Faculdade de Engenharia da Universidade do Porto

FEUP

High Voltage Laboratory: simulation, adjustment and test on electrical insulators

Manuel Angel Saboy Gabiña

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Master in Electrical and Computers Engineering - Energy

Director: Prof. Dr. António Carlos Sepúlveda Machado e Moura

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Resumo

O principal objectivo desta dissertação é a preparação do Laboratório de Alta Tensão da Faculdade de Engenharia da Universidade do Porto com a finalidade de permitir a realização de ensaios de alta tensão, particularmente ensaios ao choque de descargas atmosféricas, de isoladores eléctricos de material orgânico conforme a normativa internacional aplicável e, dar solução aos problemas encontrados no equipamento que foram detectados no começo dos trabalhos no laboratório.

As descargas de origem atmosférica produzem sobretensões nas linhas eléctricas de transporte de energia que podem atingir centenas de milhares de volts, o que causa esforços dieléctricos sob os isoladores e pode pôr em perigo uma operação, normal e com segurança, do equipamento eléctrico das estações e subestações. Os isoladores eléctricos são amplamente utilizados neste tipo de dispositivos, como por exemplo: seccionadores de tensão, terminais de transformadores eléctricos, linhas de transporte em alta tensão, ou, linhas eléctricas em infra-estructuras ferroviárias.

O trabalho é divido em três partes: a primeira parte estabelece os fundamentos teóricos necessários para a compreensão do mesmo. É imprescindível conhecer como são produzidas as descargas atmosféricas e a categoria das sobretensões que são objecto de estudo.

A segunda parte apresenta o trabalho de experimentação feito: introdução ao equipamento do laboratório disponível, simulação do processo, estudo das diferentes possibilidades e solução dos problemas que surgiram, avaliação de riscos para os utilizadores na instalação, princípios estabelecidos pelas normas internacionais, calibração do equipamento de medida e, o ensaio de isoladores eléctricos.

Para concluir, a terceira parte do trabalho mostra os resultados e conclusões obtidas. Os passos a seguir em futuros projectos no Laboratório são também descritos com a finalidade de alcançar um conhecimento mais profundo das altas tensões. Não pode ser esquecido que, neste campo, a experimentação é altamente importante.

Palavras chave: *acoplamento electromagnético, avaliação de riscos, calibração, ensaios de alta tensão ao choque atmosférico, isoladores eléctricos, Laboratório de Alta Tensão, simulação computacional.*

Abstract

The main purpose of this final project is to prepare the High Voltage Laboratory of the Faculty of Engineering of the University of Porto in order to carry out high voltage testing of electrical insulators, specifically lightning over-voltages tests, attending to international standards and solving some practical problems which were found.

These over-voltages can run up to hundreds of thousands of volts, which cause dielectric stresses on insulators and could endanger normal and safe operation in electrical equipment. Electrical insulators are widely used in power station and substation equipment; for example, insulators are used for disconnectors, transformer bushings or condenser bushings; in high voltage transmission lines and distribution lines; or, in traction current lines for railways among other things.

The work is divided into three parts: the first part sets the theoretical fundamentals. It is important to know how lightning occurs and the range of over-voltages which is object of study.

The second part presents the experimental work made: introduction to laboratory equipment available, simulation of the process and study of the different variants and problems found, assessment of possible risks of the equipment for the users, principles established by the International Standards, calibration of the measuring device and test of electrical insulators.

Finally, the third part will show the results and conclusions obtained. The steps for further work are given so that new projects can reach deeper points of knowledge and discover new aspects of high voltage engineering. It should not be forgotten that, in this field, experimentation is highly important.

Keywords: calibration, computer simulation, electrical insulator, electromagnetic coupling, High Voltage Laboratory, High Voltage lightning impulse testing, risk assessment.

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This Master's Thesis is the last step of my graduation and the first one of my professional career. For this reason, at this point of my life, I want to thank my family, friends and mates for all their support, help and encouragement during my life and, especially, during my time at the university. They all are the most important and it would have been not possible to get here without them.

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Abbreviations and symbols

List of abbreviations

AC	Alternating Current
ASINEL	*Asociación de Investigación Industrial Eléctrica*
BRK	Breaker
CMD	Capacitive Mixed Divider
CAD	Computer Aided Design
DSO	Digital Storage Oscilloscope
DC	Direct Current
EMC	Electromagnetic Coupling
EMI	Electromagnetic Interferences
EHV	Extremely High Voltage
HV	High Voltage
HVL	High Voltage Laboratory
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
LI	Lightning Impulse
LV	Low Voltage
MV	Medium Voltage
NATO	North Atlantic Treaty Organisation
r.m.s.	Root Mean Square
SI	Switching Impulse
UHV	Ultra High Voltage
VHV	Very High Voltage

List of symbols

h, h_0	Ambient absolute humidity
A	Amplitude, Area
ω	Angular frequency
b	Atmospheric pressure
t	Atmospheric temperature
C	Capacitance
U_{ch}, U_c	Charge voltage
E_s, U_0	Charge voltage per stage
R_{ch}	Charging resistance
K	Correction factor
B	Clearance limit around the sparking point
z	Conventional deviation
k_1	Correction factor for air density
k_2	Correction factor for humidity
i	Current
η	Efficiency
τ_D	Discharge time constant
p	Disruptive discharge probability
U_{50}	50% disruptive discharge voltage
d	Distance
f	Frequency
R_f	Front resistance
C_g	Generator's High Voltage capacitor
A	Height of the sparking point
k	Humidity correction factor
L	Inductance
N, n	Number of generator stages
E_t	Output voltage
ε_0	Permittivity of free space
V_p	P-percent disruptive discharge voltage
δ	Relative air density
ε_r	Relative static permittivity
R	Resistance
D	Sphere diameter
e	Sphere-gap
S	Sphere-gap spacing
b_0	Standard atmospheric pressure
t_0	Standard atmospheric temperature

L_s	Stray inductance
R_t	Tail resistance
τ	Time Constant
T_c	Time to chopping
T_p	Time to peak
E_0	Total energy stored per stage
j	Unit vector
T_1, T_f	Virtual front time, rise time
O_1	Virtual origin
Up	Voltage peak
T_2, T_t	Virtual time to half-value in the tail
U, u	Voltage

Chapter 1

Introduction

Electrical systems are strongly limited by an important characteristic of electrical energy; its storage is not possible on a large scale and it must be produced and transported to the places where it is required just at the moment.

Production and consumption points are usually far away from each other; therefore it is necessary to resort to high voltage values in order to reduce losses in electrical lines and maximizes the efficiency of the electrical transport system.

Thus, there is a wide range of values used in high voltage systems which are divided into five groups:

- MV (Medium Voltage);
- HV (High Voltage);
- VHV (Very High Voltage);
- EHV (Extremely High Voltage);
- UHV (Ultra High Voltage).

The high voltage values need an appropriate insulation level and the higher the voltage, the higher the cost. The process called Insulation Coordination determines the proper insulation levels of the components in a power system as well as their arrangements so that costs can be substantially reduced.

Insulation structure must withstand voltage and over-voltage stresses to which the system or equipment will be subjected. This area of knowledge requires simulation studies based on mathematical models (scientific modelling) and laboratory testing (tests) to precisely determine and allow for high electric field effects.

Theoretical studies are carried out based on macroscopic or microscopic models.

- Macroscopic modelling is used when voltage, current and electric fields values in equipment must be tested.

- Microscopic (or molecular) modelling is used in order to study how insulators behave under voltage and over-voltage stresses, and, especially, how ageing and dielectric breakdown mechanisms appear.

Experimental studies involve high voltage laboratory testing to measure certain parameters, but outdoor tests are also carried out when it is necessary to check electric equipment in its final place of use.

In short, it is essential to accompany theoretical studies with experimental testing in order to ensure efficient and safe installations.

But a second important feature cannot be forgotten: frequency. A right choice of mathematical models or laboratory tests must be taken into account due to the different kinds of phenomena produced by a wide range of frequencies, from alternating voltages of power frequencies (50 – 60 Hz) to full lightning impulse voltages (in the order of hundreds of kHz or even MHz).

Each model is studied and just accepted for a certain range of frequencies, considering the right hypothesis. Satisfying the requirements on the validity domain insures reliability and quality of results obtained.

Chapter 2

Theoretical fundamentals

Electrical insulators of organic material can be affected by lightning and must withstand high voltage values that are present in it. An overview of this phenomenon and their consequences are explained in this chapter. It aims to set the theoretical fundamentals and give an introduction in order to carry out other studies in this field. If further information is needed, books and articles shown in the references can be helpful.

Not a few industrial high voltage installations are placed in outdoor locations. Thus, electrical equipments are exposed to temperature and humidity changes, wind, rain and even occasionally lightning which can cause many problems in the equipments.

This work is focused on lightning impulses and they are tested at the High Voltage Laboratory. They may be caused by the next three circumstances:

1. A lightning stroke in the vicinity of a line or a substation.
2. A lightning stroke in the tower or in the ground wire of an overhead line.
3. A direct lightning stroke in the line.

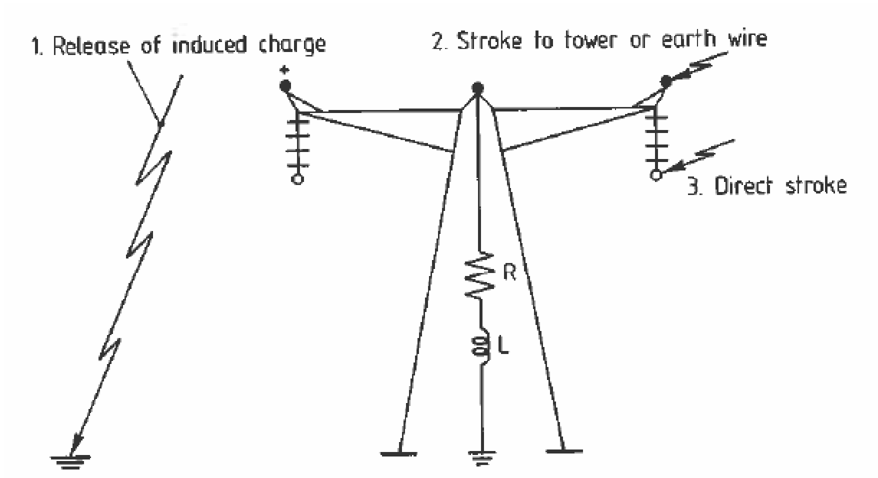


Figure 2.1 - Causes of lightning over-voltages [4].

It is necessary to study how electrical equipments behave under this kind of atmospheric phenomenon in order to establish the necessary safety level so that a certain operational capacity do not be lost.

2.1 - Lightning and thunderclouds

2.1.1 -Lightning

Lightning over-voltages are the main cause of many breakdowns that occur in electrical equipment from stations and substations. Thus, the problem must be, therefore studied in depth to understand how lightning works and the protections that may be designed in order to minimize its effects and electrical breakdown, which might be still more costly than a proper high-voltage insulation.

As defined by Uman [3], lightning is a transient, high-current electric discharge whose path length is generally measured in kilometres. Lightning occurs when some region of the atmosphere attains an electric charge sufficiently large that the electric fields associated with the charge cause electrical breakdown of the air. The most common producer of lightning is the thundercloud, known as cumulonimbus.

However, lightning also occurs in snowstorms, sandstorms, and in the clouds over erupting volcanoes. It can take place entirely within a cloud (intracloud or cloud discharges), between two clouds (cloud-to-cloud discharges), between a cloud and the earth (cloud-to-ground or ground discharges), or between a cloud and the surrounding air (air discharges).

2.1.2 -Thunderclouds: definition and origin

The thundercloud and its electric charges are the sources of lightning. Thunderclouds are formed in an atmosphere containing cold, dense air aloft, and warm moist air at lower levels. The warm air at low levels rises in strong updrafts when heated by the Sun, carrying water steam into the sky to form clouds, and the cold air aloft descends. When the hot air mingles comes into contact with colder air, the moisture condenses into water droplets. Clouds are created when these water droplets become visible. The droplets increase in size as the cloud grows and eventually become so heavy that they fall as rain. Thunderclouds are large, anvil-shaped masses that can stretch miles across at the base, and reach 12 km or more into the atmosphere.

Such atmospheric conditions occur, for example, when cold polar air masses overrun regions of warmer air or when the earth is strongly heated by the Sun and transfers its heat to the air of the lower atmosphere.

A comparison of various sizes of convective clouds that produce lightning discharges is shown in figure 2.2. Thunderclouds range in size from small clouds, which occur in the semitropics and in which the temperature may everywhere be above freezing, to giant electrical storms, which may have a vertical extent exceeding 20 km.

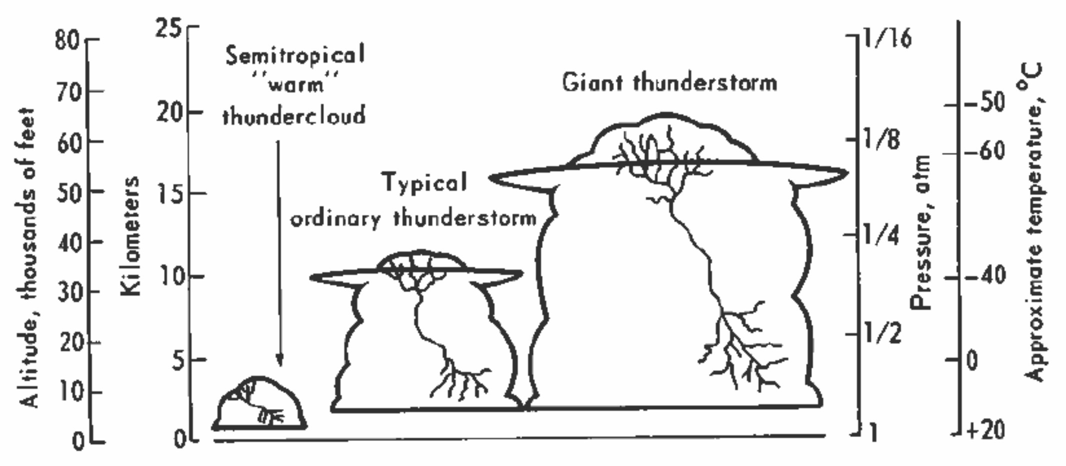


Figure 2.2 - Comparison of various sizes of convective clouds that produce lightning discharges [3].

The height of a typical thundercloud is perhaps 8 to 12 km, although, strictly speaking, typical values can only be presented for a given geographic location. Within a typical thundercloud, there is a turmoil of wind, water, and ice in presence of a gravitational field and a temperature gradient. Out of the interaction of these elements, emerge the charged regions of the thundercloud. There is not an agreement about the way or ways in that it occurs, the exact arrangement of charge in the clouds has not been yet fully understood and there are different hypothesis.

One of the models hypothesizes that the upper part of the thundercloud carries a preponderance of strong positive charge while the lower part of the cloud carries a strong negative net charge. Thus, the main charge structure of the thundercloud is an electric dipole. The charged regions of this dipole are of the order of kilometres in diameter. In addition to the main cloud charges, there may be a small pocket of positive charge at the base of the thundercloud, that is, a weak positive charge at the lower regions. A representation of this theory is shown in figure 2.3 below.

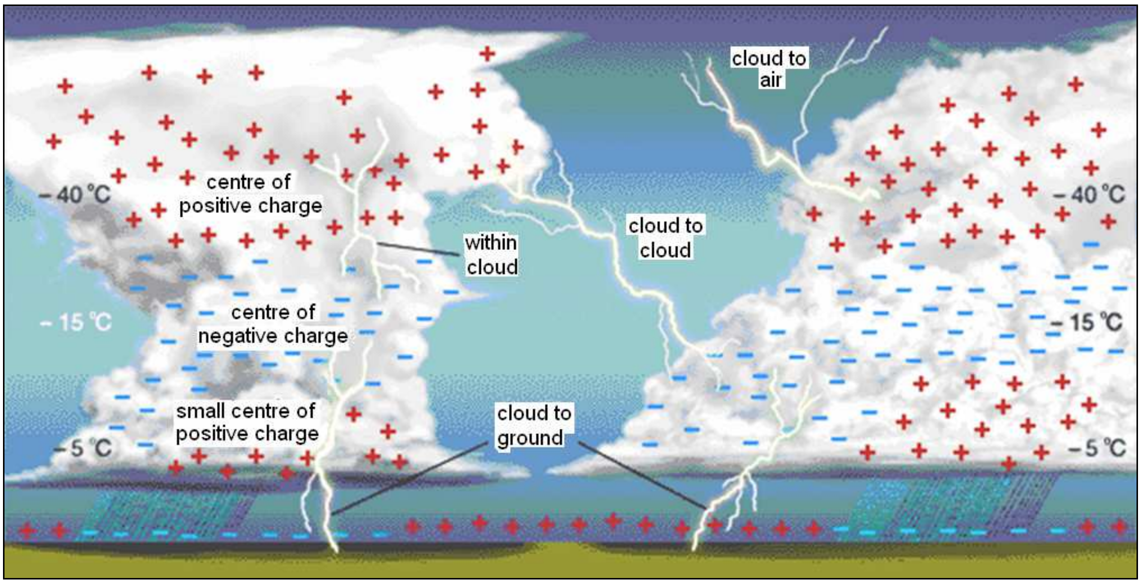


Figure 2.3 -Thunderhead. Probable distribution in a thundercloud (cumulonimbus) mostly accepted [©Encyclopaedia Britannica, Inc. (1999)].

This theory is based on the idea that heavier and larger particles tend to gain a negative charge, while lighter particles tend to gain a positive charge in collisions. Then, charged particles become separated due to differences in size and density, moving to certain levels of the cloud system.

The amount of total charge and polarity is also affected by the temperature in the layer of the cloud, the content of the water particles, and several other conditions.

This theory is the most widely accepted, although it is just one of many which attempt to explain the properties of the charge built-up in electrical storms. As it was mentioned above, there is not an universal agreement that explains the phenomena.

To make possible a lightning discharge, it is necessary that an electrical path is created and permits electric current to pass through. Since opposite charges attract, when two regions of strong and opposite charge are present, they will attract and exchange electrons. When they are separated and cannot exchange electrons through contact, they must exchange charge through a medium. In thunderhead systems, the air serves as the medium between the two regions. Since air is not conductive, electric current cannot easily pass through it and, in order for the regions to exchange electrons, the air molecules must be arranged so that electrons can pass through it.

The process of ionization performs this procedure. It is a physical process of converting an atom or molecule into an ion by adding or removing charged particles such as electrons or other ions. This happens when a large amount of charged particles attempts to pass through the neutral medium, causing the electrons and protons of the medium to separate in order to create a path between the two regions on which charge can flow.

Then, lightning occurs due to the extreme difference of charge between two regions. When the difference of charge reaches a certain point, air between both regions becomes ionized, that is, the air surround breaks down and lightning occurs. When that phenomenon happens, an extreme amount of energy is used up and is converted into light, heat and sound, which is seen as lightning and heard as thunder.

In conclusion, lightning is a form of electrical breakdown of ambient air over extreme distances due to the difference of charge between them, and, as shown in figure 2.3, there are different kinds of lightning discharge that are listed below:

a.) cloud to air;
b.) cloud to cloud;
c.) within cloud;
d.) cloud to ground, with negative and positive charge on earth's surface.

The most frequently occurring form of lightning is the intracloud discharge; however, this report only concerns of ground discharges because they are the ones that affect electric power lines and electrical equipment in stations and substations.

2.1.3 -The lightning stroke

Most of thunderclouds are negatively charged, as defined by Kreuger [4]. The potential relative to earth may amount to several hundreds of megavolts (MV).

Lightning is initiated by discharges within the cloud, from which a leader reaches down to earth in steps of about 30 meters. This leader is called stepped leader and it reaches the earth in about 10 ms. Steps of the leader are directed each time in a different direction and, thus, the zigzag shape of the lightning is built up.

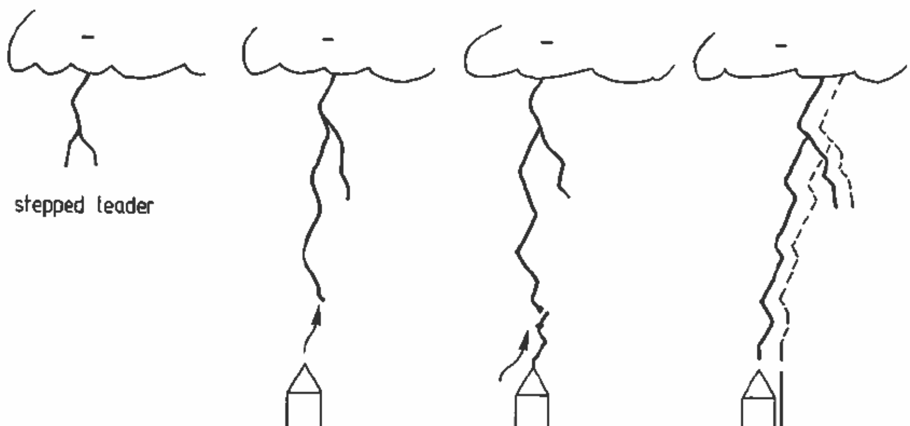
The path followed by the leader is often two to three times as long as the distance from cloud to earth. From time to time the leader is forked, so that the typical branched shape of lightning is formed. And, for this reason, cloud-to-ground lightning is sometimes referred to as streaked or forked lightning.

The light of the leader is faint and can not be observed with the naked eye. Its current is restricted, in the order of 100 A.

When the leader approaches earth, earth's electric field increases a lot and a positive leader travels upwards, preferably from a pointed object. After making contact, a travelling wave moves upwards. The front of this wave can travel with values as far as half the velocity of light. This is accompanied by intense light so that the visible stage of lightning does not strike downwards, as is commonly thought, but upwards. On its way upwards the branches are brightly illuminated. This takes about 50 μs and the current level is in the order of 20 to 100 kA.

But a cloud-to-ground lightning discharge is made up of one or more intermittent partial discharges. Uman [3] calls the total discharge, whose time duration is of the order of 0.2 seconds, a flash; and he calls each component discharge, whose luminous phase is measured in tenths of milliseconds, a stroke.

These discharges, strokes, are repeated at intervals of about 40 to 50 ms, usually 3 to 4 times but 10 to 12 times are possible. The repeated discharges follow the path of the first discharge. This manifold repetition of lightning is too fast for the naked eye, so that lightning is seen by us as one heavy flash.



(a) (b) (c) (d)

Figure 2.4 – Lightning [4].

a.) Stepped leader, the route of the steps determines the typical shape of lightning.
b.) A positive leader meets the stepped leader.
c.) A travelling wave moves upwards at about half the velocity of light; the discharge thus takes place in about 50 μs.
d.) Several repetitions may take place at intervals of about 50 ms.

Because of the heavy currents in a narrow channel, the temperature rises to about 20000ºC, and it is in the order of temperature of the surface of the Sun. The air expands in a short time and an explosion occurs that it is known as the sound of thunder.

Data for a normal cloud-to-ground lightning discharge bringing negative charge to earth are given in table 2.1. The values listed are intended to convey a rough feeling for the various physical parameters of lightning. No great accuracy is claimed since the results of different investigators are often not in good agreement. These values may, in fact, depend on the particular environment in which the lightning discharge is generated. The choice of some of the entries in the table is arbitrary.

Table 2.1 — Data concerning cloud-to-ground lightning discharge [3]

	Minimum	Representative	Maximum
Stepped leader			
Length of step [m]	3	50	200
Time interval between steps [μs]	30	50	125
Average velocity of propagation of stepped leader [m/s]	1.0×10^5	1.5×10^5	2.6×10^6
Charge deposited on stepped-leader channel [C]	3	5	20
Dart leader			
Velocity of propagation [m/s]	1.0×10^6	2.0×10^6	2.1×10^7
Charge deposited on dart-leader channel [C]	0.2	1	6
Return stroke			
Velocity of propagation [m/s]	2.0×10^7	5.0×10^7	1.4×10^8
Current rate of increase [kA/μs]	< 1	10	> 80
Time to peak current [μs]	< 1	2	30
Peak current [kA]		10 to 20	110
Time to half of peak current [μs]	10	40	250
Charge transferred excluding continuing current [C]	0.2	2.5	20
Channel length [km]	2	5	14
Lightning flash			
Number of strokes per flash	1	3 to 4	26
Time interval between strokes in absence of continuing current [ms]	3	40	100
Time duration of flash [s]	10^{-2}	0.2	2
Charge transferred including continuing current [C]	3	25	90

Energy dissipation in lightning flashes was studied by Cooray [7] at the University of Uppsala (Sweden). The amounts of energy dissipation in different stages of ground flashes were estimated by electrostatic energy considerations. Thus, energy present in return strokes and ground flashes were measured and it can be described as follows.

A typical stepped leader-return stroke process that neutralizes 5 C of charge dissipates about 5.5×10^8 J. Of this energy about 3.5×10^8 J dissipates in the return stroke stage and 2×10^8 J in the leader stage. A unit length of the first return stroke channel dissipates about 7×10^4 J/m.

A typical dart leader-return stroke process that neutralizes 1 C of charge dissipates about 12×10^7 J. Of this energy 4×10^7 J dissipates in the return stroke stage and 8×10^7 J in the dart leader stage. A unit length of the subsequent return stroke channel dissipates about 8×10^3 J/m.

A typical ground flash with four strokes dissipates about 9.5×10^8 J. Of this energy 4.5×10^8 J dissipates in the leader stages, and 5×10^8 J dissipates in the return stroke stages.

In the analysis, the following conclusions were also obtained:

- The charge that maximizes the energy dissipation during the leader stage depends on the charge density of the cloud. For the values of cloud charge densities measured in experimental investigations this optimum charge is about 5 C.
- For a given amount of charge neutralization, a cloud flash dissipates more energy than a ground flash.

2.2 - Keraunic level

There are specific areas in the world, which are particularly affected by lightning. Its origin is explained by means of three factors:

- topological factors;
- geological factors;
- air ion concentration.

In some regions, thunder clouds (cumulonimbus) can be formed more easily due to humidity and temperature conditions. Local factors as trees, some constructions, chimneys, etc. also increase the incidence of lightning strikes. And, air conductivity can be higher in some areas due to air ion concentration.

In order to describe the lightning and thunder activity in a region, usually, keraunic level is used. It is defined as the number of days during one year where thunder can be heard in a given area. Keraunic level, in some areas, will vary a lot and it is a long term average which establish a statistical data base with information for different regions. This parameter is very useful in order to design electrical installations and its protection system.

Keraunic level varies according to the part of the world; reference values are given below:

Table 2.2 — Reference values for keraunic level in a year

Temperate regions of the world	10 to 30
Alps and Pyrenees (Europe)	30
Florida (the USA)	100
African rainforest and Indonesia	180

Moreover, there are several experimental formulas which try to establish a connection between certain parameters and keraunic level, such as the annual number of lightning flashes hitting one square kilometre (km^2) of ground and the annual number of lightning flashes and the high of an object (pole, tower, chimney, etc.); but there is not any global accepted standard yet.

2.3 - Over-voltages

In some situations, electrical equipment can suffer over-voltages during its service life due to lightning or a failure in other elements of power distribution systems. For example, power systems which are not grounded are highly susceptible to over-voltage during a phase to ground fault. These over-voltages may produce arcs or sparks which reduce the safe conditions. Therefore it is necessary to properly define the voltages and over-voltages which can appear in an electrical installation.

The selection of the dielectric strength of equipment on relation to the voltages which can appear on the system is called insulation coordination. The equipment is intended for that voltage taking into account the service environment and the characteristics of the available protective devices.

The International Electrotechnical Commission (IEC) has established a number of standardized insulation levels. Moreover, IEC standards state a series of test requirements, so that manufacturers and users of equipment can make standardized agreements on the characteristics of a network component.

2.3.1 -Definition of over-voltage

There are three types of over-voltage, depending on its origin, that affect the design of insulation constructions and determine the requirements for over-voltage tests:

1. AC over-voltages.
2. Switching impulses.
3. Lightning impulses.

They cause dielectric stresses which can be simulated with the suitable computational systems. Then, laboratory testing is made in order to know how electrical components and equipments in stations and substations behave under such over-voltages.

Over-voltage is any voltage between one phase conductor and earth or between phase conductors having a peak value exceeding the corresponding peak of the highest voltage for equipment.

For any insulation configuration, an over-voltage is any voltage across its terminals higher than the peak of the power-frequency voltage existing between them when all phase terminals of the equipments are energized with the highest voltage for equipment.

2.3.2 -Classification of voltages and over-voltages

According to their shape and duration, voltages and over-voltages are divided in the following classes, as defined by the IEC 60071-1 [34]:

a.) continuous voltage.
b.) temporary over-voltage.
c.) transient over-voltage.
d.) Combined over-voltage.

A continuous voltage is a power-frequency voltage. A temporary over-voltage is a power frequency over-voltage of relatively long duration, and, a transient over-voltage is a short-duration over-voltage of a few milliseconds or less, oscillatory or non-oscillatory, and usually highly damped, as defined by the international standard [34].

In figure 2.5 below, shapes of stressing continuous voltages and temporary over-voltages are shown. Both kinds of stresses are designed as low frequency stresses. For temporary over-voltage, the over-voltage may be undamped or weakly damped. In some cases its frequency may be several times smaller or higher than power frequency.

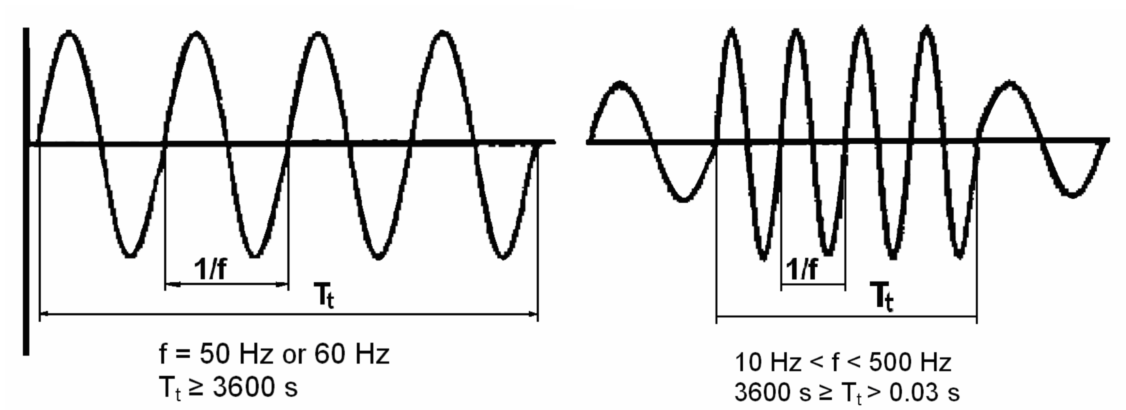


Figure 2.5 -Shapes of stressing continuous voltages (left) and temporary over-voltages (right).

Transient over-voltages may be immediately followed by temporary over-voltages. In such cases the two over-voltages are considered as separate events. Transient over-voltages are divided into:

- slow-front over-voltage. Transient over-voltage with time to peak 20 μs < Tp ≤ 20 μs, and tail duration T2 ≤ 20 ms.

- fast-front over-voltage. Transient over-voltage with time to peak 0.1 μs < T1 ≤ 20 μs, and tail duration T2 < 300 μs.

- very-fast-front over-voltage. Transient over-voltage with time to peak Tf ≤ 0.1 μs, total duration < 3 ms, and with superimposed oscillations at frequency 30 kHz < f < 100 MHz.

In next figure 2.6 it is possible to see the shapes of these three classes of transient over-voltages.

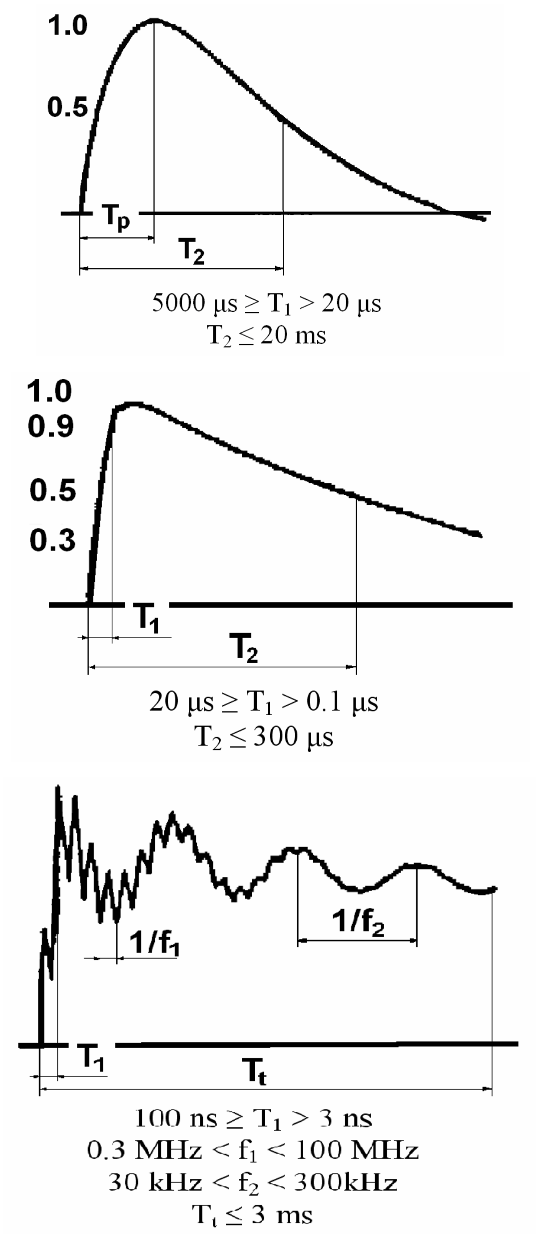


Figure 2.6 - Shapes of stressing transient over-voltages: slow-front (up), fast-front (middle) and very-fast-front (down).

A combined over-voltage consists of two voltage components simultaneously applied between each of the two phase terminals of a phase-to-phase (or longitudinal) insulation and earth. It is classified by the component of higher peak value (temporary, slow-front, fast-front or very-fast-front over-voltage).

In order to test the equipment of electric installations, the following voltage shapes are standardized [34]:

a.) The standard short-duration power-frequency voltage. It is a sinusoidal voltage with frequency between 48 Hz and 62 Hz, and duration of 60 s.

b.) The standard switching impulse. It is an impulse voltage having a time to peak of 250 μs and a time to half-value of 2500 μs.

c.) The standard lightning impulse. It is an impulse voltage having a front time of 1.2 μs and a time to half-value in the tail of 50 μs.

d.) The standard combined switching impulse. It is a combined impulse voltage having two components of equal peak value and opposite polarity (positive and negative).

This is a general introduction about voltages and over-voltages that may affect to electrical installations. From now on, this report only deals about lightning voltage impulses.

2.3.3 -Insulation Coordination

Sometimes breakdown is inevitable, so it should take place in a spark gap or a surge arrester instead of damage a more important network component.

As defined by the International Standard IEC 60071-1, the procedure for insulation coordination consists of the selection of a set of standard withstand voltages (insulation level of the various components in the network) which characterize the insulation of the equipment, and also the proper choice of protection equipment such as spark gaps and surge arresters.

It is recommended that the selected withstand voltages should be associated with the highest voltage for equipment. Anyhow, this association is for insulation coordination purposes only. The requirements for human safety are not covered by this Standard.

Lightning (or switching) impulse protective level is the maximum permissible peak voltage value on the terminals of a protective device subjected to lightning (or switching) impulses under specific conditions [34].

2.4 - Impulse voltage

The difficulty to simulate lightning over-voltages resides in the matter that its waveform and amplitude are highly changing. Several different kinds of impulses were used in Europe or the United States of America for testing purposes before there was an international standardization. More information about the current international standard for high voltage tests can be found in chapter 5.

The origin of an impulse voltage may be due to two possible causes, as defined by Kreuger [4]:

- direct stroke; or,
- lightning stroke in a tower.

If a high voltage line is struck by lightning, extremely high voltage waves appear in the line and move along it. This situation is a direct stroke and can endanger the equipment in the substations. Lightning arresters are applied at the entrance of the substation in order to protect the equipment, but electrical insulators of the power lines are also subjected to the high voltage waves, which can easily be as high as 1 MV. Therefore, it is important to know how these impulse voltages are to design insulators that withstand without deterioration not just its nominal voltage, but also high over-voltages of short duration. A flashover arc can be formed between two metal points, such as a power line and the metallic structure of its tower, which may stress the insulator (see figures 2.1 and 2.7).

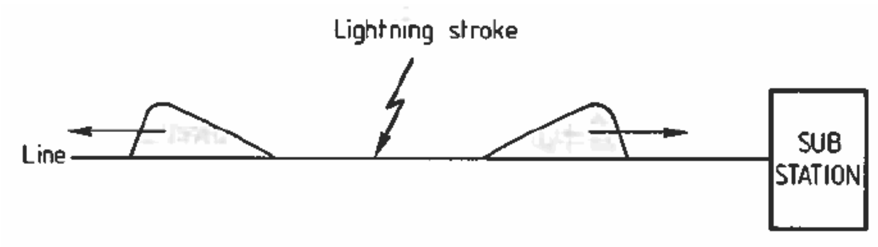


Figure 2.7 - High voltage waves caused by direct lightning stroke on a high voltage line [4].

