Miniproject High Voltage Engineering

Estefanía Ruiz, Aitor Teran, Nicolai Fransen, Jesper Kloster,
Thassilo Lang, Nicolás Murguizur Bustos

Energy Technology, INTRO-760, 2018-19

28\11\2018

STUDENT REPORT
AALBORG UNIVERSITY

Here you can write something about which tools and software you have used for typesetting the document, running simulations and creating figures. If you do not know what to write, either leave this page blank or have a look at the colophon in some of your books.

Contents

AALBORG UNIVERSITET

HIGH VOLTAGE ENGINEERING

LABORATORY EXCERCISE INSTRUCTIONS FOR MINIPROJECT

Qian Wang, *PhD. Fellow*, Claus Leth Bak, *Professor*

Department of Energy Technology, Aalborg University, Pontoppidanstraede 111, 9220 Aalborg, Denmark

Email: qiw@et.aau.dk ,clb@et.aau.dk

Introduction

The High Voltage engineering laboratory exercises will be held after the lectures in order to apply the theoretical concepts given during the lecture. There is one mandatory demonstration of HV laboratory safety. The students should read the safety rules prior to the lecture, which can be found in the following:
http://www.et.aau.dk/digitalAssets/48/48085_rules_highvoltage_lab.pdfattend.

The student MUST sign the document and return it to Claus Leth Bak before any work in the HV lab is allowed.

It is mandatory to attend the laboratory demonstrations carried out by the lecturer and his assistant (duration ½ - 1 hour). After the demonstration, the students are free to work for each laboratory exercise on their own and supervised by the lecturer or his assistant. This is highly recommended, but not mandatory.

A miniproject must be handed out at the end of the semester. The student should include all the measurements carried out during the laboratory sessions following the instructions for each laboratory exercise.

The following skills will be gained:

- Fundamentals of High Voltage Engineering
- Measurements, according to IEC standards, of high AC, DC and impulse voltages for testing purposes in the HV laboratory.
- Sphere gap measurements
- Electrostatic field theory for simple insulation systems.
- Non-destructive tests methods in HV engineering.
- Dynamic properties of dielectrics in time and frequency domain
- Insulation ageing and lifetime assessment- test methods.
- Modelling of dielectric properties by means of electrical equivalent circuits.
- Dielectric loss and capacitance measurement – the Schering Bridge
- External partial discharges, origin and practical importance for HV power system components, corona, overhead line audible noise and measurements of corona phenomena.
- Internal partial discharges, origin and practical importance for HV power system components.

1. Inductive Voltage Transformer

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

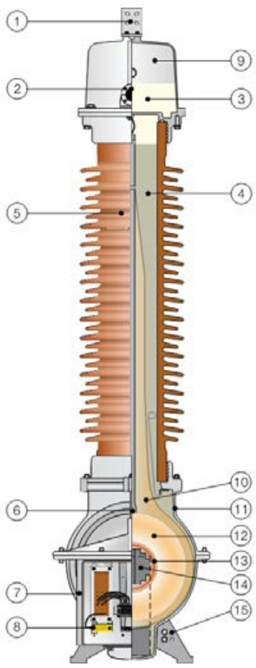
1.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- General description and understanding of inductive voltage transformer.
- Dielectric design description.
- Nameplate parameters and specifications, understanding of all the data provided by the manufacturer.
- Theoretical calculation and experimental measurement of transformer transfer ratio.

1.2 General Description

The ABB Inductive Voltage Transformer EMF (EMF 52-170) is a voltage transformer which is used for voltage metering and protection in high voltage network systems. The purpose is to transform the high voltage into low voltage adequate to be processed in measuring and protecting instruments in the secondary side. Therefore, a voltage transformer isolates the measuring instruments from the high voltage side.



The standard design of the EMF 52-170, which is depicted in Figure 1, has a single high voltage terminal and three low voltage terminals (e.g., *1a-1n*, *2a-2n* and *da-dn*). The last one, *da-dn*, is normally used for measuring ground faults, but other configurations can be made available if required.

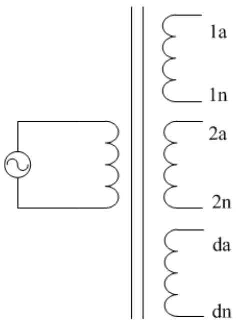


Figure 1. ABB EMF 72 kV inductive voltage transformer.

1.3 Dielectric Design

The dielectric characteristics of the inductive voltage transformer will be explained during the laboratory session. The student is expected to **take notes** and **pictures**.

There are two types of insulators; the student must point out the purpose of using them:

- Outer insulator: ceramic insulator.
- Inner insulator: oil, paper insulator, quartz filling, etc.

1.4 Nameplate

The nameplate contains information about the transformer, e.g., voltage, current, frequency, voltage factor, etc. The student is expected to take notes of the information provided by the manufacturer. The student must describe and understand the data given in the nameplate.

Table I. ABB inductive voltage transformer.

	Nameplate	**Size**	**Unit**
1	Type	EmFC72	
2	Number	8350834	
3	Isolation level	140 - 350	kW
4	Max. constant voltage	72,5	kV
5	Frequency	50	Hz
6	Norm	IEC186	
7	Voltage factor	1.9 / 8	H
8	Total mass	140	kg
9	Production year	1998	

Table II. Data described in the terminal.

	Terminal data	**A-N**	**1a-1n**	**2a-2n**	**da-dn**
10	Voltage (phase-neutral)	60000 / 3^(1/3)	110 / 3^(1/3)	110 / 3^(1/3)	110 / 3^(1/3)
11	Load	-	1 - 15	1 - 65	75
12	Class	-	0.2	0.2	3*P

1.5 Transfer Ratio

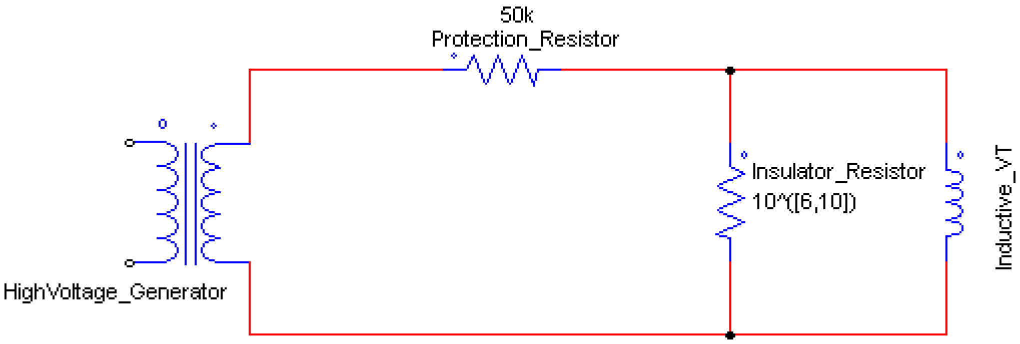
The number of turns on each winding determines the transfer ratio between the primary, which in this case is the high voltage side and the secondary, the low voltage side. The transfer ratio, m, is given by:

$$m = \frac{Vp}{Vs} = \frac{Np}{Ns}$$

The student has to calculate the rated transfer ratio with the information given on the transformer's nameplate and further on, verify the transfer ratio by means of experimental tests. Several measurements must be conducted (e.g., primary voltage range from 5 kV up to 30 kV) in order to demonstrate the good functionality and linearity of the inductive voltage transformer. The student must provide a comprehensive description of the experimental setup and explain the differences observed between the theory and experimental results:

