **80%**	L2/ 22 V **17%**	N2/ 2 V **1.5%**	
8	C	581	SIN/ 88 V	S2/ 16 V 18%	L1/ 228 V 259%	N1/ 232 V 263%	
9	C	584	SIN/ 92 V	L2/ 12 V **13%**	L1/ 224V **243%**	N1/ 228 V **248%**	**Best C-case**
10	C	587	SIN/ 88V	L1/ 224V **255%**	L2/ 20V **22%**	N2/ 4V **4.5%**	
11	D	590	SIN/ 316 V	S2/ 20 V 6.3%	L1/ 72 V 23%	N1/ 72 22%	
12	**D**	**593**	**SIN/ 312 V**	**L2/ 20V 6 %**	**L1/ 76 V 24%**	**N1/ 72 V 23%**	**Best D-case**
13	**D**	**596**	**SIN/312V**	**L1/76 V 24%**	**L2/24V 8%**	**N2/24 V 8%**	
14	**D**	**599**	**SIN/312 V**	**L1/72 V 23%**	**L2/24V** 8%	**N2/16V 5%**	

15	**C**	**602**	**SIN/1040 V**	**S2/40 V 4%**	L**1/ 1100 V** 106%	**N1/1100 V 106%**	
16	**C**	**605**	**SIN/ 100V**	L2/ **20V 20%**	L1/ **228V 228%**	N1/ **240 V 240%**	
17	C	608	SIN/108 V	L1/228V 211%	L2/20 V 18%	N2/16V 14%	
18	E	611	VIN 592V	PE1/128 V 21%	L1/ 320V 54%	N1/ 2 V 0.3%	
19	**E**	**614**	**VIN 552**	**L2 40 V 7%**	**L1/ 304 V 55%**	**N1/ 8 V 1.5%**	**Best E-case**
20	E	617	VIN 544V	*LB1/ 112V 21%*	LB2 64V 12%	N1 0.8V 0.1%	
21	E	620	VIN 552 V	LB1 / 112 V 20%	LB2/ 64 V 12%	N2 2 V 0.4%	
22	E	623	VIN 552V	L1 280 V 51%	L2 72V 13%	N2 0 V 0.00	
23	E	626	VIN/ 544 V	PE1 84 V 15%	PE2 15,2 V 2.7%	N2 0 V 0.00	
24	E	629	VIN 544 V	L1/280 V 51%	N1/320V 59%	N2 0 V	
25	F	632	**VIN 320V**	**L1 128 V 40%**	**N1 168 V 52%**	**N2 0 V 0.00**	
26	**F**	**635**	**VIN 296 V**	LB1 **100V 34%**	LB2 **20 V 6%**	**N1 108 V 36%**	
27	**F**	**638**	**VPE1 292V**	L1/ **112V 38%**	L2 **21,6 V 7%**	**N2 20,8 V 7%**	**Best F-case**
28	**F**	**641**	**VPE1 296 V**	**VPE2 24 V 8%**	**N1 116 V 39%**	**N2 0 V**	

Comparing Best A-case with best D case: D wins. Comparing best B, C, E cases: E wins.

Best F case is as good as best E-case. So the winners are the D- and E- cases, both very good: [D: Shielded cable composite pole. E: unshielded cable composite pole.]

COMPARISON CONCERNING LAMP 1, WITH PULSE INJECTED AT THE LAMP 1-HOUSING.

Table 5. Aluminium poles - shielded cables. Composite poles- unshielded cables/shielded cables. Pulses injected at PE1, the incoming Protective Earth close to Lamp1. Consequenses for Lamp1. Resistance to ground: $R_g = 0\ \Omega$.

Case	**geometry**	**Percentage of incoming pulse at L1 or N1**	**damage**	**Comments on consequenc-es for Lamp 1.**
B	Aluminium poles **Shielded cables**	72% - 81 % 572, 575, 578	intermediate	Aluminium poles are better than composite poles, but only when the cables are shielded.
C	Composite poles **Shielded cables**	108 %-240 % 602,608, 605	worst	Comment: alternative cou-pling path from incoming pulse on metal wall, directly to probes: Capacitve coupling
E	Composite poles **Unshielded cables**	50% -59 % 611, 623, 629	best	**When the pulse in injected at the lamp house of lamp1, the best combination is unshielded cables and composite poles**

COMPARISON CONCERNING LAMP 1, WITH PULSE INJECTED AT INCOMING CABLE SHIELD.

Table 6. Composite poles, unshielded cables. Pulses injected at PE1, close to Lamp1. Con-sequenses for Lamp1. Resistance to ground: $R_g = 0\ \Omega$.

Case	geometry	**Percentage of incom-ing pulse at L1 or N1**	**Damage on Lamp1**	**Comments on conse-quences for Lamp1.**
A	Aluminium poles **Shielded cables**	**34% - 45 %** 556, 557, 565	worse	No advantage with alumin-ium poles
D	Composite poles **Shielded cables**	**23% - 24 %** 590, 599, 593, 596	best	Composite poles are best when cables are shielded

COMPARISON CONCERNING LAMP 1, WITH PULSE INJECTED AT INCOMING PE.

Table 7. Composite poles, unshielded cables. Pulses injected at PE1, the incoming Protective Earth (PE) close to Lamp1. Consequenses for L1, N1. Rg1 = Rg2 = 0 Ω.

Case	geometry	Percentage of incoming pulse at L1 or N1	Damage on Lamp1	Comments on consequences for Lamp1.
F	Composite poles **Unshielded cables**	**33% - 52 %** 632	Same level as case A	Equally good as shielded cables

Case A. 00556 – 00571. Aluminium lamp houses. Shielded 3-conductors power cable. *Aluminium poles*. *Pulse at cable shield incoming to lamp 1.*

Lamp 1 is never safe in this case, even if Rg1=Rg2=0 ohm: See 00568, showing a high voltage on Line1 when Rg=0 ohm. Comment: High voltage coupling from the incoming shield to PE, and from PE to L1 inside the lamp housing of Lamp1.

Lamp 2, 3, 4 etc. can be saved if Rg1=Rg2=0 ohm, See 00571 showing low voltages on S2, L2 and N2 when Rg=0 ohm. The following lamps, no 3, no 4 etc can also be saved since the voltage on the shield, the line (L2) and the neutral (N2) are low on lamp 2. Comment: Because of the skin effect the electric charge (pulse) injected on the cable shield propagates on the outer surface of the cable shield to next lamp. If Rg1=Rg2=0 the charge can be neutralized by short circuiting the shield to ground.

Lamp 2, lamp 3 etc. will be broken if Rg = 125 ohm, or higher. (in fact probably any Rg higher than 1 ohm will give the same result. The voltage pulse will be divided between different ports in proportion to the resistance at the port in question.) See 00566 and 00570 showing high voltages on S2 and L2 when Rg=125 ohm. See also 0566 showing high voltages on L1 and L2 when Rg = 6 kohm. This implies that high voltage pulses will propagate along the line of lamps, and destroy them, in case the resistance to ground is higher than close zero.

Case B. 00572 – 00580. Aluminium lamp houses. Shielded 3-conductors power cable. Aluminium poles. Pulse injected at the outside of the lamp house of lamp 1.

If Rg1 = Rg2 = 0 ohm lamp 1 will be destroyed, because L1 is high (see 00572).

Lamp 2 can be saved because S2 and L2 get very low voltages, see 00572 and 00575.

If Rg > 0 ohm, (in our test Rg = 125 ohm, and Rg = 6kohm) both lamp 1 and lamp 2 will be destroyed, and consequently also the following lamps will be damaged.

See 00573 (L1 high) and 00576 (L1 and L2 high) when Rg = 125 ohm.

Case C. 00581 – 00589 and 602-610. Aluminium lamp houses. Shielded 3-conductors power cable. Composite poles. Pulse injected at lamp house of lamp 1.

Even when Rg=0 ohm, Lamp 1 will be destroyed. See 00581 showing high voltages on both L1 and N1**, (Line1 and Neutral 1.)**

Lamp 2 can be saved, when Rg=0 ohm. See 00581 showing low voltage on S2, when Rg=0 ohm.

See also 00584 showing low voltage on Line2, when Rg=0 ohm.

See also 00587 showing low voltage on L2 and N2, when Rg=0 ohm

If Rg> 0 ohm both lamp 1 and lamp 2 and the following lamps will be destroyed. See 00582 showing high voltages on L1, N1 and S2, when Rg=125 ohm.

See 585 showing high voltage on L2, N1, L1 when Rg=125 ohm.

See 00605: L2 low when Rg=0,

See 608: L2, N2 low when Rg=0

Case D. 00590 – 00601. Aluminium lamp houses. Shielded 3-conductors power cable. Composite poles. Pulse injected at the cable shield before lamp 1.

Lamp 1 will be destroyed independent of the ground resistance, since L1 and N1 carries high voltages when Rg = 0 ohm, 125 ohm and 6kohm. Lamp 2 can be saved if Rg = 0 ohm, but not when Rg> 0 ohms.(tested for 125 ohm and 6kohm)

Lamp 1 will get high voltages, and in practice destroyed in all cases: Rg = 0 ohm, Rg=125 ohm, Rg= 6kohm.

See 00590 showing S2, L1 and N1 for Rg=0 ohm, (low voltage on S2, too high voltages on L1 and N1)

See 00591 showing S2, L1 and N1 for Rg=125 ohm.(too high voltages on S2, L1 and N1)

See 00596 showing L1, L2 and N2 for Rg= 0 ohm. (too high voltage on L1, low voltages on L2 and N2)

Case E. 00611- 00631. Aluminium lamp houses. Un-shielded 4-conductors power cable. Composite poles. Pulse at lamp house of lamp 1.

A lightning pulse at the lamp house of lamp1, will always give a very high and dangerous voltage on L1, N1, and PE1. See 00623! Rg=0ohm, L1 high, L2 and N2 very low.

See 00624 Rg=380 ohm. L1 and L2 high. When Rg=380 ohm Bothe L1 and L2 get high pulses See 00624! L1 high L2 high.

See 00626 showing PE1 high (100V) and PE2 25% (25 V) when Rg=0 ohm. PE2 is not safe in this case.

The lamp house is directly connected to PE inside lamp1, and there is still 25% of the voltage on PE at lamp2, even if the grounding is good. (Grounding is a connection between PE and ground)

Case F. 00632 – 00640. Aluminium lamp houses. Un-shielded 4-conductors power cable. Composite poles. Pulse at PE - incoming to lamp 1.

This case (F) is expected to be rather similar to case E, since PE1 is connected to the inside of lamp 1. It is not surprising if a pulse outside lamp1 makes the same impact as a pulse at PE1. The housing of lamp1 does not offer a shield to the conductor inside the lamp, because the pole Is made of non conducting compsite material. Compare Case where the lamp house is connected to a conducting aluminium pole, conncected to a covering cable shield.

Results of Case F-experiments:

See00632 showing that the voltage on L1 and N1 is about 40% of the icoming pulse on PE1, ewhen Rg=0ohm.

The voltage level on L1 and N1 is the same as the level of the incoming pulse at PE1 when Rg=380 ohm. See 00633! It is interesting to note that the free conductor denoted LB1 at lamp1 and LB2 at lamp2 also gets about half the voltage level, although there is no connection between this conductor and PE1 (PE2) The voltage on LB1 and LB2 can only be explained by capacitive coupling between the PE conductor and the free, not used conductor. (The power cable contains 4 wires L, LB, N and PE. LB is not used in this test)

Pulse incoming on PE1. Rg= 0 ohm. Lamp 1 is not protected. See 00632 showing that the Lamp2- voltage is fairly well protected: Incoming 400 V on PE1, 20 V on Line2 and Neutral2. The voltage on lamp2 is the difference L2-N2 which is very small.

Voltage difference L2-N2 reduced to a very low value. Lamp 2 can be saved.

See 00639 showing that Lamp 1 and lamp 2 both get high voltages Rg= 400 ohm. Both lamp1 and lamp2 will be destroyed

Table 8. Shielded cables, non conducting poles. Pulses injected at (S1)the cable shield, close to Lamp1. Three levels of resistance to ground. Consequenses for L1, N1, L2, N2, S2 .

DATA FILE	Injection point	Rg1/Rg2	L1	N1	L2	N2	S2	LAMP1	LAMP2
shield 00556	S1	0/0		….	… ….	… …..		breaks	Safe..
00557	”	0/0	Hi	hi	0			breaks	Safe
00558		Cutoff /cutoff	Hi	hi	0			Breaks	Safe
00559		386/0	Hi	hi	0			breaks	Safe
00560		386/0	Hi	hi	0			breaks	Safe
00561	”	386/0	Hi	hi	0			breaks	Safe
00562	”	386/386	Hi	hi	hi			breaks	Breaks
00563		6k/6k	Hi	hi	Hi oscill.			breaks	Breaks
00564		130/130	Hi	hi	hi			Br	Br
00565		0/0	Hi	hi			0	breaks	Safe
00566		6k/6k	Hi		Hi iosc	0		Br	Br
00567		125/125	Hi		hi	0		Br	Br
00568		0/0	Hi		0	0		Br	Safe
00569		6k/6k			Hi osc	0	Hi osc	Br	Br
00570		125/125			hi	0	hi	Br	Br
00571	Cable shield	0/0			low	low	low	Br	Safe

Table 9. Shielded cables, non conducting poles. Pulses injected at the lamp house of Lamp1. Three levels of resistance to ground. Consequenses for L1, N1, L2, N2, S2.

Data id. Phys desc.	Injection point	Rg1/Rg2	L1	N1	L2	N2	S1	S2	LAMP1	LAMP2
00572	Pulse on lamp house of Lamp1	0/0	Hi	0				0		
00573 Composite non con-ducting pole and shielded Cable (ncp&shc)	Pulse on Lamp house	125/125	Hi	0				Hi	Breaks	Breaks
00574 ncp&shc	"	6k/6k	Hi	0				Hi osc	Breaks	Breaks
00575 ncp&shc	"	**0/0**	Hi	0	0				**breaks**	**Safe**
00576 ncp&shc	"	125/125	Hi	0	hi				breaks	breaks
00577 ncp&shc	"	6k/6k	Hi	0	Hi osc				breaks	Breaks
00578 ncp&shc	"	**0/0**	Hi	0	0				**breaks**	**Safe**
00579 ncp&shc	"	125/125	Hi		hi	0			breaks	Breaks
00580 ncp&shc	Pulse on lamp1-house	6k/6k	Hi		Hi osc	0			breaks	breaks

Table 10. Shielded cables, non conducting poles. Pulses injected at the lamp house of Lamp1. Three levels of resistance to ground. Consequenses for L1, N1, L2, N2, S2 .

	Inj point	Rg1/Rg 2	L1	N1	L2	N2	PE1	PE2	S1	S2	Lamp1	Lamp2
00581 ncp&shc	Pulse on lamp house	0/0	Hi	hi						0	breaks	**Safe**
00582 ncp&shc	"	125/12 5	Hi	hi						Hi	Breaks	breaks
00583 ncp&shc	"	6k/6k	Hi	hi						Hi	breaks	Breaks
00584 ncp&shc	"	0/0	hi	hi	0						breaks	**Safe**
00585 ncp&shc	"	125/12 5	Hi	hi	Hi						breaks	breaks
00586 ncp&shc	"	6k/6k	Hi	hi	Hi						breaks	breaks
00587 ncp&shc	"	0/0	Hi		0	0					breaks	**safe**
00588 ncp&shc	"	125/12 5	Hi		hi	0					breaks	breaks
00589 Comp. non conducting pole& Shielded cable	Pulse on Lamp house	6k/6k	Hi		hi	0					breaks	breaks

Table 11. Shielded cables, non conducting poles. Pulses injected, at the cable shield close to Lamp1, and at the lamp house of Lamp1. Three levels of resistance to ground. Consequenses for L1, N1, L2, N2, S2.

Data id. Phys desc.	Injection point	Rg1/Rg2	L1	N1	L2	N2	PE1	PE2	S1	S2	LAMP1	LAMP2
Shielded cable, non conducting poles = ncp&shc												
00590 ncp&shc	Cable shield	0/0	hi	hi						0	breaks	Safe
00591 ncp&shc	Cable shield	125/125	hi	hi						Hi	breaks	breaks
00592 ncp&shc	Cable shield	6k/6k	hi	hi						hi	breaks	Breaks
00593 ncp&shc	Cable shield	0/0	hi	hi	0						breaks	Safe
00594 ncp&shc	Cable shield	125/125	hi	hi	hi						breaks	Breaks
00595 ncp&shc	Cable shield	6k/6k	hi	Hi	hi						breaks	Breaks
00596 ncp&shc	Cable shield	0/0	hi		0	0					breaks	Safe
00597 ncp&shc	Cable shield	125/125	hi		hi	hi					breaks	Breaks
00598 ncp&shc	Cable shield	6k/6k	hi		hi	hi					breaks	Breaks
00599 ncp&shc	Cable shield	0/0	hi		0	0					breaks	Safe
00600 ncp&shc	Cable shield	380/380	hi		hi	Hi					breaks	Breaks
00601 ncp&shc	Cable shield	6k/6k	hi		hi	hi					breaks	Breaks
Shielded cable, non conducting poles ncp&shc												
00602 ncp&shc	*Lamp house*	0/0	hi	hi						0	breaks	Safe
00603 ncp&shc	*Lamp house*	380/380	hi	hi						hi	breaks	Breaks
00604 ncp&shc	*Lamp house*	6k/6k	hi	hi						hi	breaks	Breaks

Data id. Phys desc.	Injection point	Rg1/Rg2	L1	N1	L2	N2	PE1	PE2	S1	S2	LAMP1	LAMP2
00605 ncp&shc	*Lamp house*	0/0	hi	hi	0						breaks	Safe
00606 ncp&shc	*Lamp house*	400/400	hi	hi	hi						breaks	Breaks
00607 ncp&shc	*Lamp house*	6k/6k	hi	hi	hi						breaks	Breaks
00608 ncp&shc	*Lamp house*	0/0	hi		0	0					breaks	Safe
00609 ncp&shc	*Lamp house*	400/400	hi		hi	Hi					breaks	Breaks
00610 ncp&shc	*Lamp house*	6k/6k	hi		hi	hi					breaks	breaks

Table 12. Pulses injected at the lamp house of Lamp1, at PE close to Lamp1, at the cable shield close to Lamp1. Very low resistance to ground. Consequenses for L2, N2.

Rg1 And Rg2	**Cable type**	**Point of Impact/ Voltage**	**L2**	**N2**
0 0	**unshielded**	**Lamp house/ 600V**	**8V 1%**	**0.0V**
0 0	**unshielded**	**PE1in/300V**	**20V 7%**	**20V**
0 0	**shielded**	**Cable shield/150V**	**20 13%**	
0 0	**Shielded**	**Cable shield/150**	**30 20%**	**0.0**
0 0	**Shielded**	**Cable shield/310**	**20 6%**	
0 0	**Shielded**	**Lamp house/100**	**5 5%**	
0 0	**Shielded**	***Lamp house/100***	***10 10%***	***0.0***
0 0	**shielded**	**Lamp house/150**	**20 13%**	**20**

Unshielded cable, non-conducting poles (data files: 00611 – 00644) a lamp is considered broken if the voltage between phase and neutral is high (like VL1 – VN1)

Table 13. Pulses injected at the lamp house of Lamp1. Three levels of resistance to ground. Consequenses for L1, N1, L2, N2, PE1, PE2 .

Id no	Injec-tion point	Rg1/Rg2	L1	N1	L2	N 2	PE 1	PE 2	LB 1	LB2	LAMP 1	LAMP 2
611	Lamp house 600V	0/0	hi	Low 0.4%			hi		Ra		breaks	Saved-see 614
612	Lamp house	380/380	hi	low			hi				breaks	breaks
613	Lamp house	6k/6k	Hi	low			hi				breaks	Breaks
614	Lamp house	0/0	hi	low	low						breaks	Saved
615	Lamp house	375/375	Hi	low	hi						breaks	breaks
616	Lamp house	6k/6k	hi	low	hi						breaks	Breaks
617	Lamp house	0/0		low					Hi	low	Breaks See611	Saved See614
618	Lamp house	380/380		low					Hi	hi	Breaks see612	Breaks See615
619	Lamp house	6k/6k		low					Hi	hi	Breaks See613	Breaks See616
620	Lamp house	0/0				Low			Hi	low	Breaks See611	Saved See614
621	Lamp house	380/380				Low			Hi	hi	Breaks see611	breaks See615

Id no	Injec-tion point	Rg1/Rg2	L1	N1	L2	N 2	PE 1	PE 2	LB 1	LB2	LAMP 1	LAMP 2
622	Lamp house	6k/6k				hi			Hi	hi	Breaks See616	Breaks Breaks see616
623	Lamp house	0/0	hi		low	Low					breaks	saved
624	Lamp house	380/380	hi		hi	Low					breaks	breaks
625	Lamp house	6k/6k	hi		hi	Hi					breaks	breaks
626	Lamp house	**0/0**				**Low**	**hi**	**Hi 2%**			breaks	Saved see614
627	Lamp house	385/385				hi	hi	Hi			Breaks See612	Breaks See616
628	Lamp house	6k/6k				hi	hi	hi			Breaks See616	Breaks See616
629	Lamp house	0/0	hi	hi		Low					breaks	Saved see614
630	Lamp house	390/390	hi	hi		Hi					Breaks See612	Breaks See615
631	Lamp house	6k/6k	hi	hi		Hi					Breaks See613	Breaks See616

Remark: data denoted 00641 = 00642. In the table below 00642 is not listed.

Table 14. Pulses injected at incoming PE, close to Lamp1. Three levels of resistance to ground. Consequenses for L1, N1, L2, N2, PE1, PE2.

Data id. Phys desc.	**Injec-tion point**	**Rg1/Rg2**	**L1**	**N1**	**L2**	**N2**	**PE1**	**PE2**	**LB1**	**LB2**	**Lamp1**	**Lamp2**
632	PE1, Before lamp1	0/0	hi	Hi		Low	Vin				Breaks	**Saved? See 638**
633		390/390	hi	Hi		Hi	Vin				Breaks	Breaks
634		6k/6k	Hi	HI		HI	Vin				Breaks	breaks
635		0/0		Hi					Hi	low	Breaks	**Saved?**
636		400/400		Hi					Hi	hi	Breaks	Breaks
637		6k/6k		Hi					Hi	hi	Breaks	breaks
638		0/0	Hi		6% hi	6% hi	Vin				Breaks	Breaks
639		400/400	Hi		hi	Low					Breaks	Breaks
640		6k/6k	Hi		Hi	Low 1%					Breaks	Breaks
641		0/0		Hi		Low	Vin	low			Breaks	
643		400/400		Hi		Hi	Vin	Hi			Breaks	Breaks
644		6k/6k		Hi		Hi	Vin	Hi			Breaks	breaks

DISCUSSION PART 2.

About the chosen paths for entering high voltage lightning pulses.

When there is a real strike of lightning in nature, and the target is an electical power transmission system, the enormous energy in the original pulse will be divided and propagating in all possible directions where water under ground is the final destination. How much of the total energy is traveling in a certain direction depends on the resistance offered in respective path. The electric power feeding road lamps always is delivered via a transformer. The protective earth conductor, PE, is installed and designed for taking care of incoming lightning pulses. In case the transformer is installed inside a metal-housing, and the PE conductor is connected to the house, a big part of the energy is likely to leave the transformer house and propagate further along the PE conductor towards next passage to ground. The high energy pulse will follow the cable until next branch point, i.e. next coupling board, and go down to earth in case the resistance to ground is low enough from this point.

If the power cable is shielded, the shield should be firmly connected to the metal wall of the transformer house, or the house of any coupling board. In some rare cases a lightning may strike at the top of a lamp, made of metal or not, since the cables inside the lamp will offer a path to ground for the electric charge.

For injection of lightning pulses in the lab experiments, the following three ports were chosen:

- Via incoming PE-conductor
- Via incoming cable shield
- Via a lamp house.

About generating the test pulses.

The lightning tests in the first test series were performed using air discharges, generated by a 30 kV high voltage DC generator, with sparks up to 3 cm long. These tests showed to be very difficult to evaluate, because the air sparks gave strong electromagnetic radiation, propagating faster in air than the pulses following the cables. The heavy electromagnetic noise from the direct radiation was picked up by the oscilloscope and dominated the recordings, making it impossible to compare different coupling alternatives. The heavy noise from sparks was the reason why the use of air-discharges was abandoned, and the main part of the further testing was performed using voltage pulses from a surge generator, without sparks. When the sparks were eliminated the recorded voltage graphs became clean, and comparisons between different coupling alternatives were possible.

Pulses travelling along cables. While travelling along a cable, the front of a propagating lightning pulse is governed by the characteristic impedance of the cable, including the ground-cable geometry. This implies that the relation between voltage and current, and the attenuation depend of the cross section of the cable, including ground. In practice a propagating pulse will keep its voltage and current relatively stable until next branch, i.e. next lamp, where there is a coupling board. The velocity of such a pulse is 0.2 m/ns (meters/nanosecond).