The shape of this voltage wave shown in figure 2.7 is determined by the shape of the lightning current. This shape varies considerably from stroke to stroke, but, generally, the current reaches its peak in 1 to 5μs and falls down to a low value in about 50 to 100μs. This shape can be described as:

$$i = i_s \cdot \left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}} \right) \tag{2.1}$$

The resulting voltage wave has the shame shape and produces the travelling waves as shown in figure 2.7 above.

$$u(t) = A \cdot \left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}} \right) \tag{2.2}$$

Another mechanism that causes voltage waves is related to a lightning stroke in a tower, or in the earth conductors which protect the line. The lightning current has now to pass the impedance $(R + j \cdot \omega \cdot L)$ of the tower, as shown in figure 2.8 below.

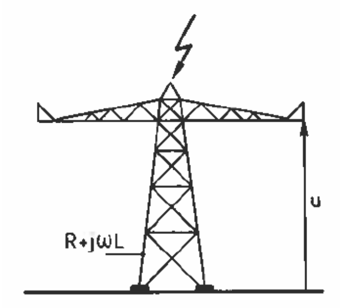


Figure 2.8 - Tower struck by lightning [4].

The self-induction *L* is determined by the size of the tower and is in the order of 20µH and, the resistance *R* is mainly determined by the earth resistance of the foundations; 10 Ω is approximately a good value for it.

When it happens, an over-voltage *U* is caused by the lightning current passing $\left(R+j\cdot\omega\cdot L\right)$. The voltage between the top of the tower and earth can be calculated by means of the next equation:

$$U=i_s\cdot\left(R-\frac{L}{\tau_2}\right)\cdot e^{-\frac{t}{\tau_2}}-i_s\cdot\left(R-\frac{L}{\tau_1}\right)\cdot e^{-\frac{t}{\tau_1}} \quad (2.3)$$

Inserting usual values like shown in table 2.3, the equation (2.3) gives a peak voltage of 1 MV.

Table 2.3 — Usual values for an impulse voltage

i_s	50 kA
τ_1	1 µs
τ_2	50 µs

The top of the tower reaches a higher potential than the line and flashover occurs from tower to line. Electrical insulators must again withstand it without deterioration as described above. This is a peculiar phenomenon because flashover takes place from the "earthed" electrical tower to the power line as shown in next figure 2.9.

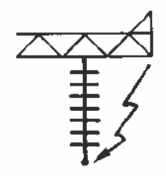


Figure 2.9 - Flashover from tower to power line due to lightning stroke in a tower [4].

Consequently, a travelling wave enters the line in the way shown in figure 2.7 causing the same consequences.

Chapter 3

Generation of High Voltage impulses and Laboratory Equipment

The purpose of the High Voltage Laboratory of the Faculty of Engineering is to test electrical components and equipments which may be stressed by lightning impulse voltages that can reach hundreds of kilovolts or even more.

Specifically, an evaluation of the effects of such over-voltages on insulators will permit to develop new electrical equipments, insulator materials, and, in general, to study high voltage phenomena.

The laboratory was only used to carry out tests on electrical indoor and outdoor post insulators, but other electrical equipment, such as high voltage cables, can also be tested doing the appropriate changes established by international standards.

Impulse voltages are generated by an impulse generator based on Marx Impulse Generator that will be described in this chapter.

3.1 - Erwin Marx: historical note

Erwin Otto Marx (1893-1980) was a German electrical engineer who first described a system to generate impulse voltages. It was in 1923 and, nowadays, the Marx Impulse Generator is widely used when high impulse voltage values are needed for laboratory testing purposes.

At the 3rd IEEE Pulsed Power Conference (June 1981), the Erwin Marx Award was created and dedicated to the memory of Professor Marx and his concept of the Cascade Impulse Voltage Generator.

Nowadays, the IEEE Erwin Marx Award, established in 1997, recognizes outstanding technical achievements in pulsed power engineering, science and technology by an individual over an extended period of time. This prize acknowledges the importance of Professor Erwin Marx and is given biennially to individuals who have made outstanding technical contributions to pulsed power technology for at least ten years.

3.2 - Marx impulse generator

The first Impulse Generator was developed by Marx at the beginning of the 20th century. This system permits to test elements of power lines under a range of over-voltages which might occur during a product's service life due to lightning or transient voltage phenomena resulting from equipment association with power distribution systems.

Basically, it consists of a stack of capacitors that are charged in parallel through charging resistors and discharged in series through discharging resistors (front and tail resistors). It is possible by means of sphere-gaps: at certain instant, when the disruptive discharge voltage is achieved in the air between the sparking points of the spheres, a flashover arc occurs and capacitors become connected in series through the short circuit.

This is probably the most common way of generating a high voltage impulse for laboratory testing because capacitors are charged in parallel and, when they connect in series, the addition of the voltages permits to reach very high voltage values, that is, the power supply used to charge all the capacitors is multiplied by means of the use of sphere-gaps.

The operation principle of the Marx Impulse Generator is explained in this section, first as a simplified generator and then as a multistage generator, because the Impulse Test System of the High Voltage Laboratory is a Marx Generator with five stages.

3.2.1 -Simplified circuit

In figure 3.1, the simplified circuit is depicted in order to explain the basic operation of an impulse generator. The design of the Impulse Test System of the High Voltage Laboratory is based in this circuit.

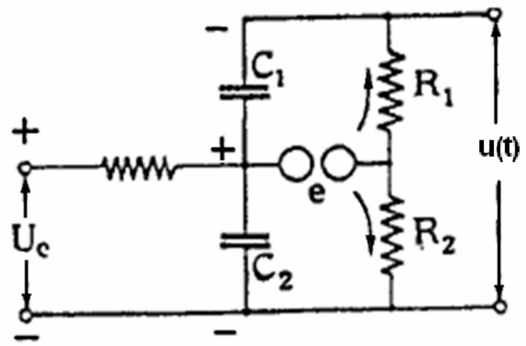


Figure 3.1 - Simplified impulse generator [1].

Capacitors C_1 and C_2 are charged in parallel by the DC power supply U_c. These capacitors are called discharge capacitances and they store the energy of the impulse generator. The group C_1, R_1 and R_2 is connected in parallel regarding to the capacitor C_2 as far as the sphere-gap is not triggered. The voltages of C_1, C_2 and the sphere-gap are zero at the beginning. When the charging process starts, the voltage at these elements start increasing, and, at a certain moment, the air between both spheres breaks down and two new circuits appear. Thus, capacitors C_1 and C_2 are discharged through R_1 and R_2, respectively.

The capacitance C_1 discharges itself through R_1 with a time constant τ_1:

$$\tau_1 = R_1 \cdot C_1 \tag{3.1}$$

And, the capacitance C_2 discharges itself through R_2 with a time constant τ_2:

$$\tau_2 = R_2 \cdot C_2 \tag{3.2}$$

In this process, a double exponential wave is generated. The output voltage *u(t)* results from the subtraction of both exponential curves due to the discharges of C_1 and C_2 as shown in figure 3.2.

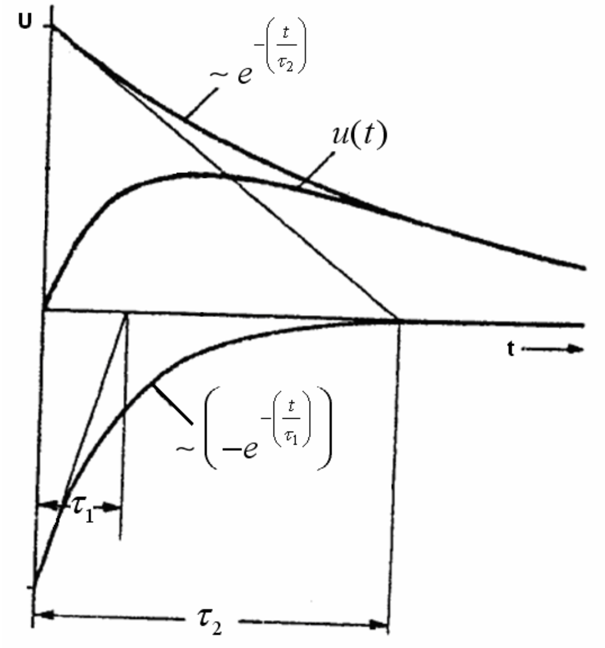


Figure 3.2 - Double exponential curve as generated by the impulse generator showed in figure 3.1 [1].

These two charge displacements cause a voltage surge of the shape:

$$u(t) = A \cdot \left(e^{-\frac{t}{\tau_2}} - e^{-\frac{t}{\tau_1}} \right) \tag{3.3}$$

The output voltage *u(t)* depends on the charging voltage U_c (showed in the equation (3.3) as *A*) and, time constants τ_1 and τ_2 that affect to rise and tail time respectively and only depend on values of R_1-C_1 and R_2-C_2.

The international standard (see chapter 5) defines the impulse voltage as a biexponential wave with 1.2µs of front time and 50µs of time to half value.

The time constants τ_1 and τ_2 bear a certain relationship to the front and half-value times, which have to be computed for every wave shape. For the 1.2/50µs wave, the relations are:

$$T_f = 2.96 \cdot \tau_1 \tag{3.4}$$

$$T_t = 0.73 \cdot \tau_2 \tag{3.5}$$

where, T_f is the front time and T_t is the time to half value.

With values for the time constants: τ_1 = 68 µs and τ_2 = 0.4 µs, T_f and T_t satisfy the requirements established by the international standard and discharge resistors (front and tail resistors) have to be set accordingly. Thus, a waveform as shown in figure 3.3 is obtained. U_p is the maximum output voltage, i.e., the peak voltage, and T_p is the time to peak voltage.

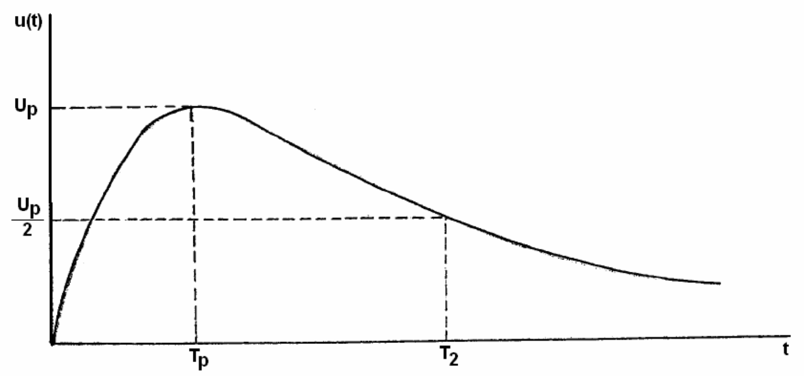


Figure 3.3 - Approximate wave shape of lightning impulse used in laboratory testing [1].

A simplified impulse generator according to the circuit showed in figure 3.1 is used for impulse voltages up to 100-200kV. For higher voltages, the multistage Marx generator is used.

3.2.2 -Multistage generators

As written above, the Impulse Test System of the High Voltage Laboratory is a Marx Generator with five stages. The analysis of this multistage system gives an introduction to point 3.3 that shows all the parts of the Laboratory in detail including the impulse generator.

Figure 3.4 shows the multistage impulse generator circuit. Surprisingly high voltages can be generated with this circuit.

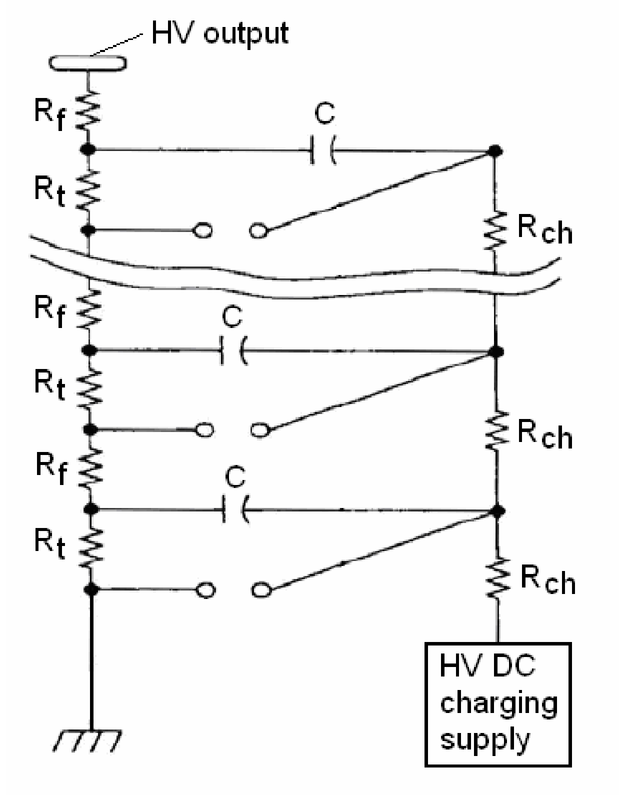


Figure 3.4 - Multistage impulse generator [11].

As described by Kreuger [4], the charging resistors R_{ch} are needed for charging the generator. The front and tail discharge resistors are R_f and R_t, respectively, may be changed in order to adjust the front time and the time to half value in the generator according to the Standard (see chapter 5).

Sphere-gaps are placed between stages. The discharge capacitors C are charged in parallel and discharged in series, what occurs when sphere-gaps are fired.

When the first sphere-gap is fired, the others follow and a voltage $(n \cdot U_c)$ is generated in the output terminal; where n is the number of stages and U_c is the charging voltage and, consequently, the voltage between capacitor's terminals of any stage at the end of the charging process.

3.3 - Laboratory equipment

In this section, equipment and operating information of the High Voltage Laboratory is described in order to familiarize personnel with the set-up and operation. The main characteristics of the equipment are described. Further information is available in manuals of the equipment when required.

The Impulse Test System of the Laboratory is the Hipotronics Impulse Generator Model IG 500-12.5 and is designed for simulating lightning or transient voltage phenomena resulting from equipment association with power distribution systems as required by IEEE and IEC international standards. This generator is designed to operate with a charging voltage of 100kV per stage and an energy rating of 12.5kJ per stage.

The need for components which will reliably withstand short duration over-voltage waveforms demands that simple and safe lightning simulators be available. This test system includes: a control console, high voltage power supply, capacitor bank with switching arrangement, capacitive mixed divider and oscillographic monitoring system.

Note:

Equipment user's guides must be read carefully before starting. This equipment employs voltages which are dangerous and may be fatal if contacted by operating personnel. Extreme caution shall be exercised when working with equipment. Never approach or touch a potentially live high voltage circuit without solidly connecting an appropriate ground conductor first.

3.3.1 -General description

The multiplier circuit of Marx has a predefined number of stages. Concretely, the generator of the High Voltage Laboratory has 5 stages and is shown in figure 3.5 below. Each stage is made up of a capacitance, a charging resistor, front resistor and tail resistor.

Figure 3.5 - Impulse generator

Figure 3.6 shows the electrical circuit of the Impulse Test System based on the circuit shown in the previous section. It is a generator with 5 stages and with the most important components, such as the high voltage charging supply, the trigger generator and the motor drive mechanism used to vary the sphere-gap spacing.

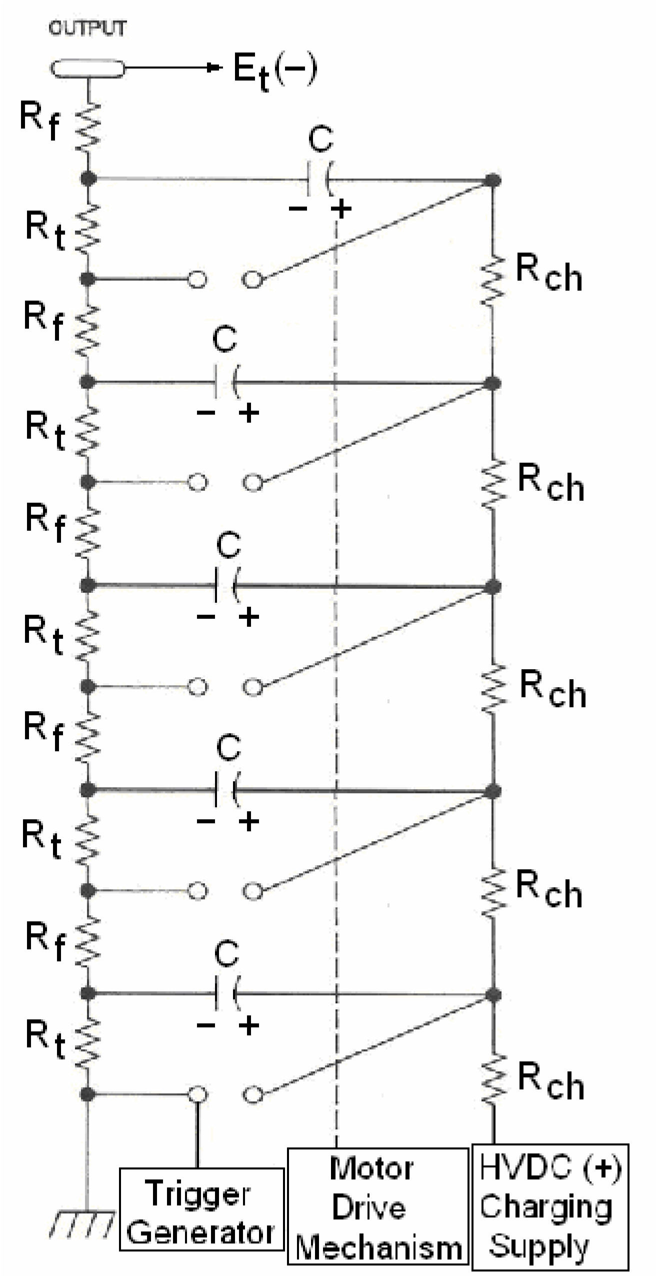


Figure 3.6 - Impulse generator circuit [11].

As said in section 3.2, all stages are charged in parallel and discharged through sphere-gaps when connected in series. This means that, after discharge, the resulting voltage is:

$$E_t = -\left(n \cdot E_{sk}\right) \tag{3.1}$$

where:

E_t .- Output Voltage;

n .- Number of generator stages used;

E_s .- Charge Voltage per stage;

k .- Losses due to system inductance.

The rest of components of the circuit, capacitors and resistors, were already defined in section 3.2.2.

Each stage is charged to voltage *(+E_s)*. When the system is triggered, a voltage of *($2 \cdot E_s$)* appears across gap 2. This is due to the fact that one capacitor high voltage plate is pulled down to zero and a negative charge redistribution appears on the other plate. The process is repeated yielding an output voltage of an opposite polarity from the charging supply.

In practice, if a positive wave is desired, the polarity of the power supply must be negative output. The negative output, equally, requires a positive charging voltage.

When a selected voltage is reached, charging process is halted by electromechanical means. At this time an isolated electronic trigger (see section 3.3.7) delivers a pulse to discharge the capacitor bank. A simultaneous oscillographic recording is made of the impulse waveform [11].

The discharge capacitance *C* should always be larger than the load C_l, as otherwise the efficiency of the generator will be too low. A factor 3 may be acceptable, but higher values are preferred, as described by Kreuger [4].

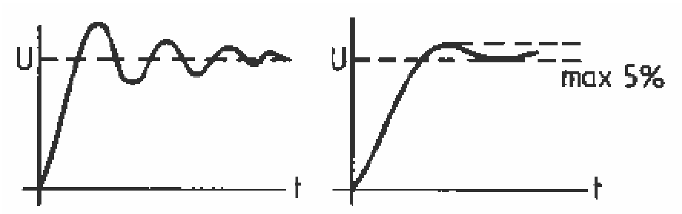
The impulse test system is set with parameters shown in table 3.1 below:

Table 3.1 — Generator parameters.

R_f	35 Ω
R_t	200 Ω
R_{ch}	18 kΩ
C_g	500 nF
N	5 stages

By means of changing front and tail resistors, R_f and R_t, it is possible to vary the discharging time and, in this way, to avoid the effect of stray inductances, because the faster the velocity change of current in the circuit, the bigger the effect of stray inductances, as it can easily be demonstrated by basic principles of electromagnetism.

In addition, the inductance of the circuit should be kept low. If too much inductance is present, a waveform as shown in figure 3.7a occurs. With front times less than 1 µs these oscillations cannot be prevented. At about 1 µs front time the oscillations have vanished but some overshoot still occurs, as shown in figure 3.7b. IEC standards allow, therefore, an overshoot of up to 5 %.



(a) (b)

Figure 3.7 - Effect of stray inductances [4].

To reach this approved wave-shape, the stray inductance Ls of the generator circuit shall satisfy next condition, as recommended by Kreuger [4]:

$$2 \cdot \sqrt{\frac{L_s}{C} + \frac{L_s}{C_l}} \leq R_f \tag{3.2}$$

The efficiency η of the generator is:

$$\eta = \frac{U_c \cdot n}{U_p} \tag{3.3}$$

where:

U_c – DC charge voltage per stage;
n – number of stages in the generator;
U_p – Peak voltage of the output waveform.

Further information about lightning impulse front time, time to half value and efficiency can be found in the instruction manual of the 100 Series Impulse Generator.

3.3.2 -Generator stack

The stack of high voltage capacitors, sphere-gaps, front and tail resistors, and charging resistors are placed in this structure. And, also, the trigger system and the motor drive mechanism are mounted on the base.

For various international standards, different wave-forms may be simulated by changing plug-in resistors located on the capacitor bank.

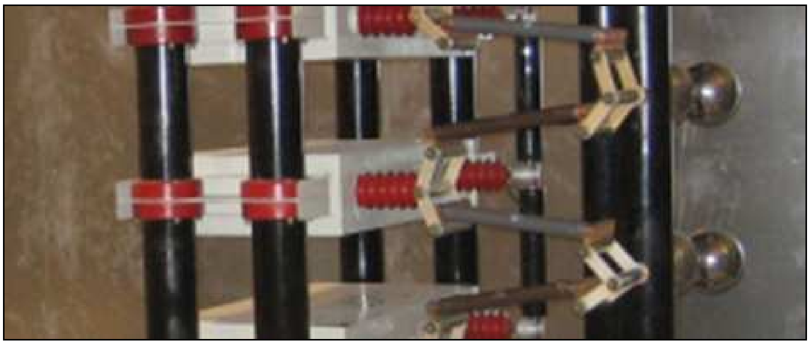


Figure 3.8 – Detail of the generator stack.

3.3.3 -High voltage capacitors

All impulse capacitors used in Hipotronics Impulse Generators are designed for a minimum of 250000 full voltage shots and provide long trouble free operation. They are single metal can, dual bushing design to minimize circuit inductance, and, are mounted on the generator stack. Their capacitances are about 500 nF per unit.

Internal construction consists of Kraft paper, Polyester film, castor oil dielectric, with swedged low inductance sections. They have an internal discharging resistor; this bleeder resistor is connected in parallel in order to discharging the energy stored in the capacitor. The internal discharge time constant is several minutes and these resistors should not be relied upon to safety ground the capacitors. The capacitor terminals and the capacitor case should always be grounded with a shorting stick before touching any parts of the generator structure by hand.

3.3.4 -Waveshaping resistors

Each stage has provision for up to 4 front and 4 tail resistors to be connected in parallel. Depending on the calculated values of resistance required to test a particular load, the appropriate combination of resistors may be plugged in accordingly. All Hipotronics' resistors are non-inductively wound.

Front and tail resistors available in the High Voltage Laboratory are shown below:

- 2 units of 20 Ω (R-6154)
- 3 units of 25 Ω (R-6196)
- 8 units of 35 Ω (R-6201)
- 3 units of 60 Ω (R-6197)
- 5 units of 75 Ω (R-6199)
- 6 units of 200 Ω (R-4966)
- 6 units of 450 Ω (R-4967)

Resistors selection must be done according to the rules below:

- To know the amount of energy necessary per stage and for the testing which will be carried out.
- To install necessary front and tail resistors in each stage according to the amount of energy per stage.
- Do not do any test with standard resistors and repetitions shall be done not before one minute after the previous voltage application.
- When resistors are placed in parallel, it is necessary to make sure that each resistor is proportional to the energy which it will absorb.
- Every stage joined in series, independently of the stages which are joined in parallel, must have the same front and tail resistors.

3.3.5 -Charging resistors

The charging resistors are of similar design to the waveshaping resistors but are typically of a higher ohmic value. The charging resistors are of sufficiently high value to allow proper firing of the impulse generator without influencing the wave-shape, but not so high as to cause unequal charging voltage on the upper stages. There are 5 units of about 18kΩ mounted on the stack.

3.3.6 -Charging supply

Each generator is supplied with a reversible polarity power supply that provides the DC voltage for charging the stage capacitors. The charging supply provides a high voltage output up to 50mA and 100kV in DC.

The circuit design for the power supplies consists of a full wave bridge rectifier. Since the load of the impulse generator is capacitive, no internal capacitors are required within the power supply, which simplifies the design. All units have a simple polarity reversal mechanism that is motorized for use with C100-M controller as a standard feature.

Internally the supply contains its own current limiting resistor and system discharge resistor. Heavy-duty solenoids provide gravity discharge of capacitor bank should system power be interrupted.

The charging units are assembled in a steel tank and are vacuum filled with mineral based transformer oil. The output connection is provided via a HV coaxial cable to allow the charging supply to be located away from the HV components of the impulse circuit.

3.3.7 -Trigger system

In order to determine the exact moment of firing, so that the time sweep of oscilloscopes and other measuring equipment can be tripped, a triggered sphere-gap according to figure 3.9 is used. A trigger impulse of 15 kV is used to break down the annular gap. This causes a distortion of the main field, ultra-violet radiation fills the gap and a source of charged particles occurs at the triggered electrode, so that breakdown of the main gap is initiated.

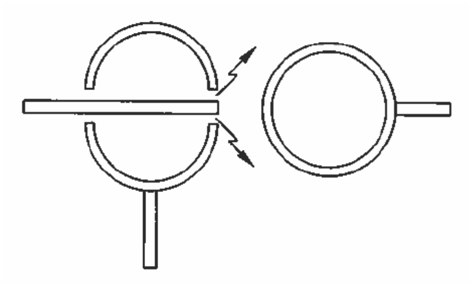


Figure 3.9 - Triggered gap [4].

The gaps should be in line and they should “see” each other. Thus, the ultra-violet light of the first gap irradiates the others so that the breakdown is initiated. If the radiation is blocked, the firing of the generator will be inconsistent and often be incomplete. Internal oscillations are prevented by dividing the front resistors R_f over the stages. It would have been more practical to concentrate the front resistance R_f in series with the generator, however, stray inductance would cause oscillations within the stages, which would spoil the wave-shape and even cause breakdown of the discharge capacitors.

The system necessary to create this impulse of 15kV is shown in figure 3.10:

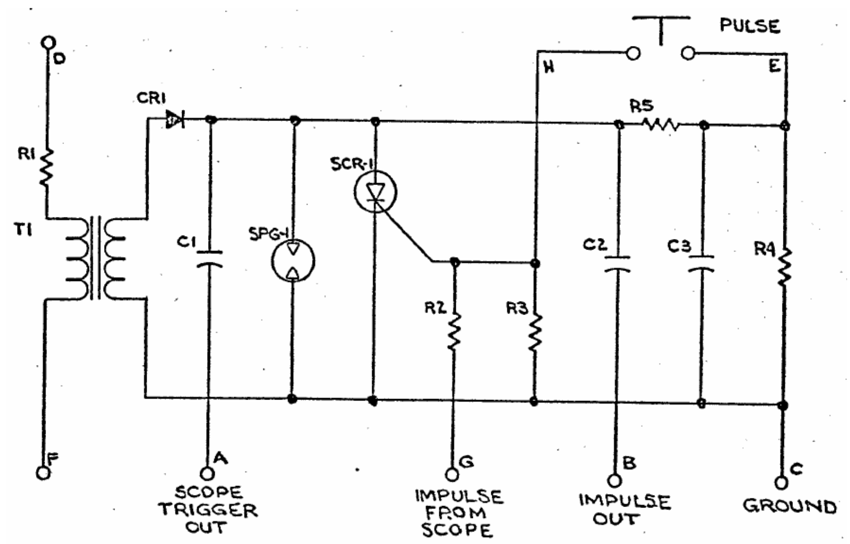


Figure 3.10 - Trigger system

The basic operation is as follows. When the pulse button on front panel of the control console (see section 3.3.10) is depressed, a short circuit across H-E is caused. And then, next sequence occurs:

1.) Scr-1 fires and discharges capacitor C2.
2.) Capacitor C2's energy is discharged into the primary of ignition coil on base.
3.) Ignition coil steps up voltage and causes ignition between stage 1 sphere gaps.
4.) Partial ionization triggers first gap and remaining stages fired.
5.) Capacitor C1 running to terminal A provides a trigger pulse for the Tektronix 507 scope.

After sparking in the first sphere gap, a sequence of sparking in the next sphere gaps occurs. This is the way how the capacitor's bank is triggered and impulse voltage for testing is obtained.

From the impulse out terminal to the trigger electrode in the first gap of the generator, there is a delay cable which is fixed length. This cable has a fixed delay equal to the transit time of the delay line, which is approximately 200ns.

Terminal G impulse from scope allows remote firing from the scope main frame.

Power supply of trigger system has the function of supplying a controlled high voltage signal which will be used to ionize the electrode of the spark gap of the first stage.

The typical triggering range for the 100 series generators is shown in figure 3.11. The impulse must be inside the highlighted area in order to ensure a successful firing of the gap.

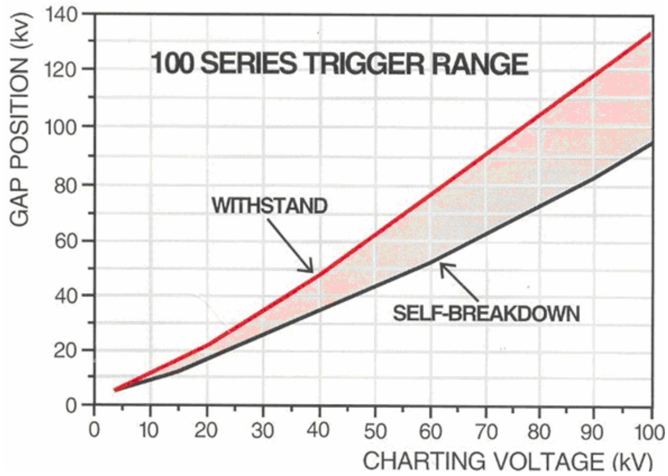


Figure 3.11 - Typical triggering range.

3.3.8 -Motor drive mechanism

As shown in figure 3.12, the design of the gap system consists of a fixed set of spheres that are connected to the waveshaping resistor provisions (on the right side) and a moving set of spheres that are connected to the stage capacitors (on the left side).

The individual spheres are fixed to the gap support tubes and adjustment is provided to set the gap spacings. The moving gap tube is connected to a DC motor drive and gear reducing package that provides remote adjustment of the gap spacing. Since the gaps are all mounted to a common tube, the spacing can be controlled with a high degree of linearity. The motor drive system also includes a 10 turn potentiometer which is used to drive the panel indicator for gap spacing.

This unit does not have any automatic drive control.

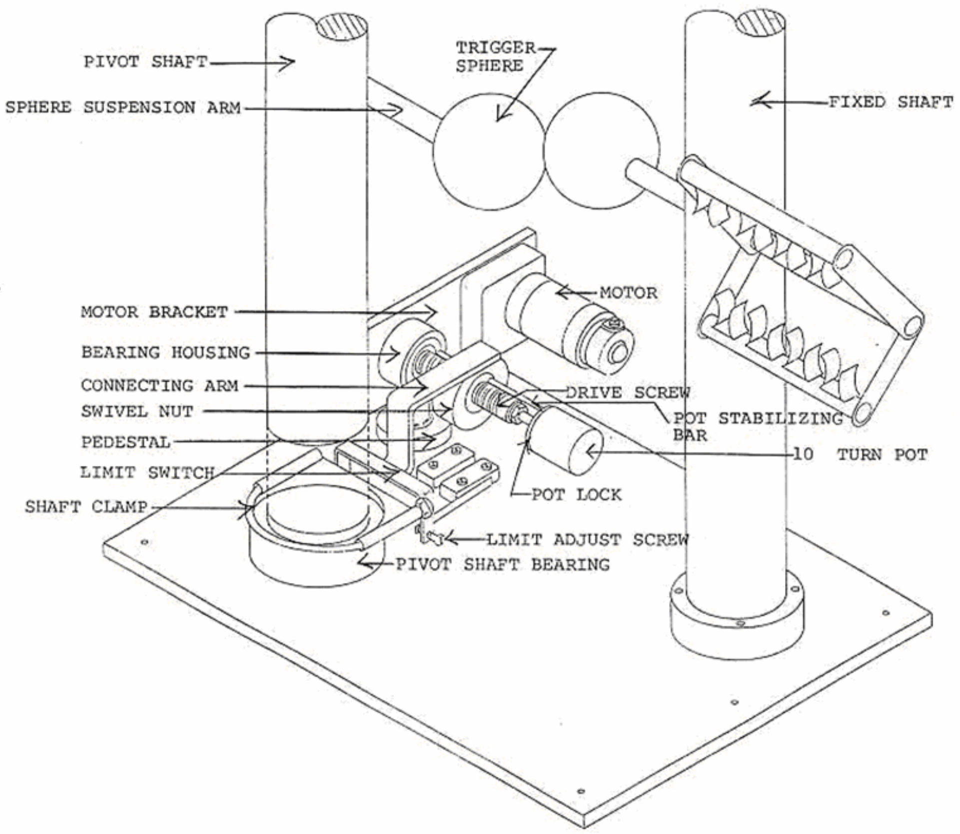


Figure 3.12 - Motor drive mechanism

3.3.9 -High voltage discharging relay

The High voltage discharge relay is an electrically operated switch that opens when the charging supply is operating and closes when power is interrupted or if the generator is turned off. The switch is connected in series with a discharge resistor that absorbs the stored energy in the generator. The design of the high voltage discharge circuit is to rapidly discharge the high voltage capacitors to zero voltage under emergency conditions.

It is an external air insulated switch that is mounted on the base of the impulse generator.

3.3.10 - Impulse generator control system

Hipotronics Impulse Generator Control System Model C-100M, is an integrated system designated to charge and control the firing of the standard IG100-2.5 generator.

The control console is shown in figure 3.13 below. The following items are found on the control console panel:

- Main power circuit breaker;
- Main power “ON” indicator lamp;
- High voltage “ON” pushbutton;

- High voltage “OFF” pushbutton;
- High voltage “ON” indicator lamp
- Pulse initiation pushbutton;
- “Interlock Open” indicator lamp;
- Three position charge rate control;
- Impulse “READY” indicator lamp;
- Dual range kilovoltmeter with high set point;
- Gap breakdown voltage meter;
- Open-Close gap motor control switch;
- Meter calibration access hatches.

Figure 3.13 - Front panel of the control console.

The high voltage charging supply is measured by means of a resistive voltage divider located on the generator structure.

3.3.11 -Capacitive mixed divider

The capacitive voltage divider shown in figure 3.14 measures the voltage of lightning impulse tests.

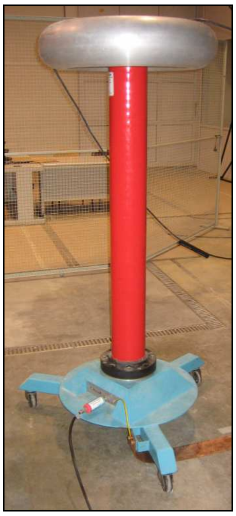


Figure 3.14 - Resistive voltage divider of the generator.

A voltage divider is a device that is intended to produce accurately a suitable fraction of the test voltage for measurement. It usually has two impedances connected in series across which the voltage is applied. One of them, the high-voltage arm, takes the major fraction of the voltage. The voltage across the other, the low voltage arm, is used for the measurement. The components of the two arms are usually resistors or capacitors (or combinations of these) and the device is described by the type and arrangement of the components [26].

The Laboratory of High Voltage has a Hipotronics Capacitive Mixed Divider, Model CMD-500. The Hipotronics CMD Series dividers are general purpose, series damped, resistive-capacitive dividers for measuring AC or impulse voltages. They are capable of measuring voltages from 50 Hz to 599 Hz, Lightning Impulses (L.I.) including Chopped Waves and Switching Impulses (S.I). The divider is comprised of a single section HV arm, a base assembly, and HV electrode, an LV arm and a coaxial measuring cable.

The following table 3.2 provides the main system specifications.

Table 3.2 — Main specifications of the capacitive voltage divider.

Working Voltage	175 kV RMS, 500 kV L.I., 450 kV (± S.I.)
High Voltage (HV) Arm, Capacitive	1500 pF ± 5 percent
High Voltage (HV) Arm, Series Resistive	50Ω
Low Voltage (LV) Arm	375 nF Nominal

The HV electrode is a single toroid type. A stress distributor (corona shield) is used at the end of the beam in order to avoid corona effect.