- Why the maximum voltage applied at the high side should not exceed 35 kV?
- How the voltage is measured on HV side? Which equipment is used?
- How the voltage is measured on LV side? Which equipment is used?
- How many secondary windings on the LV side are tested? At least two of them must be tested.
- Asses the linearity of the voltage transformer ratio. Illustrate in a graph the relationship between the voltage measured on HV side and the voltage measured on LV side.
- Asses the measurement accuracy of the measured transfer ratio, both high voltage and low voltage measurement.

Please draw a schematic of the circuit with all the equipment that has been used:



4

Why the maximum voltage applied at the high side should not exceed 35 kV?

The nameplate of the transformer states that the maximum rated voltage is 60 kV / sqrt(3) = 34.6 kV which is roughly similar to 35 kV. That means that if this voltage is exceeded it could result in the damage or destruction of the components of the test setup, because the insulation fail.

How the voltage is measured on HV side? Which equipment is used?

The voltage in the HV side is measured using a capacitive voltage divider, which is better than a resistive voltage divider for HV measurements, as capacitors can withstand higher voltages than resistors without power consumption or heating.

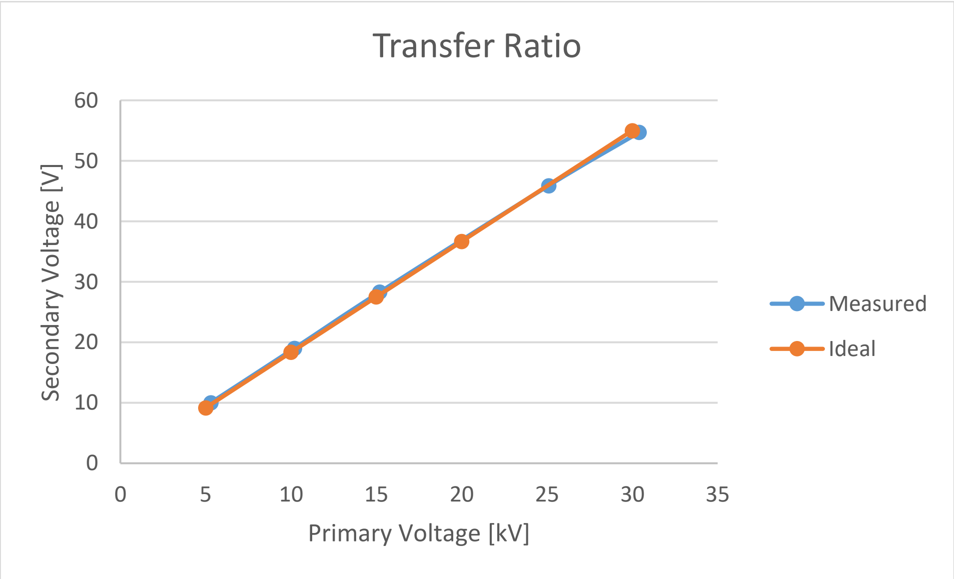
How the voltage is measured on LV side? Which equipment is used?

The voltage in the LV side is measured using a multimeter because the output is a DC low voltage signal.

How many secondary windings on the LV side are tested?

Two secondary windings on the LV side were tested, 1a-1n and 2a-2n, so it is possible to verify the functionality of the transformer by comparing the results obtained in both cases.

Asses the linearity of the voltage transformer ratio. Illustrate in a graph the relationship between the voltage measured on HV side and the voltage measured on LV side.



The response of the system shows a qualitatively linear behaviour. However, according to experimental tests, the relationship between input and output varies from 530 at Vin = 5.3 kV to 555 at Vin = 30 kV. There's a slight divergence between this data and the transfer ratio stated in the nameplate, 545.

Asses the measurement accuracy of the measured transfer ratio, both high voltage and low

Difference in Transfer Ratio	Difference[%]
-15,45	-2,83
-8,61	-1,58
-8,35	-1,53
1,39	0,25
10,30	1,89
Mean difference [%]	-0,76

Secondary winding tested: 1a - 1n

Primary side [kV]	**Secondary side [V]**	**Transfer Ratio**
5.3	10	530
10.2	19	536.8
15.2	28.3	537.1
25.1	45.9	546.8
30.4	54.7	555.7

Secondary winding tested: 2a - 2n

Primary side [kV]	**Secondary side [V]**	**Transfer Ratio**
5.4	10	540
10.2	19.1	534
15.1	28.3	533.6
25	45.8	545.9
30.2	54.5	554.1

5

2. DC Voltages Generation

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

2.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- General description of the half-wave rectifier circuit for DC voltage generation and become familiar with the experimental setup.
- Conduct DC voltage generation test and describe the procedure.
- Experimental measurement of ripple voltage and ripple factor.
- Voltage divider design.

2.2 General description

The rectification of alternating currents is the most efficient means of obtaining DC voltages. When a HV diode, a load capacitor C and a resistive load R are connected to the output of a simple HVAC transformer, a half-wave rectifier circuit is established and a DC voltage is generated. The diode opens for half-waves of one polarity and closes for the opposite polarity. It opens only as long as the AC voltage at the transformer output is higher than the voltage of the charged capacitor. As soon as the capacitor carries any charge, its discharging starts and becomes significant when the diode closes after the voltage has reached its maximum. The capacitor is discharged to a minimum voltage, until the diode opens again for a short time. This means the output voltage is not constant, and it shows a so-called ripple voltage.

A oscilloscope can be used to measure the generated DC voltage waveform along with the ripple voltage/factor. However, the maximum input voltage of the oscilloscope is much lower than the DC voltage, a voltage divider should be designed.