Arrival at a branch point. Inside next lamp pole a pulse propagating along the cable arrives at a branch point: At the coupling board, inside next lamp pole, the incoming cable meets with other cables: Usually there is a couple of wires going up to the closest lamp, one PE-wire down to ground, and one cable to next lamp. The voltage occurring at this branch point is decided by the total load impedance (="resistance") seen by the incoming pulse. If the total load resistance seen by the incoming pulse is very low, the total voltage will be low, close to zero. But on the contrary, if the total load resistance is very high (= cutoff), the voltage at the branch point will be twice as high as the incoming voltage: [$V_{total} = V_{in} + V_{reflected} = 2 * V_{in}$]

So the voltage pulse leaving a branch point, propagating towards next lamp, will start from a level decided by the load impedance ("resistance") seen by the incoming pulse, at the branch point inside the lamp pole. If the resistance to ground is close to zero, the total load resistance will be almost zero and the voltage propagating forward towards next lamp will also be zero. If the load resistance to ground, seen by the incoming pulse, is 100 ohms or higher the forward going pulse will not be very much weaker than the incoming pulse.

Shielded cables may perform well, but only if the shield is thick enough to carry the energy of the lightning pulse. If the shield is too thin it will melt away, and the lightning pulse will travel forward on the remaining wires. It is possible to make cable shields of copper-tubes, iron-tubes, or steel-tubes. The power cable may be unsymmetrically localized inside the metal tube, since the skin effect will force the high frequency lightning pulse to propagate on the outer surface of the metal tube independent of the internal geometery. In the now tested cases the shield of cable series was too sparse, to stop high frequencies for interacting with the inner conductors. A cable with double shields would probably have performed better.

Conducting metal poles or non conducting composite poles? When choosing between conducting poles and non-conducting poles, there are apparently no obvious advantages with metal poles. The important principle is that the PE conductors must have low resistance to ground, and that the PE-conductor is properly connected to the lamp house.

Conclusions regarding Lamp3, Lamp4 etc. The conclusions made for Lamp1 and Lamp2 can be extrapolated further for a row of following lamps, if their ground connections are equal.

Surge protection units. Surge protection units are often installed inside the lamp houses. It may be a better idea to install the surge protection unit at the base of the lamp pole: If a lightning strikes at the top of a lamp, the whole lamp and pole will be smashed anyhow, and the surge protection unit makes no difference.

If the incoming high voltage pulse is propagating along the incoming cable, and the surge protector is located inside the lamp house, the travelling time up and down the pole: 2* 8 = 16 meters will be lost, and it may be too late to save next lamp. Then the probability of saving next lamp, 40 meters away, will be dramatically diminished. The travelling time between two lamp poles is about 200ns = 0.2 milliseconds. In order to save next lamp, 43 m away, the switching time of the surge protection unit at the base of lamp1, must be shorter than 0.2 ms. If, on the other hand, the surge protector is installed at the base of the pole, the time delay for shortening the pulse to ground will be less, and maybe it may protect both the lamp at the top of the same pole, and the next lamp 40 meters away. But it is very important that the surge protection unit has a very low resistance to ground, which makes the arrangement expensive.

A proposal. Since good grounding and good shielding are very expensive, it may be a good compromise to concentrate the grounding and shielding efforts to those places were lightning strikes are common, and leave other places without special protection.

CONCLUSIONS.

Conducting metal poles or non-conducting composite poles? There is no indication that metal poles are better than composite poles! There are no obvious advantages with metal poles, since the Faraday-cage-principle is difficult to realize in practice. The important principle is that the PE conductors must have low resistance to ground, and that the PE-conductors are properly connected to the lamp houses.

Shielded cables. In the now tested cases the shield of cable series was too sparse, to stop high frequencies for interacting with the inner conductors. A cable with double shields would probably have performed better. Shielded cables may perform well, but only if the shields are thick enough to carry the energy of lightning pulses, without melting. A simple way to create a shield for this purpose may be to put the cable inside an ordinary metal tube. This method can be used in old installations, where lightning strikes have caused problems. These cable shields must be well connected to the walls of all metal boxes used in the system. If the shield is too thin it will melt away, and the lightning pulse will travel forward on the remaining wires. It is possible to make cable shields of copper-tubes, iron-tubes, or steel-tubes. The power cable may be unsymmetrically localized inside the metal tube, since the skin effect will force the high frequency lightning pulse to propagate on the outer surface of the metal tube independent of the internal geometry.

Surge protection units. Surge protection units are often installed inside the lamp houses. If a lightning strikes at the top of a lamp, the whole lamp and pole will be smashed anyhow, and the surge protection unit makes no difference. Since it is very important that the surge protection unit has a very low resistance to ground it may be better to install the surge protection units at the bases of the lamp poles. It is also easier to examine and exchange a damaged surge protection unit located at the base of a pole. No skylift and no stopping of traffic is needed.

Resistance to ground. The resistance to ground showed to be important. In order to protect neighbouring lamps the resistance to ground must be close to zero, otherwise the lightning pulse will propagate to next lamp, and so on, destroying a long row of lamps along the road. ("resistance to ground" denotes the resistance beween PE and ground at each pole.)

A proposal. Since good grounding and good shielding are very expensive, it may be a realistic compromise is to concentrate the grounding and shielding efforts to those places were lightning strikes are common, and the natural surroundings are favourable, and leave other places without special protection. It is not enough just to put a long metal rod deep down into ground, because the contact surface between the rod and the surrounding soil is too small. It is much better to use a large sheet of metal under ground, and connect the PE-wire to the metal sheet, creating great contact surfaces against surrounding wet soil

OSCILLOSCOPE RECORDINGS.

The numbers, 000550 etc., refer to corresponding data files.

Oscilloscope graphs The following chapter is a collection of all oscilloskope graphs from all measurement cases, covering three levels of resistance to ground, and all combinations of aluminium poles, composite poles, shielded cables, unshielded cables, and three different lightning impact points.

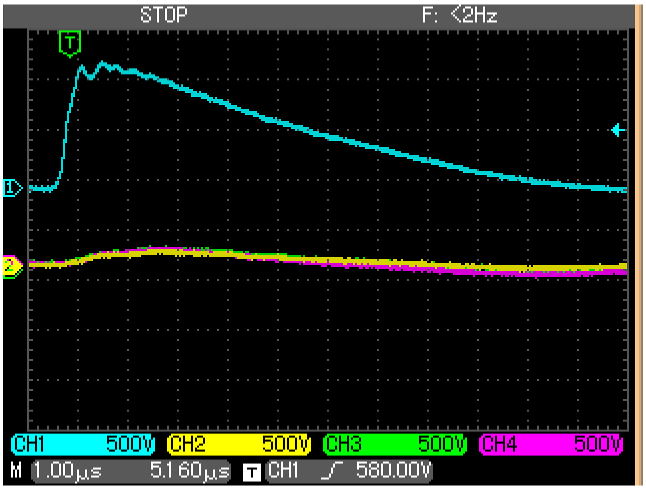

Figure 2. 00550. Pulse 4 kV from Surge generator. C1: at incoming contact on lower wall of the coupling box. The upper wall of the coupling box is connected to the cable screen. Probes: C2=C3=C4= at ground strap connected to the copper tube (=ground). This is at test of the measuring system – comparing the probes A, B, C, D and the oscilloscope channels C1, C2, C3 and C4.

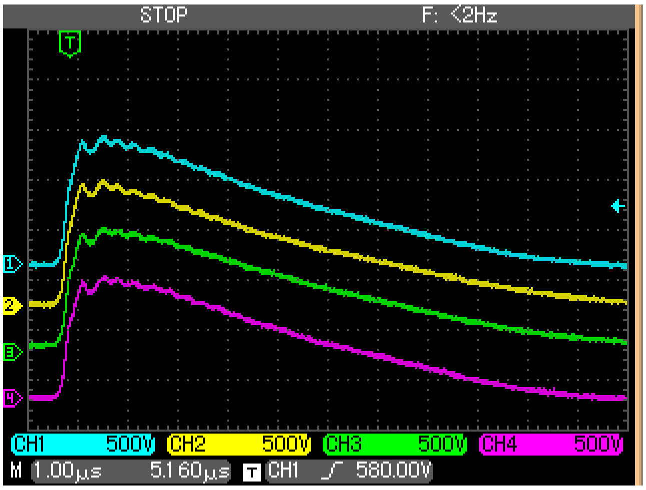

Figure 3. 00551 Shielded cable. Aluminium pole. Pulse 4 kV from Surge generator injected at the cable shield about 1.5 meters from lamp 1. All four probes connected to the same point: the incoming contact on the lower was of the coupling box.C1= C2=C3=C4. Only one of the probes has the ground crocodile clamp connected to ground. (Ground is the straight copper tube in parallel to the cable system.

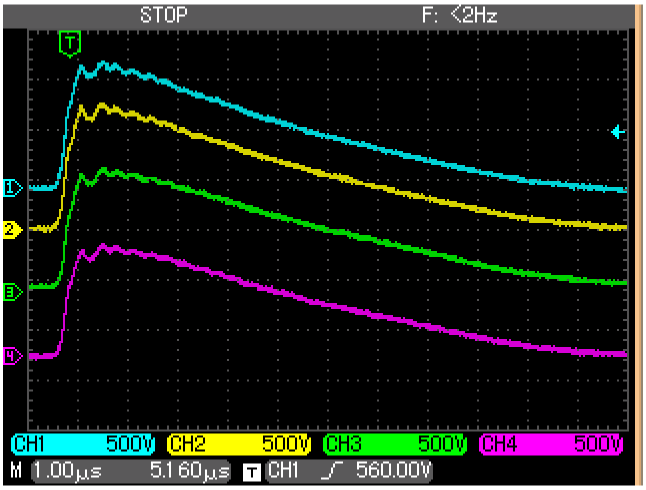

Figure 4. 00552. Shielded cable. Aluminium pole. Surge pulse 4 kV at the incoming contact point, first wall of the coupling box . C1= C2=C3=C4 connected to the same point, the in-coming contact on lower wall of the coupling box. All probes have their ground crocodiles connected to the same point at the ground tube.

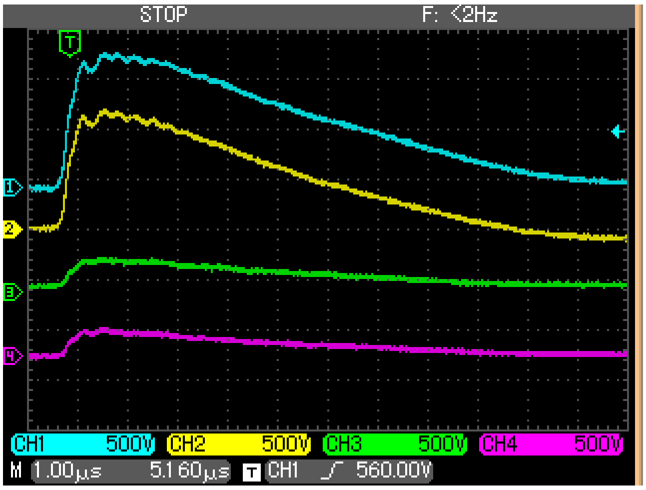

Figure 5. 00553. Shielded cable. Aluminium pole. Surge pulse 4 kV at the incoming contact point, first wall (=lower wall) of the coupling box. C1: at incoming contact on lower wall of the coupling box.   C2: at cable shield about 1 meter after the coupling box. C3: at L1 in lamp no 1. C4: at N1 inside lamp no 1. Rg1=0 ohm. Only probe no 1 has the ground croc connected to the ground tube. This will be compared to next case when all probes have ground connections to the copper ground tube, using the same length of connection wires. Note: same voltage level at the phase-1 conductor L1, and the neutral N1 inside the lamp. These two conductors get about 25% of the voltage on the incoming shield.

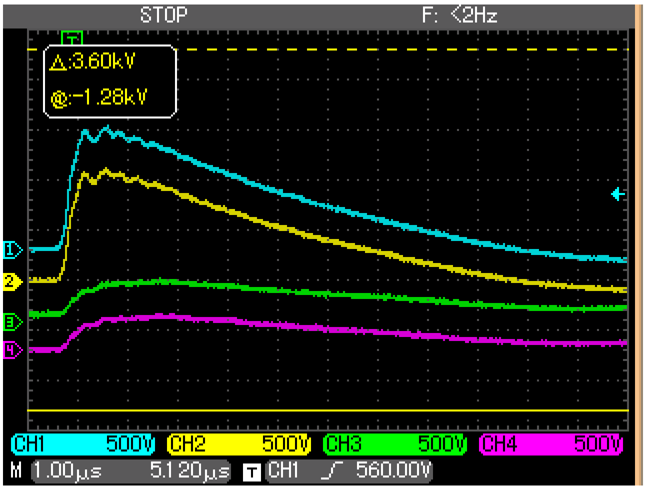

Figure 6.00554. Shielded cable. Aluminium pole. Surge pulse 4 kV on the incoming contact point, first wall of the coupling box. C1: at incoming contact on lower wall of the coupling box. C2: at cable shield about 1 meter after the coupling box. C3: at L1 in lamp no 1. C4: at N1 inside lamp no 1. All four probes have ground connections to the copper ground tube, using the same length of connection wires. Voltage levels 1.18 kV on C1 and C2, 260 V at C3 and C4. Rg_1 = 0 Ω, Rg_2 = 125 Ω.

Conclusion from 00553 and 00554, There is no difference between connecting one or four ground clamps to ground. The incoming pulse on the lower wall of the coupling box, is equally high as the pulse measure on the other side of the coupling box, about 1 meter after the box.(It is enough to measure the incoming pulse before the coupling box). A substantial part of the incoming pulse in reaching the inside of the lamp, on Line L1 and on Neutral N1.The relatively high voltage levels inside lamp1, is indicating that a great part of the pulse on the shield is transferred into the inner wires, L1 and N1.

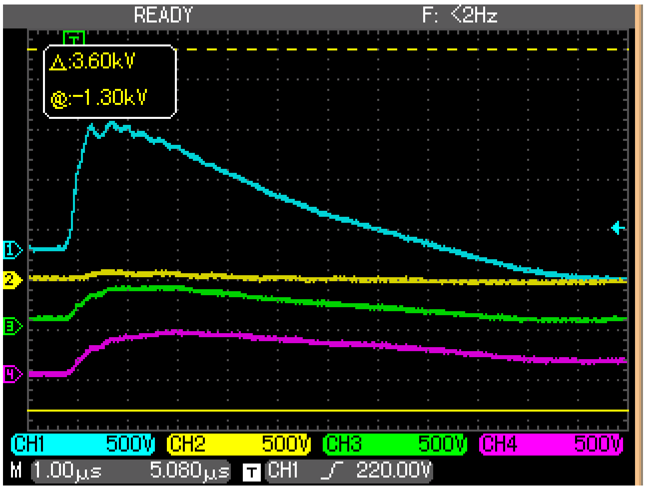

Figure 7. 00556. Shielded cable. Aluminium pole. Both ground connections are shorted: Rg_1 = 0 Ω, Rg_2 = 0 Ω. Surge pulse on incoming shield. C1: Voltage on incoming cable shield. C2: L2, C3: L1, C4: N1. Conclusion: Voltage on lamp2, Line 2 is very low, but not zero. L1 gets about 1/3 of the incoming pulse on the shield. The voltage on N1, the neutral of lamp 1 is equally high as the voltage on Line 1. Lamp 1 is not protected, but Lamp 2 is quite safe.

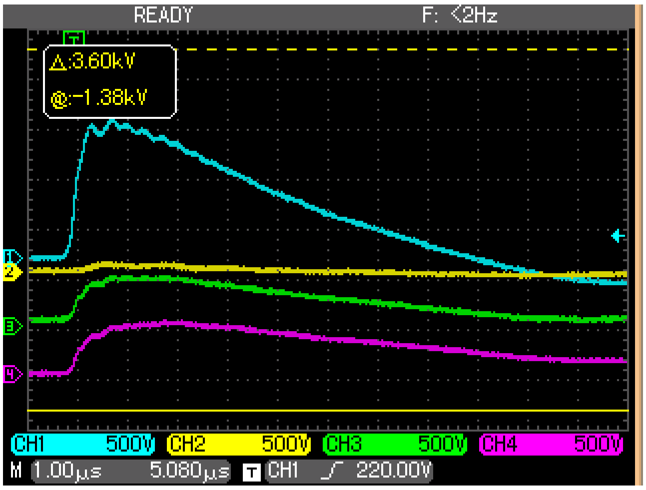

Figure 8. 000557. Shielded cable. Aluminium pole. Rg_1 = 0 Ω, Rg_2 = 0 Ω. Surge pulse on incoming shield. C1: Sin, voltage on incoming cable shield. C2: L2, C3: L1, C4: N1. Lamp 1 is not protected: high voltages on both Line1 and Neutral1. Just a low voltage on lamp 2, L2 .

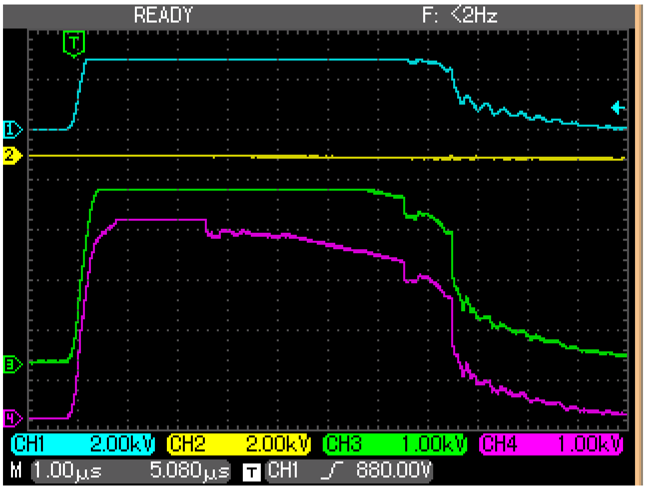

Figure 9. 00558. Shielded cable. Aluminium pole. Rg_1 = Rg_2 = cut off, open. Surge pulse on incoming shield. The strange graph shows a spark-discharge over the open ground connection. Note the voltage on L2 (Line on lamp 2) is zero. C1: Voltage on incoming cable shield. C2: L2 , C3: L1 (line on lamp1), C4: N1 (Neutral on lamp1). The strange graph shows a spark discharge over the open ground connection. Channel 1, 2, and 3 are saturated: making flat tops of the graphs. Note the voltage on L2 (Line on lamp 2) is zero.

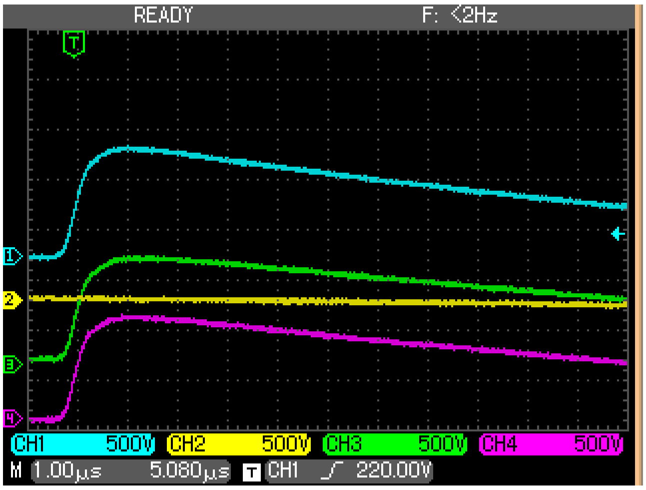

Figure 10. 00559. Shielded cable. Aluminium pole. Rg_1 = 386 Ω, Rg_2 = 0 Ω. Surge pulse on incoming shield. C1: Voltage on incoming cable shield. C2: L2 (Line on lamp2) , C3: L1 (line on lamp1), C4: N1 (Neutral on lamp1). L1 and L2 are almost identical to the incoming pulse on the shield. The pulse jumps from the shield to the inner conductors of lamp 1. Note: the voltage on L2 (Line on lamp 2) is zero. The pulse is cancelled out when arriving to lamp 2, thanks to good connection between shield and ground on lamp 2. Lamp2 is saved.

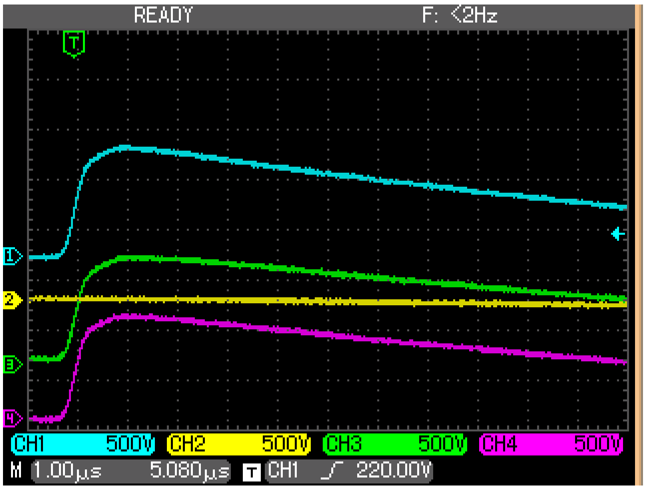

Figure 11. 00560. Shielded cable. Aluminium pole. Repeated experiment – checking the result, after exchange of resistors. Rg_1 = 386 Ω, Rg_2 = 0 Ω. Surge pulse on incoming shield. C1: Voltage on incoming cable shield. C2: L2 (Line on lamp2), C3: L1 (line on lamp1), C4: N1 (Neutral on lamp1).

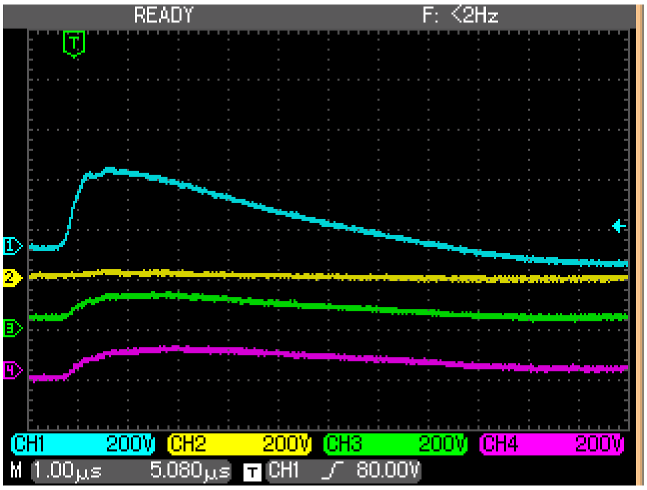

Figure 12. 00561. Note: scale 200V/div. Higher resolution check. Rg_1 = 386 Ω, Rg_2 = 0 Ω. Surge pulse on incoming shield. Aluminium pole. C1: Voltage on incoming cable shield. C2: L2 (Line on lamp2), C3: L1 (line on lamp1), C4: N1 (Neutral on lamp1). L1 and L2 are almost identical. The pulse jumps from the shield to the inner conductors at lamp 1. Note the voltage on L2 (Line on lamp 2) is very low.

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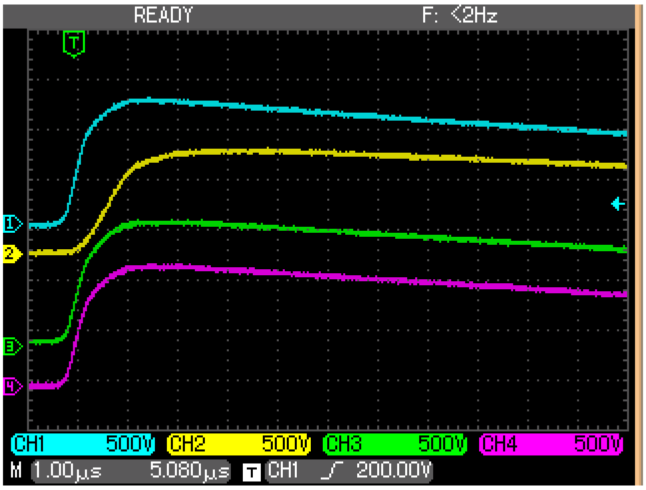

Figure 13. 00562. Shielded cable. Aluminium pole. Rg_1 = Rg_2 = 386 Ω. Surge pulse on incoming shield. C1: Voltage on incoming cable shield (S1). C2: L2 (Line on lamp2), C3: L1 (line on lamp1), C4: N1 (Neutral on lamp1). L1 and L2 are almost identical to the incoming pulse on the shield. The pulse jumps from the shield to the inner concuctors at lamp 1. Note the voltage on L2 (Line on lamp 2) is almost as high as on Lamp 1 (L1). The pulse is not cancelled out when arriving to lamp 2, because of bad ground connection on lamp 2. Note also the delay between C1=S1=Shield1 and C2=L2=Line2.