The HV arm is a series of custom made HV capacitor and series resistor elements. The capacitor sections and resistors are mounted inside an insulating tube and filled with mineral-based transformer oil.

The LV arm assembly consists of a custom made capacitor section. This capacitor, along with an impedance matching resistor, is mounted in a cylindrical metal can. The LV arm assembly connects to the output connector of the HV arm, located on the front panel at the base of the Capacitive Mixed Divider.

Figure 3.15 shows the capacitive voltage divider sketch provided by the manufacturer [12].

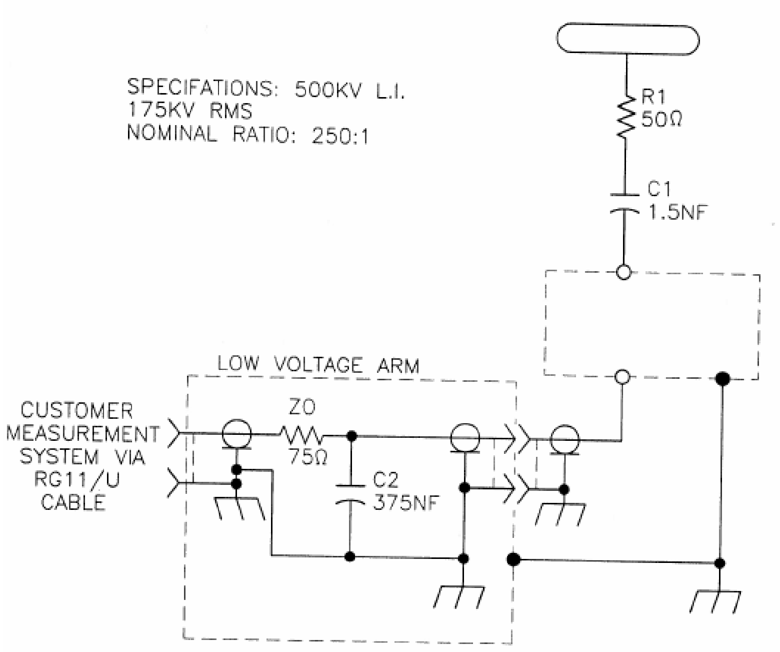


Figure 3.15 - Sketch of the capacitive voltage divider.

3.3.12 -Oscilloscope used with voltage divider

An oscilloscope is connected to the low-voltage arm of the voltage divider by a coaxial cable. This is a RG11/U cable for measuring purposes of 15 meters approximately. The signal is attenuated by means of a high-voltage passive probe of 100X. The digital storage oscilloscope (DSO) is a Tektronix TDS 340 A (see figure 3.17). A detail of the connection of these components, except the probe, is shown in figure 3.16.

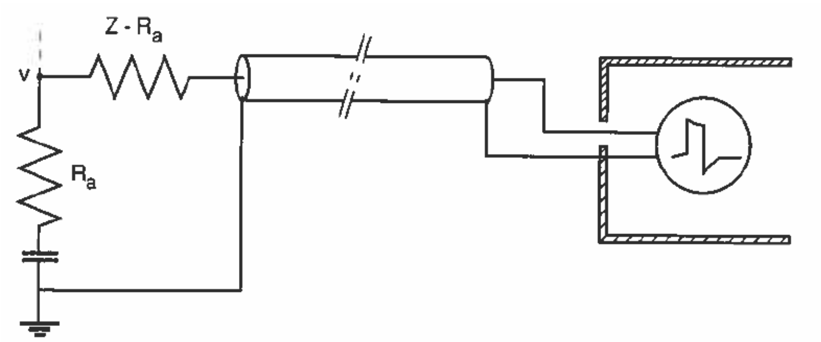


Figure 3.16 - Detail of the low voltage arm of the voltage divider, the coaxial cable and the measuring device (oscilloscope).

Figure 3.17 - Tektronix TDS 340 A.

3.3.13 -Layout of the High Voltage Laboratory

The High Voltage Laboratory (HVL) of the Faculty of Engineering is located in the room J003 of the Department of Eletrical and Computer Engineering of the Faculty of Engineering.

In operation, generator's parts are installed in a safe test area inside a Faraday cage or shield and controls are located nearby, although, the possibility of creating a control room nearby, in room J002, is proposed. In figure 3.18, the layout of the High Voltage Laboratory and location of the equipment are shown.

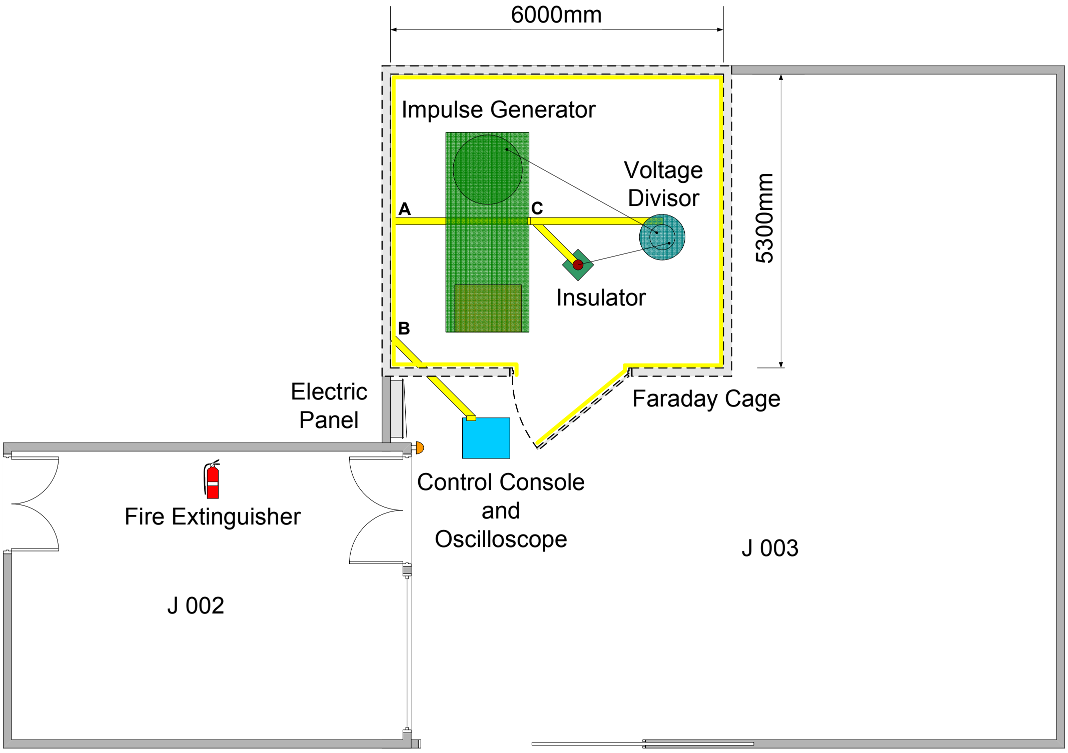


Figure 3.18 - Layout of the Laboratory and earth connections.

This plan view shows the Faraday cage, which is located in the upper right side of the room J003. Upper and left sides of this testing zone are made of metal sheet, and, right and down sides are made of metallic mesh; all of them make up the Faraday cage.

The circle on the impulse generator shows the placement of the generator stack, which is made up of capacitors, charge resistors, front and tail resistors, and the sphere-gaps, as said above.

All elements in the Farday cage must be connected to earth using star connection. The connection point must be as close as possible to the generator's structure. This point is (C) in figure 3.18.

The metallic structure of the generator, where voltage transformer, trigger system and generator stack are mounted, is connected to earth by means of copper tape from point (C) to point (A) on the metal sheet.

Voltage divider and insulator's base are connected to earth at the point (C) on the metallic structure of the generator.

The control console and the oscilloscope, located out of the Faraday shield, are connected to earth at the point (B).

All earth connection are made by means of copper tape with section (120 x 1.5) mm^2.

Figure 3.19 shows a photography of the Faraday cage of the Laboratory where connection points to earth, (A), (B) and (C), are shown.

Figure 3.19 - Detail of the earth connections of the equipment: points (A), (B) and (C).

This enclosure, the mesh of conducting material, protects electronic equipment, people and other goods from lightning strikes and other electrostatic discharges. Faraday cage shields the exterior from internal electromagnetic radiation during testing. Out of the Faraday cage the control console and the oscilloscope are located.

The electrical connection to earth is shown with a yellow line in figure 3.18. Earth connections are detailed below:

- Faraday cage's earth connection;
- Earth connection of the metallic structure. On this structure are placed the voltage transformer, the stages of the impulse generator and other elements of the equipment as the trigger system;
- Earth connection common point on the metal sheet. Metal sheets are on the building's wall and they are two sides of the Faraday cage square viewed from the top;
- Insulator tested earth connection;
- Earth connection common point of the impulse generator, the capacitive voltage divider and the insulator's base;
- Capacitive voltage divider earth connection.

The control console and the oscilloscope are connected to earth as well at point (B) in figure 3.19.

3.4 - Preparation of the test

To make a test about certain electrical equipment at the Laboratory of high Voltage, the steps which are shown below must be followed:

- To place the equipment which will be tested.
- To set the impulse generator by means of the suitable resistors.
- To calibrate the wave which is obtained.
- To execute the test based on international standards.

Lightning impulses are made up of high current values, even higher than 150 kA in some cases, and they have very short rise time. The standard wave-form rise time is 1.2 μs. It is different to internal over-voltages, which always happen with Alternating Current (AC) at power frequency, 50 Hz, so its rise time is much longer, about [ms].

Next information of the Impulse Generator is given below according to Hipotronics [11]:

- Total Number of Stages = 5
- Maximum Voltage per Stage = 100 kV
- Total Energy Stored per Stage = 2.5 kJ
- Maximum Output Voltage = 500 kV
- Net Generator Capacitance = 100 nF
- Maximum Load = 30000 pF (Maximum load without drastically effecting efficiency)
- Number of Gaps Used = 5

It is possible to calculate easily the capacitance value per stage. The total energy stored per stage is:

$$E_0 = \frac{1}{2} \cdot n \cdot C \cdot \left(U_0\right)^2 \tag{3.4}$$

Therefore, the capacitance per stage is:

$$2.5kJ = \frac{1}{2} \cdot C \cdot \left(100kV\right)^2 \Rightarrow C = 500nF \tag{3.5}$$

Chapter 4

Computer simulation

Computer simulations have become a very useful part in engineering processes. They allow to gain insight into the operation of a certain system or to observe its behaviour. They are, therefore, widely used nowadays and make possible to study, for example, different configurations of the Impulse Test System of the High Voltage Laboratory.

In this chapter, two computer simulators are used: OrCAD PSpice 9.1 (Student Version) and PSCAD v4.2.1. The first one helps to carry out a study about how parameters change according to front and tail resistors and, the second one simulates full lightning and chopped impulses.

The use of two simulators is justified. For the first part PSpice is used because it provides quick simulations and accuracy, what permit to create data tables in order to compare the results obtained. But, when chopped impulses want to be simulated, PSpice is limited; therefore, it is necessary to count on more powerful computer simulators such as PSCAD for these purposes.

4.1 - Simulation using PSpice

By means of computer simulation with PSpice, it is possible to determinate peak voltage, front time and time to half value of a test waveform, and global efficiency of the system. It allows finding the best solution to comply with international standards and to compare the results obtained.

Two simulations are made:

- Simulation of the Impulse Generator;
- Simulation of the Impulse Generator under the influence of stray capacitances between the generator stack and the metal sheet on the wall.

4.1.1 -Impulse generator: simulation parameters

As depicted in section 3.3, the impulse test system is set with the parameters shown there. Capacitors of stage are fixed, its capacitance is about 500 nF; charging resistors are also fixed, its resistance is about 18 kΩ; and, the impulse generator has a fixed number of stages, 5 stages. Therefore, there are two parameters, R_f and R_t, that may be changed in order to adjust the test waveform to requirements. These requirements may be: to obtain certain values of front time T_1 and time to half value T_2; to reach the maximum output voltage, that is, maximum peak voltage of the waveform; or to have the highest efficiency η of the system.

As the main objective of this Master's Thesis is to establish the principles in order to adjust the equipment of the High Voltage Laboratory in general, it is not chosen any of the requirements said above, but it is purposed as a further work to adjust front time and time to half value of the waveform to comply with the international standard.

As depicted in section 3.1.4, there are available waveshaping resistors with different resistances. Then, it is interesting to study how parameters of the waveform change according to resistors chosen. The generator stack has 5 stages, with two places for resistors per stage: one place for a front resistor and another for a tail resistor; therefore, the study only takes into account those resistors which there are, at least, 5 units. These resistors are shown in table 4.1:

Table 4.1 — Resistors available for the study of the impulse generator by means of simulation.

R_f	35 Ω	75 Ω
R_t	200 Ω	450 Ω

Output results are, as said above: front time T_1, time to half value T_2, peak voltage U_p and efficiency η. The peak value U_p is the maximum value of the test voltage for a lightning impulse. The front time T_1 of a lightning impulse is 1.67 times the time interval between the instants when the impulse is 30% and 90% of the peak value, that is:

$$T_1 = 1.67 \cdot \left(T_{90} - T_{30}\right) \tag{4.1}$$

The time to half-value or tail time T_2 of a lightning impulse is the time interval between the origin of the wave-shape and the instant on the tail when the voltage has decreased to half of the peak value (50% of the peak value). And the efficiency of the process is, as commonly defined:

$$Electrical\_Efficiency = \frac{Useful\_power\_output}{Total\_power\_input} \tag{4.2}$$

or, expressed in terms of the generator parameters:

$$\eta = \frac{U_{\max\_out}}{n \cdot U_c} \tag{4.3}$$

where:

η – Efficiency;
U_{max_out} – Maximum output voltage;
n – Number of stages of the generator (n = 5);
U_c – Charging voltage per stage.

All these parameters are precisely defined in chapter 5 (international standard for high-voltage testing).

The circuit used in the simulation is shown in figure 4.1 below. In the rest of the circuits used for the study, only the values of front and tail resistors are changed and. The table of results obtained is shown at the end of this section (see table 4.5).

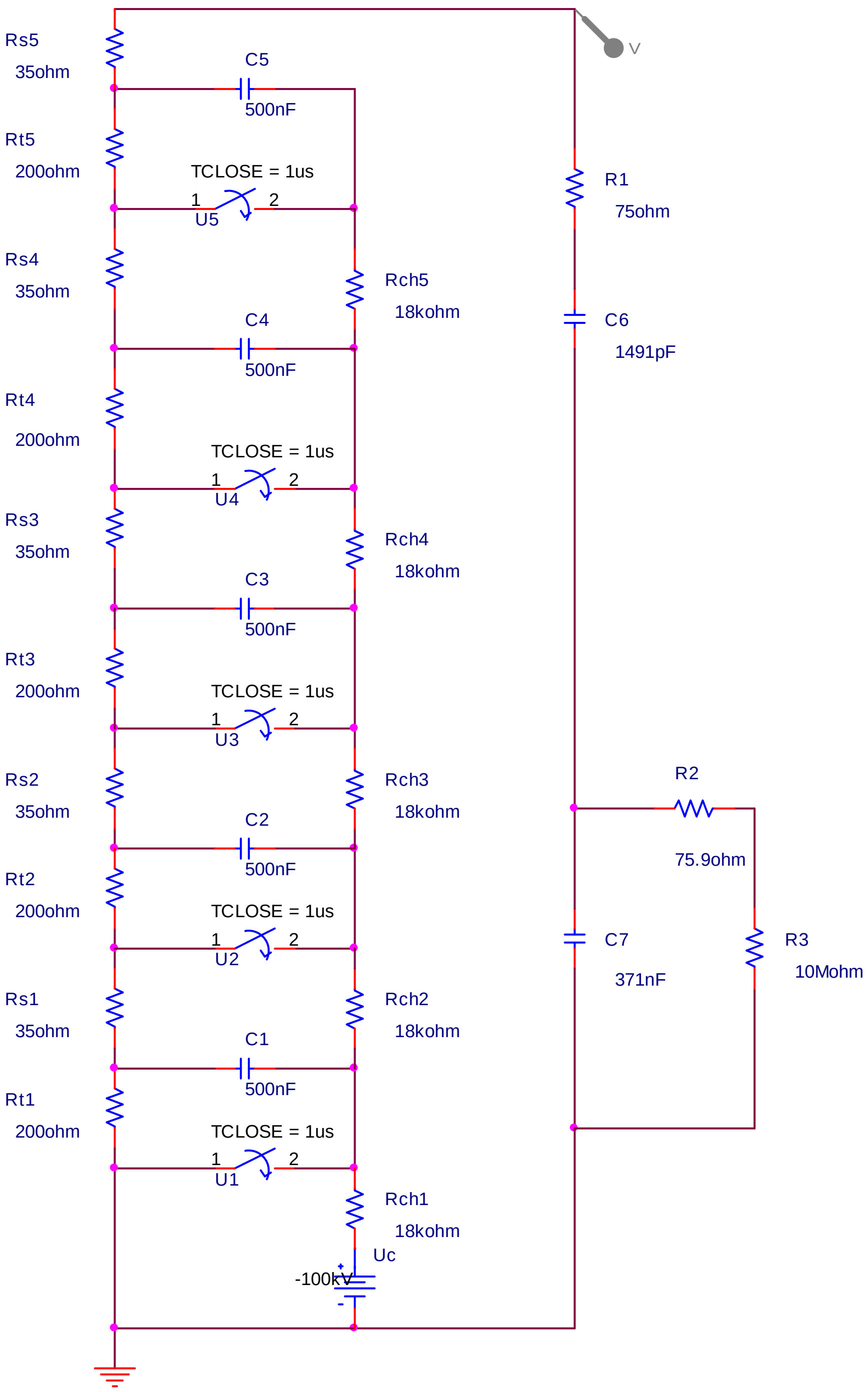


Figure 4.1 - Impulse generator circuit used in simulation with PSpice

The point V is where the maximum output voltage is measured. The lightning impulse waveform obtained for this circuit is shown in figure 4.2:

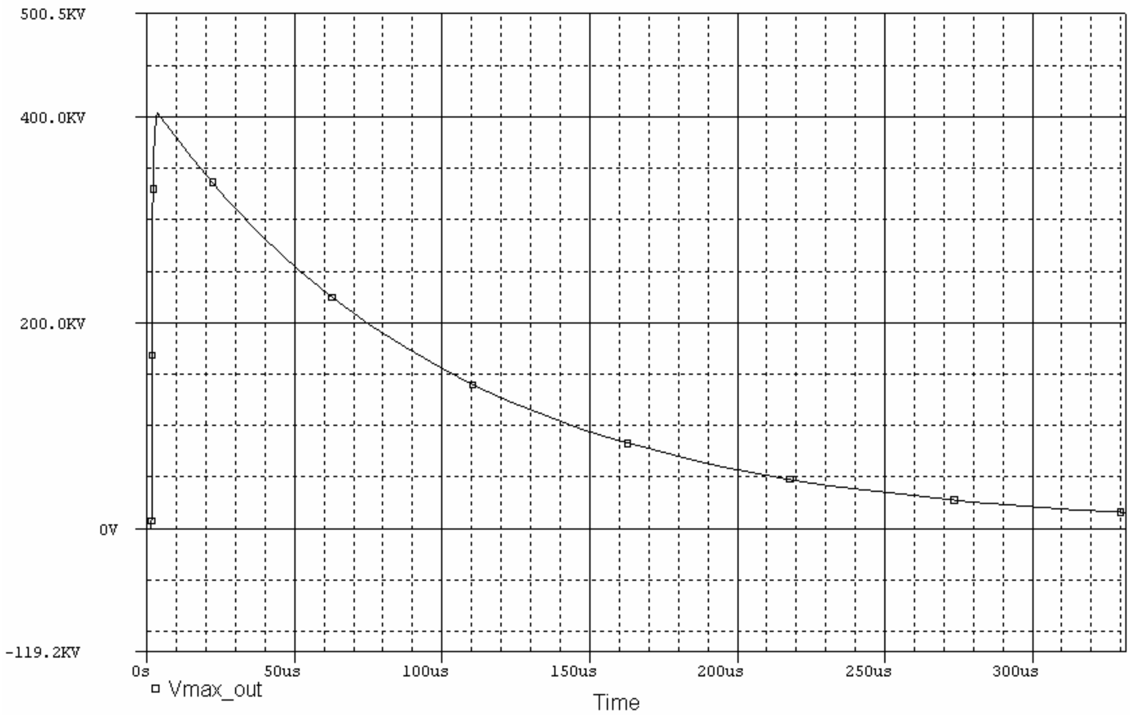


Figure 4.2 - Typical lightning impulse waveform obtained in the simulation with PSpice

The criterion chosen in order to study how parameters change according to front and tail resistors is to simulate with the highest, the lowest and medium values for front and tail resistors.

The highest values for front and tail resistors are shown in table 4.2:

Table 4.2 — Highest values for front and tail resistors.

R_{fmax}	75 Ω
R_{tmax}	450 Ω

The lowest values for front and tail resistors are obtained with front resistors connected in parallel and tail resistors connected in parallel respectively. They are shown in table 4.3:

$$R_{f\min}\left(35\Omega//75\Omega\right)=23.86\Omega \tag{4.4}$$

$$R_{t\min}\left(200\Omega//450\Omega\right)=139\Omega \tag{4.5}$$

Table 4.3 — Lowest values for front and tail resistors.

R_{fmin}	23.86 Ω
R_{tmin}	139 Ω

The medium values for front and tail resistors are calculated below and their values are shown in table 4.4:

$$R_{fmed} = \frac{23.86\Omega + 75\Omega}{2} = 49.47\Omega \tag{4.6}$$

$$R_{tmed} = \frac{139\Omega + 450\Omega}{2} = 294.5\Omega \tag{4.7}$$

Table 4.4 — Medium values for front and tail resistors.

R_{fmed}	49.47 Ω
R_{tmed}	294.5 Ω

4.1.2 -Impulse generator: obtained Results

Obtained values in the simulation process are shown in table 4.5 below. Maximum and minimum values for maximum peak voltage U_p, front T_1 and tail T_2 times, and efficiency η are highlighted.

Table 4.5 — Obtained results: values for front time

Rf [Ω]	Rt [Ω]	Umax_out [kV]	Efficiency [%]	Front time (T1) [μs]	Tail time (T2) [μs]
75,00	450,00	404,243	80,85	2,00	160,400
75,00	294,50	401,885	80,38	1,95	107,354
75,00	139,00	394,712	78,94	1,79	53,928
23,86	139,00	403,613	80,72	0,75	51,800
23,86	294,50	407,655	81,53	0,75	105,200
23,86	450,00	408,599	81,72	0,75	158,200
49,47	294,50	405,262	81,05	1,50	106,125
49,47	450,00	406,545	81,31	1,42	159,200
49,47	139,00	400,223	80,04	1,34	52,650

As a note, it is possible to say that the impulse generator with R_f = 49.47Ω and R_t = 139Ω complies with the international standard; it will be detailed in chapter 5. The standard waveform has a front time of 1.2 μs and a time to half value of 50 μs; therefore, the waveform obtained in the simulation with times 1.34 μs and 52.65 μs respectively is within tolerance limits defined by the Standard [26].

It is possible to list the main features of the impulse generator simulation extracted from data in table 4.5:

- The maximum peak voltage and, therefore, the maximum efficiency, are obtained with the minimum value of front resistor and the maximum value of tail resistor, and vice versa.

It is because, the lower the front resistance, the lower the voltage drop of the discharging circuit. And, the higher the tail resistor, the higher the discharging time and, therefore, the waveform reaches higher peak voltage.

- The higher the value of front resistor, the higher the rise time, and vice versa, the lower the front resistance, the lower the rise time.

- The higher the value of the tail resistor, the higher the tail time, and vice versa, the lower the tail resistance, the lower the tail time.

Both features can be described with the same reason. Discharge time constant of the stack of capacitors is directly proportional to resistance, as shown by equation 4.8.

$$\tau_D = R \cdot C \qquad (4.8)$$

where:

τ_D - Discharge time constant in seconds;
R – Resistance in ohms;
C – Capacitance in Farads.

The main parameters of the impulse generator test can be depicted. It easily allows seeing how they change according to values of front and tail resistors.

Figure 4.3 shows the change of the peak voltage when front resistance increases, and for a constant tail resistance of 450Ω. The higher front resistor, the lower peak voltage.

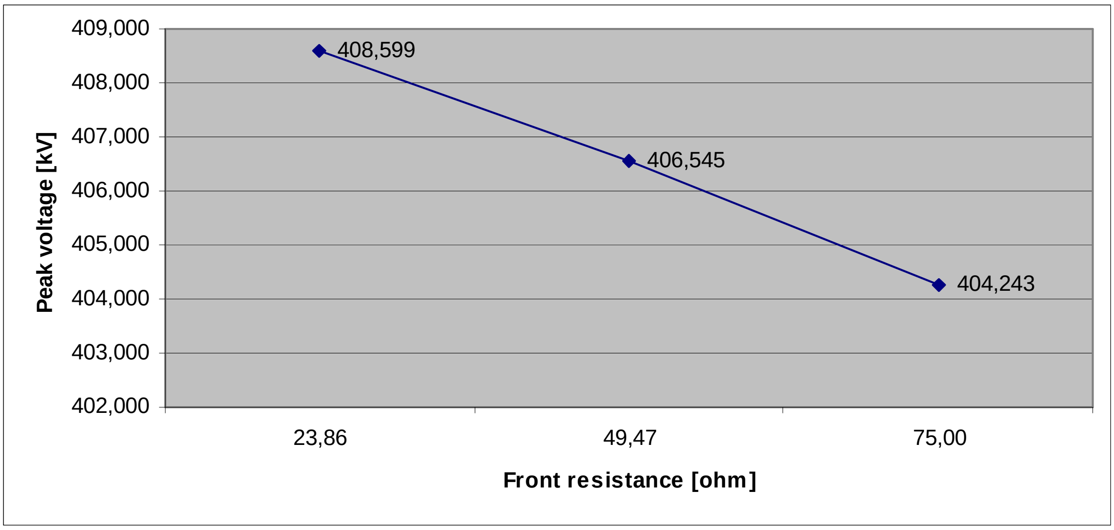


Figure 4.3 - Variation of peak voltage in kV according to front resistance in ohms. It is considered a constant tail resistance of 450Ω.

For a constant value of tail resistance, and varying front resistance, the efficiency of the system decreases like peak voltage does, that is, the higher the front resistance, the lower the efficiency. Therefore, figure 4.4 shows the variation of the efficiency according to tail resistance, for a constant value of front resistance of 75Ω. The higher tail resistor, the higher efficiency.

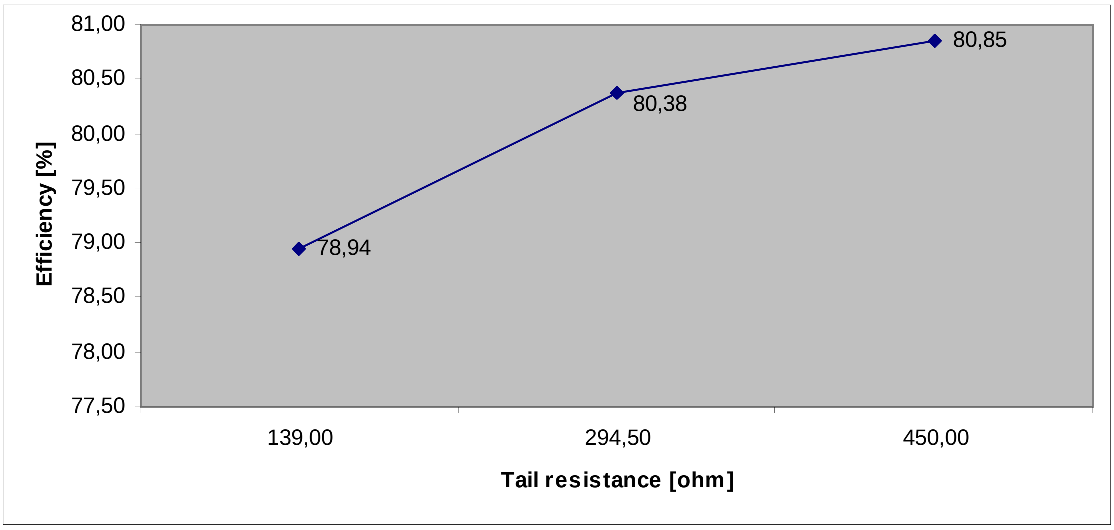


Figure 4.4 - Variation of the efficiency in percentage according to tail resistance in ohms. It is considered a constant front resistance of 75Ω.

Mainly, front and tail time vary more according to front and tail resistors respectively. Thus, figure 4.5 shows the wave "front time T_1-front resistor R_f" for a constant value of tail resistance of 450Ω, and figure 4.6 shows the wave "tail time T_2-tail resistor R_t" for a constant value of front resistance of 75Ω. It is seen that the higher front resistor, the higher front time; and, the higher tail resistor, the higher tail time.

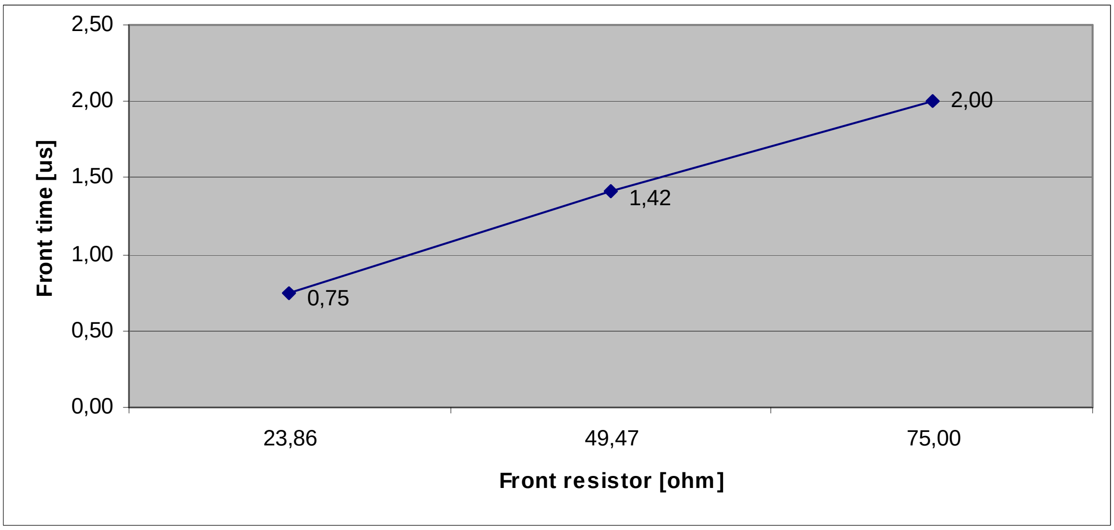


Figure 4.5 - Variation of the front time in microseconds according to front resistance in ohms. It is considered a constant tail resistance of 450Ω.

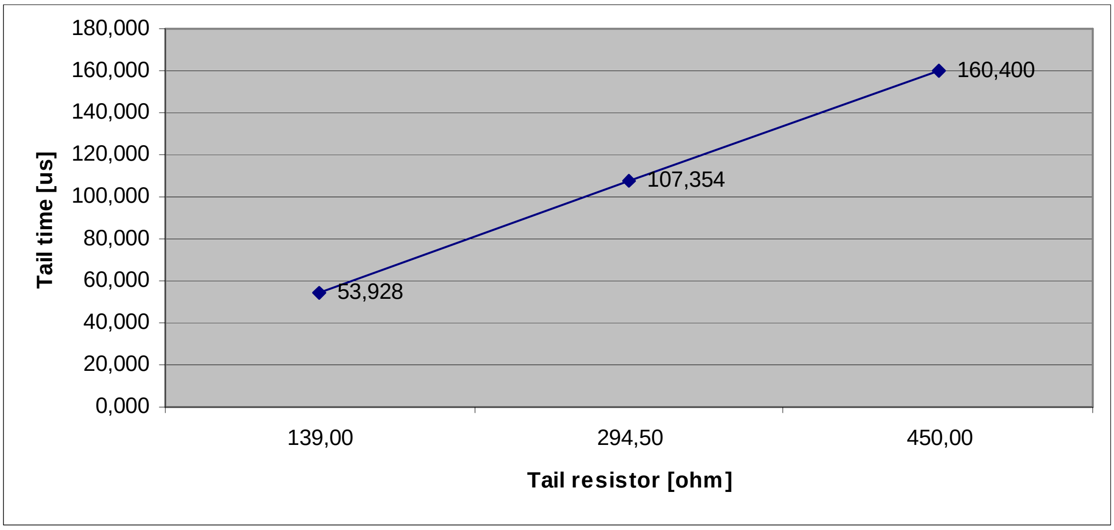


Figure 4.6 - Variation of the tail time in microseconds according to tail resistance in ohms. It is considered a constant front resistance of 75Ω.

The impulse test system is designed to reach up to 500 kV, but the efficiency of the system, around 82% according to simulation, decreases this value to about 409kV. In the real test, front and tail time, peak voltage and efficiency can be measured from the test waveform obtained by means of the measuring device, that is in the High Voltage Laboratory, the oscilloscope Tektronix TDS 340 A.

4.1.3 -Impulse generator with stray capacitances: simulation parameters

The metallic sheet on the wall inside the Faraday cage (see figure 3.19) brings about the idea that stray capacitances between the stages and the metallic sheet may affect the normal behaviour of the system, and some of the problems that are shown in chapter 6 might have their origin in this theory.

There are other stray capacitances that have influence on the normal behaviour of the generator system, but only the ones between the stages of the generator stack and the metallic sheet are simulated in this section. Thus, the stray capacitance is calculated by means of equation 4.9 below:

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d} \tag{4.9}$$

Where, the total area *A* of the stack of capacitors and spheres is shown in table 4.6. This value is divided by 5 because it is simulated with 5 stray capacitors, one per stage. The distance *d* from the generator stack to the metallic sheet on the wall, the relative static permittivity of the air between ε_r and the permittivity of free space ε_0 are also shown in this table. Values *A* and *d* are obtained by means of measuring of the parameters of the equipment.

Table 4.6 — Data for calculating the value of the stray capacitance.

A	0,8 m^2
d	2,90 m
Єo	8,85 pF/m
Єr (air)	1,0006

Thus, the value of the stray capacitance per stage is:

$$C_p = 0.489\, pF \tag{4.10}$$

Figure 4.7 shows the electric circuit used in the simulation of the stray capacitances. As the purpose is studying the possible problem which may affect the normal behaviour of the equipment at the laboratory, it is decided to use parameters shown in table 5.6, which are usually used when a high voltage test is performed at the High Voltage Laboratory. The results are compared to the simulation of the impulse generator with the same parameters shown in table 4.7 but without the stray capacitors. Elements C8 to C12 represent the stray capacitors.