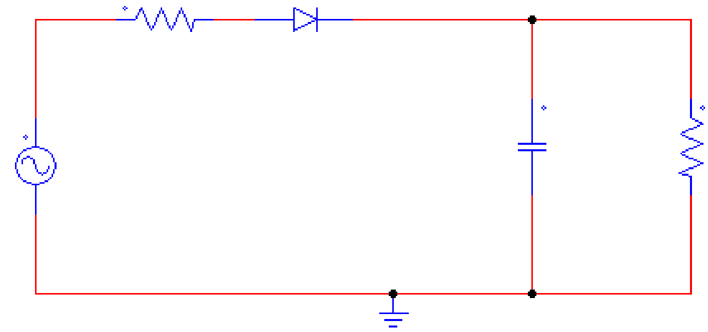
In order to generate and measure a DC voltage, a single-phase half-wave rectifier circuit is used. The student must carry out the following tasks:

- Draw as **detailed as possible** the schematic of the setup, equipment, etc., and draw the trend curve of voltage/current at the load R.
- Identify the maximum AC supplying voltage V_{max} in the circuit (hint:

consider the diode withstand voltage).

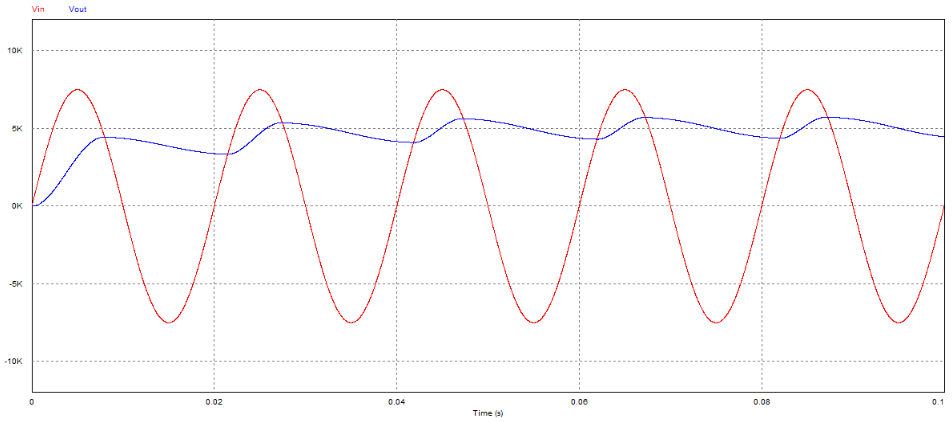
- Identify the resistance of the voltage divider and define the voltage division ratio.

Please draw a schematic of the setup with all the equipment that has been used:



· The diode used diode has a voltage rating of 140 kV. The capacitor maximum voltage will be Vmax then Vmax shouldn't eexceed V_diode_max/2 in order to ensure that the system won't damage the diode when Vin = -Vmax.

· Input voltage (red) and system response (blue) for an input peak voltage of 7.5 kV:



· The voltage divider has a total resistance of 24 MOhm.

2.3 DC voltage generation test

Once the student becomes familiar with the setup and understands the principle of the half-wave rectifier circuit, the next step is to conduct the DC voltage generation test.

The procedure will be explained during the laboratory session so the student is expected to take notes and include them in the mini-project.

The student has to give different AC supplying voltages and measure corresponding generated DC voltages. The ripple voltage δV and ripple factor S should be calculated based on the experimental waveforms captured in the tests.

AC supplying voltage [kV]	DC averaged voltage [kV]	Ripple voltage [kV]	Ripple factor [%]
5.3	4.6	2.89	62.8
19.9	22.5	5.64	25.1
29.9	34.6	7.68	22.2
34.6	40.4	8.53	21.1

3. IMPULSE VOLTAGES: LIGHTNING IMPULSE

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

3.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- General description of the lightning test procedure and become familiar with the experimental setup.
- Conduct first lightning test without DUT (Device Under Test) and describe the procedure.
- Measure the volt-time characteristics for sphere-sphere gaps and rod-rod gaps.
- Examine the effect of a surge arrester.

3.2 General Description

There are two types of overvoltage pulses which power systems should withstand – lightning and switching. In the field, these transients can take different wave shapes. Lightning overvoltage typically occur due to lightning strokes hitting the phase wires of overhead lines or outdoor bus bars. Amplitudes are very high (i.e., 1000 kV), therefore the insulation may breakdown and the voltage is chopped, however it is also possible that the insulation may not breakdown and withstand the overvoltage. In case that the insulation does not breakdown a full lightning impulse voltage shape can be observed. In case that the there is a breakdown of the insulation; the voltage can be chopped on the front or on the tail.

Lightning impulses have very fast voltage rise, the standard lightning impulse is described as 1.2/50 μs wave. On the other hand, switching impulses have slower voltage rise, typically 250/2500 μs. Switching impulses are not the scope of this laboratory session; therefore no further details are given.

3.3 Laboratory tasks

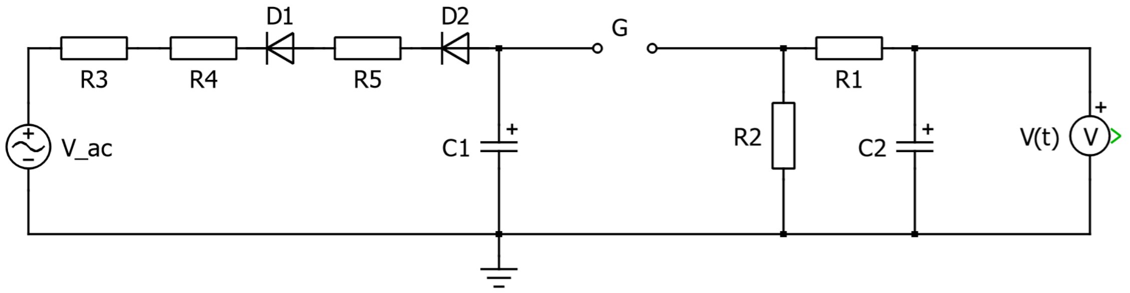
3.3.1 Experimental circuit

In order to generate a wave with $T_1/T_2 = 1.2/50\mu s$, a single-stage generator circuit is used. The student must carry out the following tasks:

- Draw as **detailed as possible** the schematic of the setup, equipment, etc., and explain the charging and discharging processes.
- Calculate the values of R_1 and R_2, as the values of C_1 and C_2 are known. Calculate the efficiency η.
- Compare the measured η, chosen values of R_1 and R_2 in the circuit with the calculated values, comment on it.
- Which type of single-stage impulse generator circuit is implemented?
- How is the impulse generator adjusted to obtain a higher impulse?
- Identify from the setup the type of lightning impulse: positive or negative? Why?

Remember to take a picture of the setup and include it in the mini-project.