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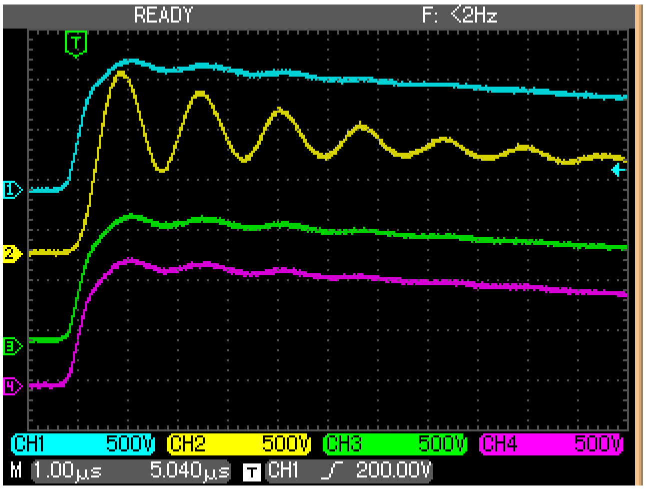

Figure 14. 00563. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 6kohm. C1: Sin, C2: L2, C3: L1, C4:N1. High resistance to ground gives oscillations on with high magnitude on Line2: (Channel 2 = Line2). Note: Delay 0.2 kus between C1:S1 and C2:L2 corresponds to 0.2 us travelling time between pole1 and pole2 (40 m cable)

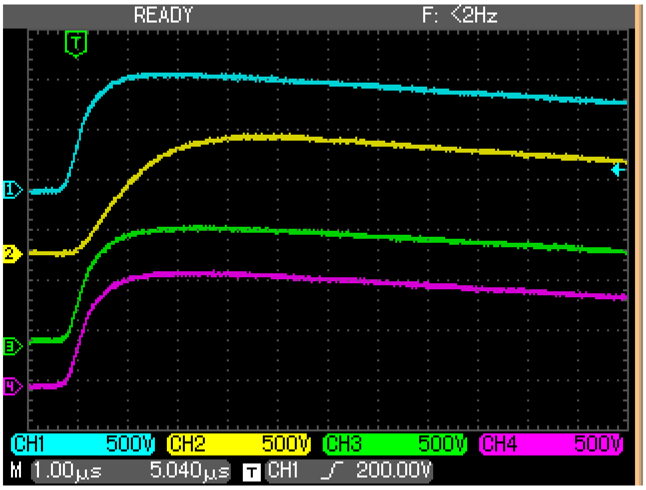

Figure 15. 00564. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 130 ohm. C1: Sin, C2: L2, C3: L1, C4:N1. Slightly higher magnitude on L2 compared to L1 depends on Rg2 mismatch. Both Lamp1 and Lamp2 considered broken.

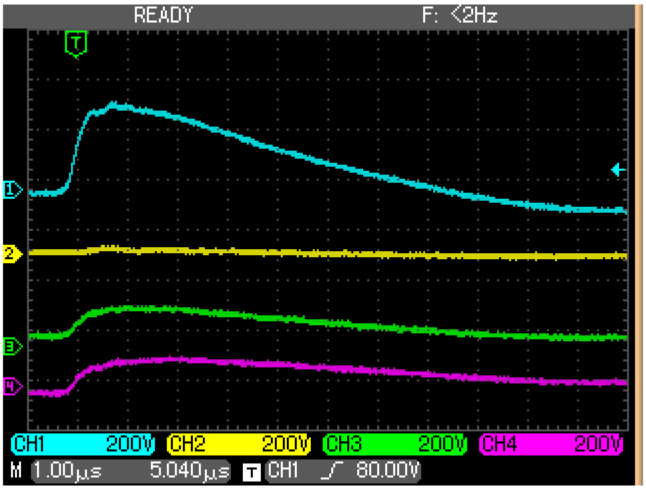

Figure 16. 00565. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 0 ohm. C1: Sin, C2: S2, C3: L1, C4:N1. Lamp1 will break, but Lamp2 is saved.

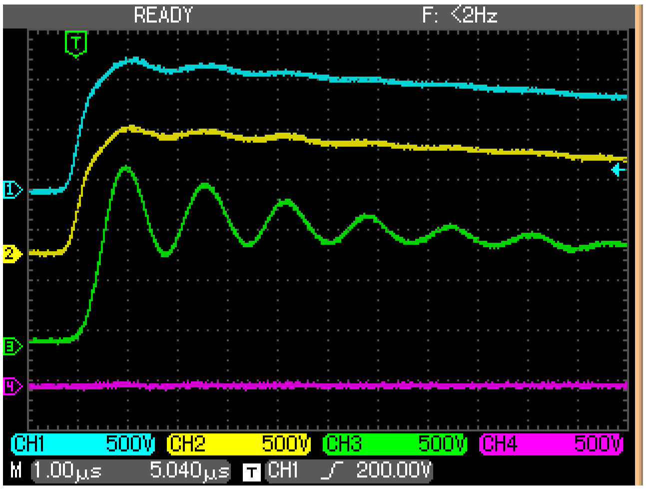

Figure 17. 00566. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 6 kohm. C1: Sin, C2: L1, C3: L2, C4:N2. Oscillations with high magnitude on L2 because of high resistance to ground. Both Lamp1 and Lamp2 considered broken.

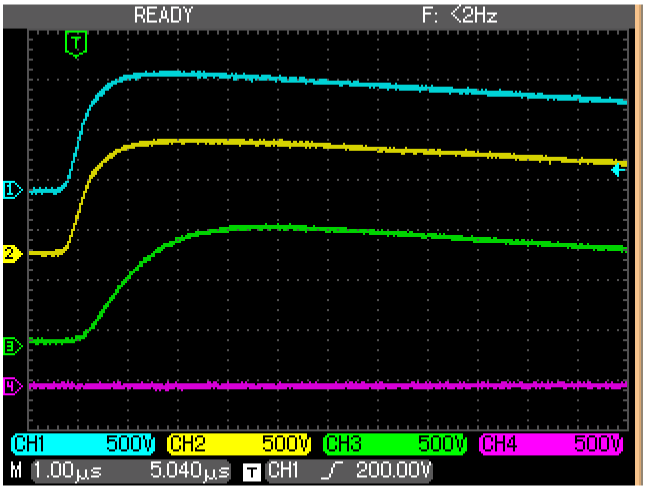

Figure 18. 00567. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 125 ohm. C1: Sin, C2: L1, C3: L2, C4:N2. Both Lamp1 and Lamp2 considered broken.

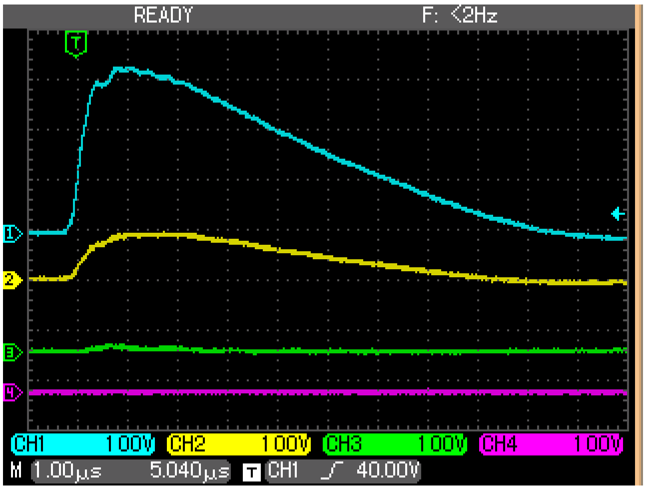

Figure 19. 00568. Shielded cable. Aluminium pole. Surge pulse on incoming shield. Rg1 = Rg2 = 0 ohm. C1: Sin, C2: L1, C3:L2, C4:N2.(max ch3 = 15 V. Max ch4 = noise 4 volt). Lamp1 considered broken, but Lamp2 saved.

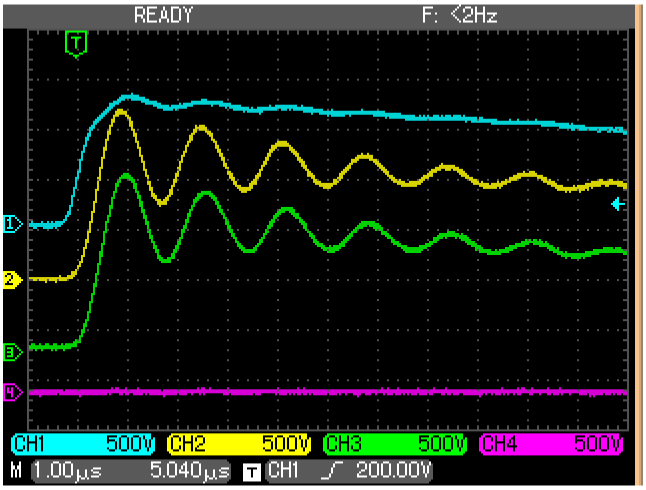

Figure 20. 00569. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 6 kohm. C1: Sin, C2: S2, C3: L2, C4:N2. High magnitude oscillations on both S2(=Shield2) and L2(=Line2) due to high value of Rg2 (Mismatch).

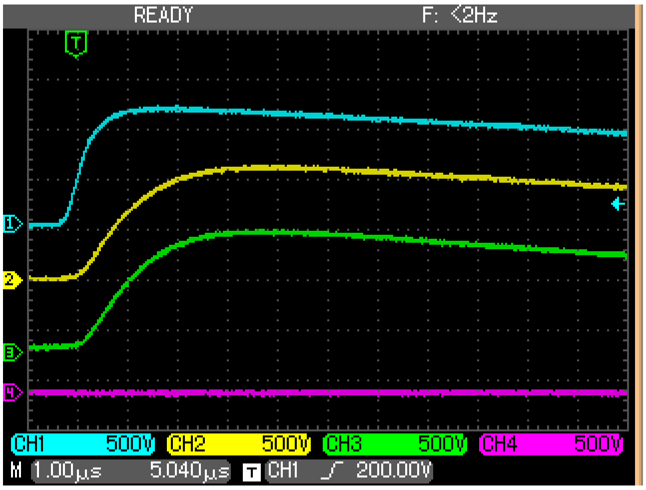

Figure 21. 00570. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 125 ohm. C1: Sin, C2: S2, C3: L2, C4:N2. Lamp2 considered broken. (And also Lamp1 broken according to 00567-Figure 17).

00570: Comment: Ground resistances 125 ohm gives high voltages on the shield of lamp 1, and the line of lamp2. The neutral of lamp 2 is safe. A ground connection of 125 ohms gives no efficient protection: The surge pulse propagates through the system to next lamp.

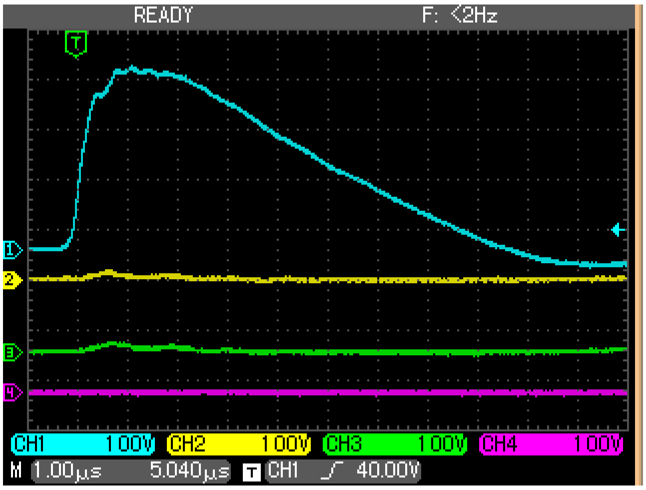

Figure 22. 00571. Shielded cable. Aluminium pole. Surge pulse on incoming shield (Sin). Rg1 = Rg2 = 0 ohm. C1: Sin, C2: S2, C3: L2, C4:N2. [Sin = Incoming Shield of lamp 1, S2 = Shield of lamp 2, L2 = Line of lamp2, N2 = Neutral of lamp2.] Lamp2 considered safe.

00571: Comment: Ground resistances 0 ohm. Allthough the voltage on the shield of lamp 1, the pulse does not reach the shield of lamp 2. The shield of lamp2, the line of lamp2 and the neutral of lamp2 are safe.

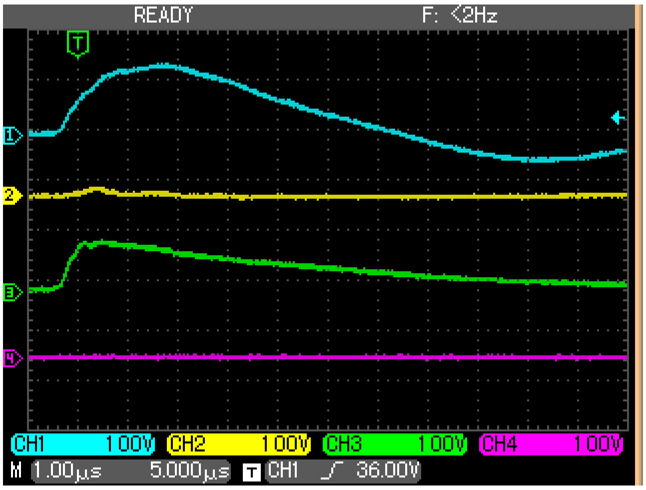

Figure 23. 00572. Shielded cable. Surge pulse on lamp1-housing(C1=Sin). Aluminium pole. Rg1 = Rg2 = 0 ohm. C2:S2, C3:L1, C4:N1. [S2 = cable-shield of Lamp2, L1= Line of Lamp1, N1 = Neutral of lamp1.]

00572: Comment: Pulse on lamp house of lamp 1: The high voltage pulse on the outside of lamp1, is also high on the shield of cable 1, because the Aluminium lamp house is connected to the cable shield of lamp1. The pulse is also high on Line 1, but very low on S2 = the shield of lamp 2. The shield of lamp2 is almost safe. The neutral of lamp 1 is safe. Low ground re-sistance, Rg= 0 ohms protects lamp 2, but not lamp 1.

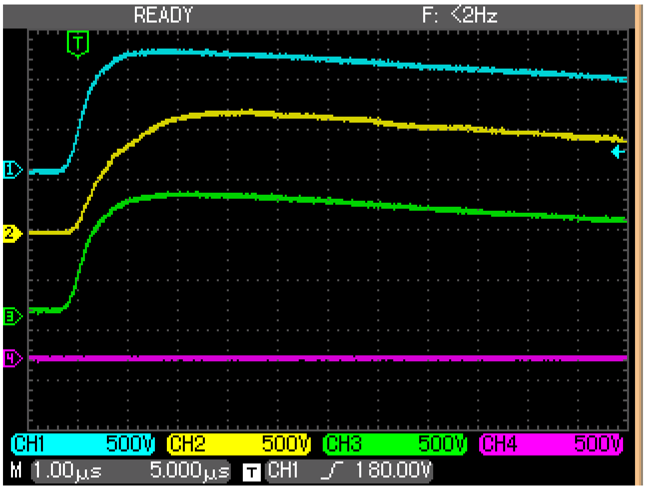

Figure 24. 00573. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 125 ohm. C1: Lamp1-house=S1, C2: S2 , C3: L1, C4:N1. Lamp1 breaks.

00573: Comment: Ground resistances 125 ohm gives high voltages on the line of lamp 1, and the shield of lamp 2. The voltages on line of lamp1, and the shield of lamp2 is almost as high as the incoming pulse on the shield, S1, on lamp1. The neutral of lamp 1 is safe. Both lamp 1 and lamp2, etc, are damaged by the pulse on lamp 1-housing when Rg=125 ohm.

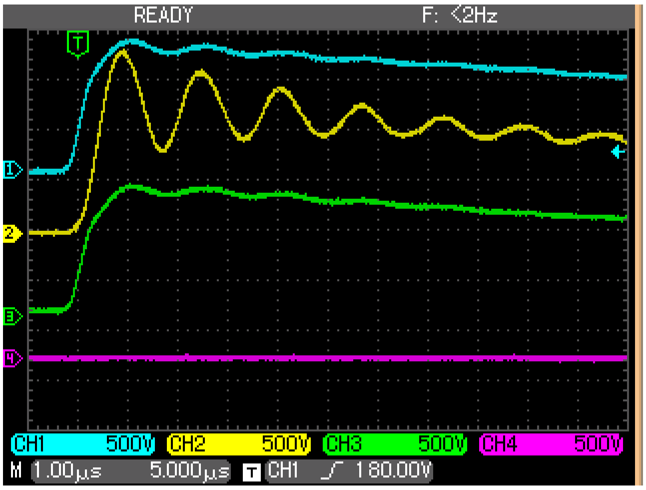

Figure 25. 00574. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 6kohm. C2:S2, C3: L1, C4:N1. High magnitude oscillations on shield of Lamp2 (S2), due to high resistance to ground.

00574: Comment: Surge pulse on lamp housing . Ground resistances 6 kohm gives high voltages on the line of lamp 1, and the shield of lamp 2. The voltage on line of lamp1, is almost as high as the incoming pulse on the shield, Sin. The neutral of lamp 1 is safe. Both lamp 1 and lamp2, etc, are damaged by the pulse on lamp 1-housin when Rg= 6kohm.

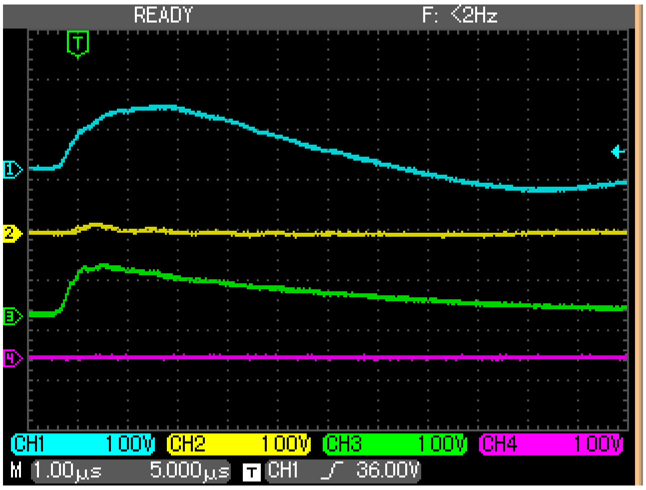

Figure 26. 00575. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 0 ohm. C2: L2,C3: L1, C4:N1. Lamp2 may be safe.

00575: Comment: Ground resistances 0 ohm gives high voltages on the line of lamp 1, but the line of lamp 2 (C2) is almost safe. The voltage on line of lamp1, is almost as high as the incoming pulse on the Lamp house, C1. The neutral of lamp 1 is safe. Lamp 1 is damaged, but lamp 2 may be safe.

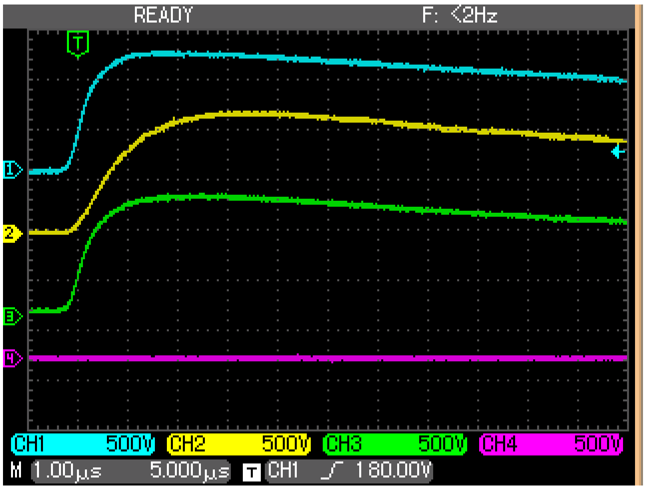

Figure 27. 00576. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 125ohm. C2: L2, C3: L1, C4:N1. Both Lamp1 and Lamp2 are considered broken.

00576: Comment: Ground resistances 125 ohm gives high voltages on both line of lamp 1, and line of lamp 2. The voltage on line of lamp1, is almost as high as the incoming pulse on the shield, C1. The neutral of lamp 1 is safe.

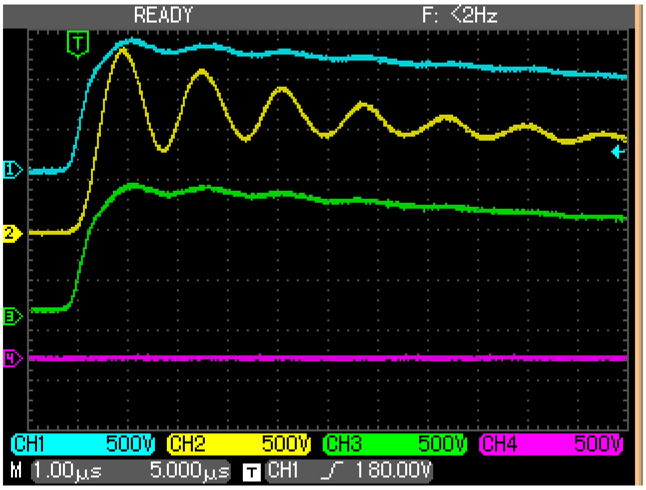

Figure 28. 00577 Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 6 kohm. C2: L2,C3: L1, C4:N1. Both Lamp1 and Lamp2 are considered broken.

00577: Comment: Ground resistances 6 kohm gives high voltages on both line of lamp 1. The line of lamp2 is very high due to mismatching. The voltage on line of lamp1, is almost as high as the incoming pulse on the Lamp1-house. The neutral of lamp 1 is safe. Both lamp 1 and lamp2 are damaged by the pulse on lamp 1-housing when Rg = 6kohm.

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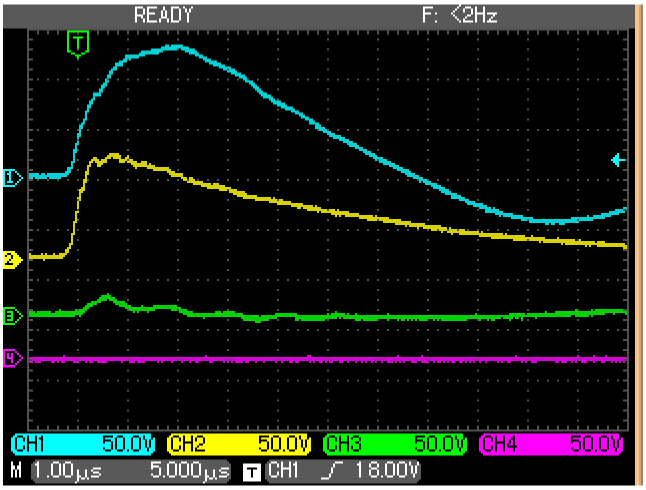

Figure 29. 00578. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 0 ohm. C2: L1, C3: L2, C4:N2.

00578: Comment: Ground resistances zero ohm gives high voltages on both line of lamp 1, but the line of lamp2 is almost safe. The voltage on line of lamp1, is almost as high as the incoming pulse on the shield, C1, and the cable shield. Lamp 2 may be safe.

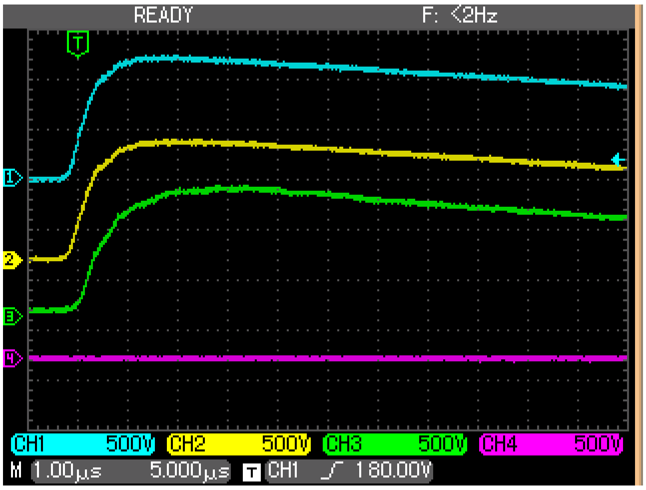

Figure 30. 00579. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 125 ohm. C2: L1, C3: L2, C4:N2.

00579: Comment: Ground resistances 125 ohm gives high voltages on both line of lamp 1, and line of lamp2. Almost as high as the incoming pule on the shield, Sin. Both lamp 1 and lamp2 will be broken when Rg = 125 ohm.

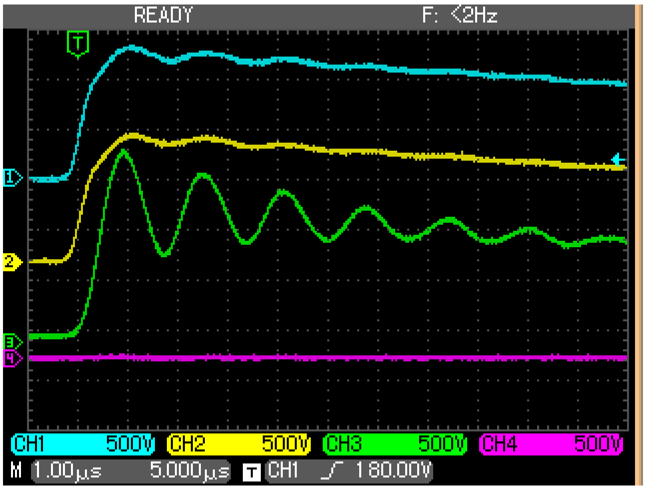

Figure 31. 00580. Shielded cable. Surge pulse on lamp housing (C1=Sin). Aluminium pole. Rg1 = Rg2 = 6 kohm. C2=L1, C3=L2, C4=N2.