Table 4.7 — Impulse test system parameters for simulation of stray capacitances

R_f	35 Ω
R_t	200 Ω
R_{ch}	18 kΩ
C_g	500 nF
Uc	- 25kV

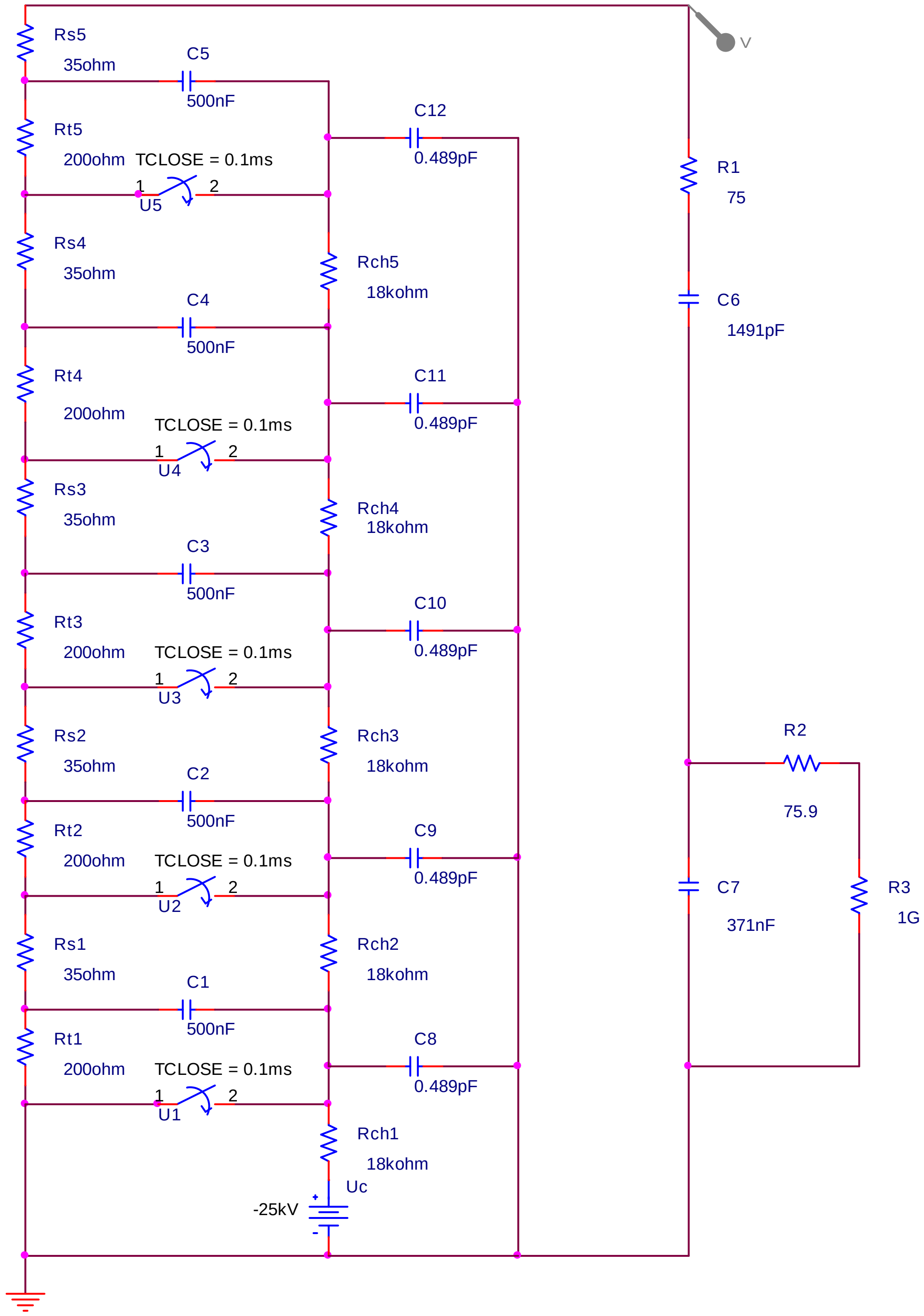


Figure 4.7 - Impulse generator circuit used in order to simulate the influence of stray capacitances with PSpice

The point V is where the maximum output voltage is measured. The lightning impulse waveform obtained for this circuit with stray capacitances is shown in figure 4.8. The firing instant of the sphere-gaps is a bit delayed until 0.1ms and the maximum step size used is 1 ns in order to pay attention to what occur before the rising edge of the waveform. It is explained in chapter 6 because it might be the reason of some “interferences” explained there.

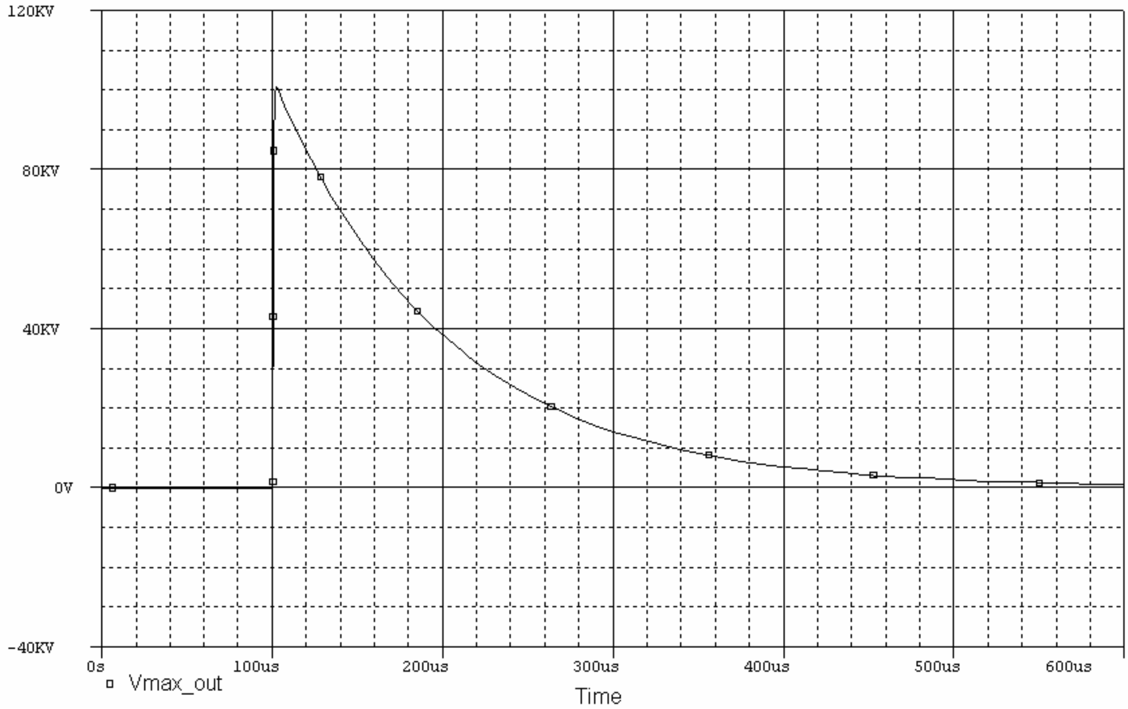


Figure 4.8 - Lightning impulse waveform obtained in the PSpice simulation with stray capacitances.

4.1.4 -Impulse generator with stray capacitances: obtained results

Obtained values in the simulation process with stray capacitances are shown in table 4.8 below. Results of the simulation with stray capacitances “2” are compared to the results of the simulation without stray capacitances “1”.

Table 4.8 — Results of the simulation with stray capacitances [2] compared to the simulation without stray capacitances [1].

Test	R_f [Ω]	R_t [Ω]	U_{max_out} [kV]	Efficiency [%]
1	35	200	101,170	80,94
2	35	200	100,961	80,77

Comparing results obtained, it is possible to say that the effect of stray capacitances between the generator stack and the metallic sheet on the wall causes a decrease of the peak voltage and, therefore, of the efficiency of the system as well. Thus, the simulation does not show any problem caused by stray capacitances as was thought to be the cause of the “interferences” before wave-front that are explained in chapter 6.

4.2 - Simulation using PSCAD

PSCAD is a computer simulator that permits to simulate more precisely the laboratory equipment. Unlike PSpice, it is possible to simulate not only full lightning discharges, but also chopped-tail and chopped-front impulses. A group of simple simulations are shown in this section in order to support future studies performed in the High Voltage Laboratory.

For full lightning discharges, a five stages generator is simulated, but for chopped-tail and chopped-front impulses, a simplified generator is used. It does not have any influence on the results obtained.

The values of the impulse generator are shown in table 3.1, but in order to be more precise, the real values were measured by means of a digital multimeter and are used in the simulation. They are shown in table 4.9.

Table 4.9 — Real parameters of the impulse generator measured and used in the simulation using PSCAD.

Stage	Front resistor [ohm]	Tail resistor [ohm]	HV capacitor [nF]	Charging resistor [kohm]
1	36.3	199.9	496	18
2	34.6	238	482	18
3	35.0	203	489	18
4	35.8	203	487	18
5	35.3	202	503	18

4.2.1 -Full Lightning Discharge

The electric circuit of the impulse generator for simulating full lightning discharge by PSCAD is shown in figure 4.9 below.

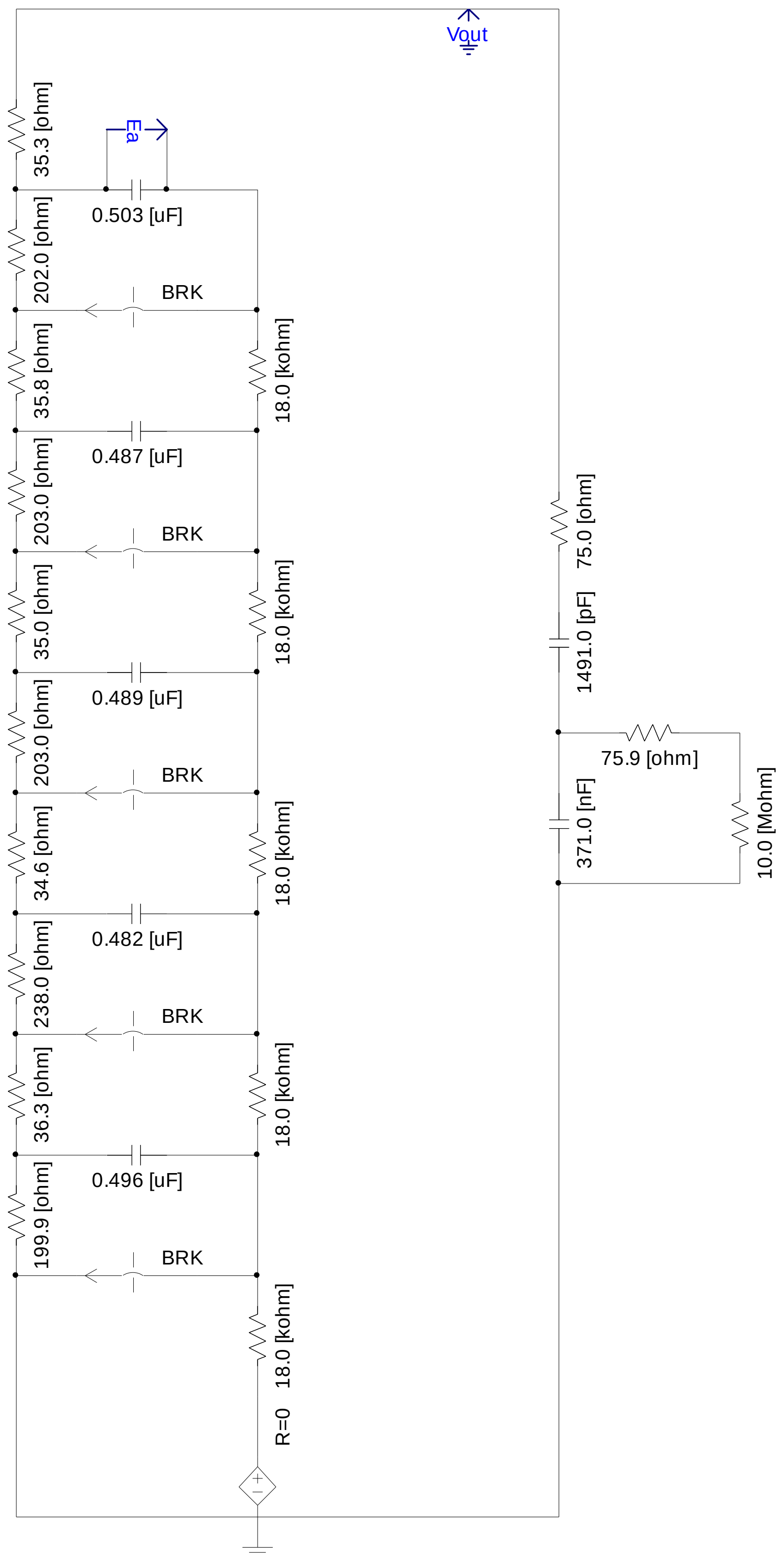


Figure 4.9 - Impulse generator circuit used in simulation of full lightning discharge using PSCAD.

Two waveforms are obtained: the lightning impulse test waveform simulated by PSCAD is shown in figure 4.10, and the charge waveform of one of the stages, in this case the fifth stage, is shown in figure 4.11. The firing of the sphere-gaps is produced after 0.52 seconds after starting the charge of the impulse generator.

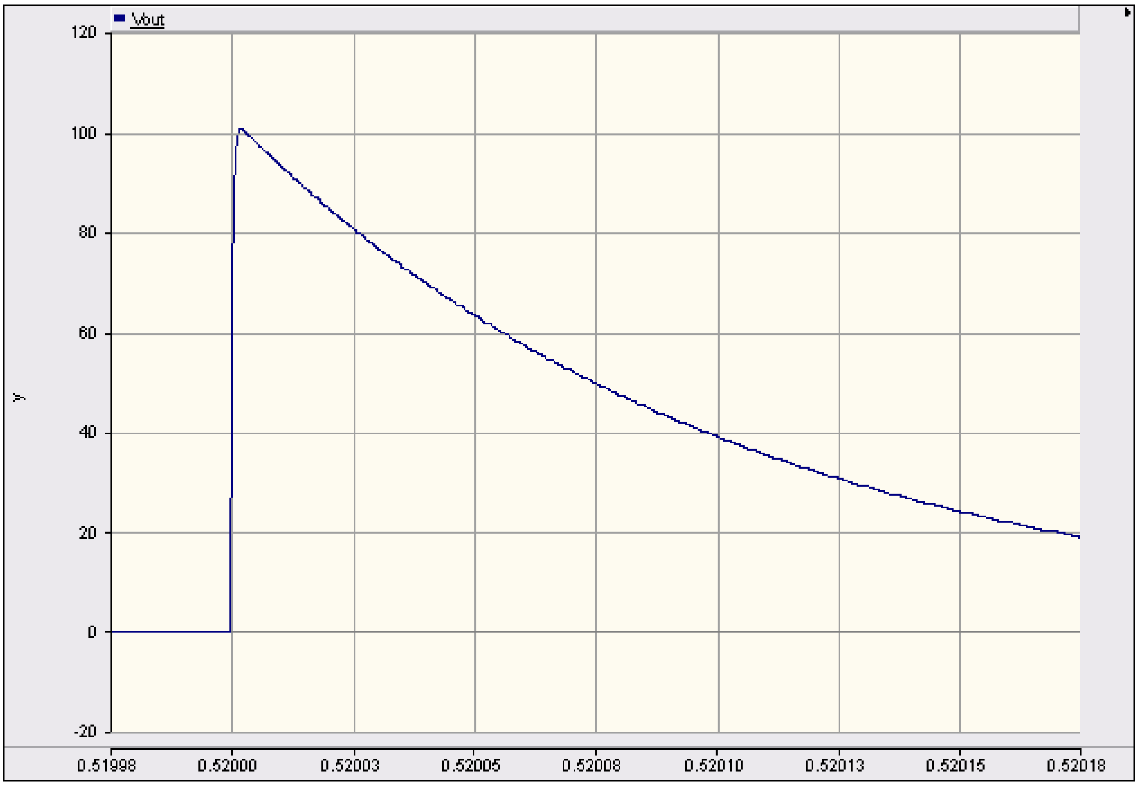


Figure 4.10 - Full lightning waveform for the impulse generator circuit simulated using PSCAD.

The peak voltage is about 100.5kV. This value is similar to the other one obtained by PSpice simulation and shown in table 4.8 above.

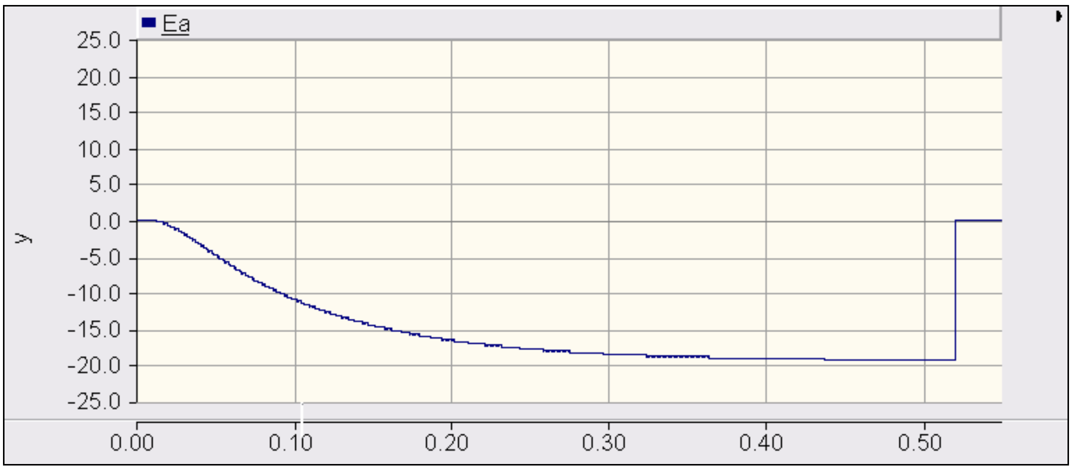


Figure 4.11 - Charge waveform for the fifth stage of the impulse generator simulated using PSCAD.

This waveform shows the typical charge of a capacitor, in this case, the capacitor of the fifth stage of the impulse generator.

4.2.2 -Chopped-tail Impulse

The electric circuit of the impulse generator for simulating a chopped-tail impulse using PSCAD is shown in figure 4.12 below. The parameters used in the simulation are shown in the figure except the charging voltage, which is -100kV. It is used a load capacitance of 2pF that simulates the behaviour of an electrical insulator.

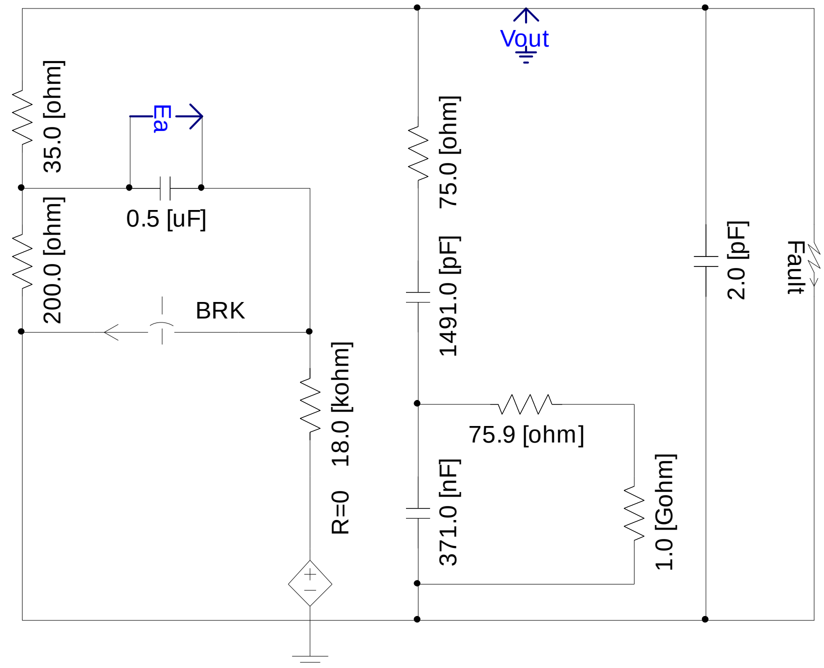


Figure 4.12 - Impulse generator circuit used in simulation of chopped-tail impulse using PSCAD.

The firing of the sphere-gap occurs after 50 ms after starting the charge of the generator and the time to chopping is of 3.5 μs after firing. The chopped-tail waveform obtained in the simulation is shown in figure 4.13. It is necessary to emphasize that front and tail time decrease for the configuration of this circuit; therefore, if it wants to be adjusted to the international standard, values for front and tail resistors must be calculated as defined by Hipotronics [11].

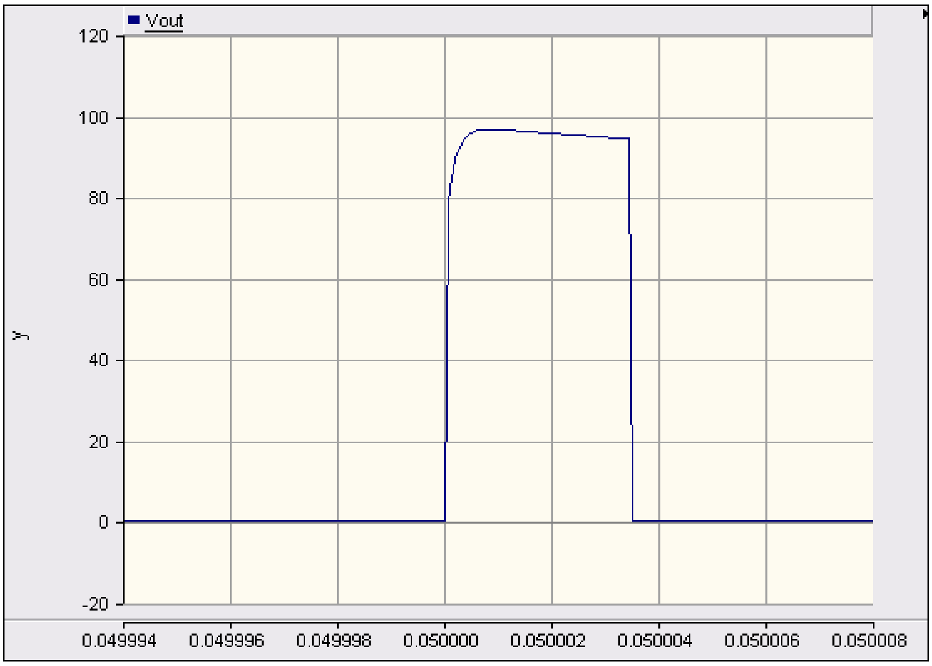


Figure 4.13 - Chopped-tail impulse waveform simulated using PSCAD.

4.2.3 -Chopped-front Impulse

The electric circuit and the parameters of the impulse generator for simulating a chopped-front impulse using PSCAD is the same as shown in figure 4.12 above.

The firing of the sphere-gap occurs after 50 ms after starting the charge of the generator and the time to chopping is of 0.1 μs after firing. The chopped-front waveform obtained in the simulation is shown in figure 4.14.

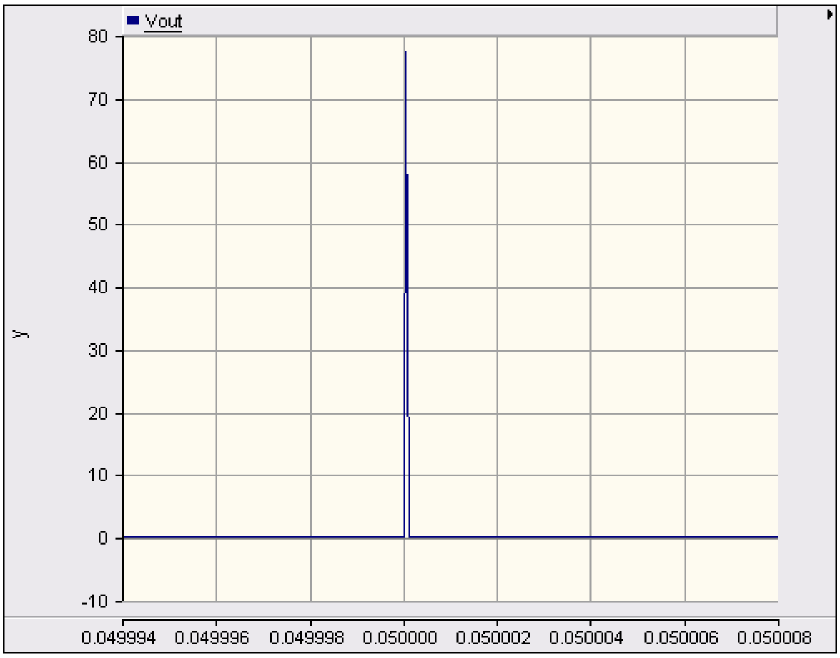


Figure 4.14 - Chopped-front impulse waveform simulated using PSCAD.

This is a very fast waveform. It would be more clearly shown if front and tail resistors are increased, because front and tail times would also increase.

4.3 - Conclusion

It is shown in this chapter how different computer simulators, such as PSpice and PSCAD, may be used in order to study the equipment of the High Voltage Laboratory.

Computer simulators attempt to simulate an abstract model of the impulse test system and help in adjustment of a part of the equipment when required.

For this reason, it is a very popular tool used not only for engineering purposes.

Chapter 5

Standard Techniques for High-Voltage Testing

Principles of High Voltage Testing are standardized in order to make possible reproduction and comparison of the results obtained worldwide. Organizations like the International Electrotechnical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) prepare these documents which, for the standard presented here, establish standard methods of measurement of high voltage and basic testing techniques.

To perform laboratory testing, it is also necessary the information described by the appropriate standard of the apparatus under test, which states its electrical and mechanical characteristics, prescribe methods of testing and acceptance criteria. This Standard is, for post insulators of organic material, the IEC 60660 [27].

In this chapter, a summary of the most important information depicted by the IEEE Standard 4-1995 is shown in order to explain the main characteristics of the standard lightning impulse waveform and test techniques used in the High Voltage Laboratory.

Whenever further information than presented here is required, the Standard IEEE Std 4-1995 [26] must be consulted.

5.1 - Introduction

The IEEE Standard here presented, defines terms of general applicability; presents general requirements regarding test equipment, objects, and procedures; and, describes methods for evaluation of test results. It is applicable to several kinds of high voltage tests, but this report has as subject only dielectric tests with impulse voltages, which are performed at the High Voltage Laboratory.

Requirements in the arrangement of the test object and definitions of the different discharges which can occur in high voltage test are shown below.

5.1.1 -Arrangement of the test object

The arrangement of the test object is absolutely important and should be specified by the appropriate apparatus standard. The electrical discharge characteristics of the test object may be affected by its general arrangement.

Its clearance from other energized or grounded structures, its height above ground level, and the arrangement of the high-voltage lead, among others, may affect the flashover voltage.

As recommended by the IEEE standard [26], a clearance to nearby structures equal to or greater than 1.5 times the length of the shortest possible discharge path on the test object usually makes proximity effects insignificant.

5.1.2 -Interpretation of discharges in high-voltage tests

This section gives the interpretation of electrical discharges in high-voltage test according to defined by the appropriate international standards.

Three different interpretations may be done and are explained below:

- Disruptive discharges
- Nonsustained disruptive discharges
- Nondisruptive discharges

- Disruptive discharge:

A disruptive discharge is a discharge that completely bridges the insulation under test, reducing the voltage between the electrodes practically to zero.

These disruptive discharges are subject to random variation and, usually, a number of observations have to be made in order to obtain a statistically significant value of the disruptive discharge voltage.

- Nonsustained disruptive discharge:

A nonsustained disruptive discharge is a discharge in which the test object is momentarily bridged by a spark or arc. During these events, the voltage across the test object is momentarily reduced to zero or to a very small value. Depending on the characteristics of the test circuit and the test object, a recovery of dielectric strength may occur and may even permit the test voltage to reach a higher value.

Such an event shall be interpreted as a disruptive discharge for post insulator tests as most of apparatus.

- Nondisruptive discharge:

Nondisruptive discharges are those between intermediate electrodes or conductors. They may also occur without reduction of the test voltage to zero but are not considered in post insulators tests because it is not possible a discharge between other points than high voltage and ground leads.

5.2 - Tests with lightning impulse voltage

An impulse without oscillations or overshoot is shown in figure 5.1. Parameters defined in this section are strictly applied to impulses like this.

The waveform obtained by the equipment of the High Voltage Laboratory has oscillations on the wave-front. When this or overshoot occur, the mean curve drawn through them shall be used for interpretation.

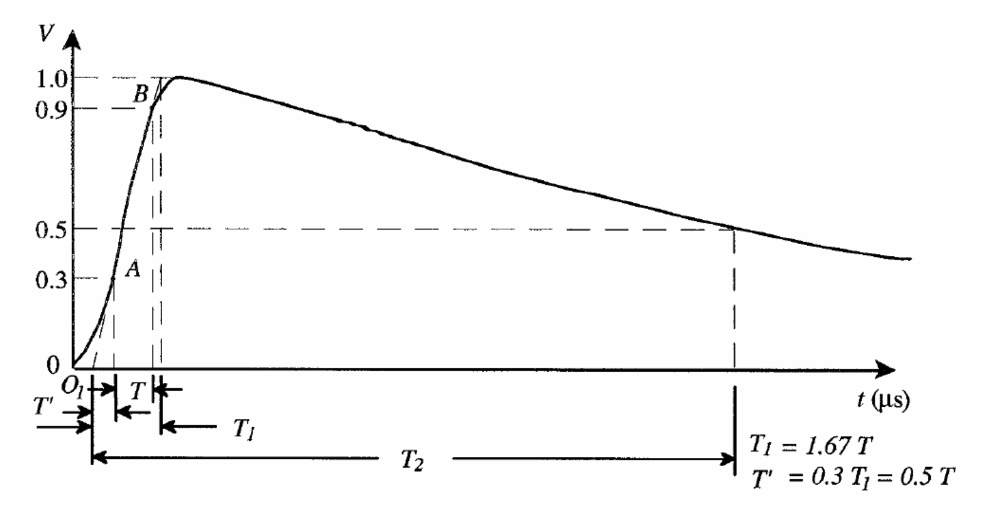


Figure 5.1 – Full lightning impulse without oscillations or overshoots.

5.2.1 -Terms used to characterize full lightning impulses

Next terms listed below are used to characterize full lightning impulses, as defined by the Standard.

- Full lightning impulse:

A full lightning impulse is a lightning impulse not interrupted by any type of discharge, as illustrated in figure 5.1.

- Value of the test voltage:

The value of the test voltage for a lightning impulse without overshoot or oscillations is its peak value.

- Virtual front time (T_1):

The virtual front time T_1 of a lightning impulse is 1.67 times the time interval between the instants when the impulse is 30% and 90% of the peak value, corresponding to points *A* and *B* in figure 5.1.

$$T_1 = 1.67 \cdot (T_{90} - T_{30}) \tag{5.1}$$

- Virtual origin (0_1):

The virtual origin O_1 of a lightning impulse is the instant preceding that corresponding to point *A* in figure 5.1 by a time $0.3 \cdot T_1$. This is the intersection with the time axis of a straight line drawn through reference points *A* and *B* on the wave-front.

- Virtual time to half-value (T_2):

The virtual time to half-value T_2 of a lightning impulse is the time interval between the virtual origin O_1 and the instant on the tail when the voltage has decreased to half of the peak value (50% of the peak value).

- Standard lightning impulse:

The standard lightning impulse is a full lightning impulse having a virtual front time of 1.2 µs and a virtual time to half-value of 50 µs. It is described as a 1.2/50 impulse and is internationally accepted.

5.2.2 -Terms used to characterize chopped lightning impulses

However, if a flashover arc occurs between both electrodes of the post insulator, the waveform results in a chopped impulse. It is characterized by an initial discontinuity, decreasing the voltage, which then falls toward zero with or without oscillations as shown in figure 5.2.

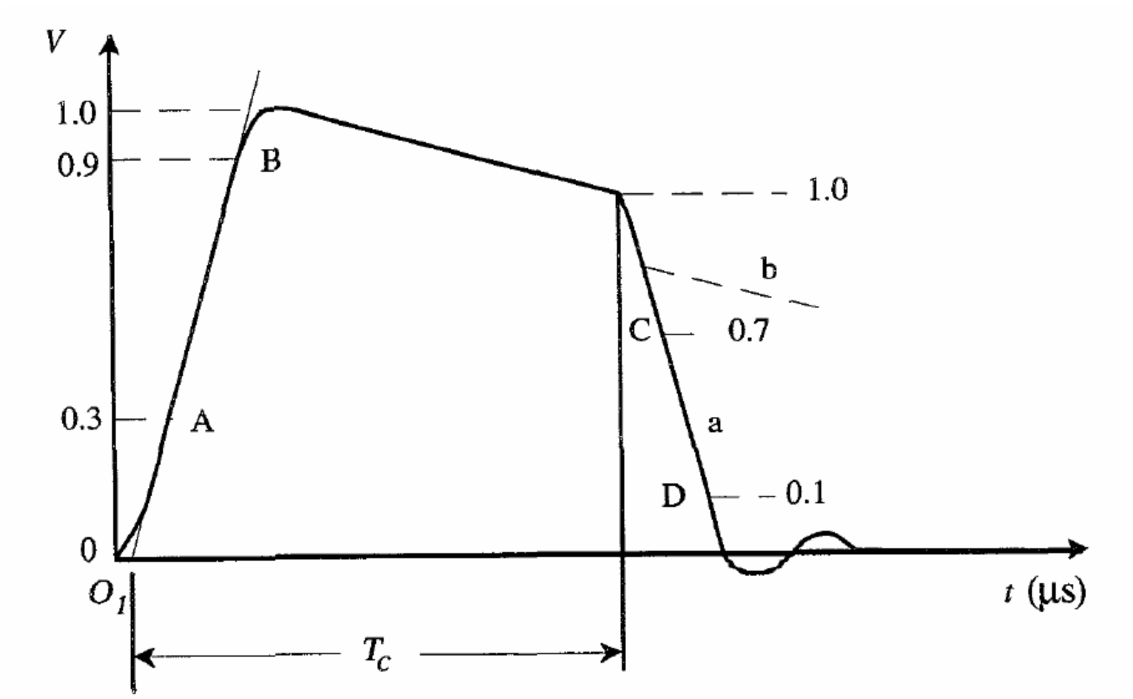


Figure 5.2 – Lightning impulse chopped on the tail.

In figure 5.2, line *a* shows a chopped wave caused by a disruptive discharge, and dotted line *b* shows a chopped wave caused by a nondisruptive discharge.

Next terms listed below characterize chopped lightning impulses.

- Chopped lightning impulse:

A chopped lightning impulse is a prospective full lightning impulse during which any type of discharge causes a rapid collapse of the voltage. The collapse of the voltage can occur on the front, at the peak, or on the tail (figure 5.2).

A chopped lightning impulse may occur because of a discharge in the internal or external insulation of a test object.

- Instant of chopping (chop time) for tail-chopped impulses:

The intersection of the 10%-70% line on the chop and the tail of the wave is shown in figure 5.2.

- Voltage at the instant of chopping:

The voltage at the instant of chopping is the voltage at chop time.

- Time to chopping (T_c):

The time to chopping T_c is the time interval between the virtual origin and the instant of chopping.

- Characteristics related to the voltage collapse during chopping:

The characteristics of the voltage collapse during chopping are defined in terms of two points, *C* and *D*, at 70% and 10% of the voltage at the instant of chopping, as shown in figure 5.2.

During chopped lightning impulse tests, the gap used for chopping shall be located as close as possible to the terminals of the test object without disrupting its electric field distribution. The impedance of the chopping circuit shall be minimized by the use of the shortest possible leads to the chopping gap.

If the undershoot during chopping exceeds 50% of the voltage at the instant of chopping, the distances can be increased but should not exceed a lead length greater than the height of the test object.

- Standard chopped lightning impulse:

A standard chopped lightning impulse is a standard impulse that is chopped by an external gap after a time between 2 and 5 μs.

- Linearly rising front-chopped impulse:

A voltage rising with approximately constant steepness, until it is chopped by a disruptive discharge, is described as a linearly rising front-chopped impulse. To define such an impulse, the best-fitting straight line is drawn through the part of the front of the impulse between 50% and 90% amplitudes (designated *E* and *F* respectively in 5.3). The impulse is considered to be approximately linear if the front, from 50% up to the instant of chopping, is entirely enclosed between two lines parallel to the line *E-F*, but displaced from it in time by $0.05 \cdot T_r$.

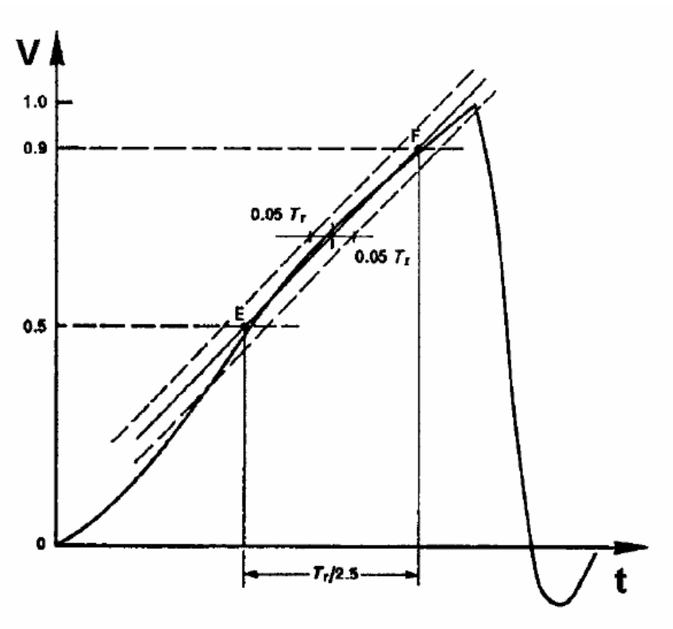


Figure 5.3 – Linearly rising front-chopped impulse.

This impulse is defined by:

a) The time to chopping T_c which is the time after point *F* where the slope of the voltage wave becomes and stays negative.
b) The voltage at the instant of chopping.
c) The rise time T_r which is the time interval between *E* and *F* multiplied by 2.5.
d) The virtual steepness *S* which is the slope of the straight line *E-F*, usually expressed in kilovolts per microsecond (KV/µs).

5.2.3 -Terms used to characterize impulses with oscillations or overshoot

In case of standard waveform shows overshoot or oscillations, the determination of the peak value for a lightning impulse depends on the oscillation frequency or overshoot duration.

If the oscillation frequency is less than 0.5 MHz or exceeds 1 µs, the peak value is taken as the maximum value of the recorded trace, as shown in figure 5.4.