Please draw a schematic of the setup with all the equipment that has been used:



3.3.2 Lightning test

Once the student becomes familiar with the setup and understands the principle of the lightning impulse, the next step is to conduct the first lightning impulse without any device under test.

The procedure will be explained during the laboratory session so the student is expected to take notes

The efficiency is calculated following the procedure described in the slides:

$C_1 := 10000\ pF \qquad C_2 := 1200\ pF \qquad \alpha_1 := \frac{1}{68.2\ \mu s} \qquad \alpha_2 := \frac{1}{0.405\ \mu s}$

$$R_1 := \frac{1}{2\ C_2} \cdot \left(\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right) - \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right)^2 - \frac{4 \cdot (C_1 + C_2)}{\alpha_1 \cdot \alpha_2 \cdot C_2}} \right) = 3.325\ k\Omega$$

$$R_2 := \frac{1}{2 \cdot (C_1 + C_2)} \cdot \left(\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right) + \sqrt{\left(\frac{1}{\alpha_1} + \frac{1}{\alpha_2} \right)^2 - \frac{4 \cdot (C_1 + C_2)}{\alpha_1 \cdot \alpha_2 \cdot C_1}} \right) = 6.085\ k\Omega$$

$$\eta := \frac{1}{1 + \frac{C_2}{C_1}} = 0.893$$

Questions:

3.3.1

-Explain the charging and discharging processes.

The capacitor C1 is charging until the breakdown voltage. If the breakdown voltage is reach, the gap will closed and current will flow trough to C2,R1 and R2. So C1 is discharging and C2 is charging at this time. The gap will open, if the voltage dropped under the breakdown voltage value.

- The measured efficiency is 0.824, while the used resistors are R1 = 485ohm and R2=9500ohm. As the resistors are different than the calculated, the efficiency is off.

-Which type of single-stage impulse generator circuit is implemented?
We use the type b.
-How is the impulse generator adjusted to obtain a higher impulse?
The gap length have to larger to obtain a higher impulse
-Identify from the setup the type of lightning impulse: positive or negative? Why?
It is a negative impulse because the diode are revearse biased

3.3.2

Explain the lighting test

AC voltage rectified by the two diodes to charge C1 with a DC voltage. The test is carried out first before without the test object to see the impulse voltage waveform that is generated in C2 and, therefore, efficiency of the system. The SW assumes the efficiency is 1 so the test need to be carried out without the test object to calculate the real efficiency. The test's procedure consists in using a software to apply a peak DC impulse voltage to C1. The distance of the sphere gap is changed automatically based on the charging voltage of C1. A negative lightning impulse voltage is applied to C1 to see the breakdown voltage between the sphere's gap. This value is noted down together with the time it takes to reach the breakdown point.

and include them in the mini-project. Figure 1 represents a typical negative lightning impulse without breakdown.

Hint: pay attention to the input voltage applied and how the sphere gap spacing adjusts when conducting the lighting test, write down the peak voltage obtained as well as T_1 and T_2.

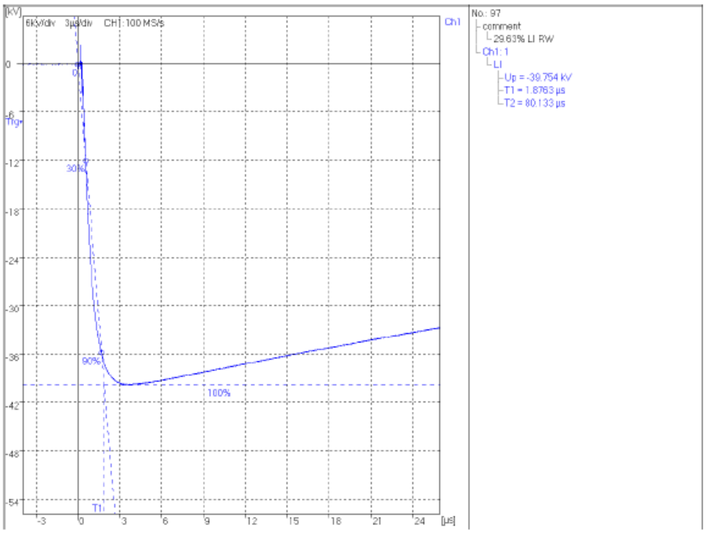


Figure 1. 40 kV negative lightning impulse without breakdown: T_1 = 1.876 µs & T_2 = 80.133 µs

3.3.3 Volt-time characteristics for sphere-sphere gaps and rod-rod gaps

When an impulse voltage of sufficiently high value is applied to a gap, breakdown will result on each voltage application. The time required (time lag) for the spark development will depend upon the rate of voltage and the field geometry. Therefore, for each gap geometry, it is possible to construct a volt-time characteristic by applying a number of impulses of increasing amplitude and noting the time required (time lag) for spark. The volt-time characteristic is an important practical property of any insulating device or structure. It provides the basis for establishing the impulse strength of the insulation as well as for the design of the protection level against over voltages. A schematic plot of such a characteristic is shown in Figure. 2.

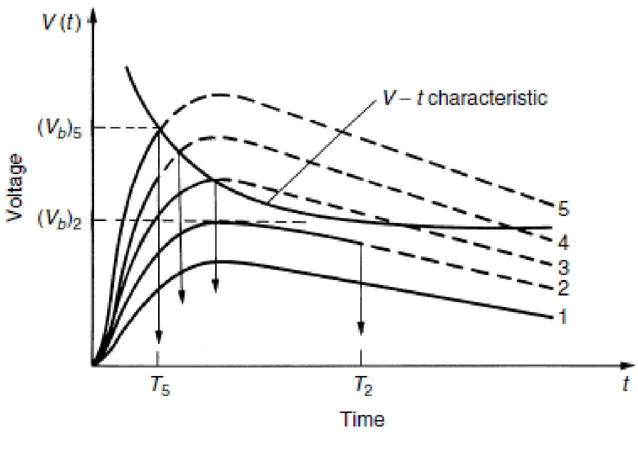


Fig.2 Impulse 'volt-time' characteristics

The students need to obtain the 'volt-time' characteristics of sphere - sphere gap and rod - rod gap

2

respectively under negative lightning impulse.