00580: Comment: Ground resistance 6 kohm gives high voltages on both line of lamp 1, and line of lamp2. Both lamp 1 and lamp2 are damaged by the pulse on lamp 1-housing when Rg = 6kohm.

tests with numbers 00581 and higher are including non conduction composite poles 00611 unshielded 4 conductors cables.

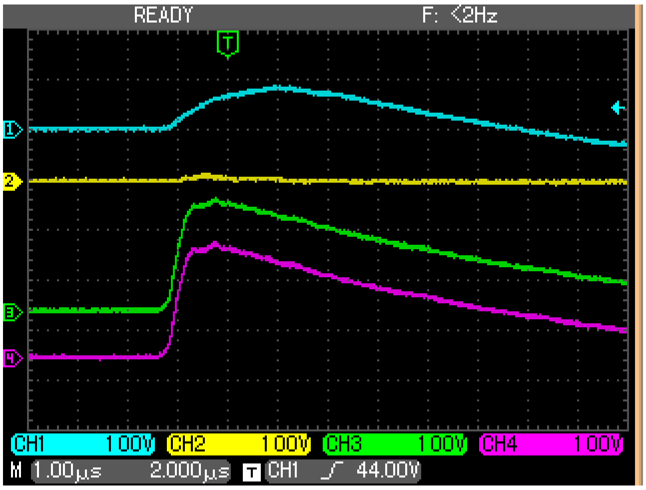

Figure 32. 00581. Shielded cable <u>non conducting pole</u>. Pulse on lamp housing (C1=Sin). Rg1=Rg2=0 ohm. C2= S2, C3=L1, C4=N1. Note high voltage on C3=Line1, and C4=Neutral1. Lamp1 is considered broken, Lamp2 saved.

Comment: Non conducting poles. Pulse on lamp housing of lamp 1. No voltage on S2 (= Shield of lamp2), when Rg = 0 ohm. It is very clear that lamp1 cannot be saved if the lightning strikes lamp-house 1, but lamp 2 can be saved if Rg = 0 ohm. This conclusion is valid both for Aluminium poles and non conducting poles!

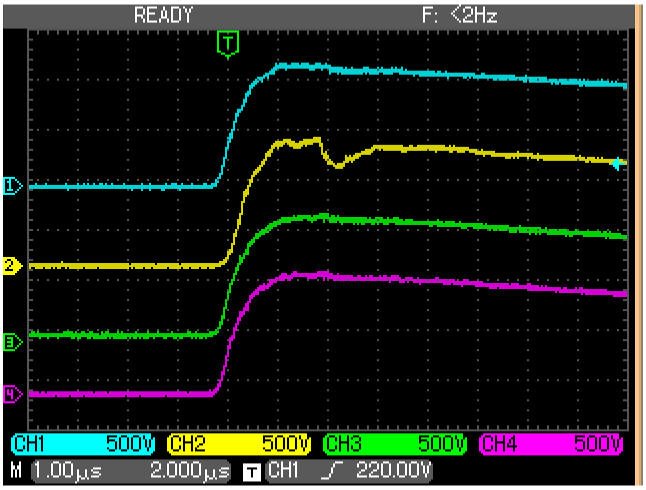

Figure 33. 00582. Shielded cable non conductiong pole. Pulse on lamp housing (C1=Sin). Rg1=Rg2=125ohm. C2= S2, C3=L1, C4=N1. High voltage both on Lamp1, and cable-shield of Lamp2(S2).

Comment on 00582: Ground resistance Rg = 125 ohm. The lightning pulse is equally high on incoming shield (Sin), Shield of lamp 2 (S2), line of lamp1 (L1) and neutral of lamp 1 (N1).

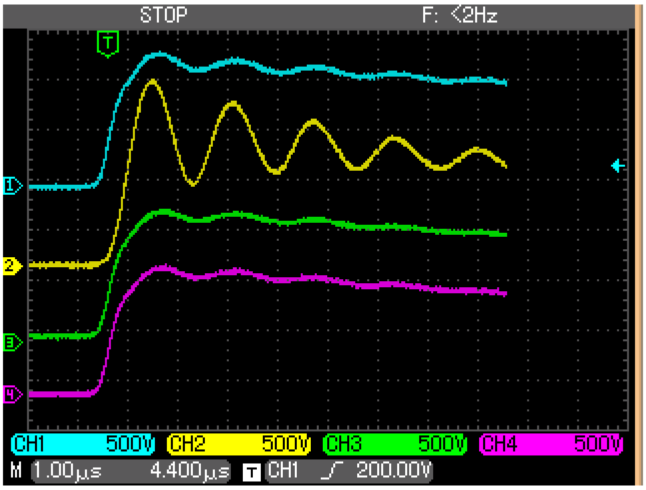

Figure 34. 00583. Shielded cable non conducting pole. Pulse on lamp housing (C1=Sin). Rg1=Rg2=6kohm. C2= S2, C3=L1, C4=N1. Note the high voltage oscillations on cable shield of Lamp2 (S2).

Comment on 00583: Ground resistance Rg = 6 kohm. The lightning pulse is equally high on incoming shield (Sin), line of lamp1 (L1) and neutral of lamp 1 (N1). The impact on cable shield of lamp2 (S2) is even higher due to oscillations.

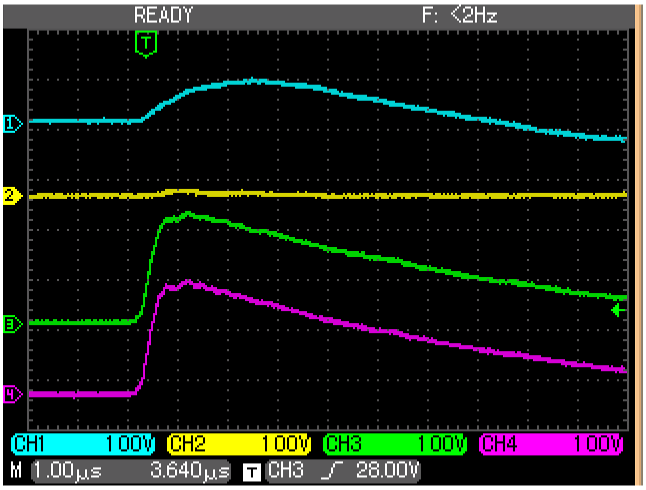

Figure 35. 00584. Shielded cable non conducting pole. Pulse on Lamp1- housing (C1=Sin). Rg1=Rg2=0 ohm. C2= L2, C3=L1, C4=N1. Lamp2 is saved, but not Lamp1.

Comment on 00584: Rg = 0 ohm.Line 2 is protected by the low ground resistance, but not Line1 and Neutral1.

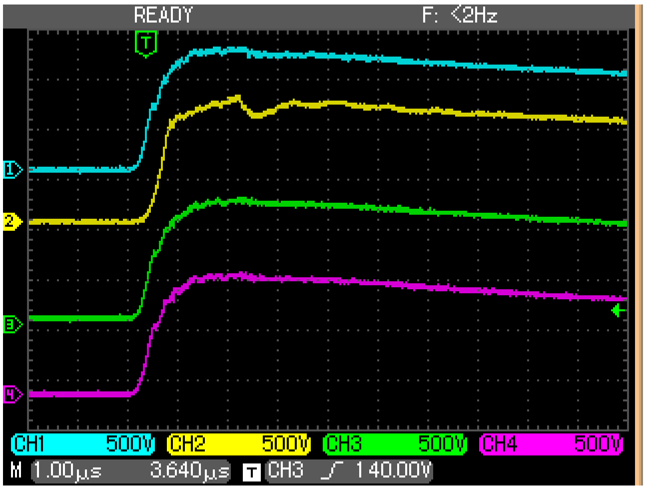

Figure 36. 00585.Shielded cable non conductiong pole. Pulse on lamp housing (C1=Sin). Rg1=Rg2=125ohm. C2=L2, C3=L1, C4=N1. High voltages on Line1, Neutral1, and Line2 means no protection for either Lamp1 or Lamp2, The reason is too high resistance to ground.

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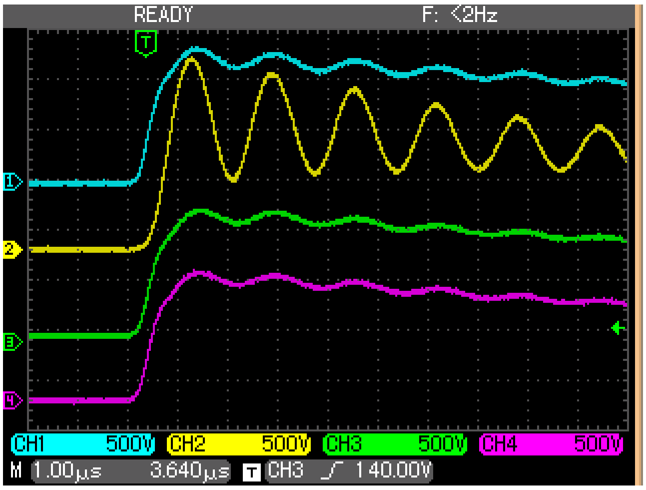

Figure 37. 00586. Shielded cable, non conducting pole. Pulse on lamp housing (C1=Sin). Rg1=Rg2=6kohm. C2=L2, C3=L1, C4=N1. High voltages on Line1, Neutral1, and Line2 means no protection for either Lamp1 or Lamp2. Even oscillations on Line2! The reason is very high resistance to ground.

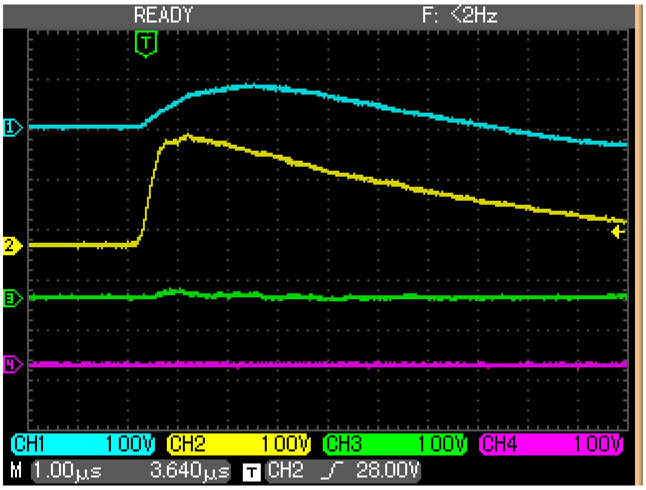

Figure 38. 00587. Shielded cable non conducting pole. Pulse on lamp housing (C1=Sin). Rg1=Rg2=0 ohm. C2=L1, C3=L2, C4=N2. Lamp2 is protected, but not Lamp1.

Comment on 00587: Rg = 0 ohm.Line 1 (L1) is not protected by the low resistance between cable shield and ground. Because of the low resistance between PE and ground, there is a near short circuit between the incoming cable shield and ground. The same voltage is injected at the Lamp1-house. Probably the lightning pulse on the lamp-house is transferred to Line 1 due to coupling between the outside of the lamp and PE and Line inside the lamp and the pole.

Line 2 and Neutral 2 (in lamp 2) are protected thanks to the low resistance between the cable shield and ground. The cable shield gives good protection to Lamp 2, but no protection to lamp 1.

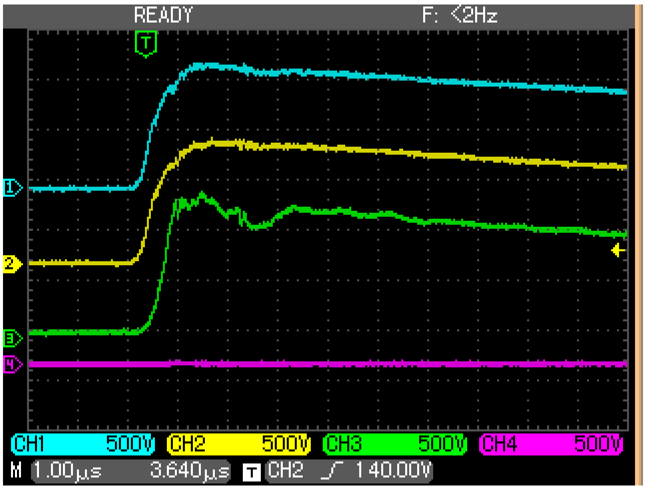

Figure 39. 00588. Shielded cable non conducting pole. Pulse on lamp housing (C1=Sin). Rg1=Rg2=125ohm. C2= L1, C3=L2, C4=N2.

Comment on 00588. Pulse on lamp-house. Non conducting pole. Shielded cable. Rg= 125 ohm. Neither lamp 1 or lamp 2 are protected by the cable shield.(because the ground resistance is too high.)

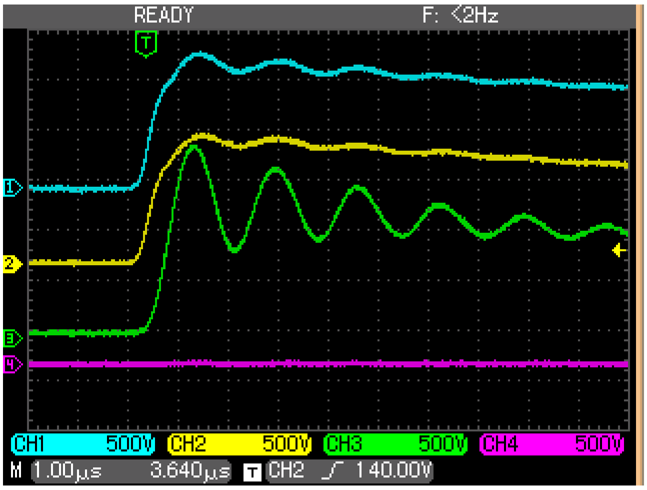

Figure 40. 00589. Shielded cable non conducting pole. Pulse on lamp housing (C1). Rg1=Rg2=6kohm. C2= L1, C3=L2, C4=N2. Both Lamp1 and Lamp2 are considered broken because of high voltage on L1 and L2.

Comment on 00589. Pulse on lamp-house. Non conducting pole. Shielded cable. Rg= 6 kohm. Neither lamp 1 or lamp 2 are protected by the cable shield.(because the ground resistance is too high.) the voltage on lamp 2 is higher than the voltage on lamp 1, because of oscillations.

<u>Summary pulse on lamp house – composite non conducting poles.</u> When the lightning pulse is striking the lamp-house of lamp 1, there is no way of protecting lamp 1 form high voltages. The high voltage the lamp house is connected to PE, inside the housing. The coupling between PE and L1, N1 can be inside the lamp and pole, since the distance between PE, L1 and N1 are very short inside the lamp house and the pole. Lamp 2 and following lamps can be protected if the cable is shielded and the resistance between the cable shield and ground is very low, but only in that case. As soon as the ground resistance is substantial the high voltage pulses are transferred to the other conductors, due to coupling inside the poles and lamps.

Composite poles, shielded cables,

Testing: incoming pulses on cable shield, and on lamp housing of lamp 1.

,

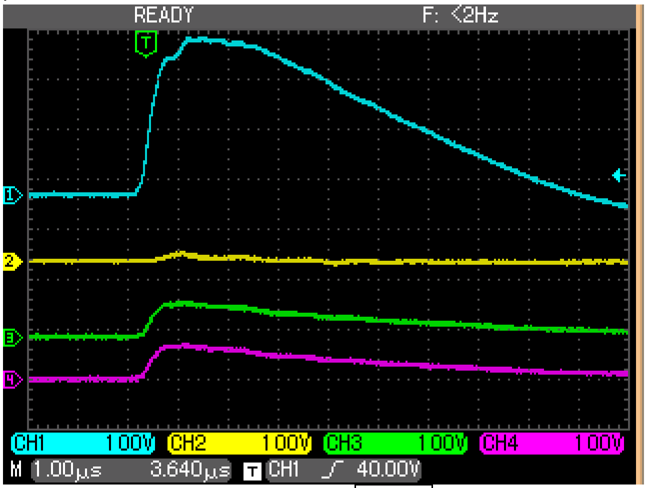

Figure 41. 00590 Shielded cable non conducting pole. Pulse on cable shield (Sin), Rg1=Rg2=0 ohm,

C1: Sin, C2: S2, C3: L1, C4: N1. The shield close to lamp2 is almost unaffected.

The voltage-pulses on lamp1-Line and lamp1-Neutral are quite substantial,

about ¼ of the incoming pulse on the cable shield.

Lamp 1 is not protected from the incoming pulse, in this case.

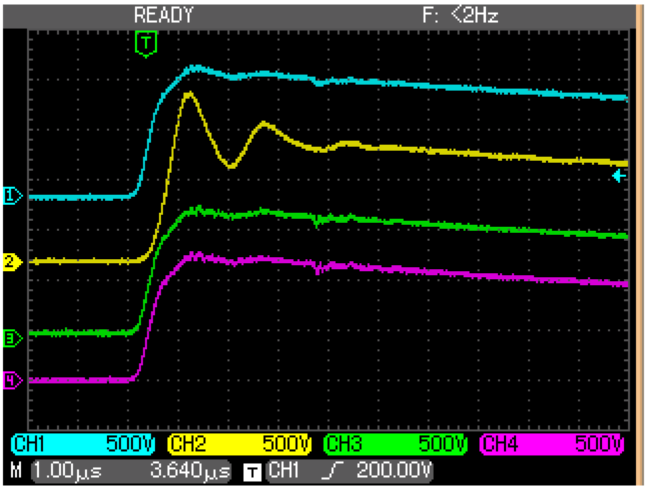

Figure 42. 00591. Pulse on cable shield (C1=Sin), non conducting pole, Rg1=Rg2=125 ohm,

C2:S2, C3:L1, C4:N1.

The voltage-pulses on lamp1-Line and lamp1-Neutral are quite substantial,

about ¼ of the incoming pulse on the cable shield. Lamp 1 is not protected from the incoming pulse,

in this case. High voltage on the cable shield close to Lamp1 and also Lamp2.

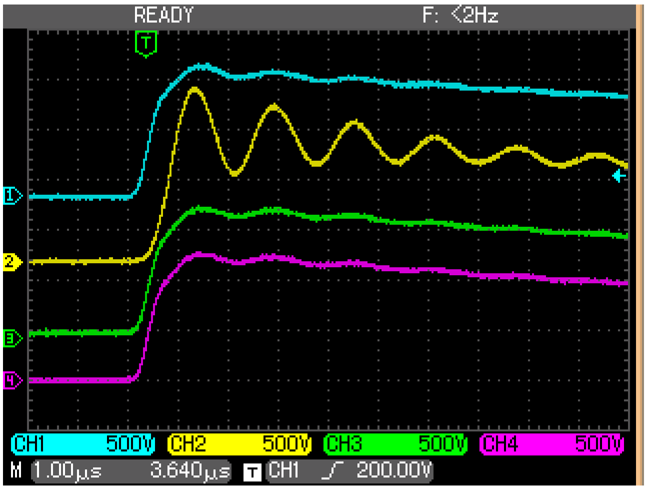

Figure 43. 00592. Pulse on cable shield (C1: Sin), non conducting pole, Rg1=Rg2=6kohm, C2:S2, C3:L1, C4:N1. Oscillating voltage at shield (S2) close to Lamp2, because of very high resistance to ground.

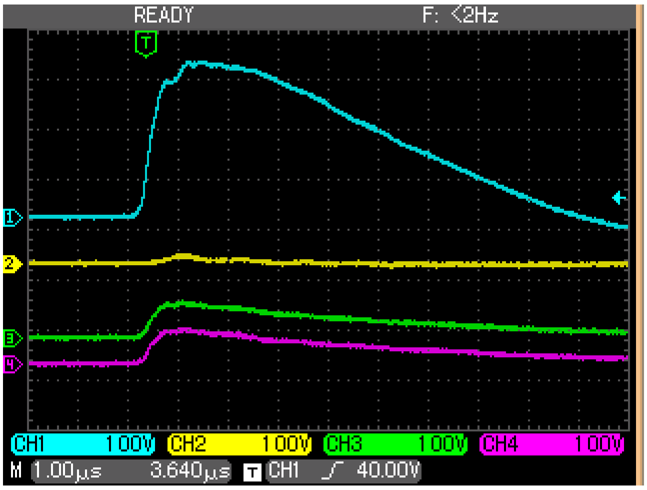

Figure 44. 00593. Pulse on cable shield (C1: Sin), non conducting pole, Rg1=Rg2=0 ohm, C2: L2, C3:L1, C4:N1. Lamp2 is saved but Lamp1 is considered broken.

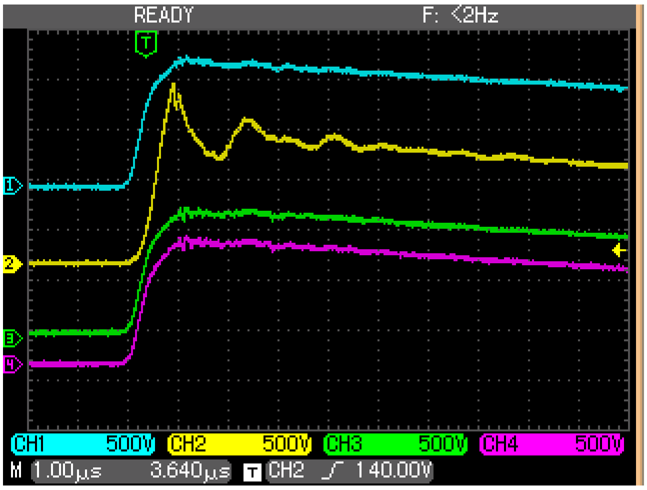

Figure 45. 00594. Pulse on cable shield (C1:Sin), non conducting pole, Rg1 = Rg2 = 125 ohm, C2:L2, C3:L1, C4:N1. Both Lamp1 and Lamp2 are considered broken.

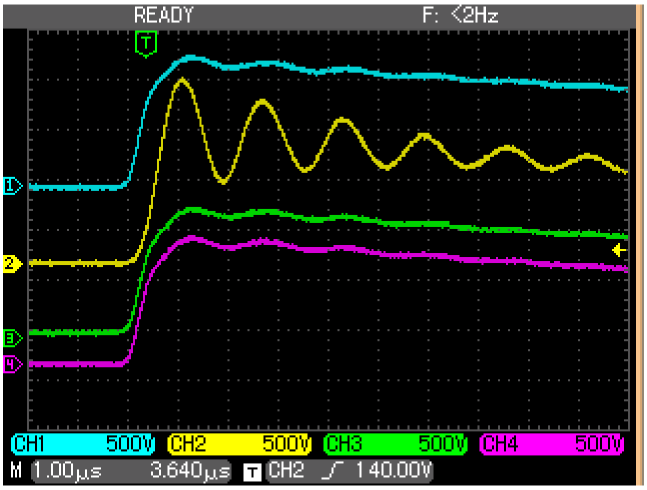

Figure 46. 00595. Pulse on cable shield (C1:Sin), non conducting pole, Rg1 = Rg2 = 6kohm, C2:L2, C3:L1, C4:N1.

.

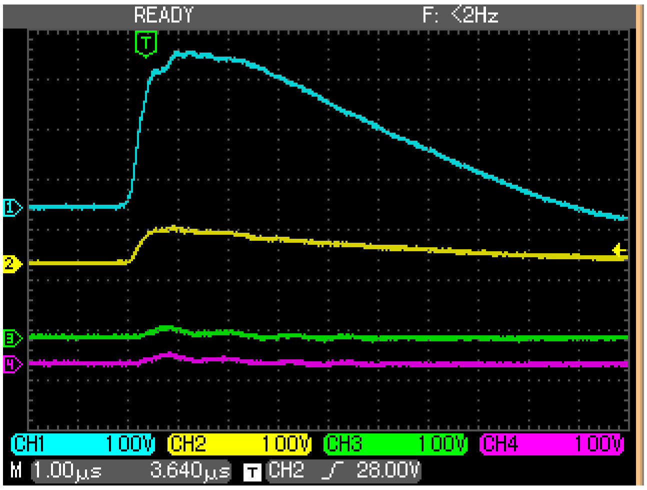

Figure 47. 00596. Pulse on cable shield (C1:Sin), non conducting pole, Rg1=Rg2=0 ohm, L1, L2, N2.

Low voltages on Lamp2.

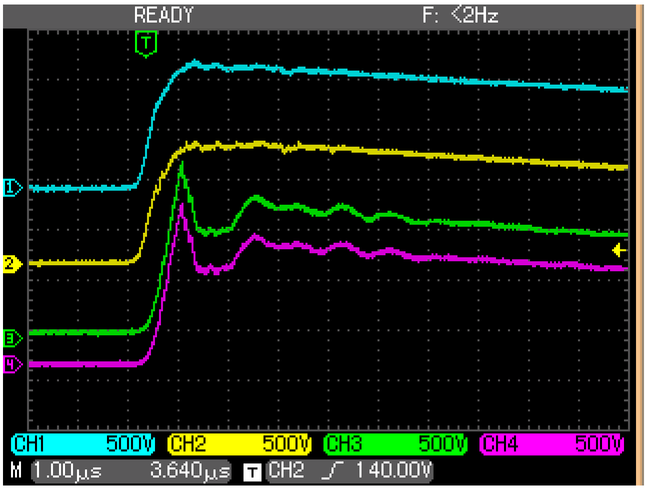

Figure 48. 00597. Pulse on cable shield (C1: Sin), non conducting pole. Rg1=Rg2=125 ohm.