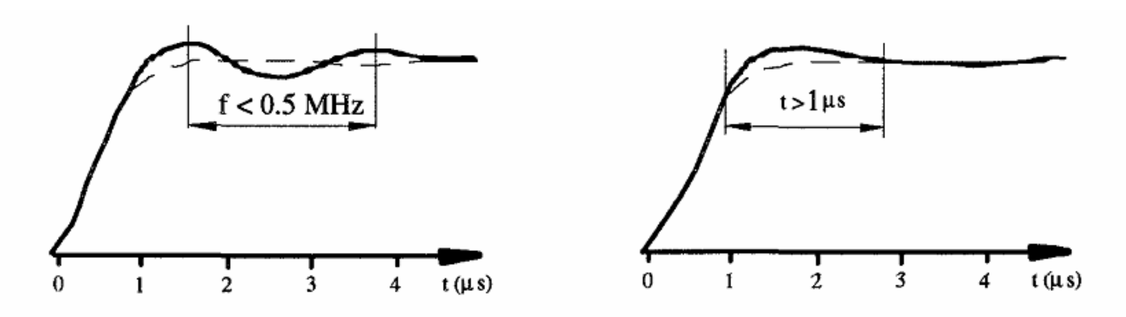


Figure 5.4 – Examples of lightning impulses with oscillations or overshoots (1).

If the oscillation frequency is greater than 0.5 MHz or less than 1 μs, the peak value is determined from the maximum value of the mean curve, as shown in figure 5.5, or from the exponential fitting of the front and tail portions.

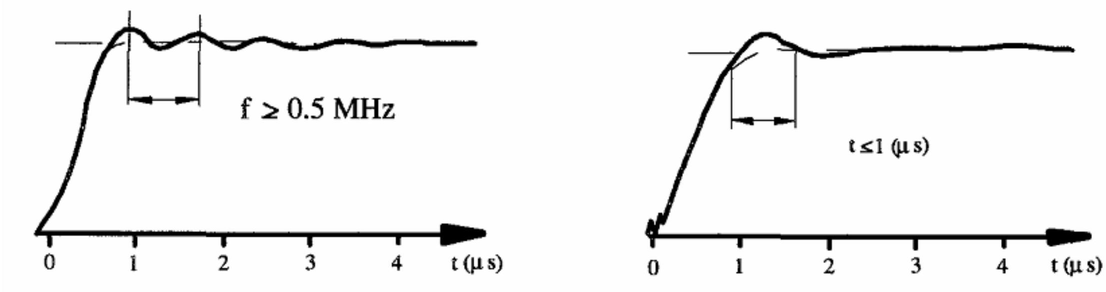


Figure 5.5 – Examples of lightning impulses with oscillations or overshoots (2). Mean curves shown as dotted lines.

If oscillations are present on the front, points *A* and *B* should be taken on the mean curve drawn through these oscillations. In the case of the waveform obtained at the High Voltage Laboratory, there is a superimposed oscillation on the wave-front.

5.2.4 -Tolerances

The following differences are accepted between values for the standard impulse and those actually recorded:

a) Peak value	±3%
b) Virtual front time	±30%
c) Virtual time to half-value	±20%

It is emphasized that the tolerances on the peak value, front time, and time to half-value constitute the permitted differences between specific values and those actually recorded by measurements. These differences should be distinguished from measuring errors, which are the differences between values actually recorded and true values.

Overshoot or oscillations in the neighbourhood of the peak are tolerated, provided that their single-peak amplitude is not larger than *5%* of the peak value. Its measurements shall be made by a system with specific properties, but this problem was not found at the Laboratory and, therefore, not studied. In commonly used impulse generator circuits, oscillations on the wave-front during which the voltage does not exceed 90% of the peak value have generally insignificant influence on test results.

Chapter 6

Practical problems emerging in measurement

Engineering is the discipline of applying technical, scientific and mathematical knowledge in real life. Sometimes, the results of this real part differ from the theoretical and practical fundamentals studied at faculties of engineering because of the negative effect of certain element. When it occurs, this is the signal that a problem occurs and a meticulous search must begin. For the engineer, it is important to find where the problem is in order to understand it, replace the damage component and recover the normal behaviour of the system.

This chapter reports on the practical problems emerging in measurement of the lightning impulse waveform of tests on insulators of organic material at the High Voltage Laboratory. Such problems do not make possible to carry out lightning impulse tests on insulators of organic material as it is described in the relevant international standards and the solution must be founded. They are, therefore, cause of multiple discussions.

To perform the study of the emerging problems in the equipment already mentioned, it was possible to count on experienced engineers who presented their ideas and enriched the process: a retired engineer with large experience in High Voltage Laboratories, an engineer specialized in calibration of this kind of equipment, and a group of professors of the Faculty of Engineering who, in different moments, helped and contributed with their experience.

6.1 - Preliminary

When the work was planned at the beginning, the main purpose of the Master's Thesis was to study how lightning impulse tests are made complying with international standards, but when the equipment started using, an unknown phenomenon appeared. In that moment, the main objective of this work changed its direction and was focused on discovering the origin of the problem and solving it, but, at the same time, without forgetting the first objective of the master's thesis.

The equipment of the High Voltage Laboratory is configured with front and tail resistors which are usually used, and, although it does not have any influence on the problem, the device under test was a standard indoor post insulator of organic material and with internal metal fittings according to IEC 60273.

All experimental waveforms that are shown in this chapter were obtained in the impulse test system configured according to parameters shown in table 6.1 and a charging voltage per stage of - 25kV. As the total number of stages *n* is five, 125 kV (positive) are obtained as maximum output voltage theoretically, but it must not be forgotten that this value is affected by the efficiency of the system as was shown in chapter 4, and therefore, it is lower.

Table 6.1 — Impulse test system parameters

Rf	35 Ω
Rt	200 Ω
Rch	18 kΩ
Cg	500 nF
n	5 stages

The process is divided in parts and each part is studied conscientiously to lead to appropriate conclusions.

Apparently, there are three different phenomena which affect the standard waveform and are explained in next section.

All waves shown in this report are captured and displayed using a Tektronix TDS 340A or Tektronix 2012B digital storage oscilloscope (DSO). Both DSOs are calibrated to national standards and use the same scope prove for X100 attenuation, compensated in accordance with the guidance of IEC 60060-2.

The DSO Tektronix 2012B does not belong to the High Voltage Laboratory, for that reason, it was not described in chapter 3.

Two oscilloscopes were used because the Tektronix TDS 340A that belongs to the Laboratory did not have as many options as the Tektronix 2012B, which were necessary to capture with more accuracy all the details of the problems. In this way, a possible influence of the measuring device on the problems was also ruled out.

As depicted in chapter 3, the measurement of impulse waveforms is performed using a capacitor divider, approved and calibrated measuring device in accordance with IEC 60060-2 and -3, where the DSO input is connected to its low voltage arm.

The study of every theory proposed to solve the problem is shown in this report.

6.2 - Description of the problems

Test waveform presents a shape different to the typical one described by the international standards (see section 5.2). Something has effect on it but its origin is unknown. They are “interferences” that appear on the wave-shape and change from time to time. Thus, the equipment is being affected by a random phenomenon, what makes the study longer and more difficult.

As said, it is a random problem, therefore, it does not appear in every voltage application and its shape and amplitude vary between them. Thus, in figure 6.1, it is possible to see a test waveform obtained in the Laboratory which is not affected by this unknown problem. Its wave-shape is the typical of a standard waveform as depicted in chapter 5, but front and tail times are not adjusted because it does not have any influence on the problem.

Figure 6.1 - Waveform for a standard lightning voltage impulse test. Volts and seconds per division rate selected: 200V/div, 50µs/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

But, usually, test waveforms are displayed with positive and negative voltage impulses on it. Most of the times, voltage amplitudes are even higher than the peak voltage of the standard wave-shape.

In figure 6.2 below, it is shown a test waveform as is normally displayed in the oscilloscope. It is possible to see a very fast positive voltage impulse before wave-front and two single negative voltage impulses after peak voltage of the standard wave-shape.

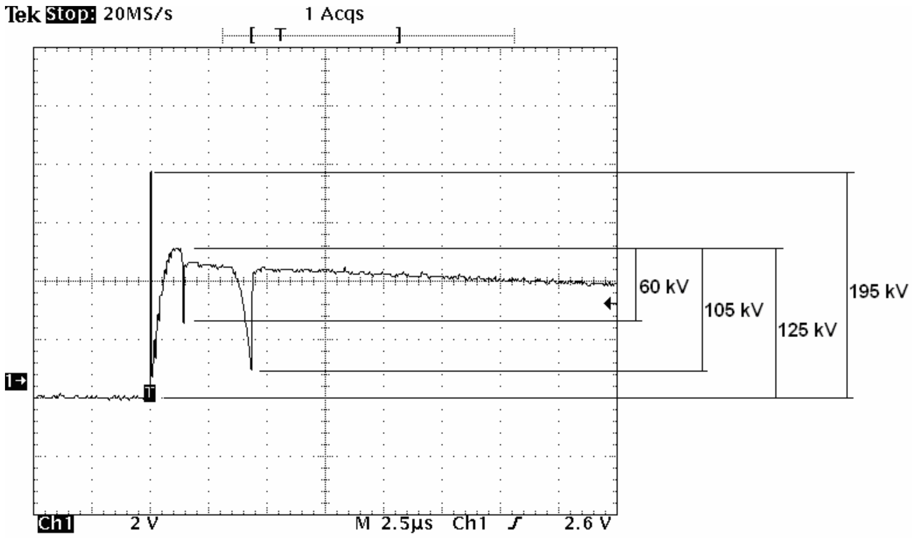


Figure 6.2 - Test wave with three "interferences": a positive voltage impulse before wave-front and other two negative voltage impulses at wave-tail. Volts and seconds per division rate selected: 2V/div, 2.5µs/div. Captured using a Tektronix TDS 340A digital storage oscilloscope.

It is seen that the second negative voltage impulse is triangular shaped and falls as ramp function and rises very fast, almost vertical, as step function.

When the wave-front is enlarged, as shown in figure 6.3, a new phenomenon became relevant: a superimposed oscillation on the rising edge. The point (A) shows the origin of the lightning impulse waveform.

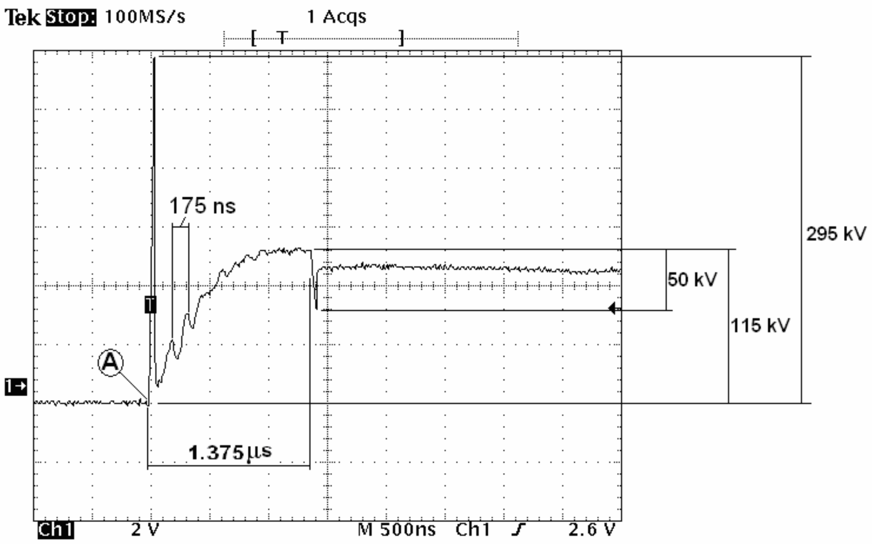


Figure 6.3 – Test wave-front with a fast positive voltage impulse and superimposed oscillation on the wave-front. Volts and seconds per division rate selected: 2V/div, 500ns/div. Captured using a Tektronix TDS 340A digital storage oscilloscope.

And, finally, when the parameter seconds per division of the oscilloscope is increased, the "interferences" on the wave-tail are shown as a run of negative voltage impulses (see figure 6.4), triangular shaped as well, with a no-constant period. Its period increased with time, and it goes from a few to tens of µs. This phenomenon is also random and usually starts when wave-tail voltage value is under 40-30% of the peak value, but, in some voltage applications, single negative voltage impulses with the same shape are captured out of the series as shown in figure 6.2.

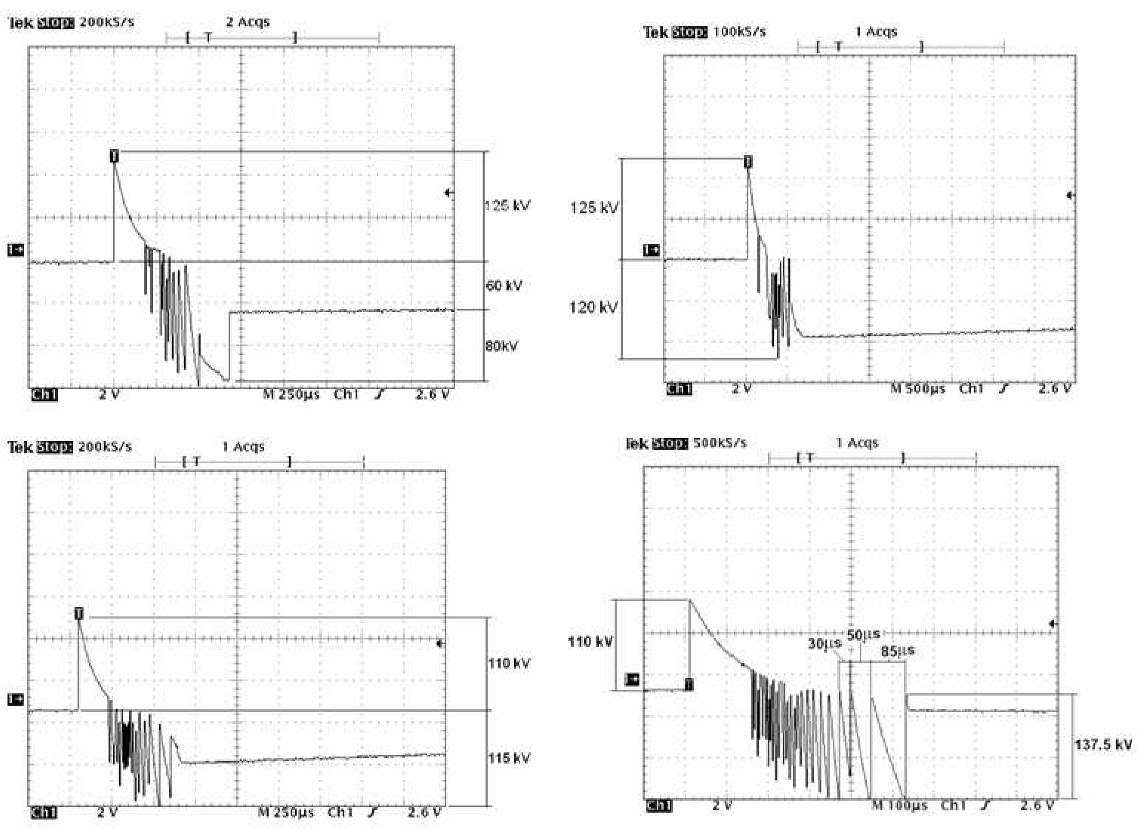


Figure 6.4 - Test waveforms that show the run of negative voltage impulses on the wave-tail. Volts and seconds per division rate selected are for all: 2V/div; 100, 250 and 500μs/div. Captured using a Tektronix TDS 340A digital storage oscilloscope.

Thus, as the origin of the “interferences” is not clearly known, it is decided to divide the study in three parts for a better understanding:

- The oscillations on the wave-front;
- The run of negative voltage impulses on the wave-tail;
- The fast positive voltage impulse before the wave-front.

These three parts are explained below. The oscillations on the wave-front have an easy explanation; therefore, this phenomenon is explained firstly and, then, the other two phenomena are discussed separately.

6.2.1 -The oscillations on the wave-front

As shown in figure 6.3, the lightning impulse waveform generated by the equipment of the High Voltage Laboratory has significant noise on the rising edge. This superimposed oscillation is clarified by Kind and Feser [25]: the firing of the impulse generator causes the shape of the voltage for lightning impulse voltages deviates considerably from the theoretically calculated on the wave-front.

Figure 6.5 shows an example of the voltage waveform with superposed oscillations. The noise on the rising edge may cause a wrong measurement of the value at which the signal is at 30% of the peak voltage. The front-oscillations result from the rapid firing of the upper stages of the multi-stage (5 stages) generator of the High Voltage Laboratory. A voltage is suddenly coupled through longitudinal capacitance of the generator stages to the connecting lead of the load capacitance, and it gets reflected at that end. This conclusion has not been obtained when the simulation of stray capacitances between the generator stack and the metallic sheet of the Faraday cage was made (see chapter 4).

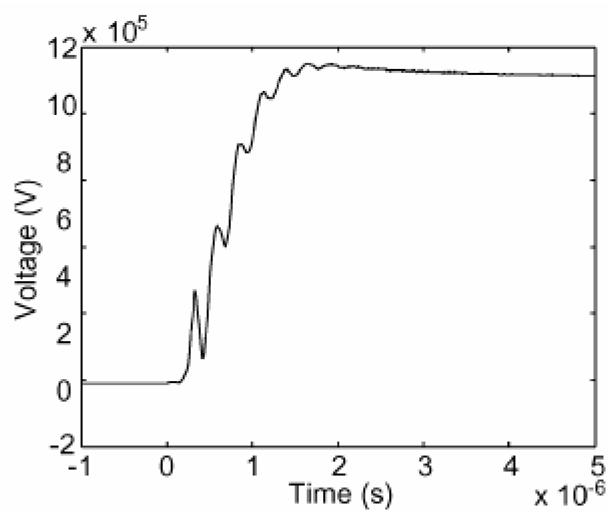


Figure 6.5 – Front-oscillation of lightning impulse voltage. IEC 601083-2 test data generator impulse waveform: Case 11.

It is necessary to obviate the fast positive voltage impulse before the wave-front, so that similarity between figures 6.3 and 6.5 can be accepted, what reveals that the theory of Kind and Feser [25] is completely fulfilled. By means of a damping resistance between the impulse generator and the load capacitance, that is the front resistance, this oscillation can be appreciably reduced. But, it is a real limitation because the front (damping) resistance has to have a specific value in order to damp the oscillations as well as to obtain a time to front according to the standards (1.2 µs). More information this phenomenon can be found in the reference [25] already mentioned.

6.2.2 -The run of negative voltage impulses on the wave-tail

At this point, the run of negative voltage impulses on the wave-tail is studied.

As shown in figure 6.2 above, the test waveform usually displays negative voltage impulses after the peak. These impulses are triangular shaped, fall as ramp function and rise very fast, almost vertical, as step function. Such phenomenon is also random and cases like shown in figure 6.2 do not appear so usually. Even when in some voltages applications, negative voltage impulses appear after the peak, it becomes evident when the wave-tail voltage falls under 40-30% of the peak value. At this time, a run of negative voltage impulses triangular shaped with a no-constant period, no-constant frequency, is shown on the waveform captured by the DSO and, just in a few voltage applications, some negative voltage impulses, triangular shaped too, are captured out of the series.

In figure 6.4, four different test waveforms captured by the oscilloscope are shown. They present four different random “interferences” on the wave-tail that affect the standard waveform and are object of study. They are captured in four different voltage applications.

These test waveforms seem to follow a kind of pattern which shows the way to discover the source of the “interference” on the wave-tail. Next figure 6.6 shows the test waveform with “interferences” on the wave-tail. As said above, its period is variable, it increases with time and goes from a few to tens of μs, and, from one voltage application to another, their amplitude change as well. After the run of negative voltage impulses, it seems that a residual voltage is kept, but it is drained away after a certain time. It is not clearly shown in this figure, but usually it is in the order of milliseconds.

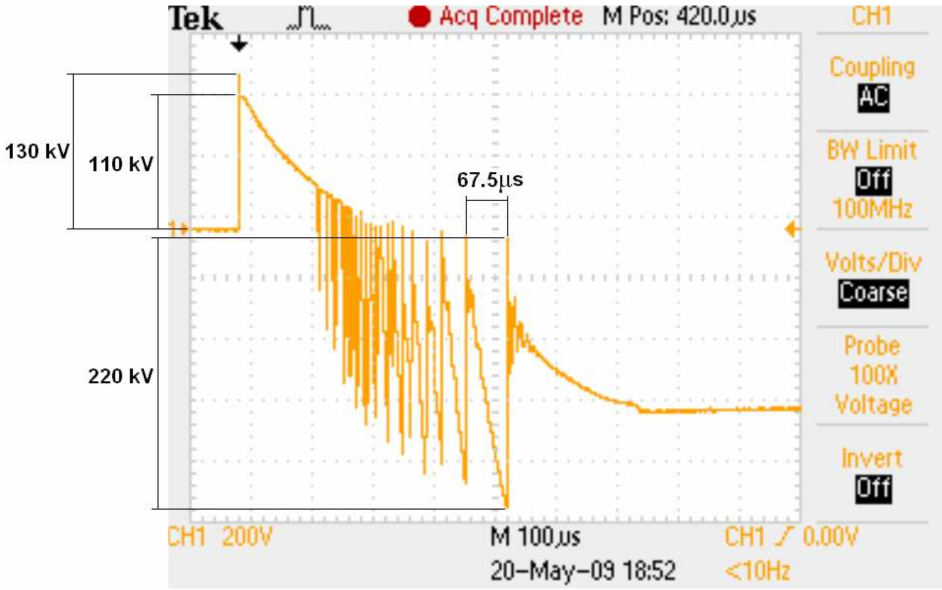


Figure 6.6 – Test waveform which shows the run of negative voltage impulses on the wave-tail. Volts and seconds per division rate selected: 200V/div, 100μs/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

It must be emphasized that such high voltage, a voltage peak-to-peak of about 220 kV as shown in figure 6.6, is unconnected with the normal behaviour of the system, therefore, all the electric circuit was checked in order to find some damage component but it was not found any which could affect the normal behaviour of the equipment and cause such voltage amplitude. These “interferences”, both, the positive voltage impulse and the run of negative voltage impulses, show a high voltage value that does not exist in any point of the system; it is not generated by the system. Moreover, if such negative voltage impulses showed in figure 6.2 were real, it would cause a sudden fall of the waveform as a chopped waveform (see chapter 5), but it does not occur. On the contrary, the waveform recovers and continues its fall as depicted by the international standard. For this reason, it is thought that a problem with the measuring system may be the origin of the “interferences”.

If the wave-tail is enlarged, the run of negative voltage impulses triangular shaped are shown more clearly (see figure 6.7). Its period is variable and it is seen that, in last triangles, they do not fall as a straight ramp but as a slightly curved ramp, what seems to be the typical charging waveform of a capacitor. The residual voltage kept seems to be a charging waveform of a capacitor but with a substantially higher charge time constant.

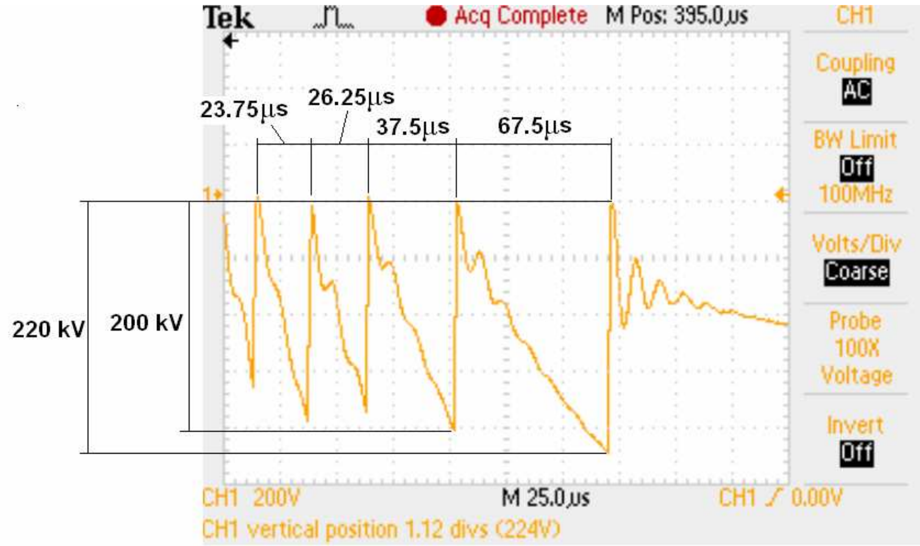


Figure 6.7 – Enlarged test waveform which shows the run of negative voltage impulses on the wave-tail. Volts and seconds per division rate selected: 200V/div, 25µs/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

When the parameter seconds per division of the oscilloscope is increased up to 25 ms/div, as shown in figure 6.8, it can be seen what really happens. The standard waveform has a length of about 100 µs, thus, it is too short time to be clearly shown with this time base. The positive voltage impulse of 80 kV is the standard waveform, and the negative voltage impulse of 110 kV is the run of negative voltage impulses. Then, there is a double exponential waveform which seems to represent the discharge of a capacitor through two different ways: one produces the positive exponential wave and another one produces the negative exponential wave. At the end, the residual voltage is drained away and the signal stays on zero.

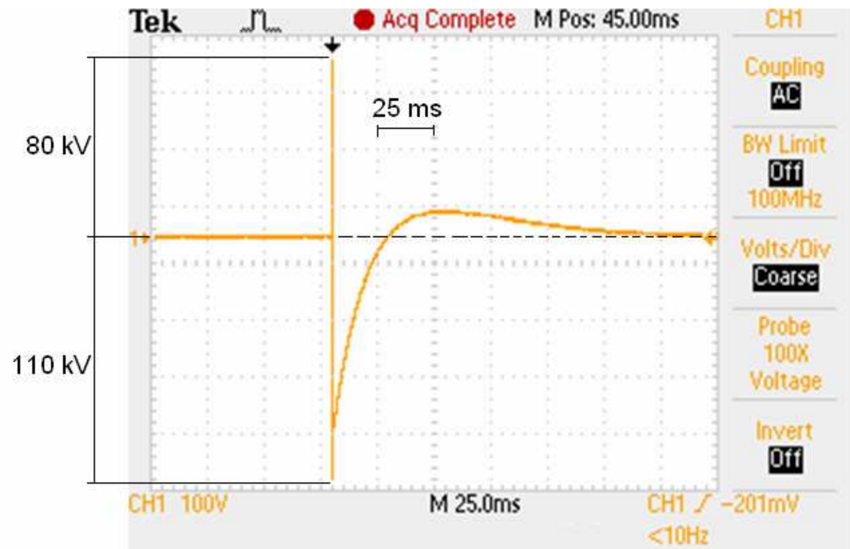


Figure 6.8 – Test waveform. Volts and seconds per division rate selected: 100V/div, 25ms/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

Another experiment is performed. Electromagnetic interferences (EMI) are thought to be the cause of the problems.

Since front, tail and charging resistors of the fifth stage of the generator stack are removed (see circuit in figure 3.6), there is an impulse generator with 4 stages but disconnected to the measuring device; therefore, the discharging of the capacitors occurs through the tail resistors, but surprisingly, being no connected the generator stack to the voltage divisor, the oscilloscope displays the waveforms shown in figures 6.9 to 6.11. The only connection that exists is a connection through a stray capacitance between the fourth stage of the generator and the top of the generator stack. The measuring cable is connected to the top of the generator stack and the capacitor of the fifth stage is short circuited during this test, as recommended by Hipotronics.

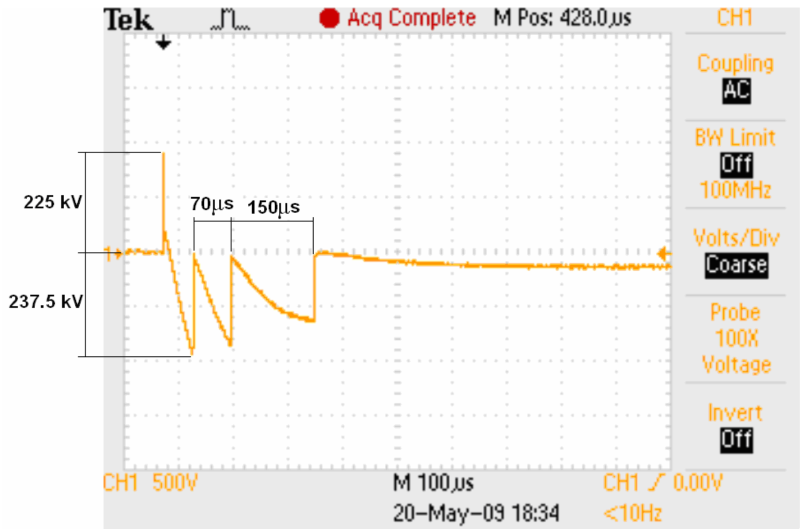


Figure 6.9 – Test waveform that shows electromagnetic interferences (EMI). Volts and seconds per division rate selected: 500V/div, 100μs/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

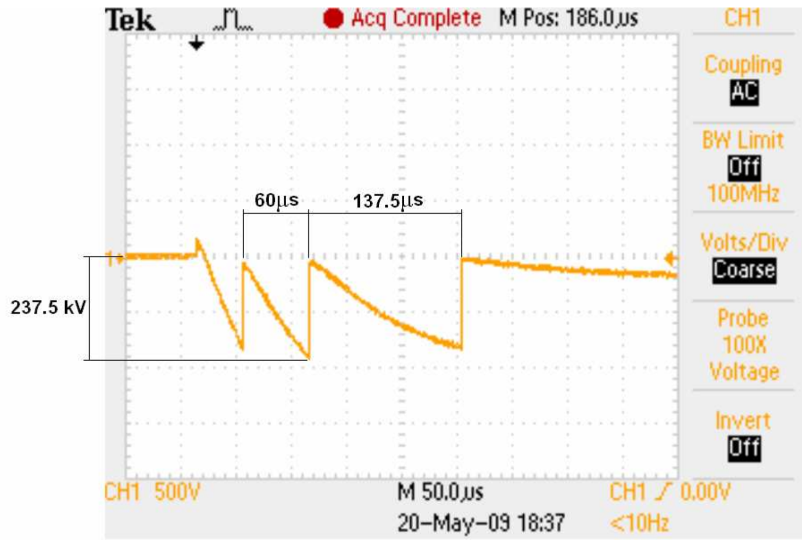


Figure 6.10 – Test waveform that shows electromagnetic interferences (EMI). Volts and seconds per division rate selected: 500V/div, 50μs/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

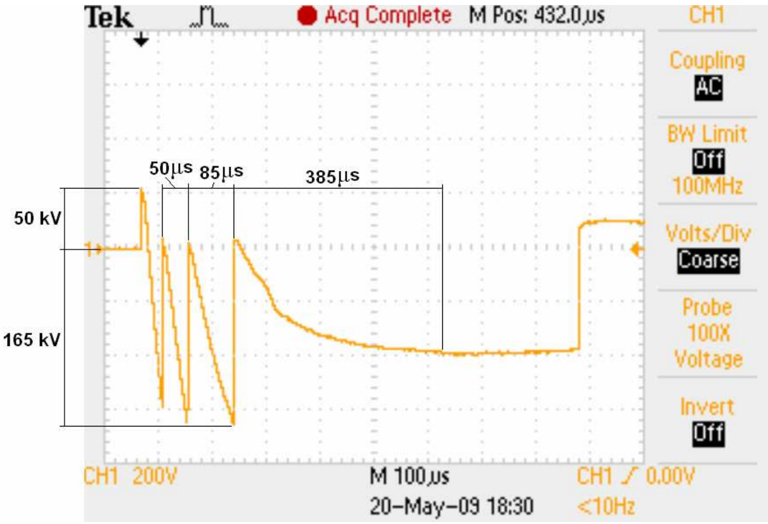


Figure 6.11 – Test waveform that shows electromagnetic interferences (EMI). Volts and seconds per division rate selected: 200V/div, 100µs/div. 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

The equipment cannot generate higher voltages than 125 kV, and the stack of capacitors is absolutely discharged after 200 µs; therefore, these "interferences" are just justified by a problem in the measuring device.

The solution of the problem is explained in section 6.4. Before, the fast positive voltage impulse before the wave-front is presented, because both problems may be related.

6.2.3 -The fast positive voltage impulse before the wave-front

The fast high-amplitude positive voltage impulse before the wave-front is a random impulse, that is, its amplitude varies between voltage applications from a few to hundreds of kilovolts (kV), and, it is even not captured in some few voltage applications.

As written before, the maximum voltage reached in the equipment is 125 kV when the voltage at the sphere-gaps reaches the disruptive voltage value, a flashover arc occurs and all the stages become connected in series. Due to this reason, it is not possible that the wave, captured using an oscilloscope, is up to 295 kV at any moment (see figure 6.3) and the right explanation to this "interference" must be discovered.

An impulse waveform generated experimentally in order to analyze a zero-phase filter design for a revision of IEC 60060-1 and -2 (High Voltage Test Techniques) shows the way to find out the reason for this fast positive voltage impulse before the wave-front.

The description made by Lewin, Tran, Swaffield and Hällström [28] in the revision mentioned above, presents an unprocessed waveform which was generated from a two-stage Marx generator with no load in circuit. This waveform displays noise near the origin and may lead to an incorrect estimation of the true origin (see figure 6.12).

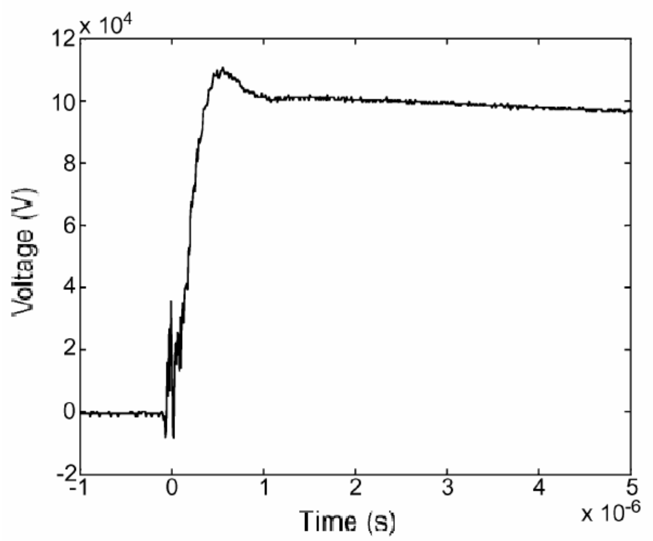


Figure 6.12 – Experimentally generated impulse voltage with noise near the start of the impulse signal [28].

The noise is due to electromagnetic coupling from the test generator to the digital storage oscilloscope (DSO) input and was deliberately permitted in order to experimentally evaluate the proposed techniques under study. These oscillations greater than the background noise due, for example, to the firing of spark gaps [29] are permissible as specified by IEC 60060-1, because it does not occur on the part of the waveform in excess of 90% of the peak voltage, but at the High Voltage Laboratory the problem is worse. In figure 6.12, this signal noise is only up to a 35% of the peak value, but at the High Voltage Laboratory, it can be up to hundreds of kilovolts (kV), values even two times higher than the peak value of the impulse voltage waveform.

Thus, this idea is taken into account and the possible electromagnetic coupling from the firing of the test generator to the DSO input is studied.

The cable which joins the top of the stack of capacitors of the impulse generator to the capacitive mixed divider is removed; this test permits to study the signal which is captured by the oscilloscope when the firing of spark gaps occurs and is just transmitted by the air, by means of stray capacitances, between components. It shows that an electromagnetic coupling occurs between them, and introduces disturbances to the lightning impulse voltage wave-shape. An exchange of electromagnetic energy in the form of radiated and absorbed power exists between them.

It is thought that electromagnetic coupling between circuits affects directly the LV arm of the capacitive mixed divider, that is the DSO input, because the electromagnetic noise should not affect the signal inside the measuring coaxial cable RG11/U; it is a shielded cable surrounded by a conductive layer earth connected, which provides protection of the signal from external electromagnetic interferences.

Electromagnetic interferences could affect the LV arm of the voltage divider because a bad contact in this element was found, but it is not possible to explain as far as shown in next section 6.4. The signal noise due to electromagnetic coupling, deliberately permitted by means of taking off the cable from the top of the stack of capacitors to the HV arm of the capacitive mixed divider, is captured by the oscilloscope (DSO) and is shown in figure 6.13.