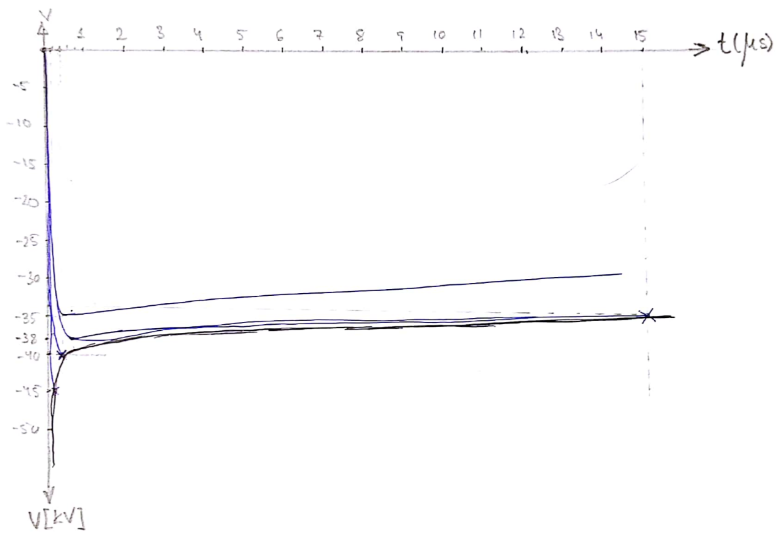
A d=100mm sphere - sphere gap with a gap length s=10mm is adapted. The students need to measure 3 points of the volt-time characteristic of the sphere – sphere gap. For each point, measure the breakdown voltage 5 times and calculate the arithmetic mean value. Remember to convert the measured values to standard atmospheric conditions. Use negative impulse voltage polarity and a charging voltage of app. 35, 45 and 55kV for the 3 points, respectively.

Pre-setting peak voltage [kV]	Average breakdown voltage [kV]	Average breakdown voltage in standard atmospheric conditions [kV]	Average time lag
-38	-37.67	-37.41	4.397 us
-45	-37.33	-37.07	0.759 us
-55	-38.14	-37.87	0.711 us

For the rod-rod gap, a gap length s = 20 mm is adapted. The students need to measure 3 points of the volt-time characteristic of the rod-rod gap. For each point, measure the breakdown voltage 5 times and calculate the arithmetic mean value. Remember to convert the measured values to standard atmospheric conditions. Use negative impulse voltage polarity and a charging voltage of app. 35, 45 and 55kV for the 3 points, respectively.

Pre-setting peak voltage [kV]	Average breakdown voltage [kV]	Average breakdown voltage in standard atmospheric conditions [kV]	Average time lag
-38	-37.55	-37.28	8.699 us
-45	-41.97	-41.67	2.563 us
-55	-43.3	-42.99	1.066 us

Please draw the 'volt-time' characteristics of sphere - sphere gap and rod - rod gap respectively under negative lightning impulse



V-t of sphere-sphere

3

Remember to **compare and evaluate** the volt-time characteristics of sphere – sphere gap and rod – rod gap. Please include your analysis in the miniproject report.

3.3.4 Effect of a surge arrester

A surge arrester is a typical overvoltage protection device in modern power transmission system. It is parallel connected to the component that needs to be protected. A proper surge arrester breaks down at lower voltage than the withstand voltage of the protected component when a transient happens, thus the component will not be overstressed. The students need to find out the effect of a surge arrester.

The students should conduct a lightning impulse test on the rod-rod gap with a gap length s=30mm and record the breakdown voltage waveform. Then connect the surge arrester over the rod - rod gap and keep the other conditions unchanged. Then conduct the lightning test again and the voltage waveform should also been recorded. The students should **compare** the two waveforms with/without the sure arrester and explain the differences.

Breakdown with or without surge arrestor

In the *Figure 1. Lightening impulse without surge arrestor.*, it can be seen the waveform of a lightening impulse without the surge arrestor. The negative voltage reaches a value of -45kV, if the system is not rated for such high absolute electrical potentials, it is possible that it breaks down. For this reason, a surge arrestor can be implemented in the circuit.

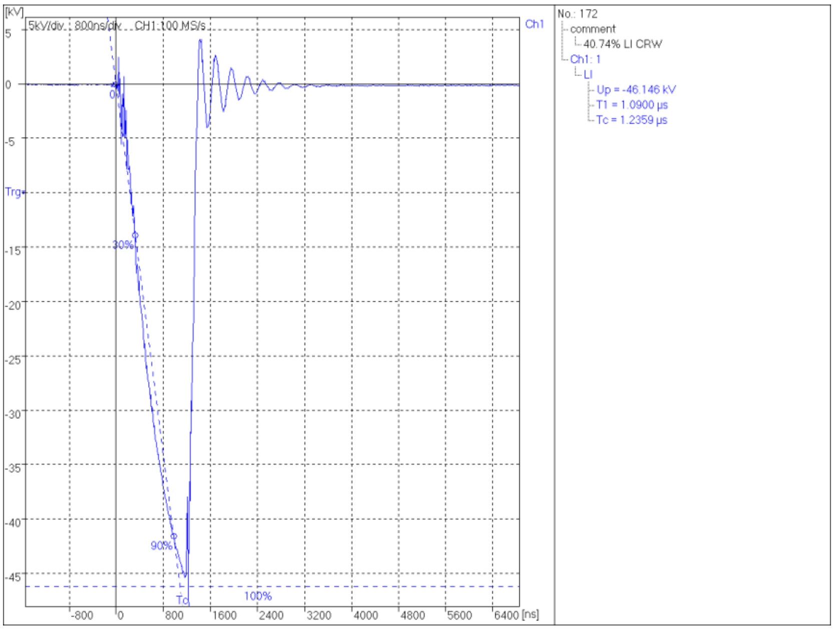


Figure 1. Lightening impulse without surge arrestor.

If the surge arrestor is implemented in the circuit, a different reaction is seen when a lightening strike occurs. In the *Figure 2. Lightening impulse with surge arrestor.*, it is shown how the maximum absolute voltage reached is about 34kV even though the input voltage strike was equal. This means that the surge arrestor has broken down before the actual circuit does, preventing it from having a breakdown.

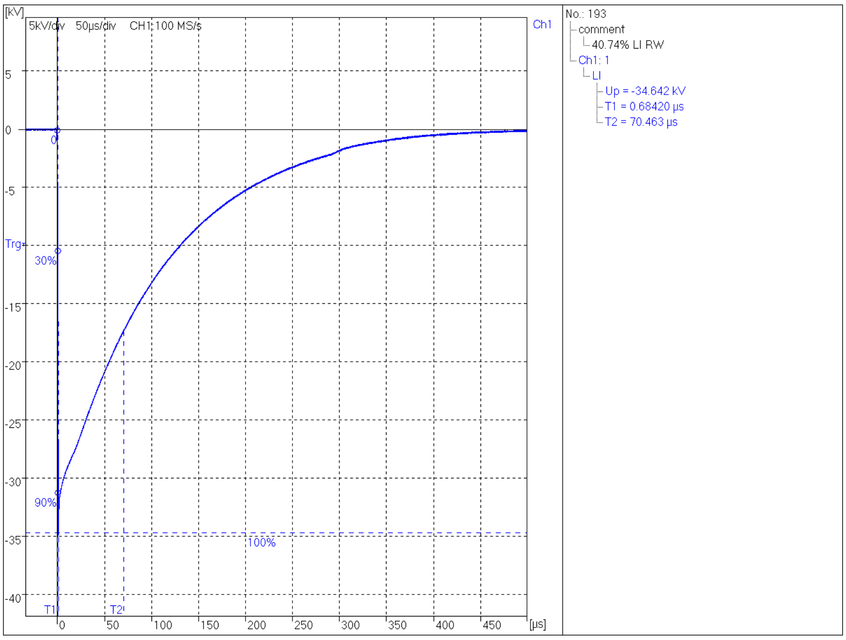


Figure 2. Lightening impulse with surge arrestor.