C2:L1, C3:L2, C4:N2.Back- and forward reflection pattern on lamp2 (L2 and N2).

Both Lamp1 and Lamp2 are considered broken.

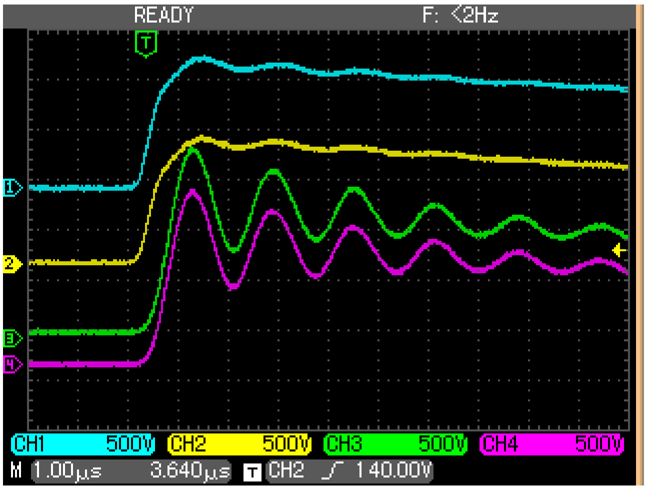

Figure 49. 00598. Pulse on cable shield (C1: Sin), non conducting pole, Rg1=Rg2= 6 kohm.

C2:L1, C3:L2, C4:N2.

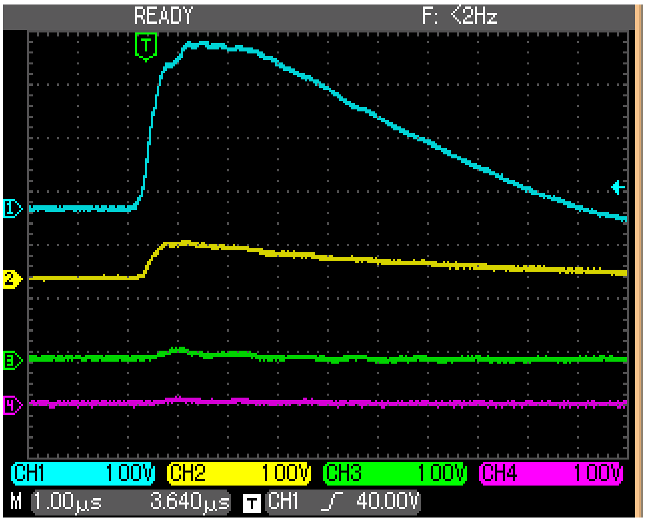

Figure 50. 00599. Shielded cable. Non conducting pole. Pulse on cable shield (C1:Sin). Rg1=Rg2=0ohms. Probes: C2:L1, C3:L2, C4:N2. (S1=Voltage on incoming shield, L1=Line in lamp1, L2=Line in lamp 2, N2=Neutral in lamp 2.). Lamp1 broken, Lamp2 saved.

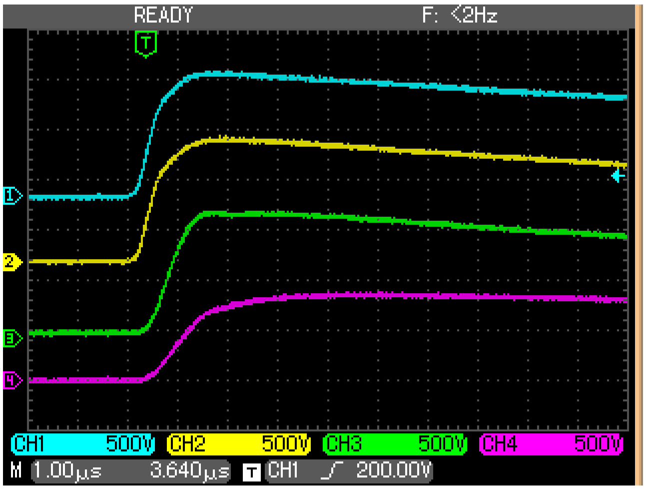

Figure 51. 000600. Shielded cable. Non conducting pole. Pulse on cable shield (C1=Sin). Rg1=Rg2=380 ohms. Probes: C2:L1,C3:L2, C4:N2. (S1=Voltage on incoming shield, L1=Line in lamp1, L2=Line in lamp 2, N2=Neutral in lamp 2.) Both Lamp1 and Lamp2 considered broken.

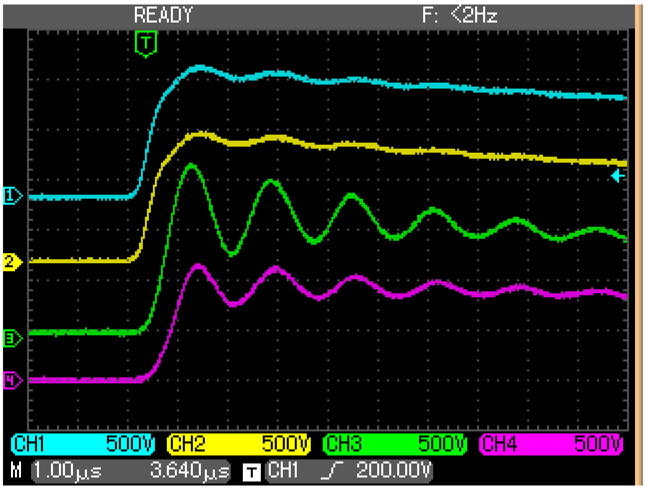

Figure 52. 00601. Shielded cable. Non conducting pole. Pulse on cable shield (C1:Sin). Rg1=Rg2=6 kohms. Probes: L1, L2, N2. (S1=Voltage on incoming shield, L1=Line in lamp1, L2=Line in lamp 2, N2=Neutral in lamp 2.) Both Lamp1 and Lamp2 considered broken.

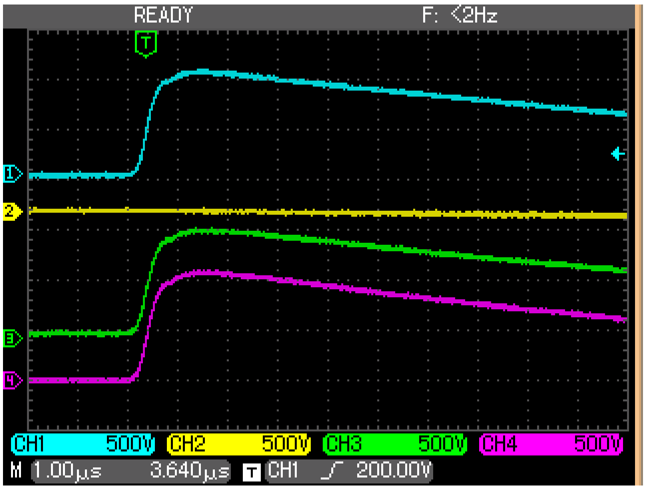

Figure 53. 00602. Shielded cable. Non conducting pole. Pulse on lamp housing $C1=Sin=V_{house1}$. Rg1=Rg2=0 ohms. Probes: S2, L1, N1. (S1=Voltage on incoming shield, S2=voltage on shield close to Lamp 2, L1=Line in lamp 1, N1=Neutral inside Lamp 1). Lamp1 considered broken.

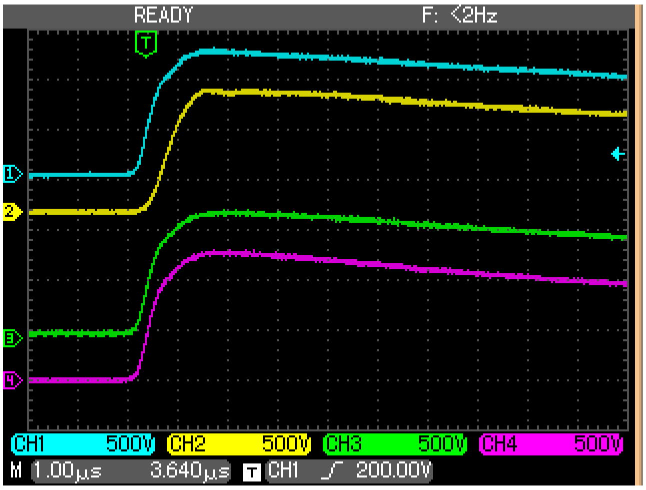

Figure 54. 00603. Shielded cable. Non conducting pole. Pulse on lamp housing ($C1=Sin=V_{house1}$). Rg1=Rg2=380 ohms. Probes: Sin, S2, L1, N1. (S1=Voltage on incoming shield, S2=voltage on shield at lamp 2, L1 = Line in lamp 1, N1=Neutral in lamp 1.). High voltage also at cable-shield2=S2 because of high resistance to ground. Lamp1 considered broken.

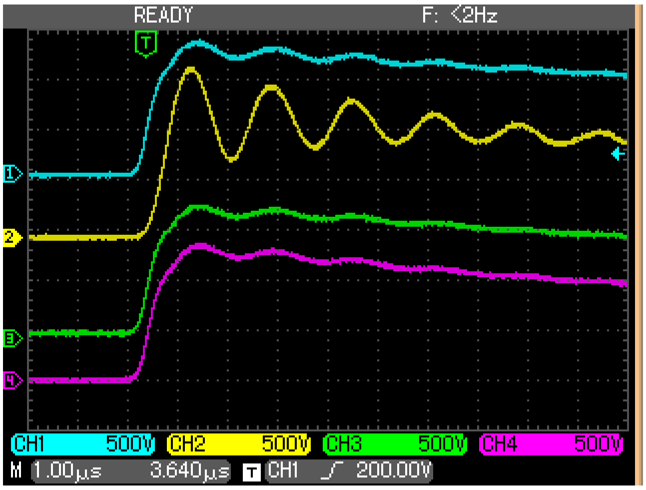

Figure 55. 00604. Shielded cable. Non conducting pole. Pulse on lamp housing ($C1=Sin=V_{house1}$). Rg1 = Rg2 = 6 kohms. Probes: C1=Sin, C2:S2, C3:L1, C4:N1. (S1=Voltage on incoming shield, S2=voltage on shield at lamp 2, L1=Line in lamp 1, N1=Neutral in lamp 1.).

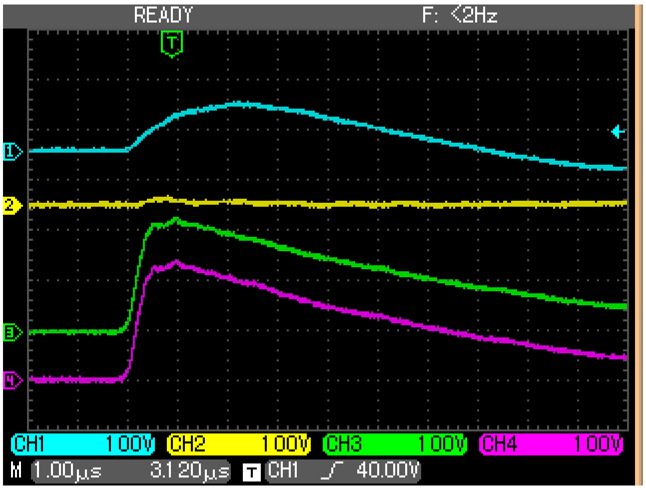

Figure 56. 00605. Shielded cable. Non conducting pole. Pulse on lamp housing ($C1=Sin=V_{house1}$). Rg1=Rg2=0 ohms. Probes: C1:Sin, C2:L2, C3:L1, C4:N1. (S1=Voltage on in-coming shield, L2=voltage on line in lamp 2, L1=Line in lamp 1, N1=Neutral in lamp 1.). Lamp1 considered broken, Lamp2 saved.

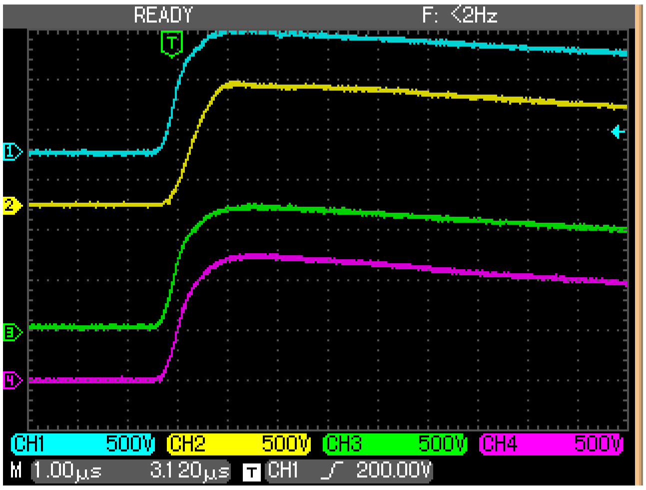

Figure 57. 00606. Shielded cable. Non conducting pole. Pulse on lamp housing (C1=Sin=V_{house1}. Rg1 = Rg2 = 400 ohms. Probes: Sin, L2, L1, N1. (S1=Voltage on incoming shield, L2=voltage on line in lamp 2, L1=Line in Lamp 1, N1=Neutral in lamp 1.). Both Lamp1 and Lamp2 are considered broken.

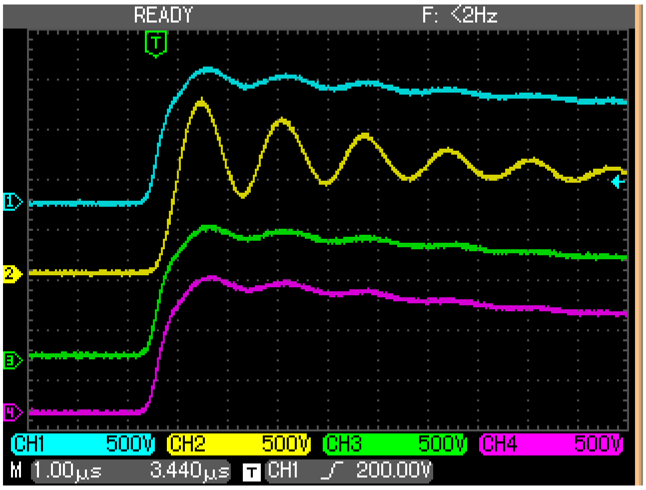

Figure 58. 00607. Shielded cable. Non conducting pole. Pulse on lamp housing C1=Sin=V_{house1}. Rg1 = Rg2 = 6kohms. Probes: C1:Sin, C2:L2, C3:L1, C4:N1. (L2=voltage on line in lamp 2, L1=Line in lamp 1, N1=Neutral in lamp 1.).

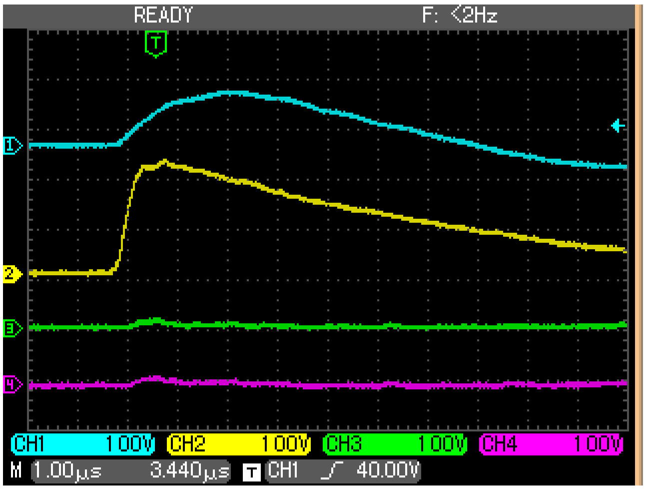

Figure 59. 00608. Shielded cable. Non conducting pole. Pulse on lamp house (C1=Sin=V_{house1}). Rg1 = Rg2 = 0 ohms. Probes: C1:Sin, C2:L1, C3:L2, C4:N2. Lamp2 safe. Lamp1 broken.

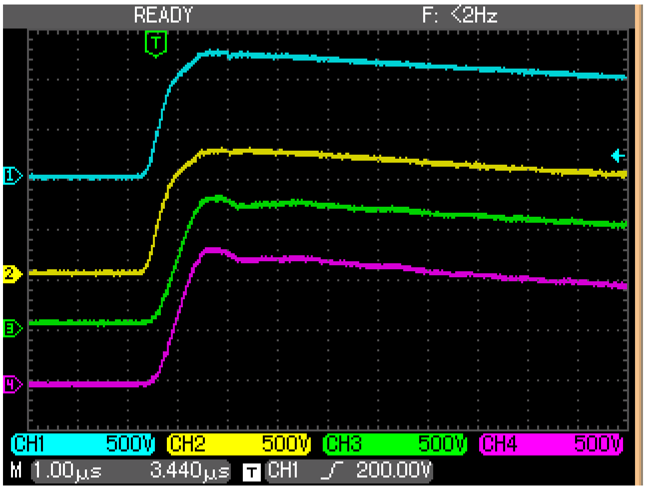

Figure 60. 00609. Shielded cable. Non conducting pole. Pulse on lamp housing (C1=Sin=V_{house1}). Rg1 = Rg2 = 400 ohms. Probes: C1:Sin, C2:L2, C3:L1, C4:N1.

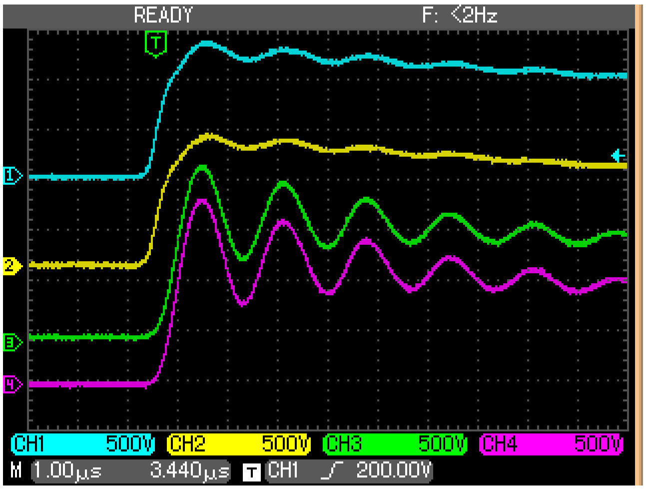

Figure 61. 00610. Shielded cable. Non conducting pole. Pulse on lamp house ($C1=Sin=V_{house1}$).Rg1 = Rg2 = 6k ohms. Probes: C1:Sin, C2:L2, C3:L1, C4:N1.

UNSHIELDED CABLE. NON-CONCUCTING POLES, MADE OF COMPOSITE MATERIAL. LIGHTNING PULSES ON THE OUTSIDE SURFACE OF THE LAMP HOUSE.

Case 1. LIGHTNING PULSES APPLIED ON THE OUTSIDE OF LAMP HOUSE 1.

See data-graphs 00611 – 00631. The most important graphs are 006xx (lamp1 destroyed), and 006xx (lamp 2 saved).

In the following test, the lamp houses are made of metal, the poles are made of composite material and the cables are not shielded . If a lightning pulse enters on the outside surface of lamp1, any ground resistance higher than 1 ohm is supposed to make damage on both lamp 1 and lamp 2 and so on. Se graphs 00xxx(lamp 1 destroyed) and xxxxx (lamp 2 saved), the important parameters to check is the voltage on L2 and N2 for saved-or-destroyed lamp2, and L1 and N2 for saved-or-destroyed lamp 1. The resistor value Rg=0 ohm, is not exact. The values were in fact Rg = 0.1- 0.3 ohm when checked. Even with these very low Rg-values in most cases there were some small voltages recorded on Lamp2 L2-N2. The resistor values Rg = 125 ohm were used in about half of the test-cases, but since the components very often were broken, the last cases were performed with Rg = 375-410 ohms. When both Rg= 125 ohm and Rg = 375 ohm were used, there were very small differences between the outcomes.

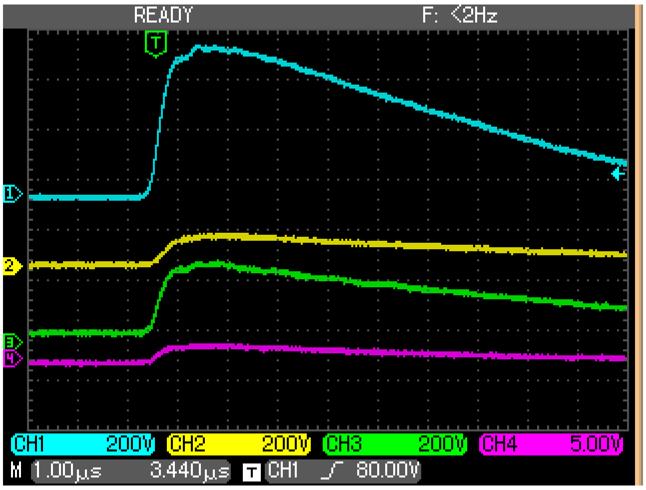

Figure 62. 00611. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house (C1=Vin=V_{house1}).Rg1 = Rg2 = 0 ohms. Probes: C1:Vin, C2:PE1, C3:L1, C4:N1. Note scales ch4: 5 V/div.

<u>Comment on 00611:</u> The incoming lightning pulse on the house of lamp1, is transferred to PE1 (protective earth of lamp1), Line1 (Line of lamp1) and N1 (Neutral of lamp1).

Rg1=Rg2=0 ohm but **<u>Lamp 1 will be destroyed</u>** by the pulse on the lamp house. The low resistance PE-ground, does not help to save Lamp 1. Regarding lamp 2: See 00614!

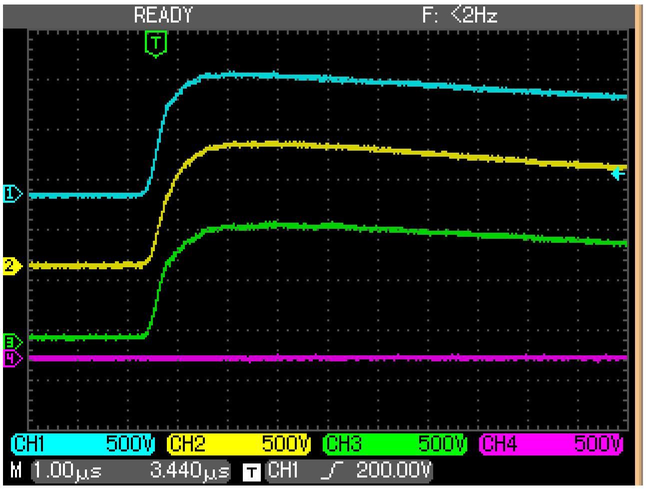

Figure 63. 00612. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 380 ohms. Probes: C1:Vin, C2:PE1, C3:L1, C4:N1.

Comment on 00612: The incoming lightning pulse on the house of lamp1, is transferred to PE1 (protective earth of lamp1), Line1 (Line of lamp1) and N1 (Neutral of lamp1).

Rg1=Rg2=400 ohm and **Lamp 1 will be destroyed** by the pulse on the lamp house.

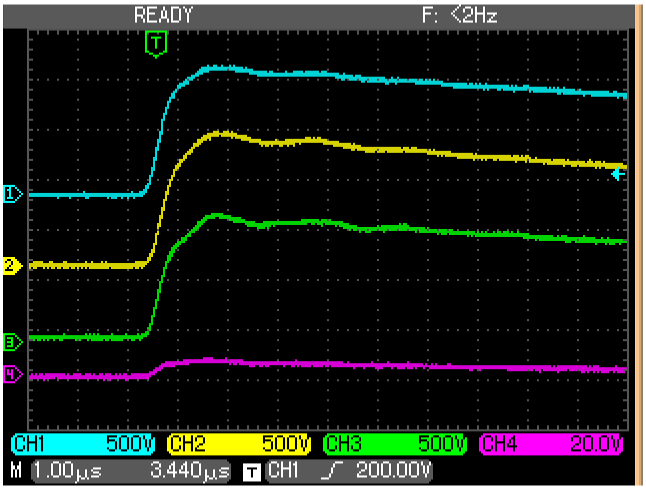

Figure 64. 00613. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 6 kohms. Probes: C1:Vin, C2:PE1, C3:L1, C4:N1. Note Ch4: 20V/div.

Comment on 00613: The incoming lightning pulse on the house of lamp1, is transferred to PE1 (protective earth of lamp1), Line1 (Line of lamp1) and N1 (Neutral of lamp1).

Rg1=Rg2=400 ohm and **Lamp 1 will be destroyed** by the pulse on the lamp house.