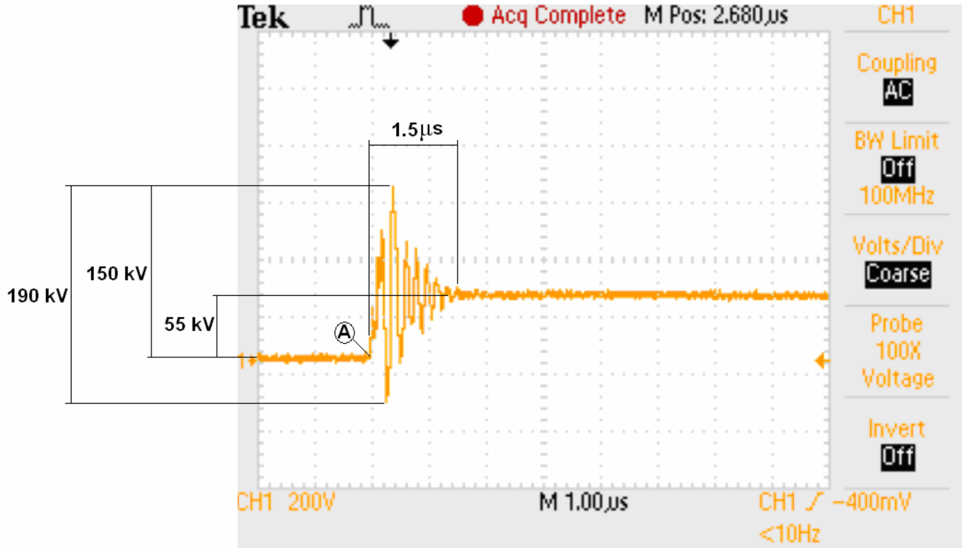


Figure 6.13 – The signal noise due to electromagnetic coupling from the stack of capacitors to the LV arm of capacitive mixed divider. Volts and seconds per division rate selected in both: 200V/div, 1µs/div, 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

The captured signal is a damped oscillatory wave. The impulse test system was configured to give rise to 125 kV as maximum output voltage, and the signal noise reaches 190 kV peak-to-peak. This value agrees with the measurement of the fast positive impulse made in figure 6.2 (195 kV), but, as written before, the amplitude of this interference varies between voltage applications, but not its period and duration. In any case, if the electromagnetic interference affects directly the LV arm, the divider ratio is not applicable, therefore, these voltages would really be lower amplitude ones. Figure 6.14 shows the magnified signal noise from figure 6.13.

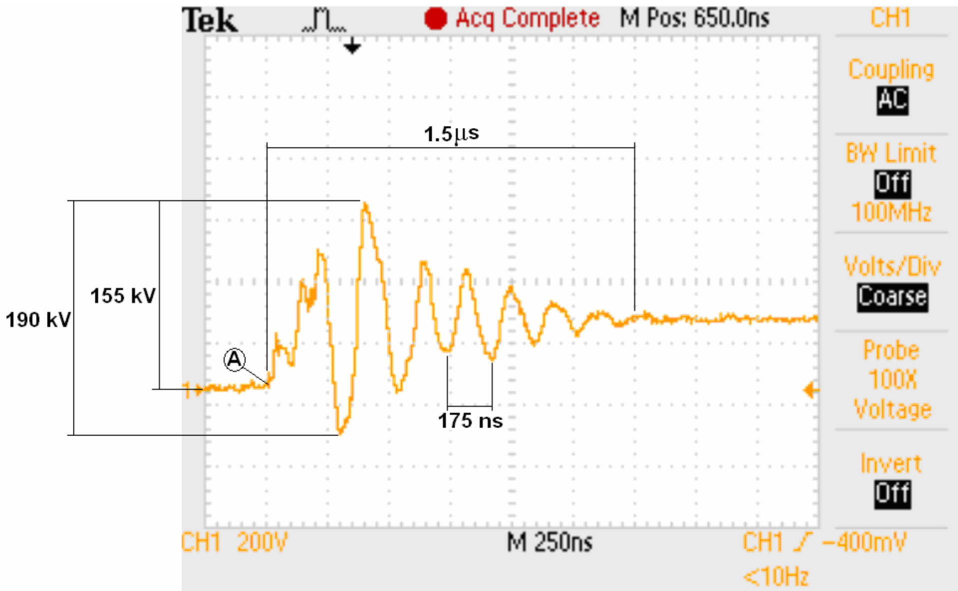


Figure 6.14 – The signal noise due to electromagnetic coupling from the stack of capacitors to the LV arm of capacitive mixed divider. Volts and seconds per division rate selected in both: 200V/div, 250ns/div, 100X probe attenuation. It was captured using a Tektronix TDS 2012B digital storage oscilloscope.

In figure 6.14, the waveform presents second order harmonics into it during the first 250 ns after the origin (A). The period of the signal noise is 175 ns, and it is equal to the period of the superimposed oscillation on the front edge as seen in figure 6.3. Its duration is 1.5 µs, and it is also approximately equal to the duration of the front edge of this wave shown in figure 6.3, which is 1.375 µs. It is necessary to remark on the fact that this waveform is affected by a negative voltage impulse which does not permit to make a right measurement; consequently, it is possible to state that both periods are equal.

To remind what is seen in chapter 5 of this report, a full lightning impulse wave-shape is specified in the international standards as having a front time T_1 of 1.2µs ± 30%, which gives the next validity interval:

$$0.84\mu s \le T_1 \le 1.56\mu s$$

Finally, it is possible to write as a conclusion that the fast positive voltage impulse before the wave-front is due to an electromagnetic coupling on the low voltage arm of the voltage divisor, but the positive impulse appears because of a problem in the measuring device that is explained in section 6.4.

6.3 - Other things which were thought as cause of the problems. Previous steps

During the search process, several engineers gave their advices and some changes were made at the High Voltage Laboratory, but they did not succeed. They are listed in this section in order to present the information of the whole process and all the steps that were made.

- Shielding of the cables between the control console and the Faraday cage by means of a metal gutter connected to earth.
- Substitution of front and tail resistors in order to make sure that the problem was not caused by a deterioration of these elements or possible inductive components.
- Adjustment of the sphere-gap spacings: it was thought that it might affect the firing and cause the “interferences” on the wave-front.
- Verification of the trigger system: it was thought that the deterioration in this system might cause the positive voltage impulse before the wave-front. The electrical circuit was checked and the maximum output signal of the trigger system is 15kV.
- The choice of earthing system has implications for the safety and electromagnetic compatibility of the power supply; therefore, it was studied together with checking the conduction of all earth connections. New earth connections were made.
- It was thought that the positive voltage impulse before the wave-front was caused by the effect of stray capacitances because of the shape of this impulse which is shown in figure 6.15 below.

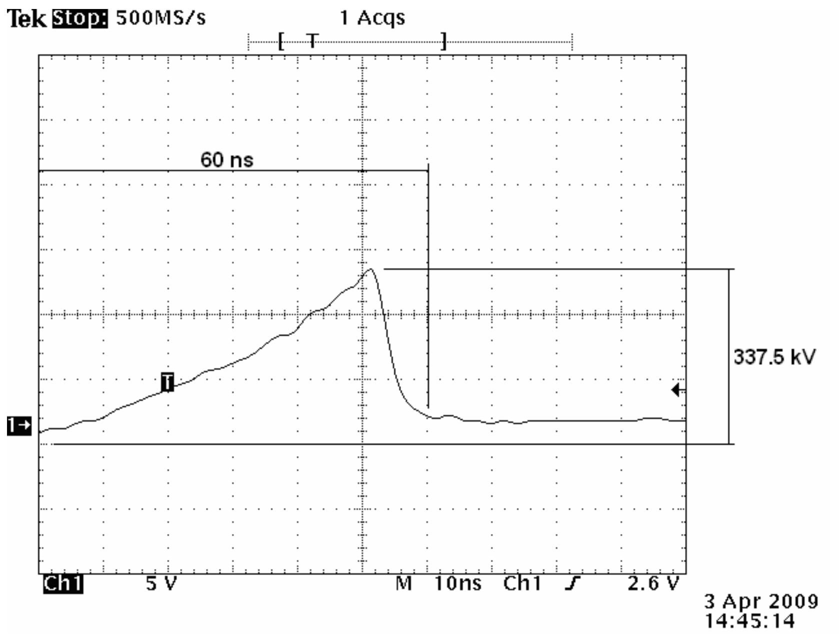


Figure 6.15 – Enlargement of the positive voltage impulse before the wave-front. Volts and seconds per division rate selected are for all: 5V/div, 10ns/div. Captured using a Tektronix TDS 340A digital storage oscilloscope.

- The equipment layout was changed to minimize the influence of the LC circuit made of stray inductances and stray capacitances of the system. But these stray capacitances have not influence on this problem, as was shown in chapter 4.
- The compensation of the probe of the oscilloscope was checked.
- All the electric circuit of the impulse generator was checked looking for any deterioration that might amplify any signal.
- Due to a potential difference between two parts of the generator structure, there was a flashover arc that caused electromagnetic interferences on the measuring equipment. This part of the equipment and the new provisional connection to earth made in order to avoid this flashover arc on the metallic structure are shown in figure 6.16.

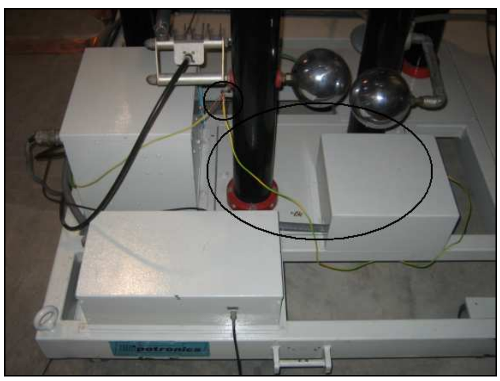


Figure 6.16 – Part of the equipment where there was a potential difference with provisional earth connection.

In short, many different tests and changes were performed in order to understand the equipment behaviour and check the validity of all the recommendations.

6.4 - Solution to the problem

Tests and studies show that the origin of the problem is in the measuring device. A puncture in any capacitor of the high or low voltage arm of the capacitive voltage divider shown in figure 3.14 may be the cause of distortion of the standard waveform. As it is a random phenomenon, this loss of dielectric strength of the capacitor is not permanent, but it got worse during the period of work at the High Voltage Laboratory.

The capacitive divider is made up of stacks of individual capacitors housed in oil filled cylinders of insulating material. This puncture permits a disruptive discharge passing the dielectric of the capacitor. Therefore, the divider ratio change and these high amplitude impulses occur, but they are never higher than the maximum output voltage of the generator.

A possible bad contact in the low voltage arm of the capacitive voltage divider was also found. In normal conditions, the capacitance of this element is 371 nF, but it was measured by means of a digital multimeter and a variable capacitance about 2 nF was discovered. It is clearly shown that the problem is caused by a deterioration of components, because after trying to repair the low voltage arm, it worked for a few time, but after some voltage applications, the "interferences" appeared again.

This bad contact in the LV arm mentioned also causes that electromagnetic interferences affect the DSO input and the fast positive voltage impulse before the wave-front occurs.

In short, it is a random phenomenon, thus, it is not possible to demonstrate it using simulation because there are two causes:

- A puncture in a capacitor that changes the divider ratio.
- A bad contact in the low voltage arm that causes the wave-tail falling as a slightly curved ramp and recovering quickly to the standard wave-shape.

This bad contact is probably made through a stray capacitance, because it seems to be the typical waveform of the charge of a capacitor with a sudden return to the standard wave-shape caused, probably, by a disruptive discharge passing the dielectric of this stray capacitor. This effect "charge of stray capacitor-disruptive discharge" is repeated up to all the energy has been drained away.

The model used to explain the problem is shown in figure 6.17.

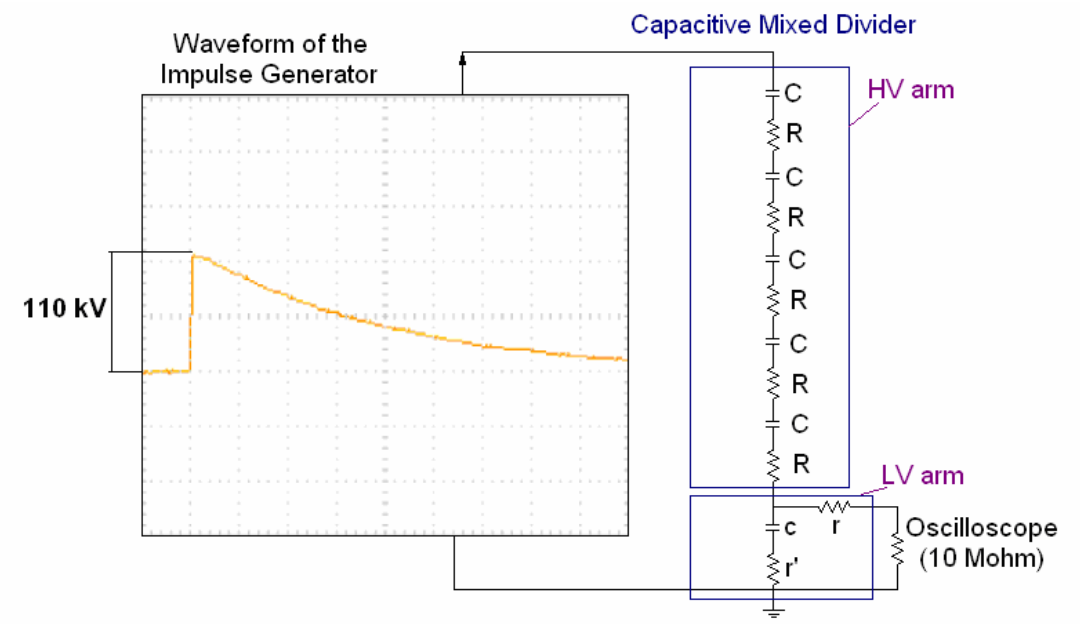


Figure 6.17 – Representation of the voltage divider

Thus, figure 6.18 shows both causes of "interferences": the puncture in a capacitor and the bad contact in the low voltage arm.

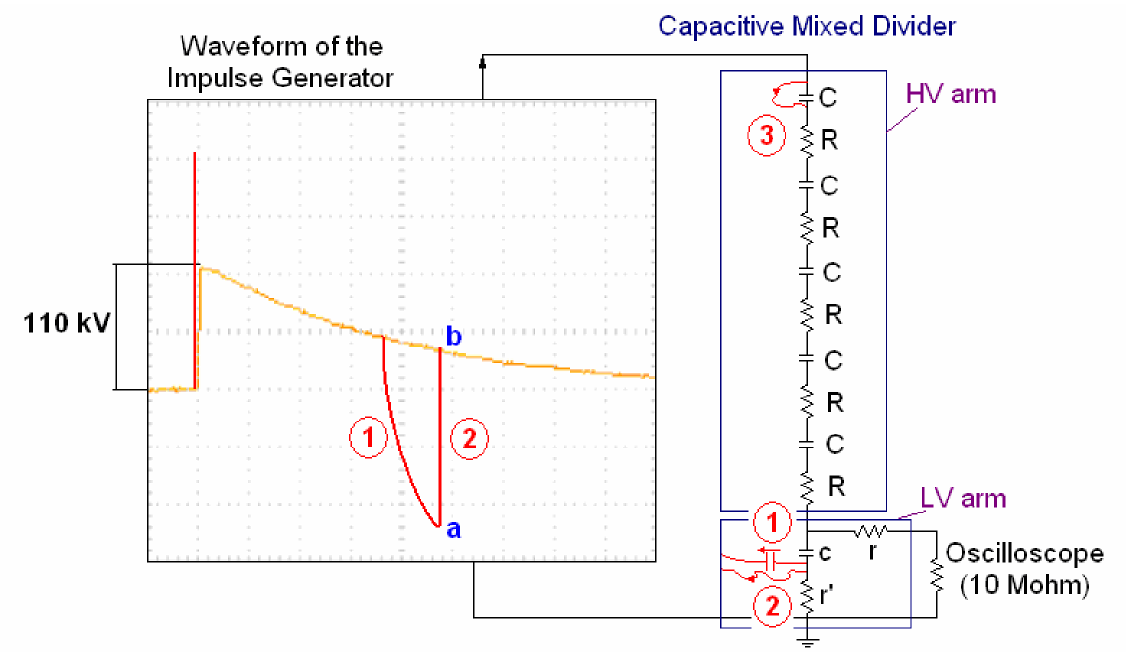


Figure 6.18 – Representation of the voltage divider with the explanation to the problems.

The puncture is shown with the number (3) in the high-voltage arm of the voltage divider. It causes that the divider ratio changes and, thus, the high amplitude of the "interferences" occurs.

The bad contact in the low voltage arm through a stray capacitance is shown with the number (1). It causes the slightly curved ramp of the negative voltage impulse on the wave-tail as the waveform of the charge of a capacitor. The number (2) shows the disruptive discharge passing the dielectric of this stray capacitor, what causes the sudden return front point (a) to (b) on the lightning impulse wave-shape. This shape changes because it is a random phenomenon and cannot be demonstrated clearly, but this theory explains all the problems that affect the standard waveform and a correct display of the test waveform.

To prove that the problem is in the capacitive voltage divider, a probe is used. This is an electrical device for making contact with a circuit test point for test purposes and it permits to measure voltages up to 40 kV.

Thus, the experiment is carried out using only the first stage of the impulse generator in order not to exceed the voltage limit of the probe. The first stage is charged up to 25 kV and no trigger is used to avoid this extra 15kV of the trigger system. Therefore, the firing is made by reducing the sphere-gap spacing to permit the disruptive discharge.

The probe is a Tektronix P6015A with an attenuation of 1000X and is shown in figure 6.19.

Figure 6.19 – Probe: Tektronix P6015A

Firstly, it is checked the voltage measurement made by the probe. The probe is used instead of the voltage divider and the result is shown in figure 6.20.

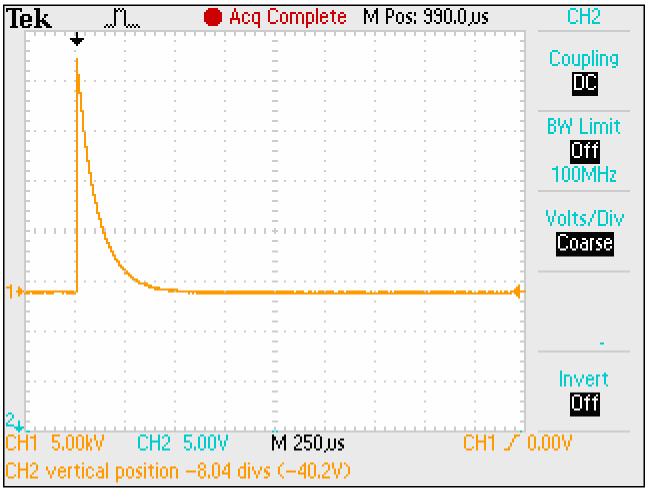


Figure 6.20 – Measurement of the test waveform made by the probe.

The figure shows the typical lightning impulse waveform. It is not shown any “interference”, what confirms the theory explained above.

Figure 6.21 shows two waveforms: the waveform number 1 is obtained by the probe, and the number 2 is obtained by the capacitive voltage divider, which is damaged as is shown.

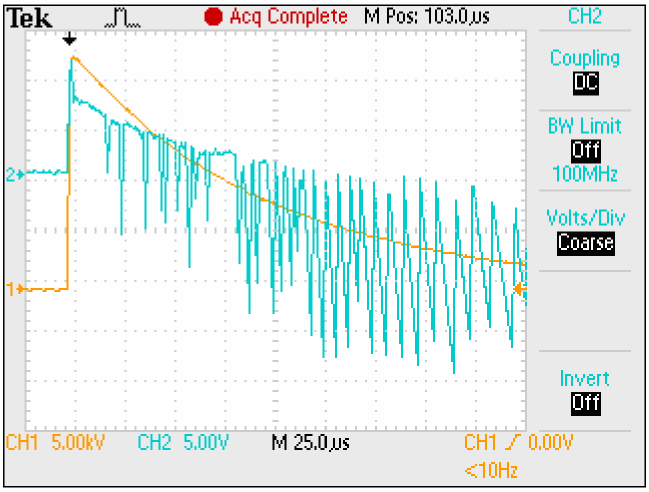


Figure 6.21 – Measurement of the test waveform made by the probe (1) and the capacitive divider (2).

This experiment demonstrates that the problem is in the capacitive voltage divider and this part of the High Voltage Laboratory equipment must be replaced. The waveform number 1 does not show any problem, but the waveform number 2 has this problem mentioned before.

6.5 - Conclusions

The problem does not affect the test, because the problem is only in the measurement device; therefore, the device under test does not have to support higher voltage values.

As the parameters of the test waveform, such front time, tail time and peak voltage, can still be read, the equipment may be used for testing purposes, but the capacitive voltage divider must be replaced if a measurement without “interferences” is required.

Chapter 7

Calibration according to IEC 60052

This chapter presents a detailed description about how to perform the calibration of the Impulse Test System according to the international standard IEC 60052 [15]. This is a standardized procedure of voltage measurement by means of standard air gaps. The experience in calibration acquired in another High Voltage Laboratory within the preparation of this work is reflected in this report. Although, verification of the control console was not possible to perform due to the need of a standard sphere-gap that was not available, this part intends to set the basis for a further work in calibration at the High Voltage Laboratory of the Faculty of Engineering.

The international standard sets forth recommendations concerning the construction and use of standard air gaps for the measurement of peak values of the following four types of voltage:

- alternating voltages of power frequencies;
- full lightning impulse voltages;
- switching impulse voltages; and,
- direct voltages.

It is necessary to calibrate the measuring system of the High Voltage Laboratory in order to ensure a reliable insulator testing. Calibration permits adjustment of the voltage measurement at the control console so that the given voltage is the real one and imprecise values are avoided.

International Standard IEC 60052 has been prepared by the International Electrotechnical Commission (IEC) in order to carry out voltage measurement by means of standard air gaps. As the purpose of this Master's Thesis is to study lightning impulse voltages, this chapter only presents a summary about this part of the international standard, which must be consulted when further information or details about the process are requested.

7.1 - Overview

Calibration is the act of correlating the readings of an instrument with those of a standard in order to check the instrument's accuracy, which allows comparison with other experimental data. The most widely known instrument for measuring high voltage is the sphere-gap, although its way of functioning makes it more a calibrating device than a measuring instrument.

Measuring high voltage with the aid of a sphere-gap is based on the fact that air of know pressure and temperature always breaks down at the same field strength: for example, air of 1 atmosphere and 20 ºC needs about 3 kV/mm to break down, as defined by Kreuger [4].

This element is used for calibration processes by determining the gap distance where breakdown takes place. A high voltage circuit and its voltage divider can be calibrated with the aid of the international IEC 60052 tables, and an inspector can check a test circuit in any laboratory anywhere in the world. The method is not very accurate, about 3 %, but it is easy and reliable.

The sphere-gap is the simplest configuration where a uniform and predictable field occurs between electrodes and has been used as a simple and reliable method for measurement of peak voltage in many industrial test facilities for more than 75 years. Moreover, the mentioned standard provides values for laboratory testing which have been accepted as an International Consensus Standard of Measurements.

7.2 - Standard sphere-gap

The standard sphere-gap is a peak voltage measuring device, constructed and arranged in accordance with the standard IEC 60052. It consists of two metal spheres of the same diameter with their shanks, operating gear, insulating supports, supporting frame and leads for connection to the point at which the voltage is to be measured. The standard specifies reference values and tolerances for specific requirements on sphere shape and surface conditions. The spheres shall be carefully made so that their surfaces are smooth and their curvature is as uniform as possible, and the diameter of each sphere shall not differ by more than 2% from the nominal value.

As shown in figure 7.1, the spheres can be arranged in two different ways: one of which is typical of sphere-gaps with vertical axis and the other of sphere-gaps with horizontal axis. Both of them show the high voltage conductor with series resistor connected to the high voltage sphere and the other sphere is connected to ground.

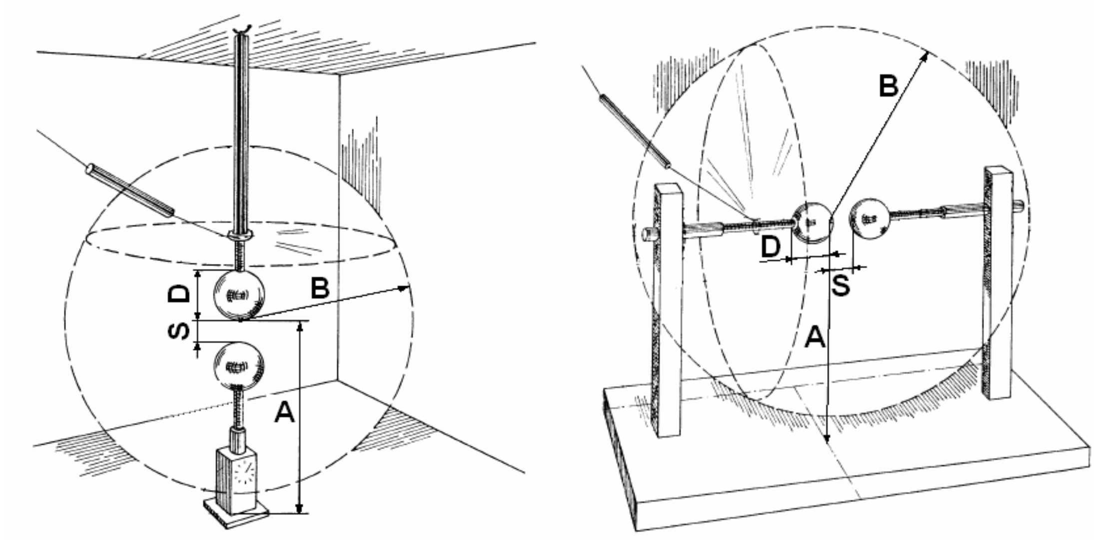


Figure 7.1 - Vertical sphere-gap (left side) and horizontal sphere-gap (right side) [15].

The points on the two spheres that are closer to each other are called the sparking points. In figure 7.1, *D* is the diameter of the spheres, *S* is the spacing between them, *A* is the height of the sparking point, and *B* is the distance from the sparking point of the high-voltage sphere to any extraneous objects.

In order to reduce the influence of the shank of the high voltage sphere on the disruptive discharge voltage when the spheres are arranged vertically, it shall be free from sharp edges or corners and the standard sets its dimensions. It also specifies the dimensions of a stress distributor (corona shield) if it is necessary to be used at the end of the shank.

The earthed shank and the operating gear have a smaller effect and their dimensions are therefore less important.

As shown in figure 7.1, some clearance limits around the spheres are defined by this standard. Thus, the distance from the sparking point of the high-voltage sphere to any extraneous objects (such as ceiling, walls, and any energized or earthed equipment), and also to the supporting frame work for the spheres, if this is made of conducting material, shall not be less than a distance *B*.

The value of this distance *B* depends on the sphere diameter *D* and the spacing between spheres *S*. A spacing of 10 cm has been considered in figure 7.2 in order to represent how the minimum value of distance *B* changes according to their values. It is possible to see that the smaller the sphere diameter *D*, the bigger the minimum limit distance *B*. These values were taken from table 1 of the Standard IEC 60052.

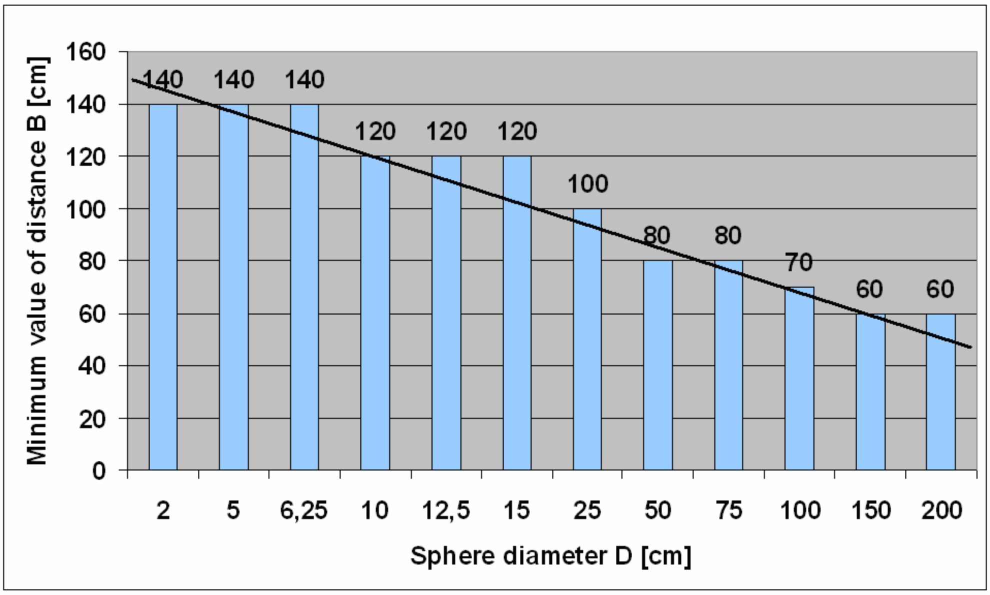


Figure 7.2 - Clearance limit: minimum value of distance *B* depending on sphere diameter *D*, both in cm, for a spacing between spheres of *S* = 10 cm.

Supporting frameworks for the spheres made of insulating material are exempted from this requirement, provided that they are clean and dry and that the spheres are used for the measurement of alternating or impulse voltages only.

Other clearance limit showed in figure 7.1 and defined by the standard is the height *A* of the sparking point of the high-voltage sphere above the earth plane of the laboratory floor. It only depends on the sphere diameter *D* and shall be within the limits shown in figure 7.3. It is seen that the bigger the sphere diameter *D*, the bigger the minimum and maximum limit distances *A*. These values are taken from table 1 of the Standard IEC 60052.

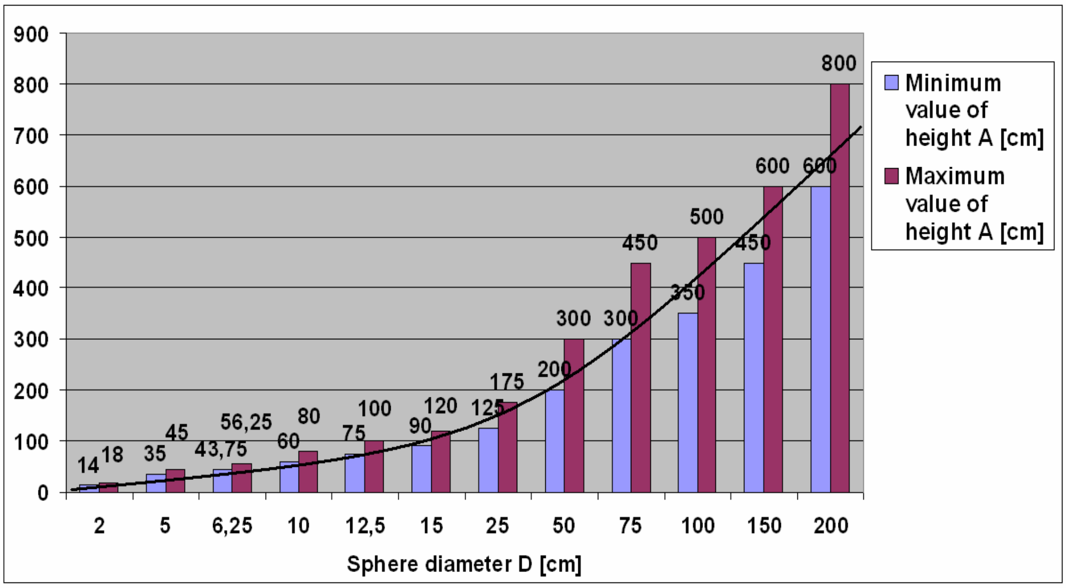


Figure 7.3 - Clearance limit: minimum and maximum values of height *A* depending on sphere diameter *D*, both in cm.

The peak values of disruptive discharge voltages shown in the IEC 60052 (tables 2 and 3 of the Standard) are only valid for clearances around the spheres within the limits given in figures 7.2 and 7.3.

It is important that the circuit is arranged so that at the test voltage there is:

- no disruptive discharge to other objects;
- no visible leader discharge from the high-voltage lead or shank within the space defined by *B*;
- no visible discharge from other earthed objects extending into the space defined by *B*.

7.3 - Connections

The sphere-gap shall be connected in accordance with the next specified requirements, which have been standardized by the international standard IEC 60060-2.

7.3.1 -Earthing

Normally, one sphere shall be connected directly to earth.

7.3.2 -High voltage conductor

The high-voltage conductor, including any series resistor not in the shank itself, shall be connected to a point on the shank away from the sparking point of the high-voltage sphere. This distance must be at least two times the diameter of the spheres ($2 \cdot D$).

Within the region where the distance to the sparking point of the high-voltage sphere is less than B, the high-voltage conductor (including the series resistor, if any) must not pass through the plane normal to the axis of the sphere-gap. This plane is situated at the connection point on the shank and shown in figure 7.1.

7.3.3 -Protective resistor for measurement of impulse voltages

As depicted by the international standard [15], series resistance is needed with large diameter spheres to eliminate oscillations in the sphere-gap circuit which may cause a higher voltage to occur between the spheres and, if connected, across the test object. A series resistance may also be needed in order to reduce the steepness of the voltage collapse which might introduce undesirable stresses in the test object.

The resistor shall have a non-inductive construction (not more than 30 μH) and its resistance should not exceed 500 Ω, as specified by the standard. In the circuit, the resistor is positioned at the high voltage conductor and shown in figure 7.1.

7.4 - Use of the sphere-gap

A sphere-gap is an IEC standard measuring device when the conventional deviation z (see note below) at the time of use is, for lightning impulse voltages, less than 1%.

The conventional deviation *z* is affected by the condition of the sphere surfaces, the availability of free electrons (sufficient irradiation), the dust contained in the air and the measurement procedures. This requirement for the conventional deviation *z* ensures that the requirements for the surface conditions have been met.

Note: (4.4 of the Standard IEC 60060-1)

Disruptive discharge voltages are subject to random variations and, usually, a number of observations must be made in order to obtain a statistically significant value of the voltage. The test procedures are generally based on statistical considerations.

The *p%* disruptive discharge voltage of a test object is the prospective voltage value which has *p%* probability of producing a disruptive discharge on the test object.

The conventional deviation *z* of the disruptive discharge voltage of a test object is the difference between its 50% and 16% disruptive discharge voltages. It is often expressed in per unit or percentage value, referred to the 50% disruptive discharge voltage.

7.4.1 -Conduction of the sphere surfaces

An accurate field distribution is obtained by satisfying the following requirements in this section.

The curvature of the surface of the spheres shall be constant. The surfaces, in the neighbourhood of the sparking points, shall be cleaned and dried but they do not need to be polished. They must be smooth, free of defects and free of dust. In normal use, the surfaces of the spheres become roughened and pitted. When it occurs, the surface should be treated. If the spheres become excessively roughened or pitted in use, they shall be repaired or replaced.

Moisture may condense on the surface of the sparking points in conditions of high relative humidity causing measurements to become erratic.

No air currents may be present in order to ensure accuracy; however, minor damage to the surface of the sphere beyond the region of sparking point is not likely to affect the use of the sphere as a measuring or calibrating device.

7.4.2 -Irradiation

The disruptive discharge voltage of a sphere-gap depends upon the availability of free electrons in the gap between the spheres at the moment of application of voltage. Actions should be taken if the requirements for conventional deviation *z* are not met.

Irradiation is usually required for measurements below 50 kV peak for all sphere diameters, and for measurement of voltages with spheres of 12.5 cm diameter and less for all voltage shapes.

For impulse voltage, direct exposure of a sphere-gap to the light from the impulse generator gaps may be sufficient; otherwise, when sufficient irradiation is not available, the uncertainly associated with the values for disruptive discharge given in the standard should be increased.

7.5 - Reference values

The disruptive discharge voltages for various spacing between spheres are given in tables 2 and 3 of the Standard IEC 60052 for the standard atmospheric conditions for temperature and pressure:

Temperature	$t_0 = 20$ °C
Pressure	$b_0 = 101.3$ kPa

The values were obtained under conditions of absolute humidity *h* between $5 g \cdot m^{-3}$ and $12 g \cdot m^{-3}$, with an average of $8.5 g \cdot m^{-3}$.

In tables 2 and 3 of the Standard are given the values in impulse tests of the 50% disruptive discharge voltages U_{50} in kV for full lightning impulse voltages of negative and positive polarity respectively. These tables are not valid for the measurement of impulse voltages below 10 kV. For impulse voltages, these values given have an estimated uncertainty of 3% for a level of confidence not less than 95%.

Note:

It is recommended that the sphere-gap spacing should not be less than $0.05 \cdot D$, as it may be difficult to measure and adjust the gap with sufficient accuracy if the ratio of spacing to diameter is very small.

No level of confidence is assigned to those values in brackets.

Figure 7.4 is shown in order to give an idea about how the peak voltage U_p at which a sphere-gap breaks down as a function of the sphere-gap spacing and the sphere diameter *D*. This relationship is used for calibrating impulse voltages. This figure, showed by Kreuger [4], is valid only for estimations; therefore the exact values are well documented in tables of the IEC standard.