4. Unit step response of an impulse measuring system

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

4.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- General description of problems in the impulse voltage measurement derived from the dynamic behavior of measuring system;
- General description of unit step response (USR) method;
- Evaluation of measurements of transient voltages measured with a capacitive voltage divider system;
- Design of capacitive voltage divider impulse voltage measuring systems for specific cases.

4.2 General Description

4.2.1 Measuring system for impulse voltage

Impulse voltages are fast (ns-ms) transients with a relatively high (kV-MV) amplitude. To measure the impulse voltages, it will be necessary to reduce (downscale) the amplitude to a magnitude recordable by the chosen measuring equipment, normally an oscilloscope or an impulse voltmeter. The reduced voltage should ideally be an accurate, downscaled copy of the physical high voltage impulse impressed to the test object with a known, non-varying transfer ratio against all frequency components and other parameter. For practical applications one should be aware of the fact that the measured voltage (on the oscilloscope) would differ from the "real" high voltage because:

- Limitations in the transfer function of the measuring system;
- Noise signals induced/influenced to the measuring system.

Generally speaking measuring problems grows worse the larger and faster the voltages are.

Figure 1 shows the principle layout and components of the impulse voltage measuring system. Every possible current and voltage waveform present in the connection (supply) lead can be resolved into two waves travelling in each direction with a speed of $v[m/s]$. The waves would, in the case of a lossless conductor, satisfy the condition stating that the ratio of the voltage and current in any point of the conductor would be constant and equal to the characteristic impedance of the supply conductor. This characteristic impedance is pronounced Z_B and can be determined on the basis of inductance and capacitance per unit length according to:

$$Z_B = \sqrt{L/C}\,, \qquad v = \sqrt{1/LC} \qquad (1)$$

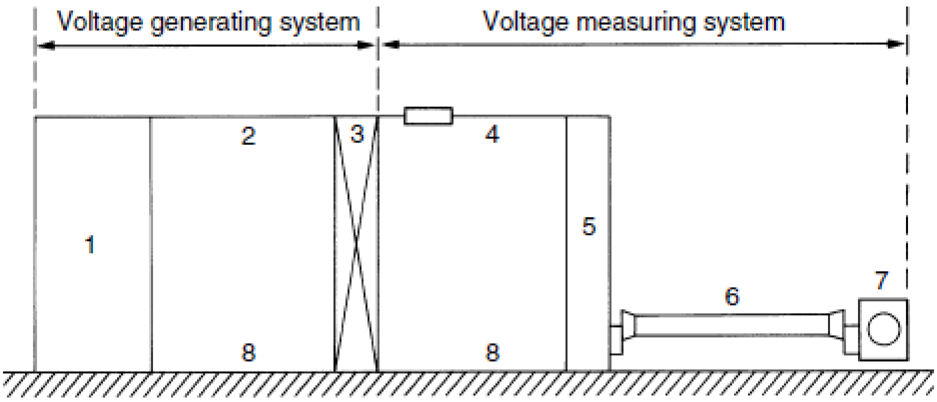


Fig.1 Impulse voltage test setup (principle drawing), 1. Impulse voltage generator (IVG), 2. Conductor between IVG and EUT, 3. Equipment under test (EUT), 4. Conductor for voltage divider, 5. Voltage divider, 6.measuring cable, 7. Oscilloscope, 8. Ground return conductor

The speed of the waves (wave propagation speed) would for a lossless conductor in the air be equal to the speed of light, $v_{light} = 30\ cm/ns$. The characteristics impedance Z_B would normally equal approximately 400 -500Ω.

The voltage $u(t)$ at the top (HV terminal) of the voltage divider would be given by the impressed impulse voltage and the reflection / transmission of the waves propagating in time on the supply conductor.

This voltage $u(t)$ at the HV terminal of the voltage divider will be divided into a lower voltage impressed to the measuring cable. The voltage divider is in principle constructed be means of two serial connected impedances.

The primary HV impedance Z_1 is normally of a high value while the secondary LV impedance Z_2 is very small in comparison to Z_1. Sometimes one uses the simple method by using the characteristic impedance of the measuring cable as LV impedance.

The transfer ratio of the voltage divider can be calculated by:

$$n = (Z_1 + Z_2\,)/Z_2$$

This value, n, will be practical applications normally be equal to the ratio of the input-to-output voltage and could be pronounced nominal transfer ratio.

4.2.2 Unit step response

The measuring system can be analyzed in the laboratory by means of the transfer function (amplitude and phase frequency characteristics) or the **unit step response**.

Fig. 2 below shows the principles of the unit step response method for analyzing the dynamic behavior of the impulse measuring system.

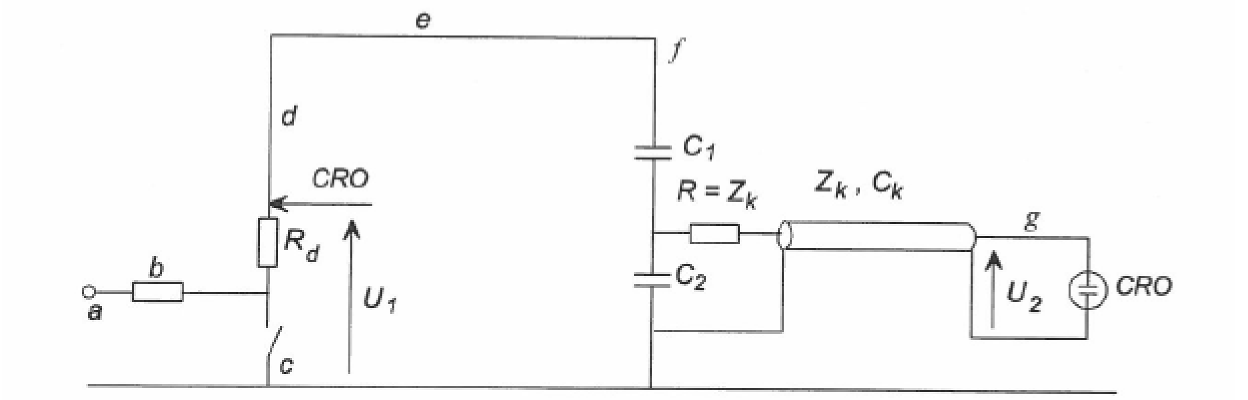


Fig.2 Experimental setup for the determination of the unit step response of an impulse measuring system. a. DC supply; b, charging resistor; c. mercury relay; d. vertical conductor with impedance matching R_d; e. supply conductor with length l and height h above ground; f. capacitive voltage divider; g. to oscilloscope.