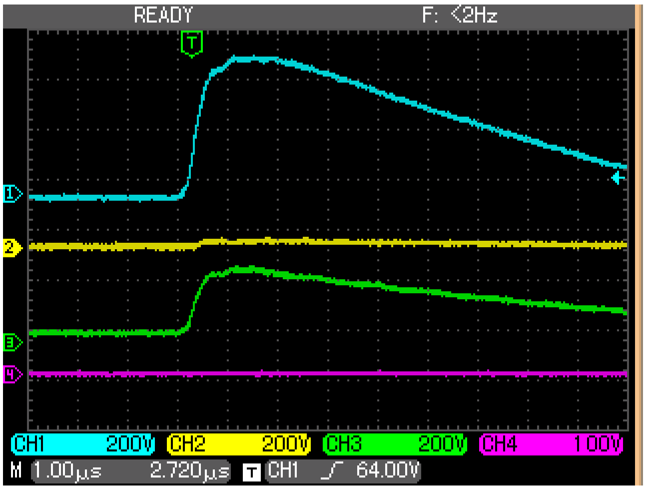

Figure 65. 00614. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house($C1=Vin=V_{house1}$). Rg1 = Rg2 = 0 ohms. Probes: C1:Vin, C2:L2, C3:L1, C4:N1. Note Ch4: 100V/div. Note the low voltage on Line2, i.e. lamp2. Lamp2 saved.

Comment on 00614: The incoming lightning pulse on the house of lamp1, is transferred to L1 (Linelamp1), Line1 (Line of lamp1) and N1 (Neutral of lamp1). Lamp 2 can be safe, because L2 is very low.

Rg1=Rg2= 0 ohm and **Lamp 1 will be destroyed** by the pulse on the lamp house.

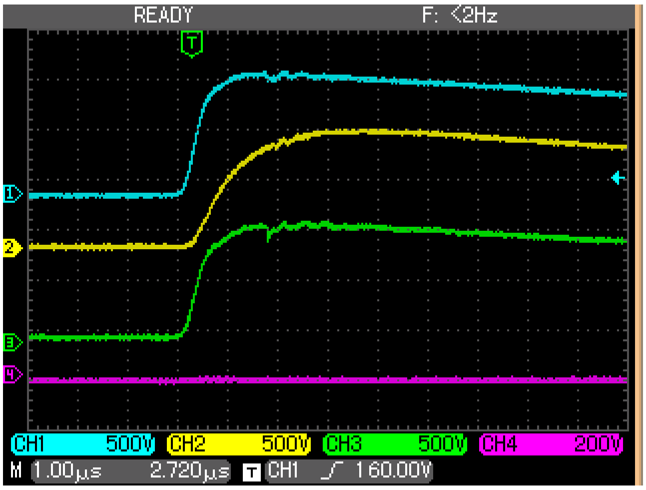

Figure 66. 00615. Ch4 200V/div. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house($C1=Vin=V_{house1}$). Rg1 = Rg2 = 375 ohms. Probes: C1:Vin, C2:L2, C3:L1, C4:N1. Note Ch4: 200V/div. Both Lamp1 and Lamp2 destroyed -too high resistance to ground.

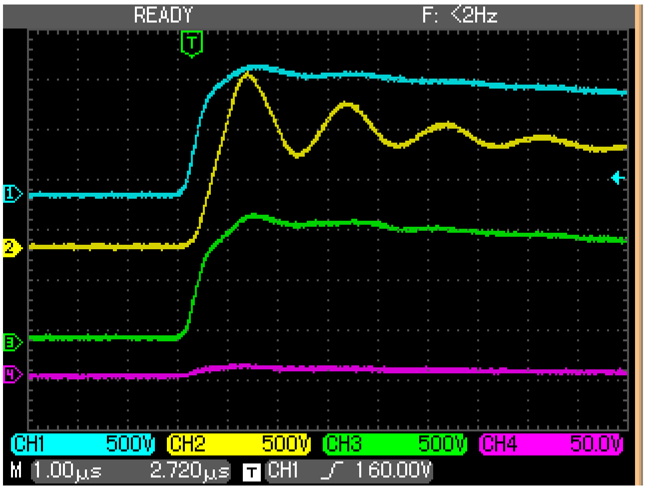

Figure 67. 00616. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 6 kohms. Probes: C1:Vin, C2:L2, C3:L1, C4:N1. Note Ch4: 50V/div. Both Lamp1 and Lamp2 destroyed -too high resistance to ground.

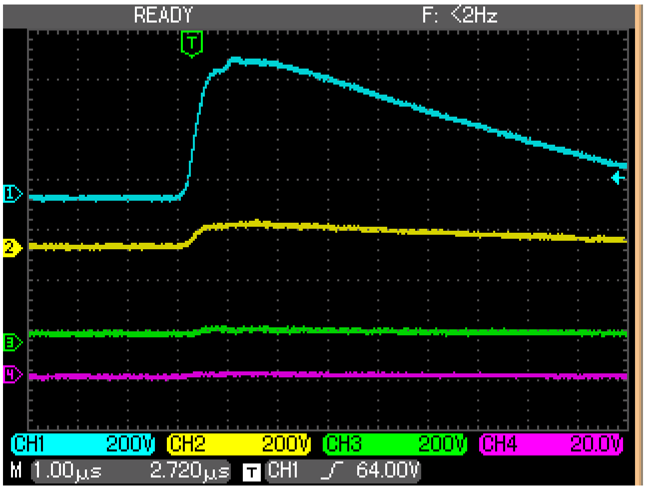

Figure 68. 00617. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 0 ohms. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N1. Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.)

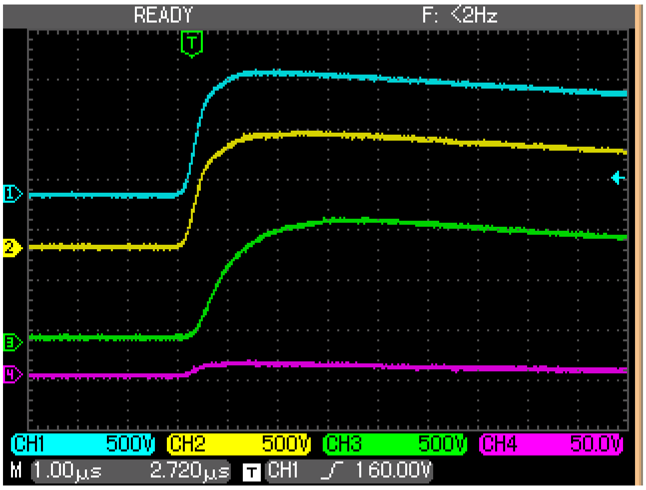

Figure 69. 00618. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 380 ohms. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N1. Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.)

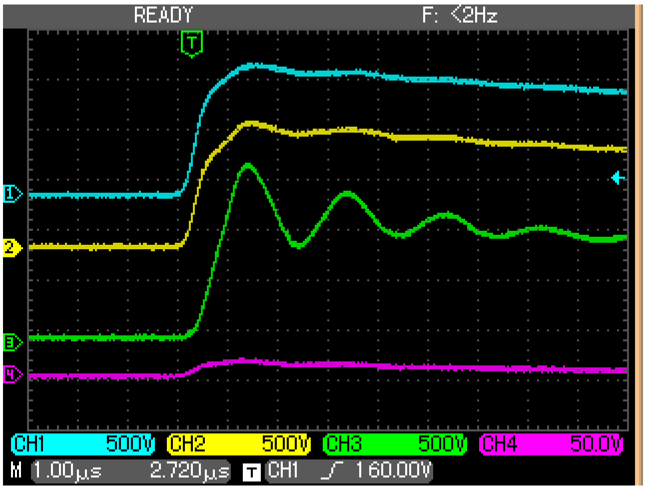

Figure 70. 00619. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 6 kohms. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N1. Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.)

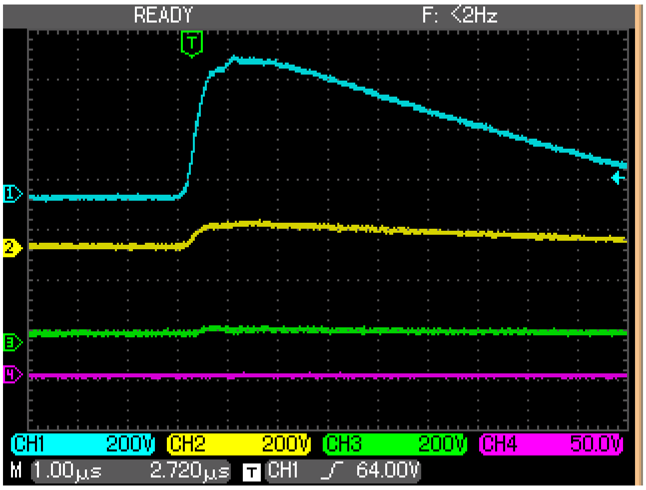

Figure 71. 00620. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 0 ohm. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N2 Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.)

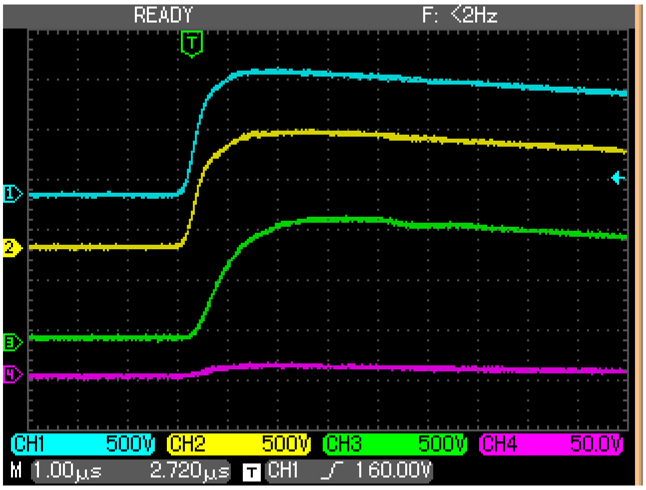

Figure 72. 00621. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 380 ohm. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N2 Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.)

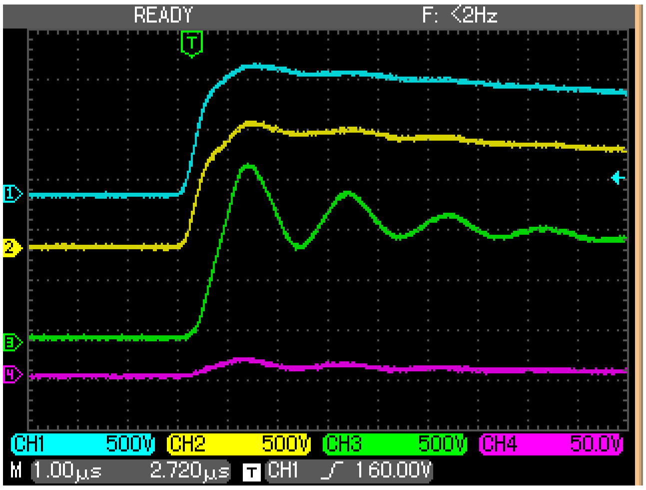

Figure 73. 00622. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 6 kohm. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N2. Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.)

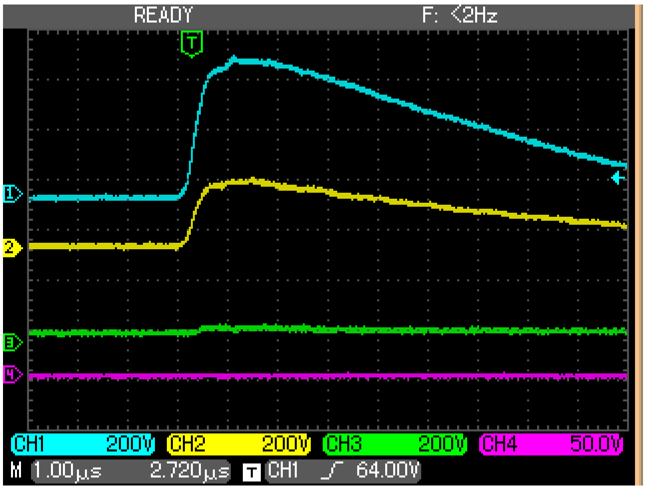

Figure 74. 00623. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1= Vin =V_{house1}). Rg1=Rg2 = 0 ohm. Probes: C1:Vin, C2:L1, C3:L2, C4:N2. Note Ch4: 50V/div. (LB1: Not used Line conductor in lamp 1. LB2: Not used line conductor in lamp 2. This conductor goes forward without being used.

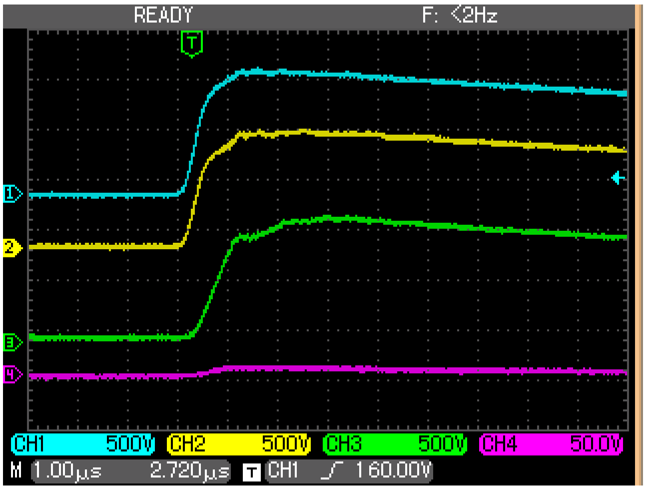

Figure 75. 00624.Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on lamp house(C1= Vin =V_{house1}). Rg1 = Rg2 = 380ohm.

Probes: C1:Vin, C2:L1, C3:L2, C4:N2. Note Ch4: 50V/div.

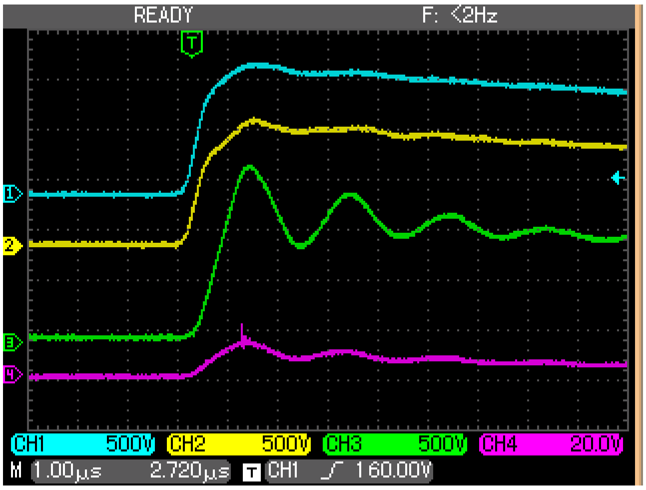

Figure 76. 00625.0020. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp Vin=V_{house1}). Rg1 = Rg2 =6 kohm. Probes: C1:Vin, C2:L1, C3:L2, C4:N2. Note Ch4: 50V/div.

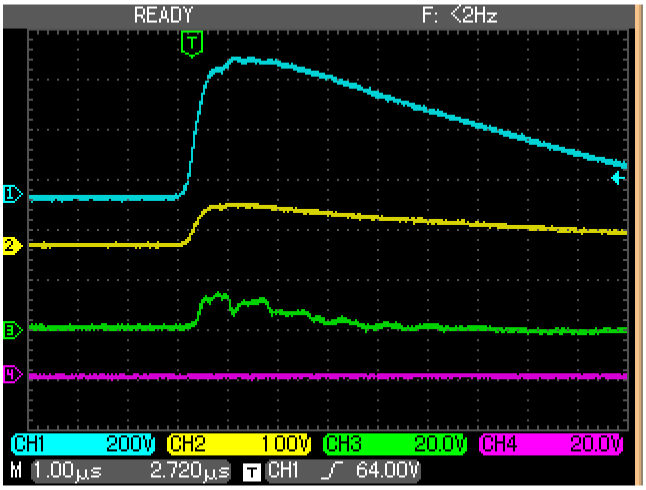

Figure 77. 00626. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 0 ohm.

Probes: C1:Vin, C2:PE1,C3: PE2, C4:N2. Note Ch4: 20V/div.

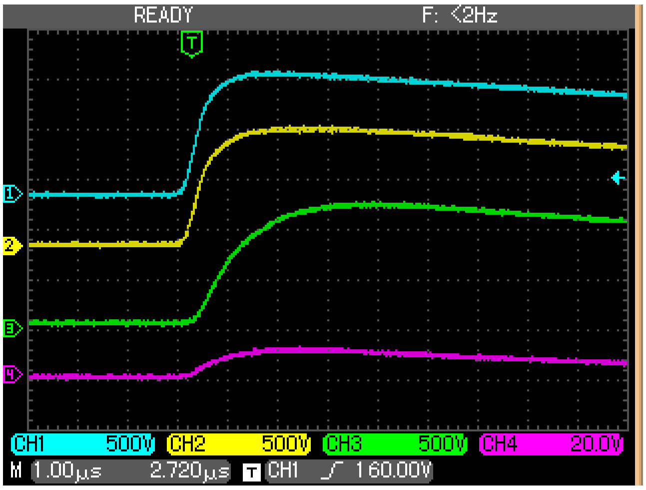

Figure 78. 00627. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 =385 ohm.Probes: C1:Vin, C2:PE1,C3: PE2, C4:N2. Note Ch4

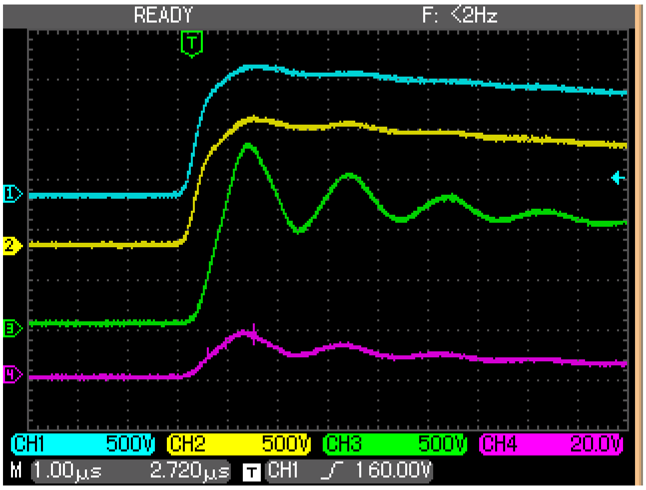

Figure 79. 00628. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 6kohm. Probes: C1:Vin, C2:PE1,C3: PE2, C4:N2. Note Ch4

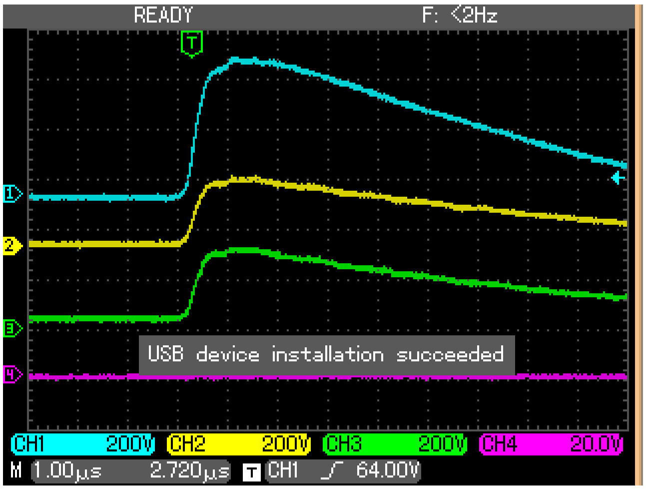

Figure 80. 00629. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 0 ohm.Probes: C1:Vin, C2:L1, C3:N1, C4:N2. Note Ch4: 20

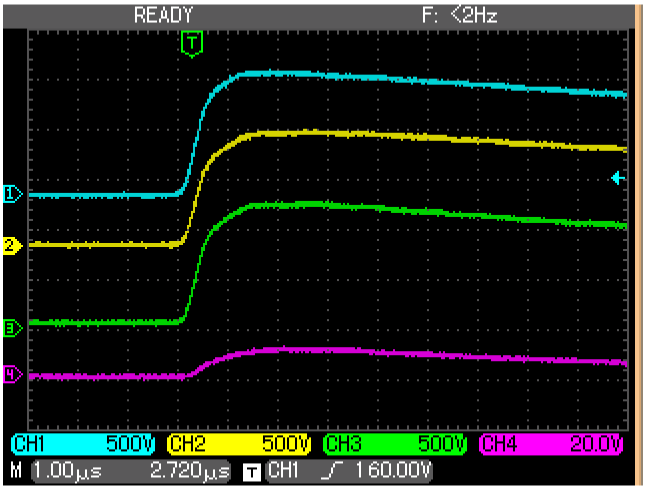

Figure 81. 00630. Un-shielded 4-conductors-cable. Non conducting pole. Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 390 ohm.Probes: C1:Vin, C2:L1, C3:N1, C4:N2.

Note Ch4: 20V/div.

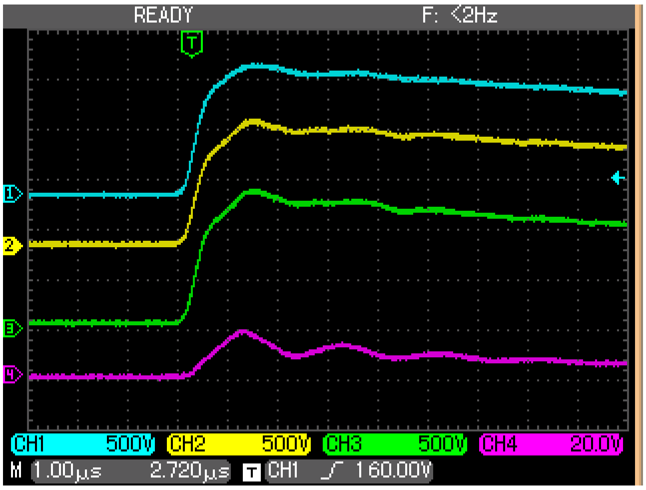

Figure 82. 00631. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on lamp house(C1=Vin=V_{house1}). Rg1 = Rg2 = 6kohm.Probes: C1:Vin, C2:L1, C3:N1, C4:N

Note Ch4: 20V/div.

NON-CONDUCTING POLES, MADE OF COMPOSITE MATERIAL.

UNSHIELDED CABLES.

Case 2. LIGHTNING PULSES ON THE INCOMING PROTECTIVE EARTH, PE1, OF LAMP NO 1.

Surge pulses on the incoming protective earth, PE1: See data-graphs 00632 – 00644.

The most important graphs are 00632-lamp1 destroyed, and 00638-lamp 2 saved.

Damage on lamp 1 but not necessary on lamp 2. See 00632!

Showing that high voltage on PE1 is transferred to Line1 and Neutral 1 in lamp1 even when Rg=0 ohm. **Pulse on incoming protective earth, PE1, of the first lamp.**

Conclusion. Lamp no 1 cannot be protected in any constallation.

Lamp no 2 is well protected if protective earth is well grounded

CONCLUSION: If a lightning pulse enters on protective earth before lamp1, PE1, any ground resistance higher than 1 ohm is supposed to make damage on both lamp 1, and lamp 2 and so on. Se graphs 00632 (lamp 1 destroyed) and 00638 (lamp 2 saved), the important parameters to check is the voltage on L2 and N2 for saved-or-destroyed lamp2, and L1 and N2 for saved-or-destroyed lamp 1.

The resistor value Rg=0 ohm, is not exact. The values were in fact Rg = 0.1- 0.3 ohm when checked. Even with these very low Rg-values in most cases there were some small voltages recorded on Lamp2- L2-N2. The resistor values Rg = 125 ohm were used in about half of the test-cases, but since the components very often were broken, the last cases were performed with Rg = 375-410 ohms. When both Rg= 125 ohm, and Rg = 375 ohm were used, there were very small differences between the outcomes.

If a lightning pulse enters on any of the four conductors: L1, L2, N or PE, the high voltage will be transferred to all the other conductors, unless the first conductor is shorted to ground. A very low resistance to ground is the only way to avoid spreading of the incoming pulse to the other conductors.

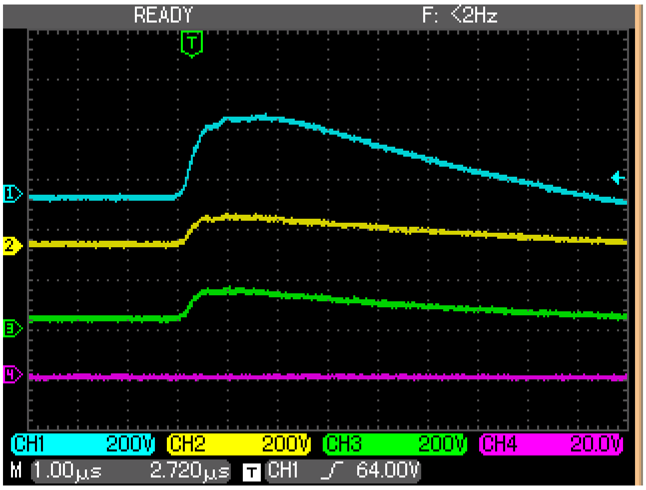

Figure 83. 00632. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on incoming PE1, Rg1 = Rg2 = 0 ohm.

Probes: C1:Vin, C2:L1, C3:N1, C4:N2. Note Ch4: 20V/div.

Conclusion: Damage on lamp 1 but not necessary on lamp 2.

The high voltage on PE1 is transferred to Line1 and Neutral 1 in lamp1 even when Rg=0 ohm.