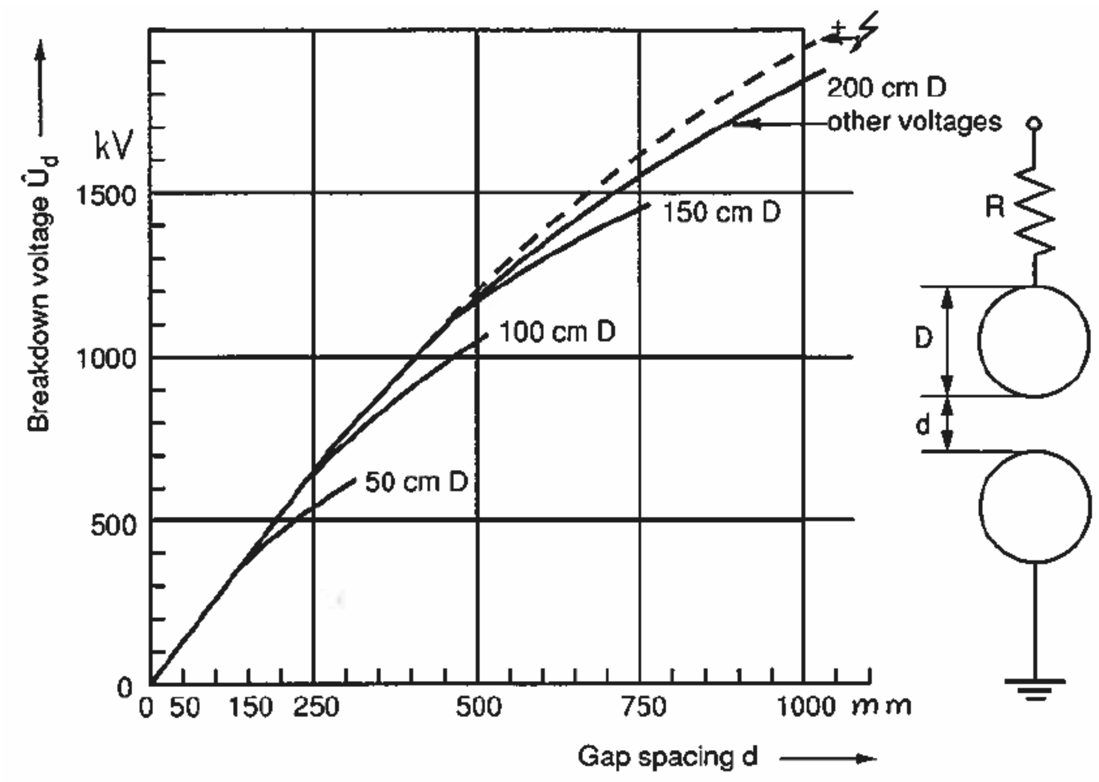


Figure 7.4 - Correlation between the breakdown strength and the gap distance [4].

In impulse tests, the sphere-gap is usually protected by a resistance R < 300 Ω.

Correction factors.

As indicated in IEC 60052, when the atmospheric conditions are not the standard as defined in this section, small corrections are made for air pressure, temperature and humidity.

Thus, there are two correction factors: for air density (temperature and pressure) and air humidity.

The correction factor for air humidity is usually small, below 2%, and, as recommended by Kreuger [4], measurements shall not be made over 90% of relative humidity. The results obtained may be unreliable due to condensation of water at the sphere surfaces.

- Air density correction factor.

Disruptive discharge voltages corresponding to a given sphere-gap spacing *S* under atmospheric conditions other than those specified as standard are obtained by multiplying the values in tables 2 and 3 of the Standard by a correction factor corresponding to the relative air density δ.

The relative air density δ is defined by:

$$\delta = \frac{b}{b_0} \times \frac{273 + t_0}{273 + t} \tag{7.1}$$

where:

- the atmospheric pressures b and b_0 are expressed in the same units (kPa);
- t and t_0 are the temperatures in degrees Celsius.

Standard atmospheric conditions for temperature and pressure are:

Temperature	t_0 = 20 °C
Pressure	p_0 = 101.3 kPa

- Humidity correction factor:

The disruptive discharge voltage of a sphere-gap increases with absolute humidity at a rate of 0.2 % per $g \cdot m^{-3}$.

The average value of absolute humidity h under which values in tables 2 and 3 of the Standard were obtained is 8.5 $g \cdot m^{-3}$. These values shall be corrected for humidity by multiplying the values in those tables by the humidity correction factor k given by the following equation:

$$k = 1 + \left(0.002 \times \left(\frac{h}{\delta} - 8.5 \right) \right) \tag{7.2}$$

with the ambient absolute humidity h in $g \cdot m^{-3}$.

7.6 - Advantages and disadvantages

The sphere-gap is widely used because of its advantages; although it also presents some disadvantages. Both are presented in this section based on the information depicted by Kreuger [4].

The advantages are:

- It is a simple device and universally applicable;
- It measures the crest voltage which usually is decisive in dielectric testing;
- It measures all types of voltages: lightning impulses and, also DC, AC and switching impulses;
- It has a large scope: from a few kVs with small spheres of some centimetres diameter to MVs with spheres of some metres diameter.

The disadvantages are:

- Its accuracy is modest (about 3 % at impulses);
- It does not give a voltage reading but is used to calibrate the readings of the voltage divider in the case of the High Voltage Laboratory;

- Time consuming: in order to obtain full accuracy, long test series are needed to determine the 50 % disruptive discharge voltage U_{50} or, also called, breakdown value.

7.7 - How to perform the calibration process

The use of standard air gaps permits checking the approved measuring systems of the High Voltage Laboratory.

A measurement of voltage by means of sphere-gap consists of establishing the relation between a voltage in the test circuit, as measured by the standard air gap, and the peak value of the voltage obtained from the measuring device of the Laboratory, that is the digital storage oscilloscope (DSO), connected to the low voltage arm of the measuring system (the Capacitive Mixed Divider).

If it is possible to access to low voltage unit of the Capacitive Divider, by means of intentionally changing capacitance of the variable capacitor of this unit, the divider output ratio can be changed and adjusted according to the voltage measured by the standard air gap in order to obtain a true voltage value in the oscilloscope.

As this operation cannot be made at the High Voltage Laboratory, because it is not possible to access to low voltage arm of the Divider, the calibration process must consist of establishing the relation between voltages by means of a function. The peak value of the voltage obtained from the oscilloscope can be related to the true voltage in the test circuits by a mathematical function. This function can be represented as a straight line, a linear function.

Values of the calibration presented in this report are not real and can be used only as indicative values. Thus, this section aims to set the principles and give an example in order to make the correct calibration of the High Voltage Laboratory in the future.

7.7.1 -Layout with clearance limits

The general arrangement of the sphere-gap at the High Voltage Laboratory was considered vertical as shown in figure 7.1 (left side). The layout shown in figure 7.5 makes possible to perform the calibration of the system complying with clearance limits established.

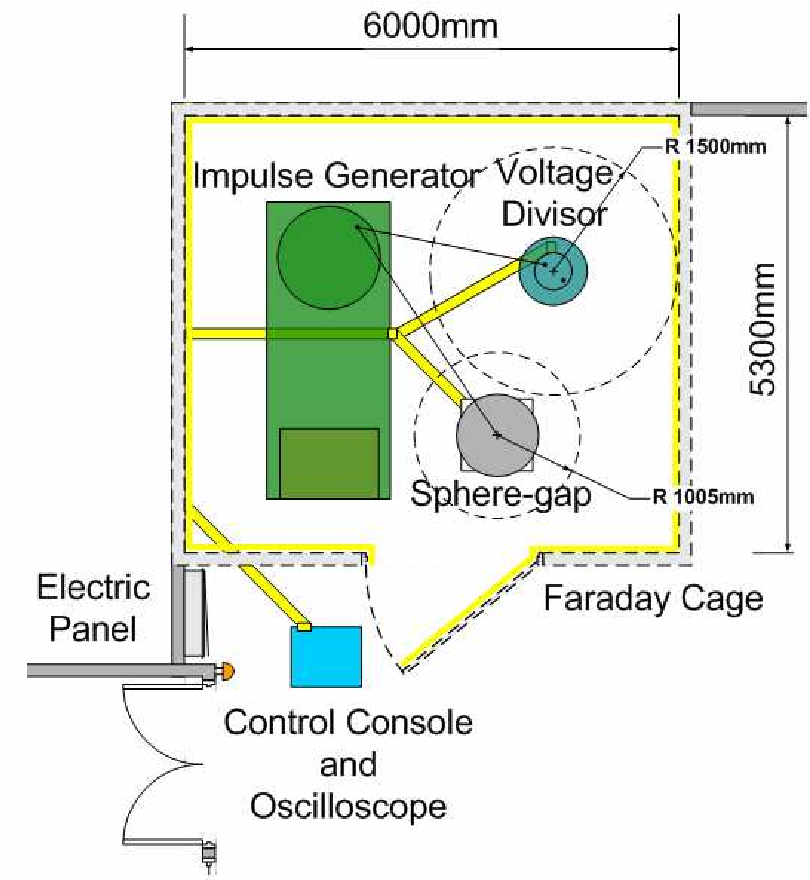


Figure 7.5 - Layout of the Laboratory necessary to calibrate the measuring system according to IEC 60052.

As it is explained in chapter 8 (risk assessment), it is not safe to use an output voltage higher than 325 kV with the current layout of the Laboratory, because the Faraday cage is too small according to safety distances recommended by Hipotronics [12] between the block of capacitors and any other grounded object, as well as the divider should be operated without any ground objects within 1.5 meters of the high voltage arm, that is 1.5 meters.

For a sphere diameter *D* of 75 cm, for example, the voltage in the test circuit can be measured by the standard air gap up to 315 kV according to tables 2 and 3 of the Standard [15], complying with the safety requirement above mentioned. This maximum peak value of disruptive discharge voltage for full lightning impulse may be of negative or positive polarity and the sphere-gap spacing *S* must be equal to 12 cm; therefore, the minimum clearance limit *B* around the sparking point must be 96 cm according to tables 2 and 3 of the Standard [15]. In figure 7.5 an area of about 1 meter is drawn around the sparking point of the sphere-gap.

If the area of the Faraday cage would be increased, as recommended in next chapter (risk assessment), higher values of voltage could be used and bigger clearance distances should be set. In figure 7.6, for a sphere diameter *D* = 75cm, the minimum values of distance *B* depending on sphere-gap spacing *S* are represented. Data were taken from table 1 of the IEC 60052 [15].

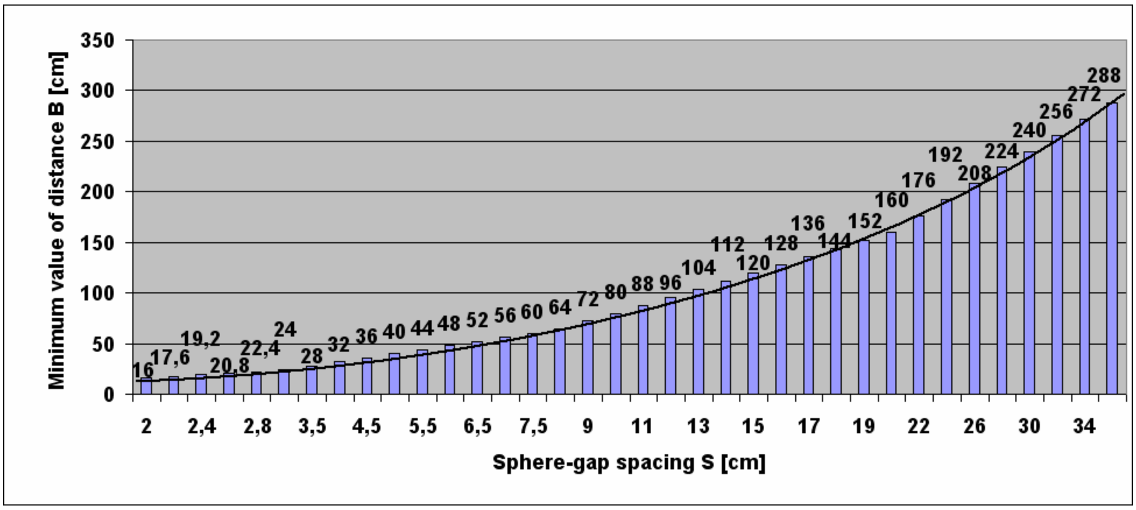


Figure 7.6 - Clearance limit: minimum value of distance *B* in cm depending on sphere-gap spacing *S* in cm, for a sphere diameter *D* = 75 cm.

Peak values of disruptive voltages for full lightning impulse voltages only depend on the sphere-gap spacing *S* and the sphere diameter *D*. Figure 7.7 shows these voltage values of negative polarity, for a sphere diameter *D* = 75cm, as established by the table 2 of the Standard IEC 60052 [15].

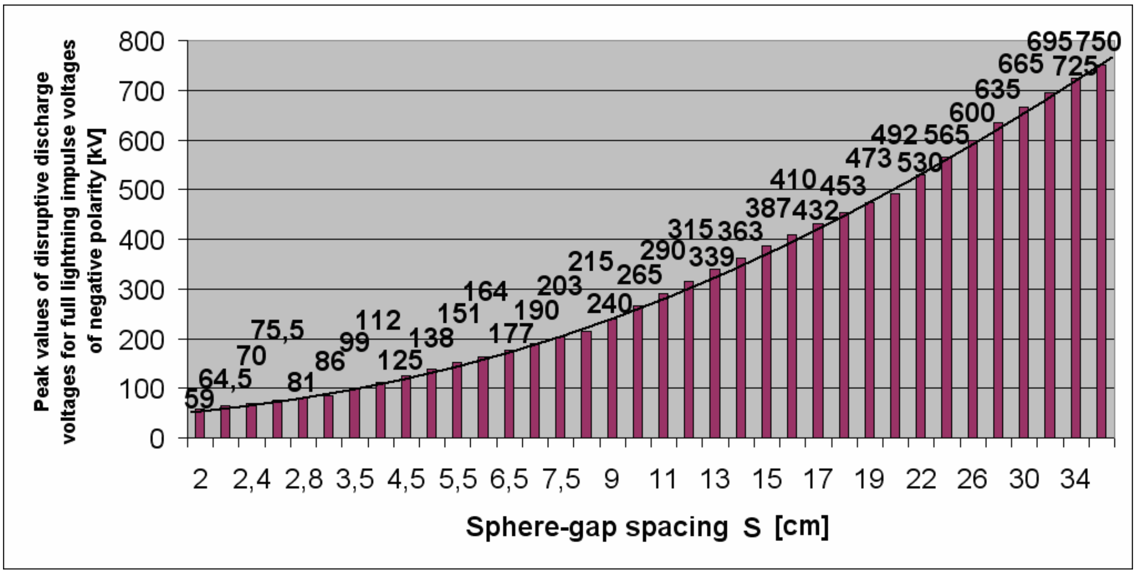


Figure 7.7 - Peak values of disruptive discharge voltages in *kV* for full lightning impulse voltages of negative polarity depending on sphere-gap spacing *S* in cm, for a sphere diameter of *D* = 75 cm.

7.7.2 -Measurement of peak value of full lightning impulse voltages

The 50% disruptive discharge voltage U_{50} and the conventional deviation *z* shall be determined. The value of the conventional deviation *z* shall be not more than 1% for full lightning impulse voltages.

This can be done by a multiple level test. A minimum of 10 voltage applications at each of five voltage levels in approximately 1% steps of the expected disruptive discharge value is needed to obtain U_{50} and to check the conventional deviation z for a fixed sphere-gap spacing S.

Table 7.1 shows an example. On the left, the 50% peak value of disruptive discharge voltage, after being corrected by air density and humidity correction factors, is shown, and, on the right, the process of determination the 50% disruptive discharge voltage and the conventional deviation is performed.

Table 7.1 —Example of measurement.

	Winter		V peak oscilloscope [kV]		
Temperature [°C]	9.2	1	220		
Atmospheric pressure [mbar]	1023	2	218		
Relative humidity [%]	70	3	218		
		4	222		
Air density correction factor (δ)	1.05	5	221		
Humidity correction factor (k)	0.995	6	200		
		7	220		
Sphere diameter D [cm]	75	8	223		
Sphere-gap spacing S [cm]	8	9	220		
U50 Lightning Impulse (LI) [kV]	215	10	221		
Corrected value (U50·δ·k) [kV]	224.62	Mean value	220.33		
		Conventional deviation	1.7	<	1% (220.33)

Correction factors are applied according to the Standard.

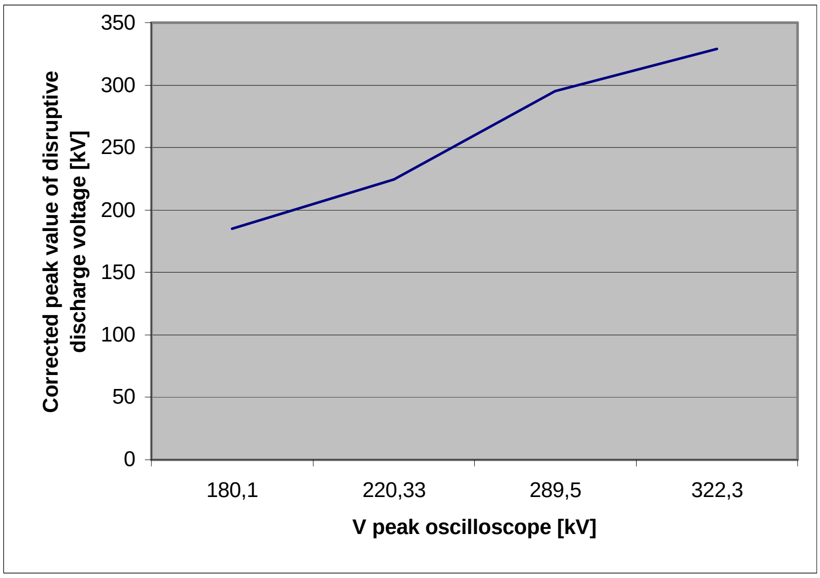
When there is a peak voltage measured by the oscilloscope, which deviates from the expected voltage value, it must be removed so that it does not affect the mean value and the conventional deviation. One of the values has been highlighted for this reason.

The criterion for the conventional deviation z shall be checked by applying 15 impulses at the voltage level of (U_{50} - 1%) for lightning impulse voltages. There shall be not more than two disruptive discharges.

The interval between voltage applications shall be not less than 30 s.

As it is not possible to adjust the divider ratio of the voltage divider, the calibration must be done by means of creating a table of equivalences between the peak voltage displayed in the oscilloscope and the peak value of disruptive discharge voltage in the sphere-gap. This is only an example, because the necessary equipment was not available, but it shall be obtained a table as shown in table 7.2. It shows a linear function that links both parameters. With this relation it is very easy to know the real peak value of the standard waveform for any laboratory testing.

Table 7.2 — Relation between peak value of disruptive discharge voltage in the sphere-gap and peak voltage measured in the oscilloscope.



To obtain the table of equivalences of the equipment of the High Voltage Laboratory is purposed a further work.

Chapter 8

Risk assessment

In last 10 or 15 years, human safety and risk management in the workplace have become more and more important. Nowadays, workers and administrators are aware of the risks which are present at their workplace. A risk assessment is an important step in protecting all the people who work or, temporarily, visit the workplace, as well as complying with the law and protecting the institution image.

This chapter states necessary actions to prevent somebody might be harmed and those risks with the worst potential consequences at the High Voltage Laboratory of the Faculty of Engineering. The Impulse Test System is equipment potentially dangerous, thus, safety must be priority in order to carry out safe lightning impulse tests.

The current importance of this field is shown by all the information which is possible to find about it. In last time, new journals on risk and safety have appeared, longer established journals in the risk and safety field have gone from strength to strength, and, the large amount of recent research literature that has been generated in the risk and safety field is reflected in several completely new books which have been published.

8.1 - What is risk assessment?

A risk assessment is a careful examination of what, in the workplace, could cause harm to people. Workers and others as visitors have a right to be protected from harm caused by a failure to take reasonable control measures. The responsible engineer of the High Voltage Laboratory is legally required to assess the risks in the workplace so that it is put in place a plan to control the risks. An accident can affect the institution image and a business.

When an update of the risk assessment of the Laboratory is necessary to do, it should be made sure that the responsible engineer and all the users are involved in the process. She or he will have useful information about how the work is done that will make the update of the assessment more thorough and effective; what guarantees a successful process.

The process is not complicated, the risks are well-known and the necessary control measures are, in this case, easy to apply.

As defined by Glendon, Clarke and McKenna [17], the varieties of technical approach to risk as applied to safety, health, and environment issues have their origins in engineering. An example of this approach is shown below:

"Risk = Probability x Magnitude"

It assumes rationality, considering risk as being primarily about seeking safety benefits, such that acceptable risk decisions are deemed to be matters of engineering judgement.

8.2 - How to assess the risks in the workplace

A hazard is anything that may cause harm, such as electricity at the High Voltage Laboratory. The risk is the chance, high or low, that somebody could be harmed by these and other hazards, together with an indication of how serious the harm could be.

To assess the risks in the laboratory, there are five steps that must be followed by the person in charge of the assessment for a correct plan. They are explained below.

- Identify the hazards;
- Decide who might be harmed and how;
- Evaluate the risks and decide on precautions;
- Decide further actions that must be implemented;
- Review the assessment and update if necessary.

8.2.1 -Identify the hazards

Hazards of the High Voltage Laboratory are basically divided in two:

- Charges retained by capacitors;
- Safety distances too short.

In this high voltage installation of the Laboratory, people could be harmed mainly by an unexpected high voltage discharge if someone enters the zone delimited by the Faraday cage and touches a part of the equipment inside the Faraday cage that has a dangerous potential and it was unexpected for the user. These dangerous potentials may exist in the circuit due to charges retained by capacitors.

Therefore, special care must be taken, especially, when the discharge of the capacitors does not occur because a wrong adjustment of the sphere-gap spacings.

The safety distance around the impulse generator, as well as other points that reach dangerous potentials, such as the high voltage arm of the capacitive divisor or the device under test (insulator), must be properly calculated before carrying out any lightning impulse tests.

These safety distances make possible to avoid electrical discharges between two points of different electrical potential such as the top of the stack of capacitors of the impulse generator, which can reach 500 kV, and objects connected to earth in the vicinity.

It is recommended to avoid touching the Faraday cage when laboratory testing with extremely high voltages are being performed. Ground potential can rises quickly, if an electrical discharge to earth by the air occurs, and peak values of very high voltage may appear in the cage and be fatal.

The current safety distance around the stack of capacitors is about 1.7 m and has been checked as an appropriate safety distance just up to 325 kV as maximum output voltage. As recommended, this safety distance is not enough if tests from 325 kV to 500 kV want to be performed. The actual layout of the Laboratory is shown in figure 8.1 below.

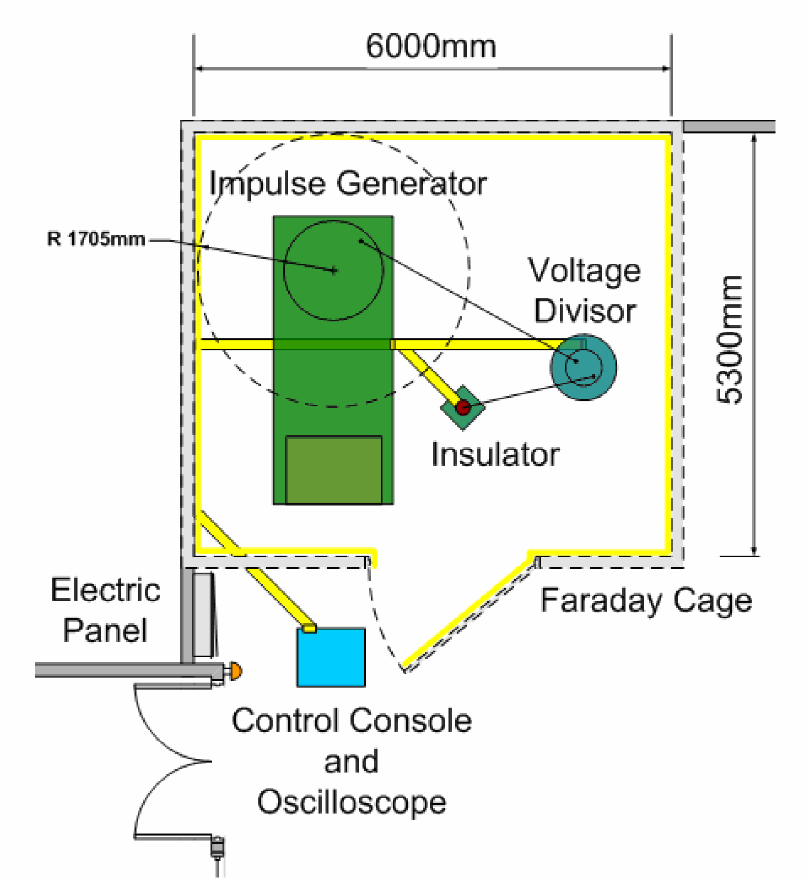


Figure 8.1 - Current layout of the Laboratory at room J003 of the Faculty of Engineering.

The Faraday cage is not big enough to fulfil the minimum safety distance; thus, if higher voltage values want to be used, it is recommended to enlarge the cage in order to have a bigger safety area.

As shown in figure 8.2, it is necessary to increase the safety distance up to, at least, a distance equal to the height of the stack of capacitors of the impulse generator, that is, 2.5 meters. Once the new layout is mounted, several voltage applications of increasing values, between 325 kV and 500 kV, must be carefully performed step by step in order to make sure that only expected electrical discharges occur. This suggestion is an optimized layout, according to recommendations of Hipotronics [11], when tests with voltages up to 500 kV want to be performed.

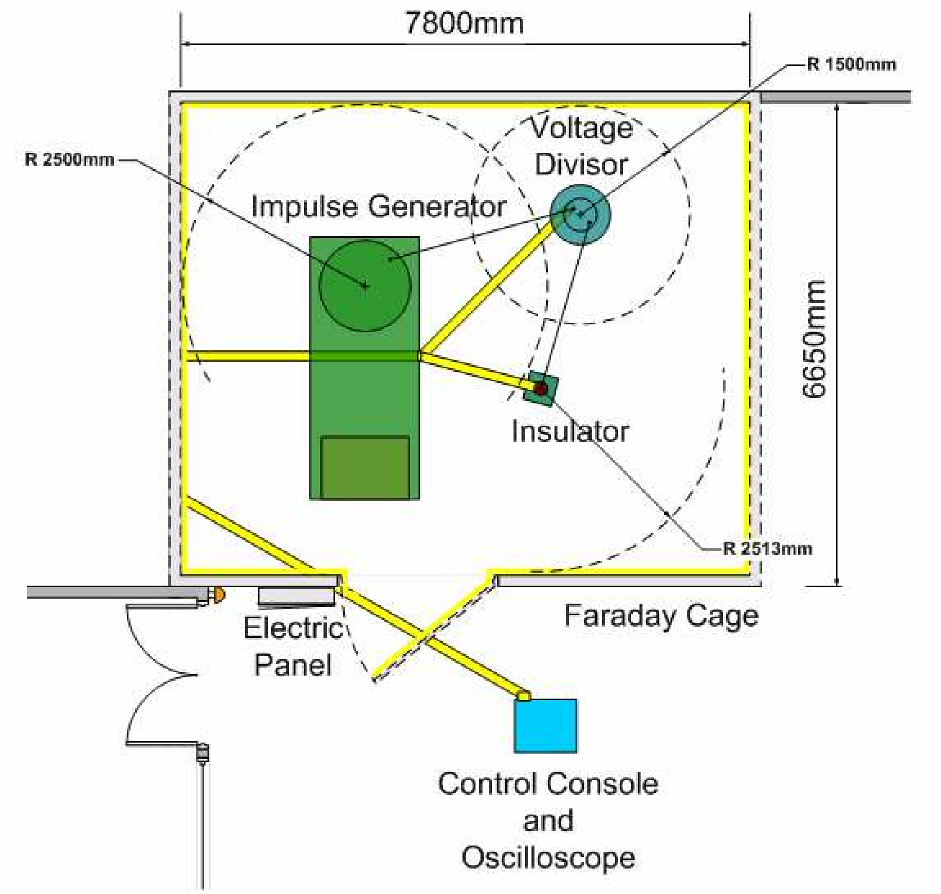


Figure 8.2 - New suggested layout at room J003 of the Faculty of Engineering.

In figure 8.2, it is also included other two safety areas around the device under test (insulator) and the capacitive divider, which makes the new layout safer. As recommended by Hipotronics [12], the divider should be operated without any ground objects within 1.5 meters of the high-voltage arm, that is, 1.5 meters. Metallic objects and protrusions present within this distance may affect measurements (ratio and response time) and cause flashovers or incorrect partial discharge readings.

8.2.2 -Decide who might be harmed and how

First of all, it is assumed that the user has a basic understanding of electrical equipment and the functions to be performed by this laboratory equipment. Only trained and qualified personnel should operate this equipment.

Special care must be taken whit groups of students or other inexperienced visitors. All the people must always bear in mind that extreme caution (prudence, care) is required in order to be present at a lightning impulse test.

8.2.3 -Evaluate the risks and decide on precautions

This section presents safety systems currently used at the Laboratory in order to prevent risks and, shows precautions which must be taken by the users of the Laboratory.

To establish precautions necessary for working with the equipment, the door of the Faraday cage has a safety system which can be compared with a limit switch (see figure 8.3). When the door is open, it cuts off the electrical supply of the control console of the impulse generator and, prevents from charging the impulse test system.

Figure 8.3 - Example of a limit switch (OMRON Industrial Automation) on the left, and the safety system of the Faraday cage on the right.

Whit voltage supply on, a light alarm signal shown in figure 8.4 warns about extremely high voltages are being generated and, therefore, special care must be taken.

Figure 8.4 - Light alarm signal of the High Voltage Laboratory.

In case of someone enter the safety area, inside the cage, without permission, an emergency stop switch shown in figure 8.5 makes possible to stop the electrical supply of the system instantly.

Figure 8.5 - Emergency stop switch of the High Voltage Laboratory.

The control console and measuring system (oscilloscope) must be placed in a clean room, dust-free, preferably equipped with air conditioned. Temperatures below 0ºC or above 40ºC may damage the electric and electronic circuits of the equipment. The High Voltage Laboratory may be a very cold room for the equipment in winter.

Control console and oscilloscope must be placed out of the Faraday cage and, at least, 2meters away of it. Another suggested option for the future is to place the control console and measuring system in the room J002 nearby.

All the electrical cables between the Faraday cage and the control console must be protected by a metallic gutter as shown in figure 8.6. Moreover, if this protection is connected to earth, the metallic gutter placed around conductors works as a shield; electromagnetic interferences (EMI) may be avoided in this way. Thus, inside it, the noise voltage on conductors is reduced to zero, as described by Ott [19].

Figure 8.6 - Metallic gutter which protects electrical cables.

Human error can happen; for this reason, these safety systems were implemented in the Laboratory. Objects like paper or cardboard must not be left inside the Faraday cage because they may catch fire if touched by a flashover arc. If a fire occurs, there is available a fire extinguisher in room J002, as shown in figure 3.18.

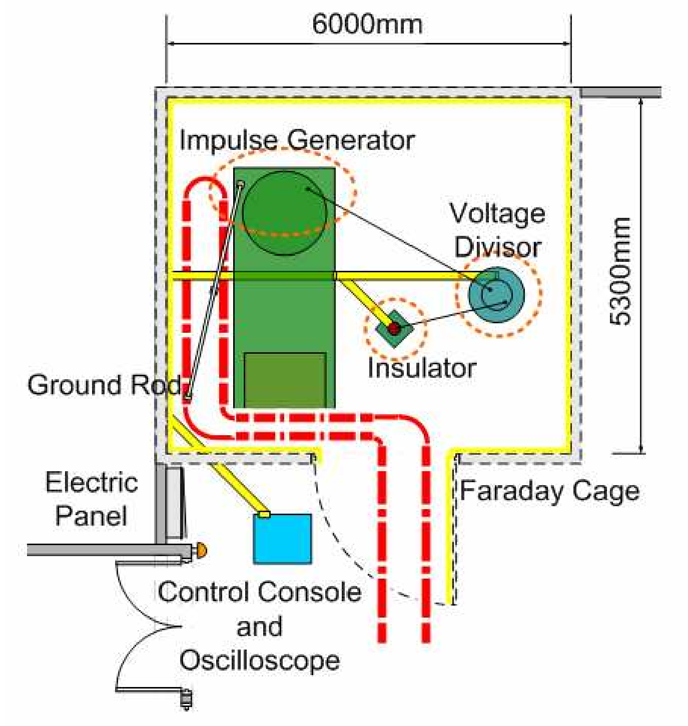
8.2.4 -Decide further actions that must be implemented

Two further actions are mainly suggested here: a safety way and improvement of the safety system; both in order to improve and insure a safe workplace.

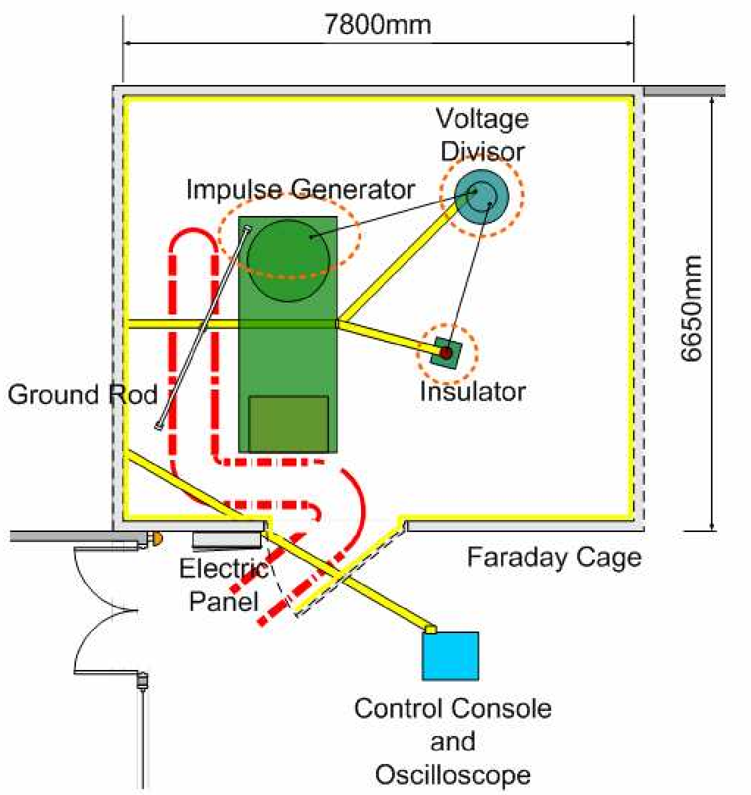
The ground rod should always be employed, after shutting off all power, to ensure that circuits are electrically "dead" before touching any potentially dangerous point of the system, as recommend by Hipotronics [11].

It might be forgotten due to a human error at any time, for this reason, a safety way was designed and is ready to be implemented, as shown in figures 8.7a (for the current layout) and 8.7b (for the suggested layout above mentioned). This design aims to highlight the way which must always be followed when operating and maintenance personnel enter the Faraday cage and remind them to discharge circuits by using of the ground rod.

It is an absolutely important safety rule because the points highlighted in orange in figure 8.7a and 8.7b (impulse generator, insulator and capacitive divisor) may have charges retained by capacitors and it might be produced an electrical discharge, fatal for the users when touched before discharging.



(a.)



(b.)

Figure 8.7a and b - Layout of the Laboratory. It shows a possible safety way that aims to avoid human error which may be fatal for the users if an electrical discharge occurs. The design shown in figures (a.) and (b.) was made for the current and the suggested layouts of the Laboratory respectively.

This section also introduces a new safety system which may be implemented and is proposed as a further work (see chapter 11).

The laboratory safety system, depicted in section 8.2.3, becomes a more active system if, as suggested, it is included a system designed by using optical sensors which can be implemented to prevent risks.

When charges are retained by the stack of capacitors and someone enter the Faraday cage, dangerous potentials exist in the circuit and may be fatal. These points, already shown, highlighted in orange, in figures 8.7a and 8.7b, may have charges retained by capacitors which might be fatal for the users if an electrical discharge occurs.

Thus, this suggested safety system would raise an alarm when someone tries to cross the dangerous area before discharging capacitors by means of the ground rod. The optical sensor used in the design might be one as shown in figure 8.8. The placement of this sensor is shown in figure 8.9.

Figure 8.8 - Optical sensor (Monarch Instrument) which might be used in the design of the safety system.

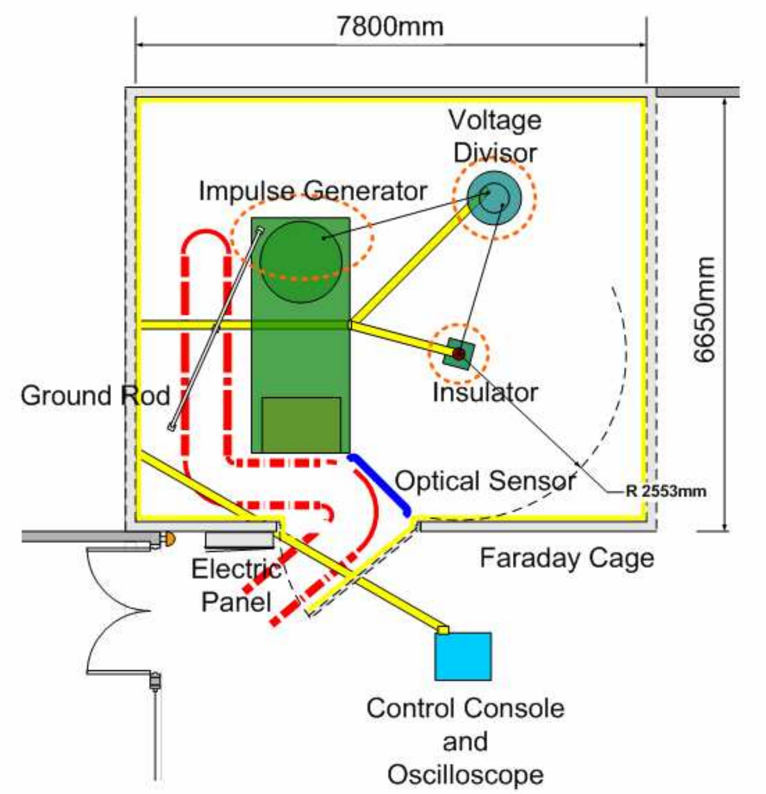


Figure 8.9 - Suggested layout for the Laboratory. It shows the placement of the optical sensor (blue), together with the potentially dangerous points (orange dotted line) and the safety way above purposed.