An unit step voltage is impressed on the measuring system via resistor b. This unit step voltage is present at point d and will be the reference input signal for the unit step response test. The reply of the measuring system on this unit step unit is pronounced the step response of the measuring system and can be recorded with the oscilloscope connected in g. By means of the step response it will be possible to predict the transfer function of the measuring system and thereby be able to estimate the measuring error for an arbitrary input voltage.

The step response of the measuring system provides information on the following characteristic parameters:

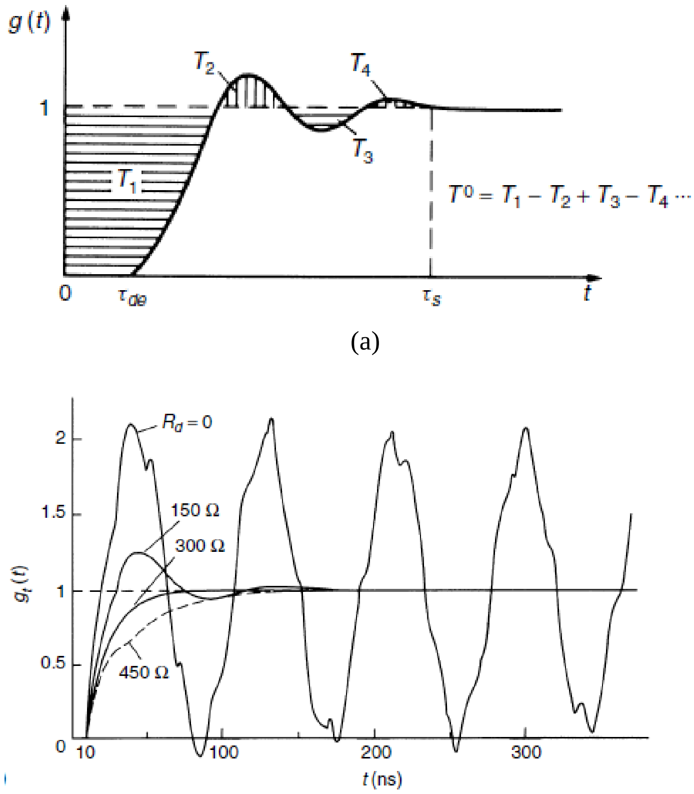
- The rise time of the step response reflects the upper frequency limit of the measuring system.
- Oscillations in the step response reflects the resonant frequency of the measuring system.
- The area between the unit (amplitude =1) step unit voltage and the normalized step response (limiting value) is pronounced response time T and defined in the following way:

$$T = \int_0^\infty (1 - g(t))dt$$

With g(t) as the voltage waveform of the step response as a function of time. This is illustrated in Fig. 3(a), where the response time $T = T_1 - T_2 + T_3 - T_4 + T_5$.

The principle unit step response of the system shown in Fig. 2 with different values of R_d is shown in Fig. 3 (b).

Oscillations in s step response normally originate from reflections on the supply conductor, because of the impedance mismatch between the characteristic impedance of the conductor and the high (in comparison to the conductor) impedance of the voltage divider and at the other end of the conductor – to HV generator mismatch.



(a)

(b)

Fig. 3 Unit step response of a measuring system

The impedance of a practical impulse measuring application would not be zero, but in the range of the characteristic impedance of the supply conductor. This explains the use of the resistor R_d ≈(characteristic impedance of supply conductor) in Fig. 2. The principle response of a practical measuring system would be more like curves in Fig. 3(b) with $R_d = 300\Omega\ or\ 450\Omega$, and pronounced "infinite line response".

It can be shown that the measuring system would react linearly to varying input voltages beyond the time, where the "infinite line" response has reached its final value.

A mathematical approximation of the infinite-line response would be a double-exponential function, which for practical applications would have reached the final value after 4-5 times the response time of the "infinite lime" response (pronounced T_∞ and defined according to the hatched area of Fig 3 (b)).

Practical measuring systems normally react in a way, which will justify the use of the infinite-line response time T_∞ as a guideline to the performance of a measuring system in connection with measuring fast rising voltages.

I t can also be shown that the peak voltage measuring error $\Delta V[kV]$ for linearly rising voltages can be calculated as the product of the response time $T[s]$ and the steepness $S\ [kV/s]$ of the rising voltage according to Fig. 4.

$$\Delta V = S \cdot T$$

International standards for impulse measuring systems are given in IEC 60-1 to 60-4 “High Voltage test techniques”.

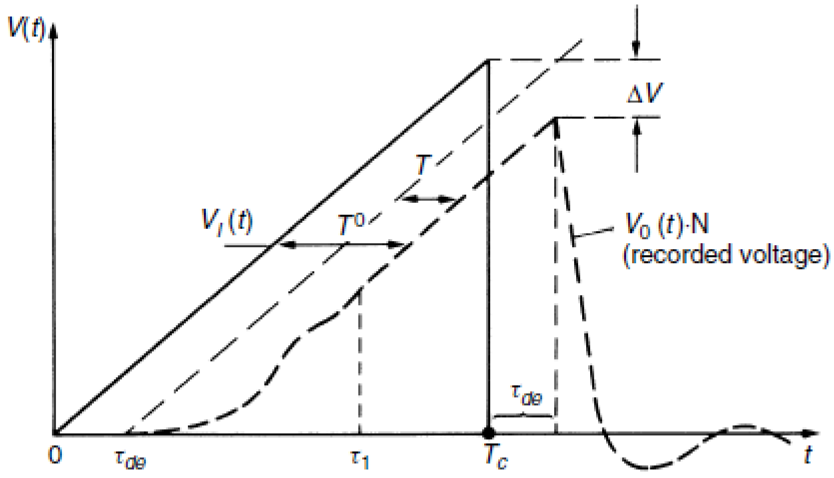


Fig.4 Peak voltage measuring error

4.3 Laboratory tasks

The main task is to use the principles outlined above by testing one of the capacitive impulse measuring systems of the high voltage laboratory.