Comment on 00632: About 50% of the incoming pulse is transferred to Line1 (L1) and Neutral 1. Neutral 2 is flat. Nothing or very little of the incoming pulse reaches Neutral of lamp2 (N2).

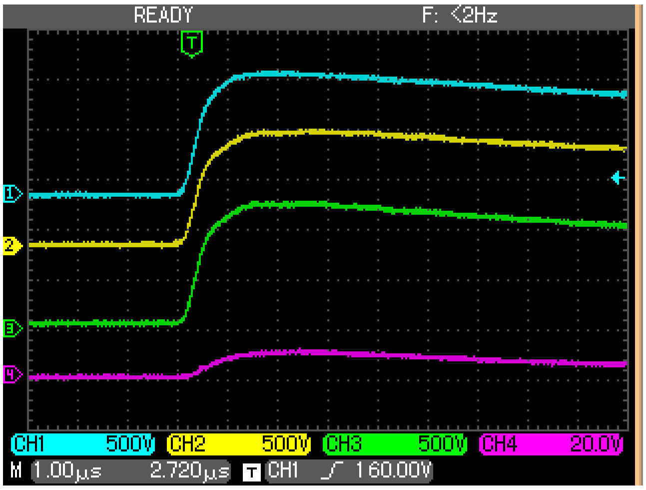

Figure 84. 00633. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on PE1 incoming, Rg1 = Rg2 = 390 ohm.

Probes: C1:Vin, C2:L1, C3:N1, C4:N2. Note Ch4: 20V/div.

Comment to 00633 Line and Neutral 1 are heavily affected by the incoming pulse on PE1.

Neutral 2 is hit by about 1 % of the incoming magnitude.

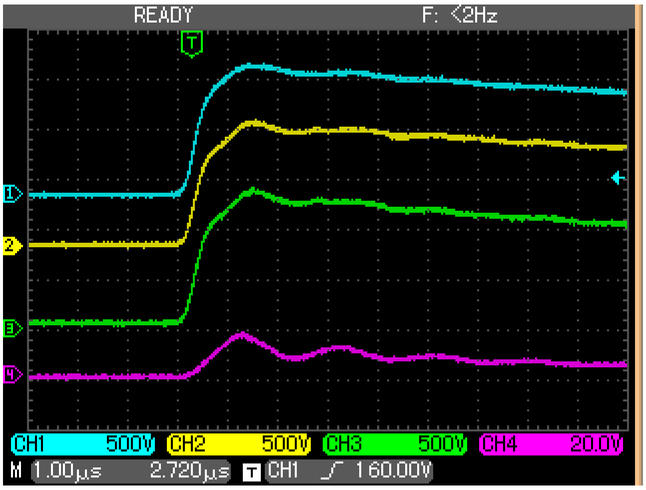

Figure 85. 00634. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on PE1 incoming, Rg1 = Rg2 =6kohm.

Probes: C1:Vin, C2:L1, C3:N1, C4:N2. Note Ch4: 20V/div.

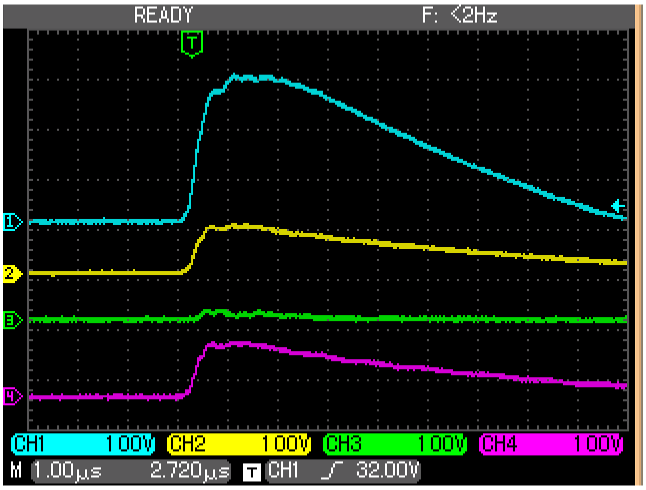

Figure 86. 00635. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on incoming PE1. Rg1 = Rg2 = 0 ohm. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N1.

Note Ch4: 20V/div.

Pulse incoming on PE1. Rg= 0 ohm. The pulse is transferred from PE1 to the free conductor LB1,inside lamp1, but very little of that voltage is remaining when the pulse reaches lamp2 (LB2). Lamp1 will be destroyed. Very low voltage on free conductor LB2, but not on LB1. Lamp 2 can be saved, but not lamp 1.

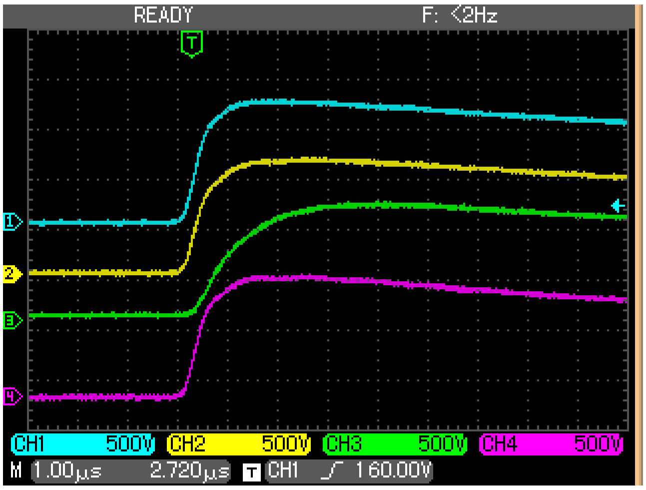

Figure 87. 00636. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on incoming PE1, Rg1 = Rg2 = 400 ohm. Probes: C1:Vin, C2:LB1, C3:LB2, C4:N1.

Pulse incoming on PE1. Rg= 400 ohm. The pulse goes forward on the free, not used conductor. All voltages are high.

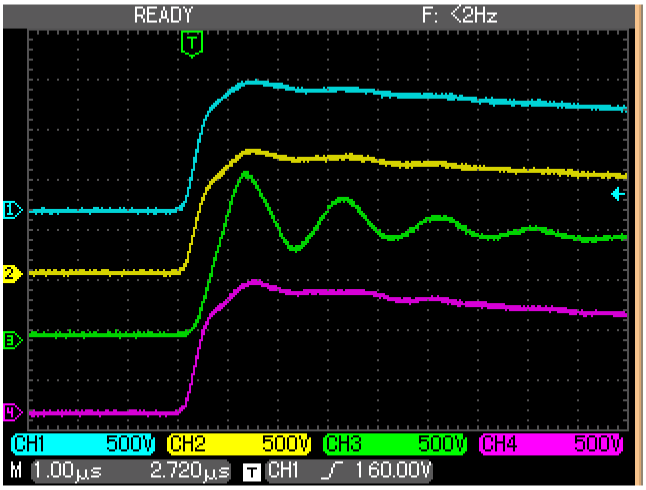

Figure 88. 00637. Un-shielded 4-conductors-cable. Non conducting pole.

Pulse on incoming PE1, Rg1 = Rg2 = 6 kohm.

Probes: C1:Vin, C2:LB1, C3:LB2, C4:N1.

Pulse incoming on PE1. Rg= 6kohm. The pulse goes forward on the free, not used conductor. All voltages are high.

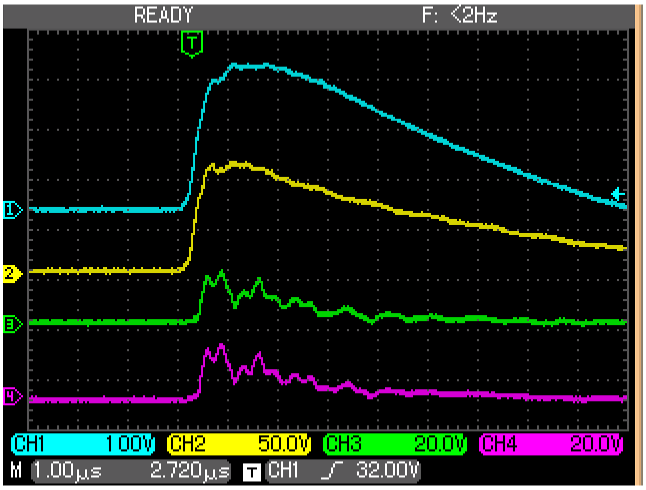

Figure 89. 00638. Unshielded cable. Non conducting pole. Pulse on PE1, Rg1=Rg2= 0ohm. Probes C1:Vpe1, C2:L1, C3:L2, C4:N2. Note the scales: Ch3 and Ch4 20 V/div. Line2 and Neutral 2 have low voltages (incoming 400 V on PE1, and 20 V on Line2 and Neutral2. The voltage over lamp2 is the difference L2-N2 which is very small.Pulse incoming on PE1. Rg= 0 ohm. Lamp 1 is not protected. Lamp 2 voltage is fairly

well protected:

Voltage difference L2-N2 reduced to a very low value. Lamp 2 can be saved.

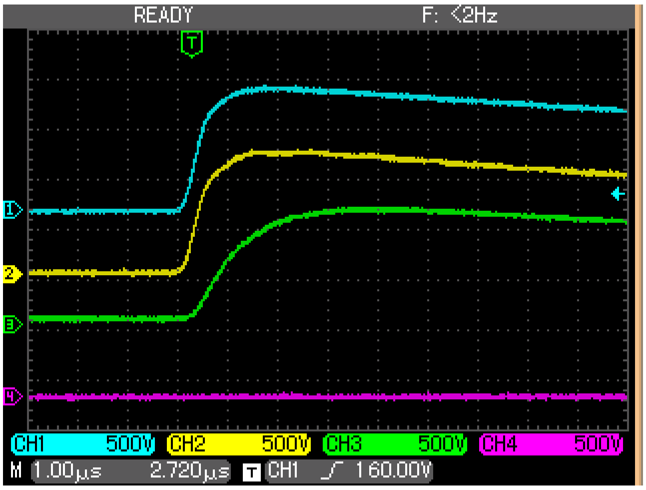

Figure 90. 00639. Unshielded cable. Non-conducting pole. Pulse on PE1, Rg1=Rg2= 400 ohm.

Probes C1:Vpe1, C2:L1, C3:L2, C4:N2. Both lamp1 and Lamp2 will be destroyed.

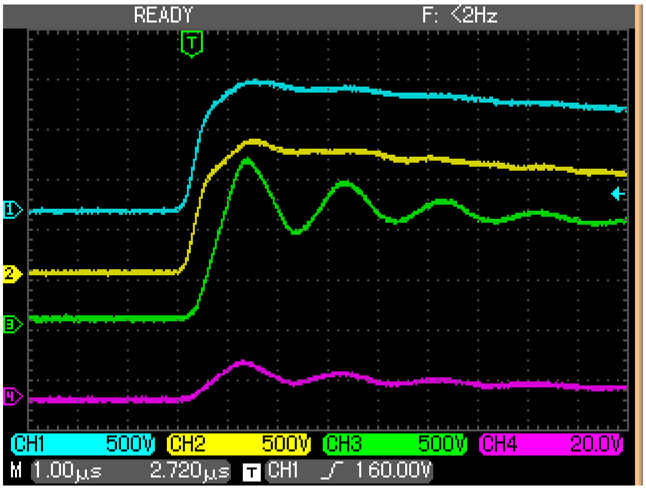

Figure 91. 00640. Unshielded cable. Non-conducting pole. Pulse on PE1, Rg1=Rg2= 6k ohm.

Probes C1:Vpe1, C2:L1, C3:L2, C4:N2. High voltages on both L1, L2, and N2.

Both Lamp1 and Lamp2 will be destroyed.

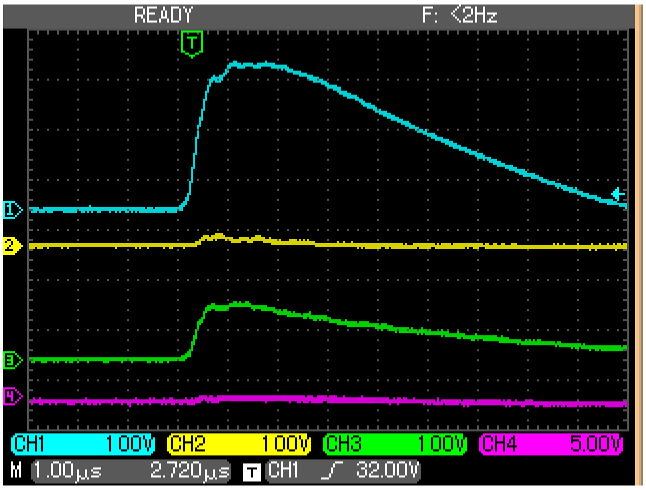

Figure 92. 00641. Unshielded cable. Non-conducting pole. Pulse on PE1, Rg1=Rg2= 0 ohm. C1:Vpe1, C2:Vpe2, C3:N1, C4:N2. Lamp1 destroyed but Lamp2 may be saved.

Rg= 0 ohm: the incoming pulse on PE1 jumps over to N1 with less than half the magnitude. The pulse does not propagate from PE1 to PE2 when the ground connection resistance is Rg=0. Neutral 2 is also protected. Lamp1 will be destroyed, but lamp 2 may be saved.

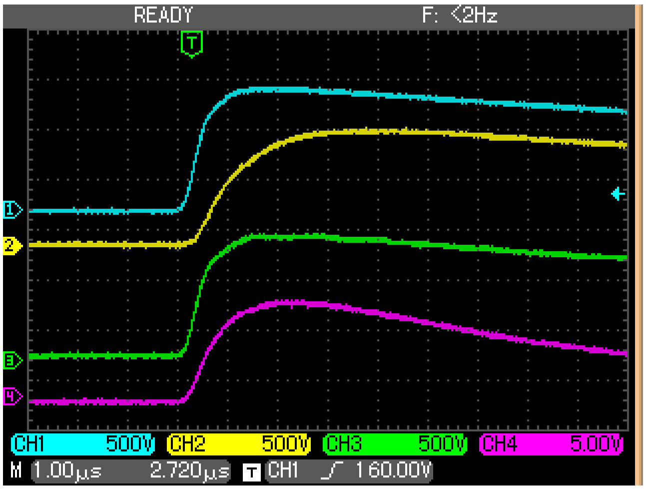

Figure 93. 00643. Unshielded cable. Non-conducting pole. Pulse on PE1, Rg1=Rg2=400 ohm. C1:Vpe1, C2:Vpe2, C3:N1, C4:N2. Both Lamp1 and Lamp2 will be destroyed.

Rg= 400 ohm: the incoming pulse on PE1 jumps over to N1 with equal magnitude.

The pulse goes forward from PE1 to PE2 with equal magnitude.

Both lamp1 and lamp2 will be destroyed.

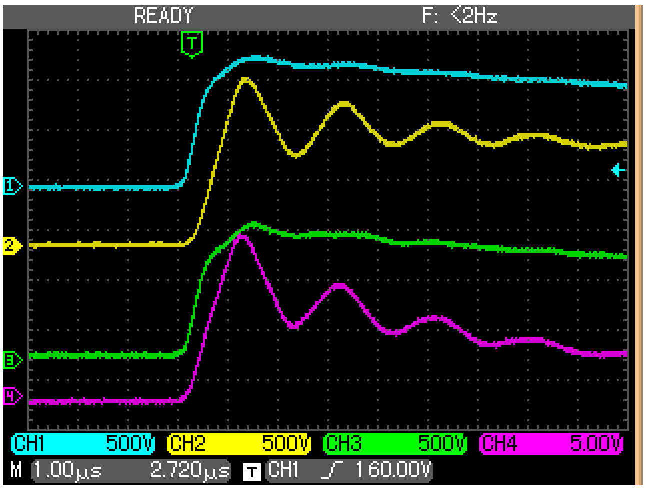

Figure 94. 00644. Unshielded cable. Non-conducting pole. Pulse on PE1, Rg1=Rg2=6kohm. C1:Vpe1, C2:Vpe2, C3:N1, C4:N2. Both Lamp1 and Lamp2 will be destroyed.

Comment on 00644: Rg=6 kohm: T**he incoming pulse on PE1 jumps over to N1 with equal magnitude. The pulse goes forward from PE1 to PE2 and starts to oscillate at PE2 with high magnitude. Both lamp1 and lamp2 will be destroyed.**

PICTURES FROM LAB SITUATIONS.

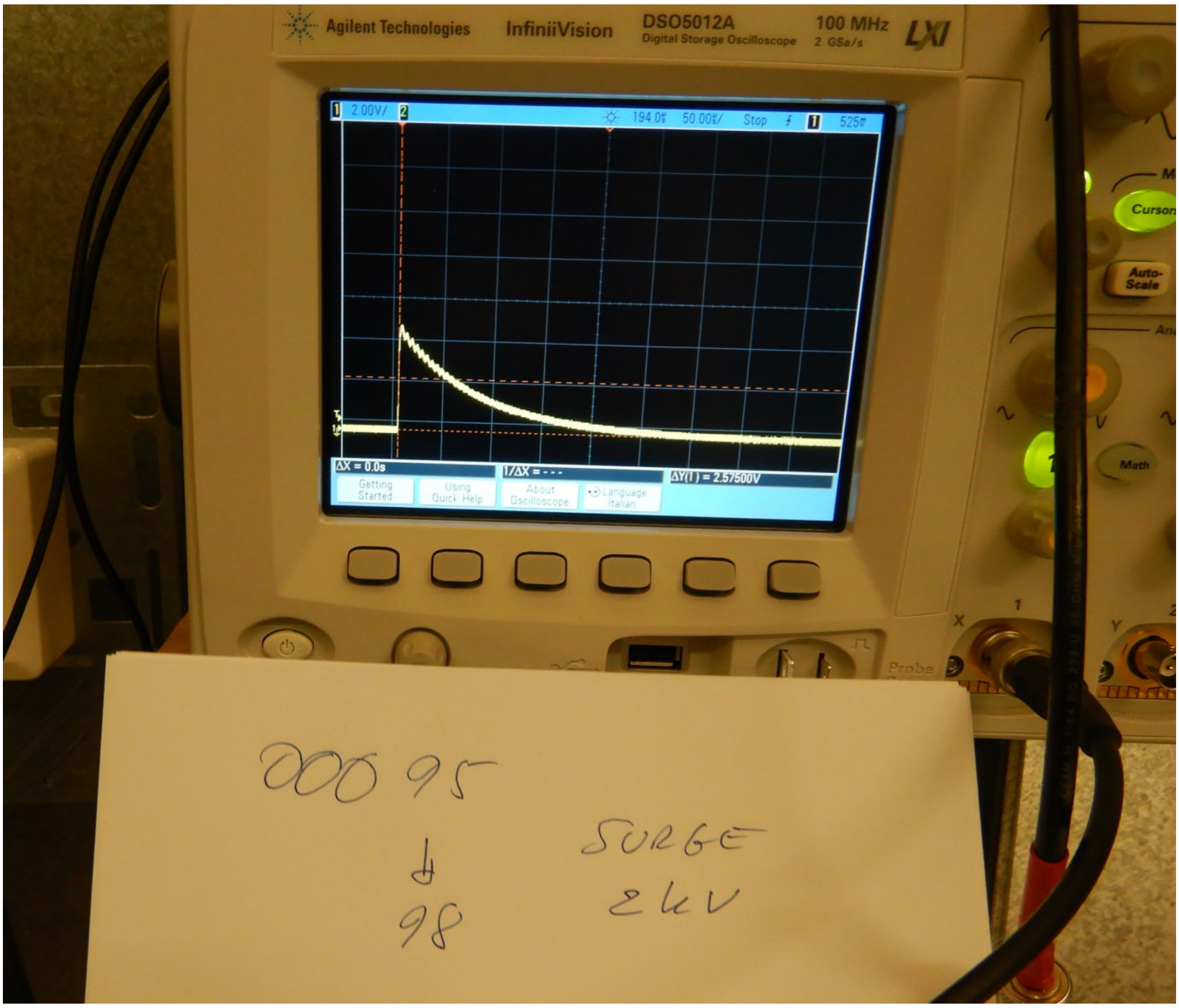

Figure 95. A typical surge pulse monitored at the generator output.

Horizontal scale: 50 us/div. Vertical scale: 1 kV/div.

Pulse magnitude 2 kV, pulse duration 50 us.

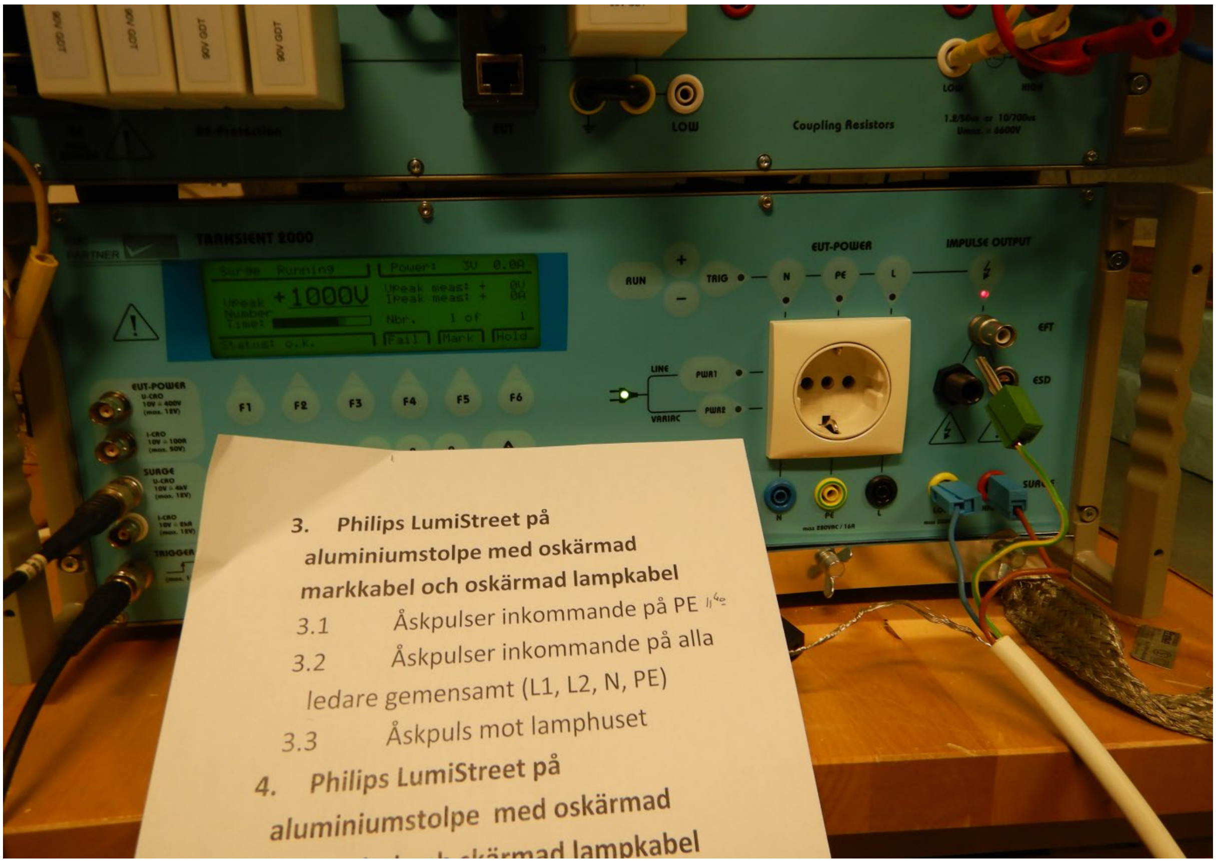

Figure 96. Front of Surge generator T1000. In this case: Peak voltage 1000 V.

The surge-pulses propagates inside the white cable to the chosen injection point.