As a conclusion, another further action that must be implemented is recommended. In order to show and mind all the safety rules to potential users of the High Voltage Laboratory, a poster can be designed, printed and placed on a wall of the Laboratory, in a visible location.

8.2.5 -Review the assessment and update if necessary

The High Voltage Laboratory is a workplace that stays the same; usually there are no significant changes, therefore, reviews or updates of this risk assessment are only necessary if new equipment is brought or layout is changed.

If there is a significant change in the High Voltage Laboratory, the risk assessment here presented must then be checked and amended where necessary. It is the best to think about the risk assessment when the change is being planned and it leaves more flexibility to solve other possible problems.

8.3 - Conclusions

This equipment employs voltages which are substantially dangerous when contacted by operating personnel. Therefore, extreme caution shall be exercised when working with equipment. While every practicable safety precaution has been incorporated, the following rules must be strictly observed, as stated by Hipotronics [11]:

- Operating and maintenance personnel must all times observe all safety regulations.
- The equipment must be kept away from live circuits.
- Do not change components or make adjustments inside equipment with voltage supply on. Under certain conditions, dangerous potentials may exist in circuits with power controls in the off position due to charges retained by capacitors.
- To avoid accidents, always remove power, then discharge and ground by use of grounding rod, prior to touching any parts.
- Do not tamper with interlocks.
- Do not depend upon door switches or interlocks for protection, but always shut down high voltage rectifiers and other power equipment.
- Under no circumstances should any access gate, door or safety interlock switch be removed, short circuited, or tampered with in any way, except by authorized maintenance personnel when considered unavoidable, nor should reliance be placed upon the interlock switches for removing voltages from the equipment.
- Never switch on the equipment while anybody is inside the Faraday cage.

As recommended, before anyone begin using the equipment, please read manuals and user’s guides carefully in order to be aware of the risks.

Nowadays, a social pressure for greater personal safety in workplaces exists. It is necessary a safety culture, a leader and a supervisor for a safe performance of every work, in this case, laboratory testing.

Using safety rules and systems depicted in section 8.2, insures safety without a wrong use of the available space, which will be, therefore, optimized.

Chapter 9

Test on electrical insulators of organic material

The function of electrical overhead transmission lines' insulators is to keep the conductor isolated from ground and another conductor, and mechanical cable holding. They must bear cable's mechanical load which is transmitted through them to the tower, and keep an electrical isolation between conductor and tower. They must resist normal and abnormal voltages, and over-voltages as far as maximum ones planned. Both insulating material, and its surface, and air surrounding must resist peak voltage values.

Insulators have to be tested in the same conditions as they will support during their service life. They must comply with minimum standard requirements so that customers accept the quality of the product.

9.1 - Insulator parameters

Insulator parameters are specified in every catalogue and they are defined below for a better understanding.

Puncture voltage is the minimum voltage that causes a portion of an insulator to become electrically conductive. A partial or total break of the insulator can happen due to an electrical arc which goes through it. It is the voltage across the insulator (when installed in its normal manner) which causes a breakdown and conduction through the interior of the insulator. The heat resulting from the puncture arc usually damages the insulator irreparably.

Flashover voltage consists of an electric arc through the air between two points of the insulator which have, normally, nominal voltage. This voltage causes that air around or along insulator's surface break down and be able to conduct through it. A flashover arc along insulator's outside occurs, but they are designed to withstand this phenomenon, usually, without damage.

Power frequency withstand voltage, dry (kV), is the r. m. s. (root mean square) value of sinusoidal power frequency voltage that the equipment can withstand during tests made under dry conditions and for a specified time.

Power frequency withstand voltage, wet (kV), is the r. m. s. (root mean square) value of sinusoidal power frequency voltage that the equipment can withstand during tests made under raining conditions and for a specified time.

Lightning impulse is a voltage impulse, applied during dielectric tests complying with standards, with a front duration in the order of one microsecond (especially for standard lightning impulses 1.2/50 microseconds) and a time to half value in the order of 50 μs.

Lightning impulse withstand voltage (kV peak value) is the maximum lightning voltage which can be supported by an insulator without any damage in it.

Creepage distance (mm) is the shortest distance along the surface of the insulating material between two conductive parts. It is also called leakage distance.

Clearance distance (mm) is the shortest air distance between conductors.

Maximum mechanical strengths such as **tensile strength, flexural strength, compressive strength and impact strength** are also insulator parameters, but, as they are not electrical ones, they are not define in this chapter.

High voltage insulators are designed with a lower flashover voltage than puncture voltage so that they will flashover before they puncture to avoid any damage.

The insulator designing requirement is that electrical discharge must take place through the air and not to puncture the insulator. It is important an adequate geometrical design so that there will not be a big electrical field concentration which might break the insulator material.

Dirt, pollution, salt, and particularly water on the surface of a high voltage insulator might create a conductive path across it and cause leakage currents and flashovers. Flashover voltage can be lower than 50% when insulator's surface is wet. High voltage outdoor insulators are shaped to maximize the length of the leakage path along the surface from one end to the other, called the creepage length, to minimize these leakage currents.

9.2 - Characteristics of indoor and outdoor post insulators

Characteristics of indoor and outdoor post insulators for systems with nominal voltages greater than 1000 V are standardized by IEC 60273.

This standard applies to post insulators of organic material intended for indoor service in electrical installations or equipment operating on alternating current systems with a nominal voltage greater than 1000V and a frequency not greater than 100Hz. They are primarily intended for use in isolator switches, disconnectors or as bus-bar or fuse support.

The post insulator tested in the High Voltage Laboratory is an indoor post insulator of organic material and with internal metal fittings, as shown in figure 9.1.

Figure 9.1 - Post insulator under test.

This standard is intended to establish standard values of those electrical characteristics, mechanical characteristics and dimensions which are essential for the interchangeability of post insulators and post insulator units of the same type.

Each post insulator is designated for a specific lightning impulse withstand voltage based on the standardized values given in IEC 60071-1. The minimum height to be chosen is determined by one of the electrical characteristics given in the standard, i.e. dry lightning impulse withstand voltage, wet power frequency withstand voltage and wet switching impulse withstand voltage as applicable and according to the relevant insulation coordination requirements. The operating voltage is not specified because depending on service conditions, especially contamination, it cannot strictly be correlated with the height of the post insulator.

The composition of the post insulator, i.e. the number, the size and the positioning of insulator units is not specified. For a given height of a post insulator, however, the composition together with insulator profile and size and shape of metal parts can all affect the electrical performance of the post insulator especially the wet switching impulse withstand voltage value.

9.2.1 -Mechanical characteristics

Post insulators are standardized in mechanical strength classes based on values of the specified failing load in the bending test.

9.2.2 -Dimensional characteristics

The following dimensional characteristics are specified:

- overall height;
- maximum nominal diameter of the insulating part;
- fixing arrangements;
- tolerances;
- minimum nominal creepage distance (for outdoor post insulators only).

The composition of the post insulator is not specified.

The amount by which the creepage distance of an insulator may be increased within the specified dimensions varies according to the design and size of the insulator, and, where increased creepage distance is required, it should be the subject of agreement between the manufacturer and the purchaser in order to avoid designs which are unsuitable for service in polluted atmospheres.

9.2.3 -Table of characteristics

Table II of the Standard IEC 60273 shows the characteristics of indoor post insulators of organic material and with internal metal fittings. A part of this table is shown in table 9.1 below.

Table 9.1 — Indoor post insulators of organic material and with internal metal fittings.

1	2	3	4	5	6	7	8	9	10	11
Désignation du support isolant Post insulator designation	Tension de tenue aux chocs de foudre Lightning impulse withstand voltage	Tension de tenue à fréquence industrielle à sec Power-frequency withstand voltage, dry	Hauteur du support isolant Height of post insulator	Diamètre nominal maximal de la partie isolante Maximum nominal diameter of insulating part	Charge de rupture à la flexion Failing load bending		Différence maximale entre flèche à 20% et 50% de la charge de rupture spécifiée Maximum difference in deflection between 20% and 50% of the specified failing load	Trou central de fixation supérieur (taraudé) Top fitting centre hole (tapped)	Trou central de fixation inférieure (taraudé) Bottom fitting centre holle (tapped)	Distance axiale maximale entre face inférieure et extrémité inférieure du filetage de la base Maximum distance between bottom face and lower end of bottom thread
	(kV)	(kV)	h (mm)	D (mm)	P_u (N)	P_{50} (N)	(mm)	d_1	d_2	l (mm)
JO2-60				60	2 000	1 300		M12	M12	
JO4-60				75	4 000	2 600		M12	M16	
JO6-60				80	6 000	3 900		M12	M16	
JO8-60	60	28	95 ± 1	85	8 000	5 200	1,5	M16	M16	15
JO10-60				95	10 000	6 500		M16	M16	
JO16-60				125	16 000	10 500		M16	M20	
JO25-60				145	25 000	16 400		M16	M20	
JO2-75				60	2 000	1 450		M12	M12	
JO4-75				75	4 000	2 900		M12	M16	
JO6-75				90	6 000	4 350		M12	M16	
JO8-75	75	38	130 ± 1	100	8 000	5 800	2,0	M16	M16	25
JO10 75				105	10 000	7 200		M16	M20	
JO16-75				125	16 000	11 600		M16	M20	
JO25-75				145	25 000	18 000		M16	M20	

The insulator under test in the high voltage laboratory is:

“JO4-125”

where:

JO – indoor post insulator of organic material.
4 – mechanical strength class (4000N).
75 – lightning impulse withstand voltage (in kilovolts) = 125 kV

Thus, “IEC post insulator Type JO4-125” indicates an indoor post insulator of organic material of strength Class 4 and with lightning impulse withstand voltage 125 kV.

9.3 - Test on indoor post insulators of organic material

The international standard IEC 60660 states the way to perform tests on indoor post insulators of organic material for systems with nominal voltages greater than 1000 V up to but not including 300 kV.

This is applicable to post insulators of organic material for indoor service in electrical installations or equipment operating in air at atmospheric pressure on alternating current with a nominal voltage greater than 1000 V up to, but not including, 300 kV, as defined by range I of IEC 60071-1, and a frequency not greater than 100 Hz. Composite insulators are not covered by this standard.

9.3.1 -Values which characterise a post insulator of organic material

According to the Standard, a post insulator of organic material is characterised by the following values where applicable:

- the specified dry lightning impulse withstand voltage;
- the specified dry power-frequency withstand voltage;
- the specified lightning impulse puncture voltage (for post insulators of design category B only);
- the specified mechanical failing loads;
- the specified significant dimensions;
- the maximum difference between the deflection at 20 % and 50 % of the specified mechanical failing load.

Service voltage is not considered as a characteristic of a post insulator.

The withstand voltages of post insulators under service conditions may differ from the voltages under standard testing conditions.

9.3.2 -Normal service conditions

Normal temperature and relative humidity service conditions are defined as follows by the Standard:

- the ambient air temperature does not exceed 40 ºC and its average value, measured over a period of 24 h, does not exceed 35 ºC.
- the minimum ambient air temperature is -5 ºC, -15 ºC or -25ºC;
- the altitude does not exceed 1000m;
- the ambient air is not materially polluted by dust, smoke, corrosive or flammable gases and vapours or salt;
- the average value of the relative humidity, measured over a period of 24 h, does not exceed 95 %;
- the average value of the relative humidity, measured over a period of one month, does not exceed 90 %;

9.3.3 -Classification of tests

The tests are divided into three groups as follows:

a.) Type tests:

The type tests are intended to verify the main characteristics of a post insulator of organic material, which depend mainly on its design, the material used and the manufacturing process.

They are usually carried out on one insulator, and once only for a new design or manufacturing process, and then subsequently repeated only when the design, material or manufacturing process is changed. When the change only affects certain characteristics, only the test(s) relevant to those characteristics need to be repeated. For this, the type tests are divided into three sub-groups according to their applicability.

Type tests shall be carried out only on insulators from a lot which meets the requirements of all the relevant sample and routine tests not included in the type tests

b.) Sample tests:

The sample tests are carried out to verify the characteristics of an insulator, which can vary with the manufacturing process and the quality of the component materials of the insulator. Sample tests are used as acceptance tests on a sample of post insulators, taken at random from a lot which has met the requirements of the relevant routine tests.

c.) Routine tests:

The routine tests are intended to eliminate defective insulators and are carried out during the manufacturing process. Routine tests are carried out on every insulator.

9.3.4 -General requirements for electrical tests

International standards states the requirements listed below for lightning impulse tests:

a.) Lightning impulse test methods shall be in accordance with IEC 60060-1.
b.) Lightning impulse voltages shall be expressed by their prospective peak values. When the natural atmospheric conditions at the time of test differ from the standard values, it is necessary to apply the appropriate correction factors.
c.) The post insulators shall be clean and dry before starting the electrical tests.
d.) Precautions shall be taken to avoid condensation on the surface of the post insulator, especially when the relative humidity is high.

The standard 1.2/50 lightning impulse shall be used (see IEC 60060-1) with the following tolerances:

- peak value: ±3 %;
- front time: ±30 %;
- time to half-value: ±20 %.

The standard reference atmospheric conditions for tests shall be in accordance with IEC 60060-1:

- temperature: t_o = 20 °C
- pressure: b_0 = 101.3 kPa (1013 mbar)
- absolute humidity: h_0 = 11 g/m3

The correction factors shall be determined in accordance with IEC 60060-1. If the atmospheric conditions at the time of test differ from the standard reference atmosphere, then the correction factors for air density (k1) and humidity (k2) shall be calculated, and the product K=k1·k2 determined. The lightning impulse test voltages shall then be corrected as follows:

- -withstand voltages: applied test voltage = K multiplied with the specified withstand voltage;

- -flashover voltages: recorded flashover voltage = measured flashover voltage divided by K.

9.4 - Test waveforms

A full lightning impulse test can have three possible results. Firstly, a high voltage insulator of organic material under test that withstands the voltage applied without damage. Air around or along insulator's surface does not break down and is not able to conduct through it, therefore, a flashover arc along insulator's outside does not occur. The test waveform is shown in figure 9.2 below.

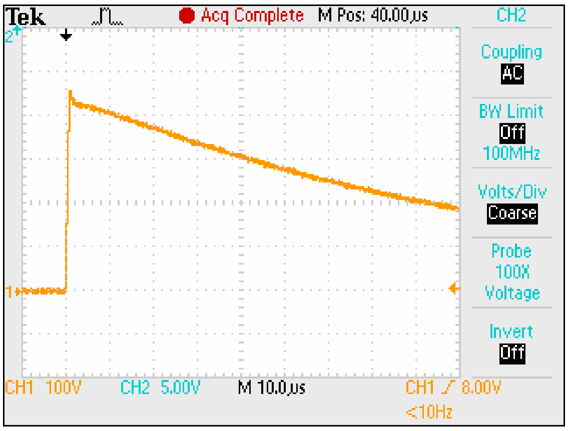


Figure 9.2 - Test waveform of an insulator of organic material. 25kV per stage were applied (125kV). Volts and second per division rate selected: 100V/div, 10µs/div. Prove attenuation: 100X.

If voltage applied on electrical insulator is higher than the maximum lightning voltage which can be supported, then the air around breaks down and a flashover arc occurs along its outside. Air around is then able to conduct electricity through it and capacitors discharge their stored energy through this way. A short circuit is created. This effect is shown in figures 9.3 and 9.4, the wave falls quickly, almost instantaneous because the maximum lightning impulse withstand voltage for the electrical insulator tested here, JO4-125, is 125 kV.

Figure 9.3 and 9.4 show a chopped-tail and a chopped-front waveforms respectively.

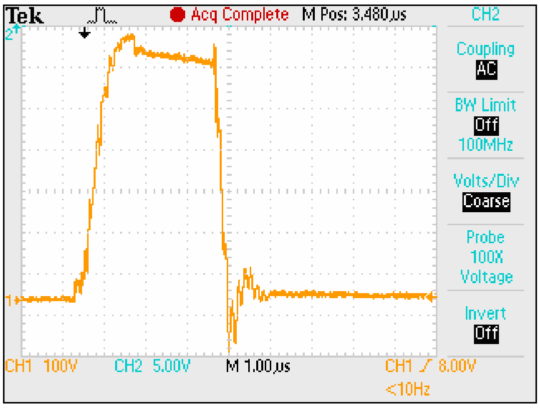


Figure 9.3 - Test waveform of an insulator of organic material. 35kV per stage were applied (175kV) and it is possible to see a positive peak, and, interferences and a damped oscillation after flashover arc occurs; they are object of study. Volts and second per division rate selected: 200V/div, 5µs/div. Prove attenuation: 100X.

If the maximum lightning voltage which can be supported by the insulator under test and air around is reached before the peak voltage value, the flashover arc occurs during the wave-front period (see figure 9.4). However, normally, the flashover arc will occur during the wave-tail period, that is because insulator under test is able to withstand the peak lightning voltage without damage, but air around it breaks down after some time under the effect of this high voltage value (see figure 9.3).

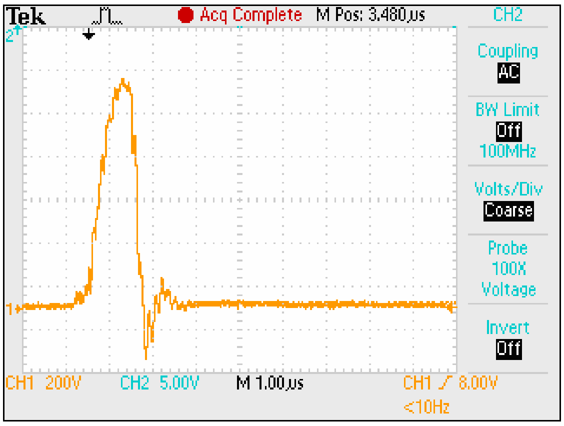


Figure 9.4 - Test waveform of an insulator of organic material. 65kV per stage were (375kV) applied and it is possible to see a positive peak and it is possible to see a positive peak, and, interferences and a damped oscillation after flashover arc occurs; they are object of study. Volts and second per division rate selected: 200V/div, 5µs/div. Prove attenuation: 100X.

These are the three possible results of the test on an electrical insulator. After calibrating the equipment, it will be possible to check the real lightning impulse withstand voltage, which must be, for the insulator under test JO4-125, of 125 kV, and to study if this electrical insulator under test is accepted.

No conclusions has been presented in this chapter in order not to conclude wrong information about the device under test without the accuracy required.

Chapter 10

Results

In this Master's Thesis has been necessary to study all the equipment conscientiously in order to carry out tests in the High Voltage Laboratory.

Firstly, the theoretical fundamentals and the equipment available in the High Voltage Laboratory have been presented in order to set a theoretical base and get to know the function of each part of the equipment, what is necessary to understand how it works and may help in studying future problems in the equipment.

Secondly, it has been shown two computer simulators that can be used in order to study the equipment. On one hand, Pspice is a quick simulator that allows obtaining results with accuracy in order to compare different configurations of the equipment. On the other hand, PSCAD is much better computer simulator but slower. Chopped waveforms may only be simulated with this second one.

Both have their advantages and disadvantages; therefore, the appropriate one must be chosen according to the requirements and the information given in chapter 4. The main ideas in designing and simulating an impulse test system were shown.

There were some problems in the measuring device that emerged when tests on electrical insulators wanted to be performed. Therefore, the main objective of this Master's Thesis changed and focused on searching and solving the problem. After a thorough study and conversations with engineers specialized in High Voltage Engineering, it was discovered that the problems were caused by the measuring system. Actually, there is not any problem, because these "interferences" does not affect to the parameters calculated in the test, but if the standard wave-shape wants to be displayed, it will be necessary to replace the damaged voltage divider with a new one.

Electromagnetic interferences also affect the low-voltage arm of the voltage divider due to a bad contact; therefore the digital storage oscilloscope (DSO) input may be affected by this effect.

The international standard IEC 60052 has been studied in depth in order to shown the way how the calibration of the measuring system must be performed. As shown, it is possible to obtain a linear function that links the peak voltage in the sphere-gap and the peak voltage measured by the oscilloscope. It will assure accuracy in the results obtained.

In every High Voltage installation, it is necessary to comply with the law assessing risks at the workplace. This part has been studied in depth showing the safety systems that already exist in the Laboratory, and suggesting new ones to be implemented in the future in order to make a safer workplace. It is recommended to enlarge the zone inside the Faraday cage in order to permit tests using higher voltages, up to 500 kV.

Finally, a summary of the international standards applicable to electrical insulator tests has been presented, what shows the first steps for future works in the High Voltage Laboratory.

Chapter 11

Further work

Suggested further works may be:

- Adjustment of front and tail times of the generator’s waveform by means of simulation and implement the findings in the real equipment of the Laboratory according to international standards here depicted.

- As said, electromagnetic interferences (EMI) affect the normal behaviour of the equipment. A study about how they affect and how to prevent them is a very interesting future work.

- To perform the calibration of the laboratory equipment. With the information showed in chapter 7 and the necessary equipment, a table of equivalences may be obtained, which will permit to test elements with more accuracy.

- Implementation of a safety system using an optical sensor. Design of the control electronic circuit and the best place to locate it in order to avoid human errors that may be fatal in the High Voltage Laboratory.

Chapter 12

Conclusions

A wide knowledge of the High Voltage Laboratory is presented in this Master's Thesis, from theoretical fundamentals to application of the international standards. This work has studied most of the possible future projects which may be carried out and set important points such as the safety in a high-voltage installation or the solution to the problems with the measuring device.

The practical part of this work has given a very useful experience in solving real problems in electrical equipment and it has been collected in this work, so that it can be helpful in the High Voltage Laboratory.

In short, this report presents a collection of the most important information necessary for further works at the Laboratory, what will allow reaching deeper points of knowledge in High Voltage Engineering.

Chapter 13

Glossary of terms

The most relevant terminology of this report is shown in this chapter. In every engineering work, it is necessary to define the most important terms applicable in a proper way.

A

accuracy: The degree of agreement between a measured value and the true value.

assured disruptive discharge voltage: The prospective value of the test voltage that causes disruptive discharge under specified conditions.

B

breakdown voltage is the voltage at which the insulation between two conductors breaks down. It is the minimum voltage that causes a portion of an insulator to become electrically conductive. The electrical breakdown of an insulator due to excessive voltage can occur in one of two ways: puncture voltage or flashover voltage.

C

chopped lightning impulse: A prospective full lightning impulse during which any type of discharge causes a rapid collapse of the voltage.

chop time is the time interval between virtual origin and break down.

conventional deviation of the disruptive discharge voltage (z): The difference between the 50% and 16% disruptive discharge voltages.

creepage distance: Shortest distance along the contours of the external surfaces of the insulating parts of the post insulator between those parts which normally have the operating voltage between them. However, to take account of the metal fittings attached to the post insulator, the distance which in service conditions is covered by metal fittings is not included in the creepage distance.

corona discharge is the discharge with slight luminosity produced in the neighbourhood of a conductor, without greatly heating it, and limited to the region surrounding the conductor in which the electric field exceeds a certain value [14].

cumulonimbus: heavy masses of cloud with great vertical development, the upper parts having a fibrous appearance and often spreading out in the shape of an anvil. Associated with violent vertical currents and thundery conditions.

D

design category: Post insulators of organic materials are divided into two different design categories according to their construction. The design categories covered by this standard are:

Design category A
Cylindrical post insulators with internal metal fittings in which the length of the shortest puncture path through solid insulating material is equal to or greater than one-third the external arcing distance between the metal fittings.

Design category B
Cylindrical post insulators with internal metal fittings in which the length of the shortest puncture path through solid insulating material is less than one-third the external arcing distance between the metal fittings.
The term “cylindrical insulators” is intended to cover insulators of the truncated conical form.

dielectric loss factor: The factor by which the product of a sinusoidal alternating voltage applied to a dielectric and the component of the resulting current having the same period as the voltage have to be multiplied in order to obtain the power dissipated in the dielectric.

discharge: The passage of electricity through gaseous, liquid, or solid insulation.

disruptive discharge: A discharge that completely bridges the insulation under test, reducing the voltage between the electrodes practically to zero. Syn: electrical breakdown.

disruptive discharge probability (p): The probability that one application of a prospective voltage of a given shape and type will cause a disruptive discharge.

disruptive discharge voltage: The voltage causing the disruptive discharge for tests with direct voltage, alternating voltage, and impulse voltage chopped at or after the peak; the voltage at the instant when the disruptive discharge occurs for impulses chopped on the front.

dry lightning impulse withstand voltage: Lightning impulse voltage which the dry post insulator withstands under the prescribed conditions of test

50 % dry lightning impulse flashover voltage: Value of the lightning impulse voltage which has a 50% probability of producing flashover on the dry post insulator under the prescribed conditions of test.

duration of the wave-front (Rise time): The duration of the wave-front of an impulse voltage is the total time occupied by the impulse-voltage in rising from zero to the peak value. For the sake of convenience of measurement, the nominal value T1 of the duration of the wave-front is defined as 1.25x the time interval between points on the wave-front where the voltage is 10% and 90% of the peak value. T1 is expressed in microseconds

E

error: The difference between the measured value of a quantity and the true value of that quantity under specified conditions.

external insulation: The air insulation and the exposed surface of the solid insulation of a piece of equipment, which are subject to both electrical stress and the effects of atmospheric and other conditions such as contamination, humidity, vermin, etc.

F

fifty percent disruptive discharge voltage (V50): The prospective value of the test voltage that has a 50% probability of producing a disruptive discharge.

flashover: Disruptive discharge external to the insulator, and over its surface, connecting those parts which normally have the operating voltage between them. The term "flashover" used in this standard includes flashover across the insulator surface as well as disruptive discharges by sparkover through air adjacent to the insulator.

full lightning impulse: A lightning impulse not interrupted by any type of discharge.

G

H

I

indoor post insulator. A post insulator not intended to be exposed to outdoor atmospheric conditions. For indoor installations subject to excessive condensation, outdoor post insulators or special indoor post insulators may be used.

impulse: An intentionally applied transient voltage or current that usually rises rapidly to a peak value and then falls more slowly to zero.

instant of chopping: The instant when the initial discontinuity appears.

insulation coordination: The selection of the dielectric strength of equipment in relation to the voltages which can appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available protective devices. By "dielectric strength" of the equipment, is meant here its rated or its standard insulation level as defined below.

internal insulation: Insulation comprising solid, liquid, or gaseous elements, which are protected from the effects of atmospheric and other external conditions such as contamination, humidity, vermin, etc.

J

K

L

lightning impulse: An impulse with front duration up to a few tens of microseconds.

M

N

nondisruptive discharge: A discharge between intermediate electrodes or conductors in which the voltage across the terminal electrodes is not reduced to practically zero.

nonself-restoring insulation: Insulation that loses its insulating properties or does not recover them completely after a disruptive discharge.

nonsustained disruptive discharge: A momentary disruptive discharge.

O

overshoot: The value by which a lightning impulse exceeds the defined crest value.

P

partial discharge: A discharge that does not completely bridge the insulation between electrodes.

peak value of impulse voltages: The maximum value of impulses that are smooth double exponential waves without overshoot.

post insulator of organic material: Post insulator intended to give a rigid support to a live part which is to be insulated from earth and from another live part. The whole or part of the material composing the post insulator consists of organic materials, i.e. of material pertaining to the chemistry of the compounds produced from carbon or to the chemistry of the compounds produced from carbon and silicon. These organic materials may be used alone or in conjunction with other materials (mineral or organic) as fillers, reinforcements, etc.

p-percent disruptive discharge voltage (Vp): The prospective value of the test voltage that has a p-percent probability of producing a disruptive discharge.

precision: The discrepancy among individual measurements.

prospective characteristics of a test voltage causing disruptive discharge: The characteristics of a test voltage that would have been obtained if no disruptive discharge had occurred.

puncture: A disruptive discharge passing through the solid insulating material of the insulator which produces a permanent loss of dielectric strength.
A fragment breaking away from the rim of a shed or damage to the insulator due to the heat of the surface discharge is not considered as a puncture.

Q

R

random error: Errors that have unknown magnitudes and directions and that vary with each measurement.

root-mean-square (rms) value of alternating voltage: The square root of the mean value of the square of the voltage values during a complete cycle.

S

self-restoring insulation: Insulation that completely recovers its insulating properties after a disruptive discharge.

sparkover: A disruptive discharge between electrodes in a gas or liquid.

standard chopped lightning impulse: A standard lightning impulse chopped by an external gap after 2 - 5 µs .

standard lightning impulse: A full lightning impulse having a virtual front time of 1.2 µs and a virtual time to half-value of 50 µs.

surge: A transient voltage or current, which usually rises rapidly to a peak value and then falls more slowly to zero, occurring in electrical equipment or networks in service.

switching impulse is a voltage impulse applied during dielectric tests complying with standards, with a front duration of 0.1 to 0.3 ms, and a time to half value of a few milliseconds [14].

switching impulse time to crest is the time interval between real origin and peak value of the wave.

switching impulse half value is the time interval between real origin and 50 % of peak value on the wave tail.

systematic error: Errors where the magnitudes and directions are constant throughout the calibration process.

T

time to half value of the wave tail (Tail time) of an impulse voltage is the total time occupied by the impulse-voltage in rising to peak value and declining from that place to half the peak value of the impulse. For the sake of convenience, the nominal value T2 is measured between the nominal starting point (virtual origin) of the wave and the point on the wave-tail where voltage is one-half of the peak value. T2 is expressed in microseconds (µs).

U

uncertainty: An estimated limit based on an evaluation of the various sources of error.

undershoot: The peak value of an impulse voltage or current that passes through zero in the opposite polarity of the initial peak.

V

value of the test voltage for lightning impulse voltage: The peak value when the impulse is without overshoot or oscillations.

value of the test voltage for an impulse is the peak value which can be read in the oscilloscope.

virtual front time (T1) of an impulse is defined as time interval between 30 % and 90 % of the peak value multiply by 1.67.

$$T1=1.67\cdot(T90-T30) \qquad (13.1)$$

virtual origin (01): The intersection with the time axis of a straight line drawn as a tangent to the steepest portion of the impulse or response curve

virtual origin (O1) is the point where the straight line traced on 30 % and 90 % of the wave front cut on X axis.

virtual time to half-value (T2): The time interval between the virtual origin and the instant on the tail when the voltage has decreased to half of the peak value.

voltage at the instant of chopping: The voltage at the instant of the initial discontinuity.

voltage ratio of a voltage divider: The factor by which the output voltage is multiplied to determine the measured value of the input voltage.

W

withstand voltage: The prospective value of the test voltage that equipment is capable of withstanding when tested under specified conditions.

References

[1] A. Almeida do Vale: “Técnica das Altas Tensões (apontamentos)”, Faculdade de Engenharia, Universidade do Porto, Portugal , 1997.

[2] António C. Sepúlveda Machado e Moura: “Técnicas de Alta Tensão (apontamentos)”, Faculdade de Engenharia, Universidade do Porto, Portugal, 2002/03.

[3] Martin A. Uman: “Lightning”, McGraw-Hill, 1969.

[4] F. H. Kreuger: “Industrial High Voltage”, Volume 1 and 2, Delft University Press, 1991.

[5] Fink Micah: “How lightning works”. Available on-line: http://www.pbs.org/wnet/savageplanet/03deadlyskies/01lforms/indexmid.html Access on 30/May/2009.

[6] PBS Teachers: “Physics of Electrical Storms”. Available on-line: http://library.thinkquest.org/03oct/00758/en/disaster/lightning/physics.html Access on 30/May/2009.

[7] Vernon Cooray: “Energy dissipation in lightning flashes”, Institute of High Voltage Research, University of Uppsala, Uppsala, Sweden, 1997. Available on-line: http://www.agu.org/pubs/crossref/1997/96JD01917.shtml

[8] C. M. Pinto Oliveira, E. S. da Silva Ferraz, H. J. de Sousa Teixeira, T. F. Ferreira dos Santos: “Descargas Atmosféricas”, Técnicas de Alta Tensão, Faculdade de Engenharia, Universidade do Porto, Portugal, 2006.

[9] Vasco Fernandes Flores: “Relatório de Actividades do Novo Laboratório de Alta Tensão da Faculdade de Engenharia da Universidade do Porto”, 2007.

[10] A. J. Neves de Sousa: “Simulação do Gerador de Choque de Alta Tensão”, Projecto Seminário Trabalho Final de Curso, Faculdade de Engenharia, Universidade do Porto, Portugal, 2006/07.

[11] Impulse Test System User’s Manual, Model IG 500-12.5, Serial Number 75-23474, Part Number DS 25-242, Hipotronics, Inc.

[12] Capacitive Mixed Divider User’s Guide, Model CMD-500, Part Number AS45-326, Hipotronics, Inc.

[13] Website of the Institute of Electrical and Electronics Engineers (IEEE). Available on-line: http://www.ieee.org/

[14] IATE, The European Union’s multilingual term base. Available on-line: http://iate.europa.eu/

[15] IEC 60052, Voltage measurement by means of standard air gaps, International Electrotechnical Commission, Switzerland, 2002.
[16] 100 Series Impulse Generators, Instruction Manual, Hipotronics, 1992.
[17] A. I. Glendon, S. G. Clarke, E. F. McKenna: Human Safety and Risk Management. Taylor & Francis Group, 2006.
[18] HSE (Health and Safety Executive): Five steps to risk assessment. United Kingdom, 2006.
[19] Henry W. Ott: Noise Reduction Techniques in Electronic Systems, Wiley-Interscience, 1988.
[20] Francisco Crespo: Sobretensiones en las redes de Alta Tensión, ASINEL, 1975.
[21] IEC 60273, Characteristics of indoor and outdoor post insulators for systems with nominal voltages greater than 1000V, International Electrotechnical Commission, Switzerland, 1990.
[22] IEC 60060-1, High Voltage Test Techniques Part 1: General Definitions and Test Requirements, International Electrotechnical Commission, Switzerland, 1989.
[23] IEC 60060-2, High Voltage Test Techniques Part 2: Measuring Systems, International Electrotechnical Commission, Switzerland, 1994.
[24] IEC 60060-3, High Voltage Test Techniques Part 3: Definitions and Requirements for on-site testing, International Electrotechnical Commission, Switzerland, 2006.
[25] D. Kind, K. Feser: High Voltage Test Techniques. Available on: http://books.google.com/books?id=nHqQnSM71_cC&pg=PP1&dq=high+voltage+test+techniques+kind+feser&client=firefox-a&hl=es (Section 1.3.2). Access on 30/May/2009.
[26] IEEE Std 4-1995, Standard Techniques for High-Voltage Testing, Institute of Electrical and Electronics Engineers, USA, 1995.
[27] IEC 60660, Insulators. Tests on indoor post insulators of organic material for systems with nominal voltages greater than 1000 V up to but not including 300 kV, International Electrotechnical Commission, Switzerland, 1999.
[28] P. L. Lewin, T. N. Tran, D. J. Swaffield, J. K. Hällström: Zero-Phase Filtering for Lightning Impulse Evaluation: a K-factor Filter for the Revision of IEC60060-1 and -2.
[29] D. J. Swaffield, P. L. Lewin, N. L. Dao, J. K. Hällström: Lightning impulse wave-shapes: defining the true origin and its impact on parameter evaluation.
[30] D. Kováč, I. Kováčová: Electromagnetic Coupling of the Electrocal Drive – EMC (Part II).
[31] AGARD, Advisory Group for Aerospace Research & Development: Electromagnetic Interference and Electromagnetic Compatibility. NATO.
[32] EMC PARTNER AG Company Brochure, Designing and manufacturing portable test and measurement equipment for lightning tests.
[33] D. Kováč, I. Kováčová: Electromagnetic Coupling of the Electrocal Drive – EMC (Part I).
[34] IEC 60071-1, Insulation coordination. Part 1: Definitions, principles and rules, International Electrotechnical Commission, Switzerland, 1993.
[35] G. L. Ángel: OrCAD/PSpice Tutorial, 2003.
[36] Guía de Iniciación a la Herramienta OrCAD/PSpice, Departamento de Tecnología Electrónica. Universidade de Vigo.
[37] Orcad Capture. User's Guide, 2000.