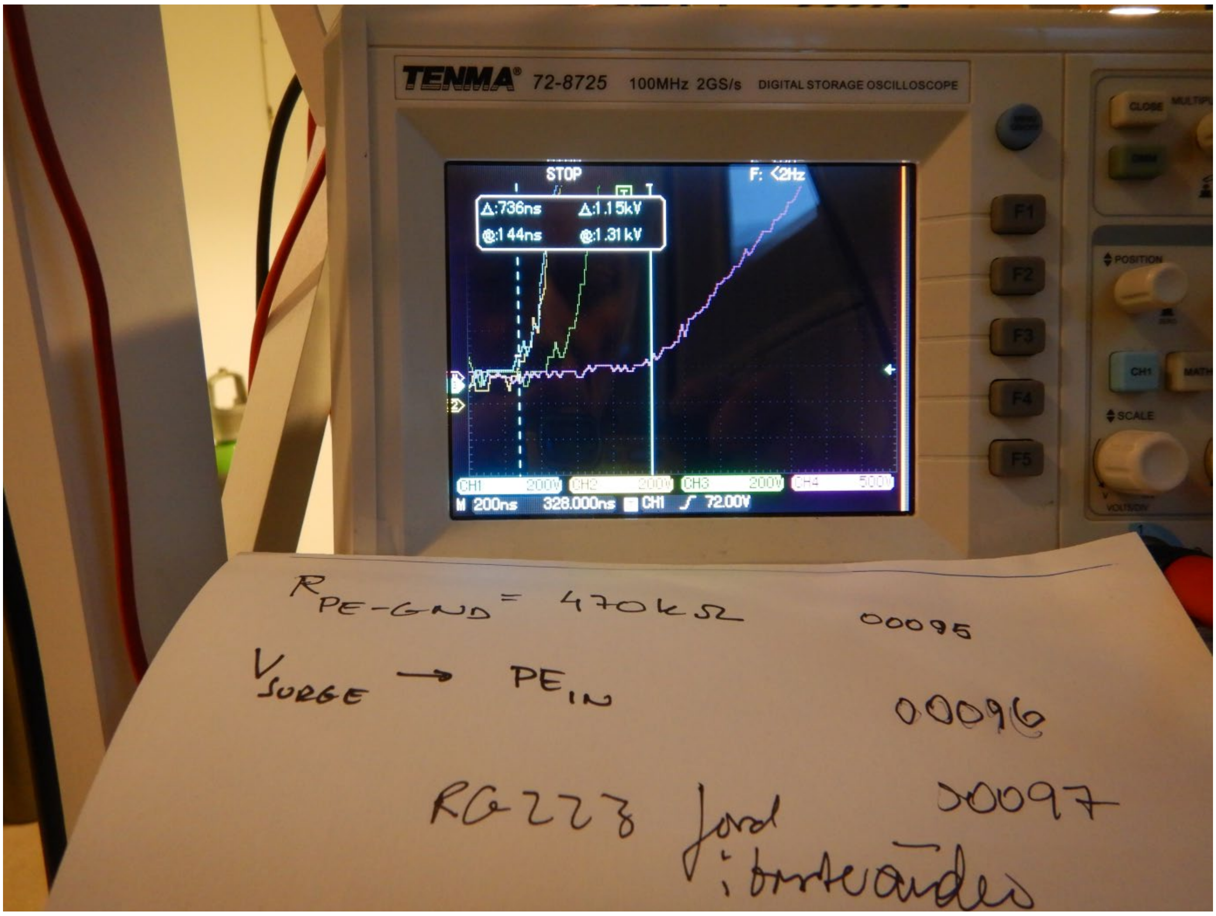

Figure 97. The same original pulse recorded at Lamp1 (two close tracks), Lamp2 and at Lamp4. The Lamp4-pulse is a bit less steep after travelling 120 meters.

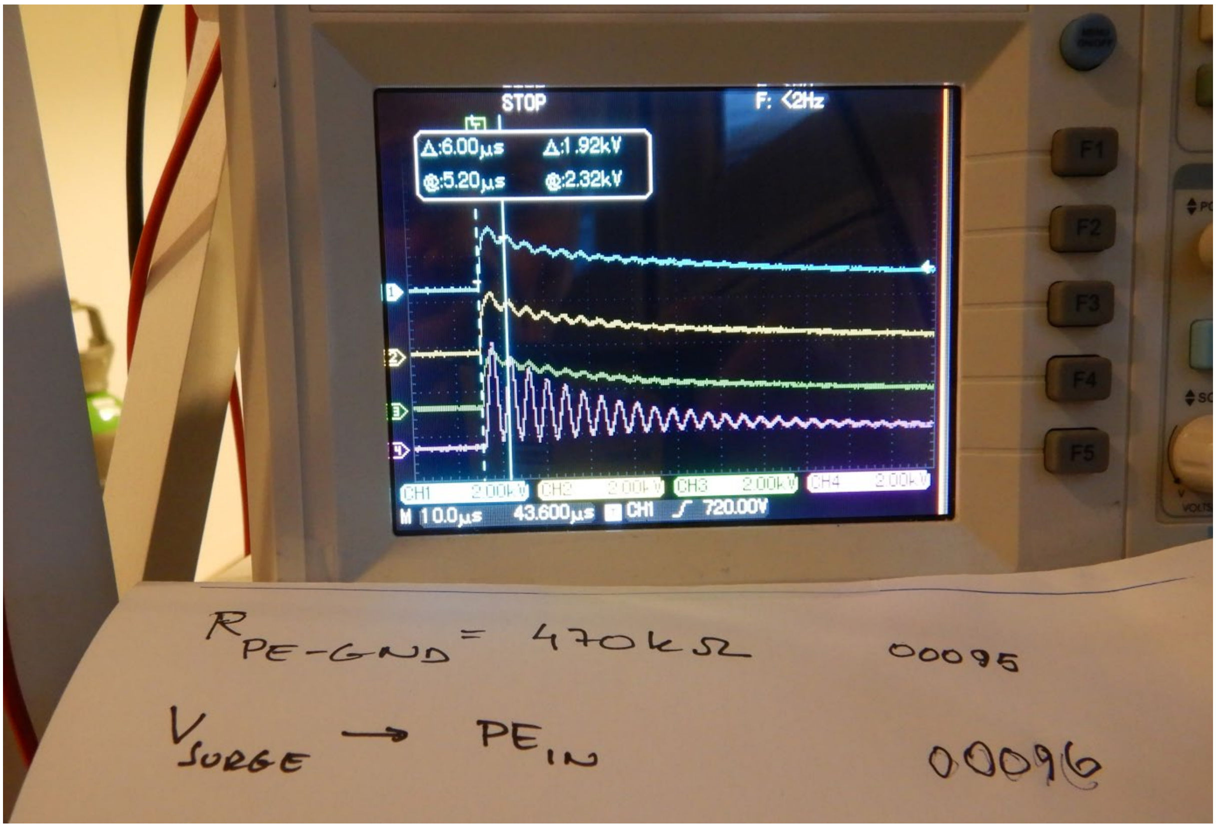

Figure 98. High impedance load caused oscillations (channel 4). Mismatch.

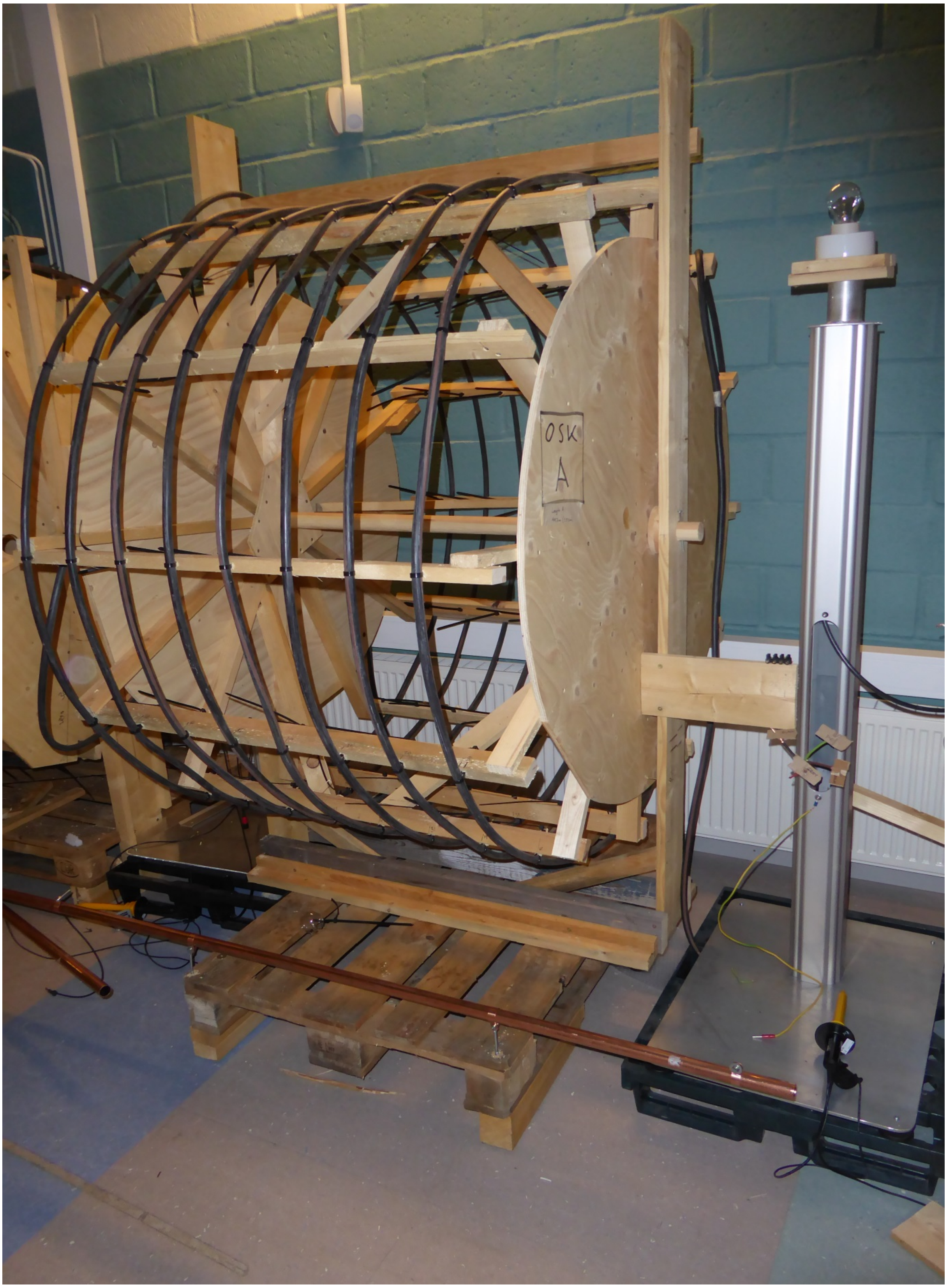

Figure 99. 40 m cable fixed on a wooden frame. 8 turns, distance between turns 0.12 m, diameter 1.59 m. Each turn 5 meters. Unshielded cable. The copper-tube-ground below the coil is fixed to the wooden structure.

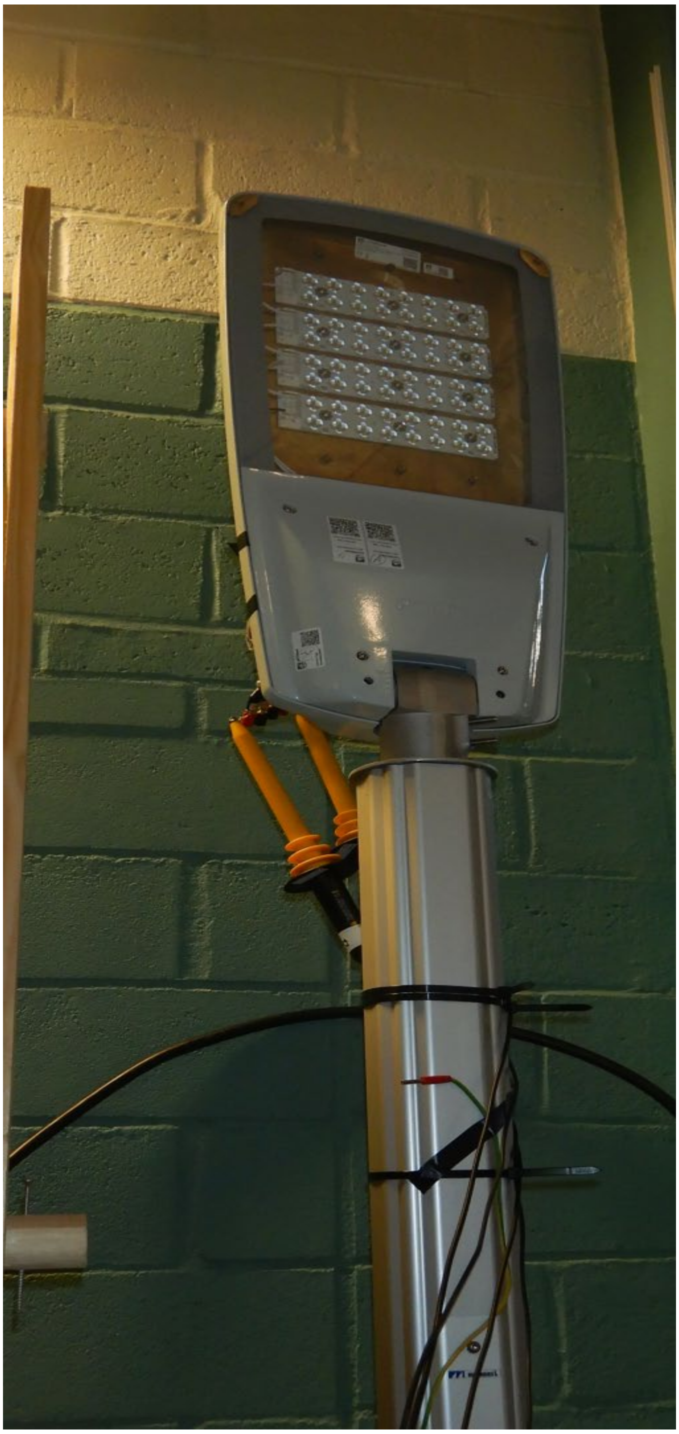

Figure 100. Front view of Lamp1 with aluminium pole. High voltage probes connected to the ports for Line1 (L1), and Neutral1 (N1) at the back of the lamp.

Figure 101. Front of Lamp2. Line2 (L2) and Neutral2 (N2) are connected to the left. There is one PE-screw to the right and also a second PE-screw close to L2 and N2.

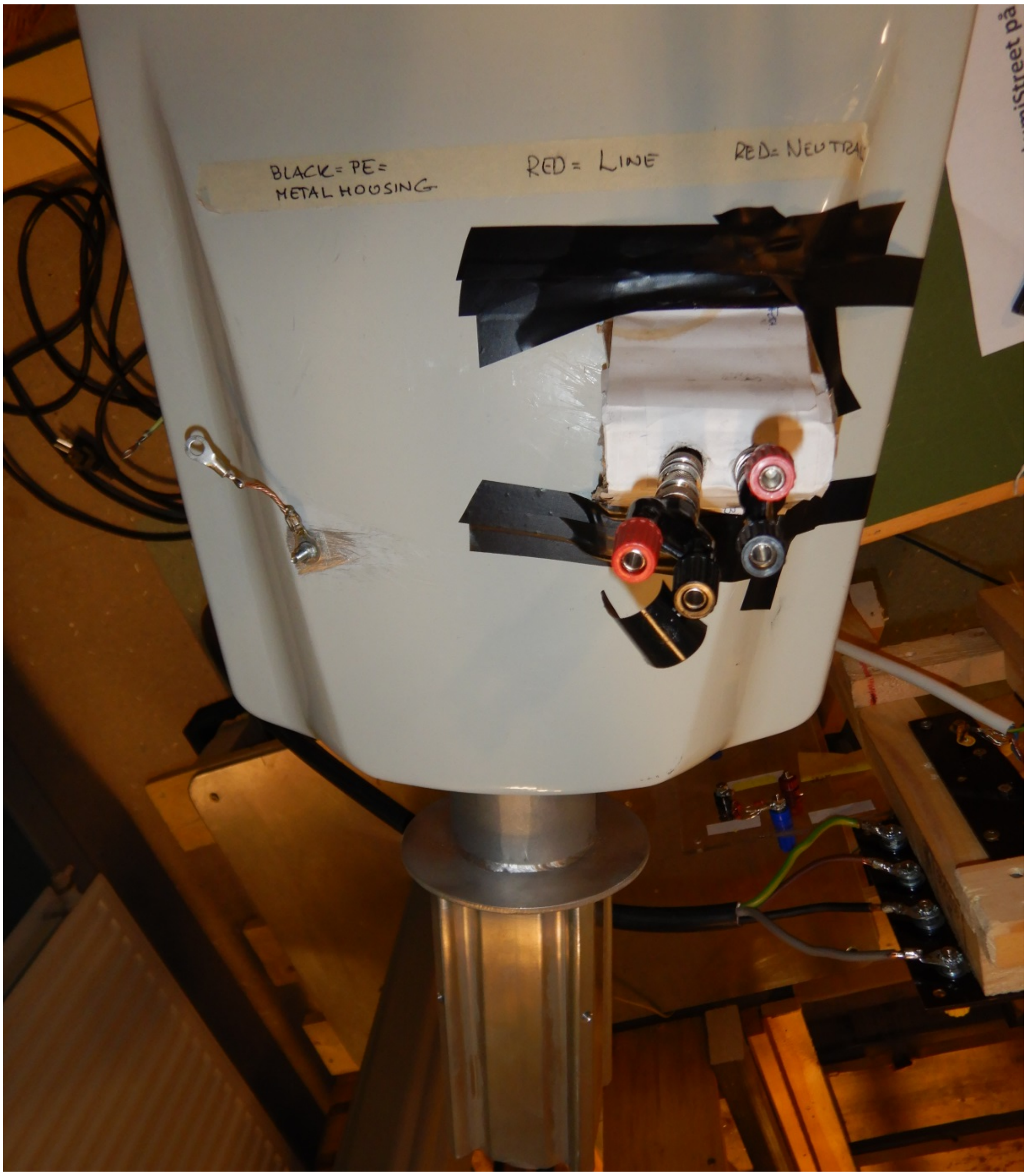

Figure 102. Back of Lamp1, with shielded cables for measuring voltages at Line1, and Neutral1. The input port for injection of direct pulses at the outside of Lamp1 is located to the left, at the lower part of the picture, without isolation, in contact with the metal housing.

Figure 103. 8 m power cable winded before installation inside the lamp-pole.

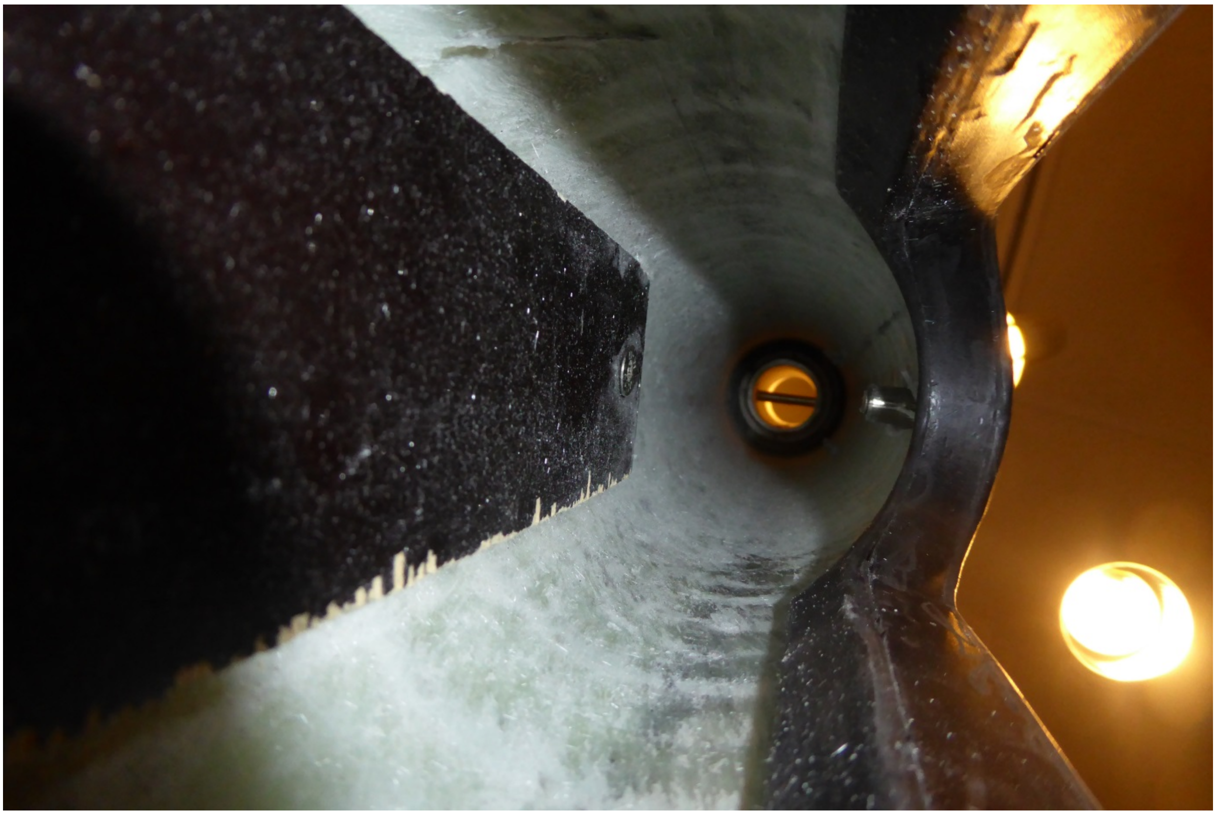

Figure 104. Interior view of a composite pole. To the left: A piece of plywood for coupling gear.

Figure 105. Exterior of a composite pole. Metal lid removed.

Figure 106. The top of a composite pole.

Figure 107. Shielded power cable . The shield is made of relatively sparse web of copper wires, without metal foil.

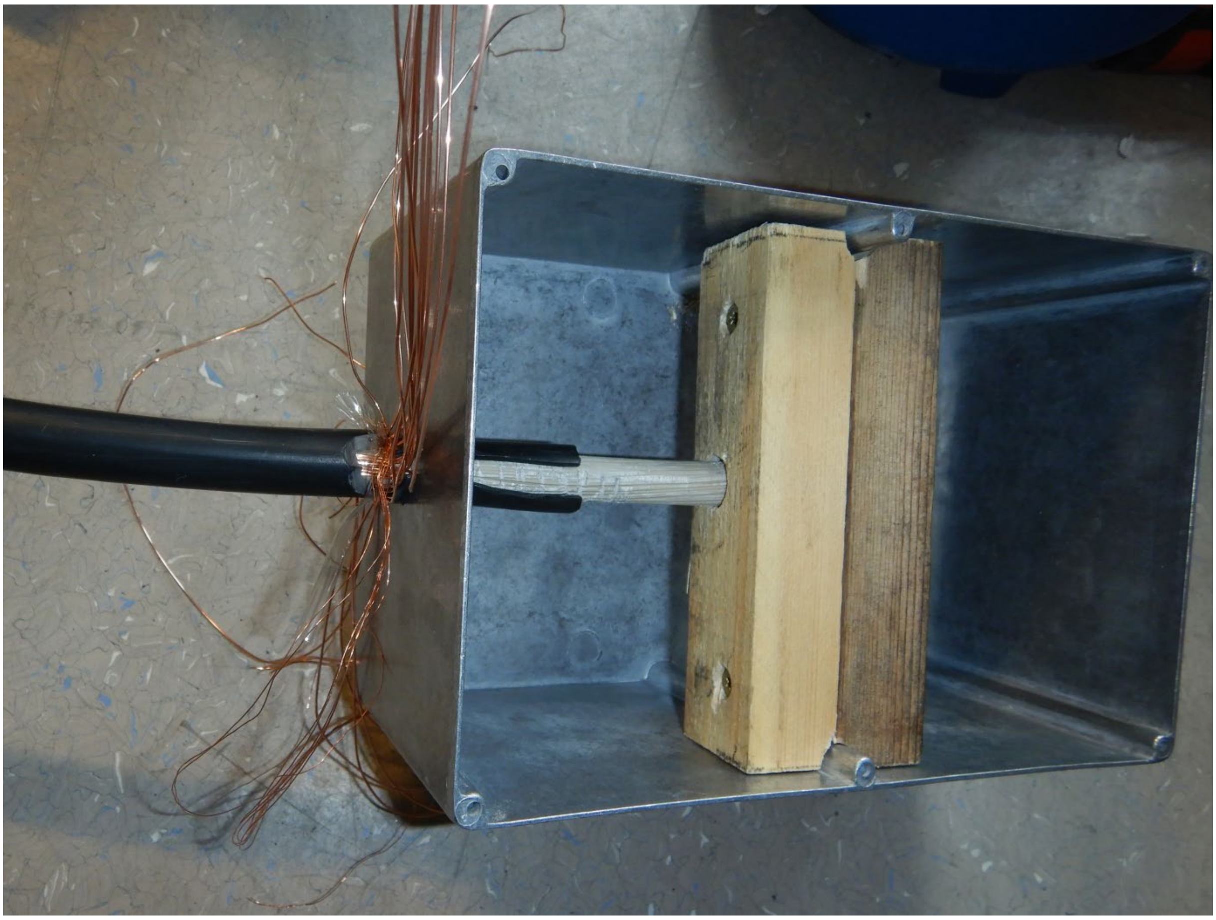

Figure 108. This aluminium box was used for injecting lightning (surge) pulses at the cable shield. The endings of the three cable-conductors (N, L, PE) are locked to the center of the box by two pieces of wood. The cable shield consists of a sparse web of copper wires. These shielding-copper wires were pressed against the outside of the left wall, covered with aluminium foil, and taped against the external surface of the box. The surge pulses were injected by means of pressurized contact against the external surface of the right wall. The openting was covered by an aluminium lid, making a Faraday cage.

Figure 109. The aluminium box with the copper-wire-shield attached to the exterior of the metal wall. The contact point for injection of lightning pulses was located at the exterior surface of the opposite wall. This arrangement was made to secure that the pulses should be injected only at the cable shield without coupling to the inner conndductors (Line, Neutral and PE). High frequencies stay on the exterior surfaces because of the skin effect. A similar Faraday-cage-arrangement was made at the bottom of the lamp poles when the metal lamp poles were tested.

Table 15. LIST OF FIGURES. DATA IDENTIFICATION NUMBERS. CAPTIONS.