4.3.1 Calculations

The students should take a picture of the USR test circuit and explain the components and how they work.

Please explain components in the circuit and how they work.

First there is a DC source use to generate a voltage step of 5V through a charging resistor of value 1.5MΩ. The step signal is a reverse step to avoid a short-circuit in the system.

Between the charging resistor and the voltage divider there is a damping resistor Rd used to prevent overshoot in the voltage measurement. According to the theory if the value of Rd is similar to the value of the impedance of the lead it is possible to avoid a non-desired time response.

The capacitive voltage divider is formed by C1= 600 pF and C2= 119.5 nF. C2>>C1 to have a voltage lower at the output.

After the voltage divider again is necessary to use another damping resistor in order to measure the real value of the voltage. The value of this damping resistor is R=Zk (impedance conductor).

The conductor is connected to an oscilloscope to measure the output voltage and compare it with the input voltage.

The
The

Horizontal supply conductor is a 10m long wire with a diameter of 2mm. It has an average height of 1.6m over the ground plane. Based on arrangements and dimensions of circuit, the students need to conduct following calculations:

- Calculate the impedance of horizontal supply conductor Z_{hor};
- Calculate the capacitance C and inductance $L$of the supply conductor;
- Calculate the wave propagation velocity$v$ in the lead;
- Calculate the transfer ratio n based on values of the capacitors.

4.3.2 Unit step response test

The students need do following tasks:

- Conduct the unit step response test according the circuit constructed in section 4.3.1.
- Measure $u_1(t)$ and $u_2(t)$ with an oscilloscope, and comment the appearance of the curves. Then import the date files to eg. MATLAB to calculate the response time T.
- Short circuit R_d and measure $u_1(t)$ and $u_2(t)$ again. Calculate the response time T in this case.
- Calculate the impulse voltage peak measuring error ΔV for the linearly rising impulse voltages with different front steepness $S = 2MV/\mu s,\ 200kV/\mu s$ and $20kV/\mu s$.

Horizontal supply conductor is a 10m long wire with a diameter of 2mm. It has an average height of 1.6m over the ground plane. Based on arrangements and dimensions of circuit, the students need to conduct following calculations:

− Calculate the impedance of horizontal supply conductor;

$$(Z_L)_{\text{hor}} = A\frac{1}{2\pi}\sqrt{\frac{\mu_0}{\varepsilon_0}} = 60 \times A(l, d, H) \quad [\Omega]$$

$$A = \ln\left[\frac{2l}{d}\sqrt{\frac{\sqrt{\{1+(2H/l)^2\}}-1}{\sqrt{\{1+(2H/l)^2\}}+1}}\right]$$
$$= \ln\left(\frac{4H}{d}\right) - \ln\frac{1}{2}(1+\sqrt{1+2(H/l)^2})$$

A = 8.3045 Ω

$$\boldsymbol{(Z_L)_{hor} \ = \ 60 * A \ = \ 498.27\,\Omega \sim 500\,\Omega}$$

− Calculate the capacitance C_L and inductance $L_L$of the supply conductor;

$$C_L = \frac{2\pi\varepsilon_0 l}{A};$$

ε_0 = 8.85 ×10^{-12} F·m^{-1}

$$\boldsymbol{C_L = 66.95\,pF \sim 67\,pF}$$

$$Z_L = \sqrt{\frac{L_L}{C_L}},$$

$$\boldsymbol{L_L = 12.85\,\mu H \sim 13\,\mu H}$$

− Calculate the wave propagation velocity v in the lead;

$$v = \sqrt{1/LC}$$

$$\boldsymbol{v \ = 33.88 \times \frac{10^6\mathrm{m}}{\mathrm{s}} \sim 3.38\mathrm{cm/ns}}$$

– Calculate the transfer ratio n based on values of the capacitors.

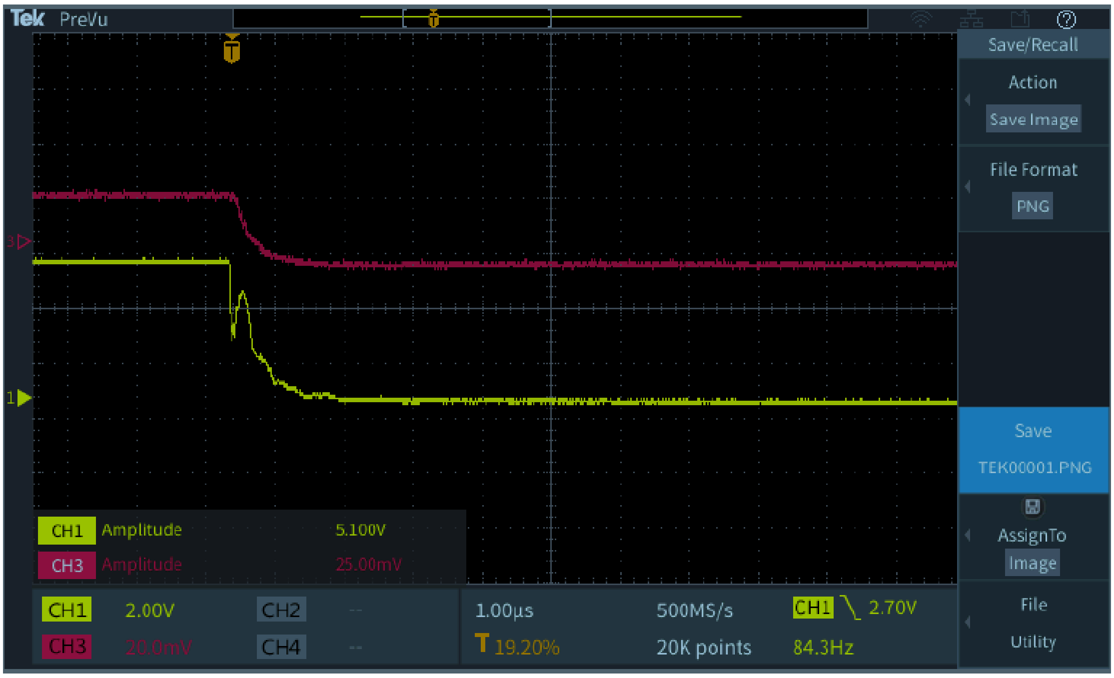
$$n = (Z_1 + Z_2)/Z_2$$

$$n = \frac{C_1 + C_2}{C_1}$$

$C_1 = 600\ pF$; $C_2 = 119.5\ nF$

$$\boldsymbol{n} = \mathbf{200.166} \sim \mathbf{200}$$

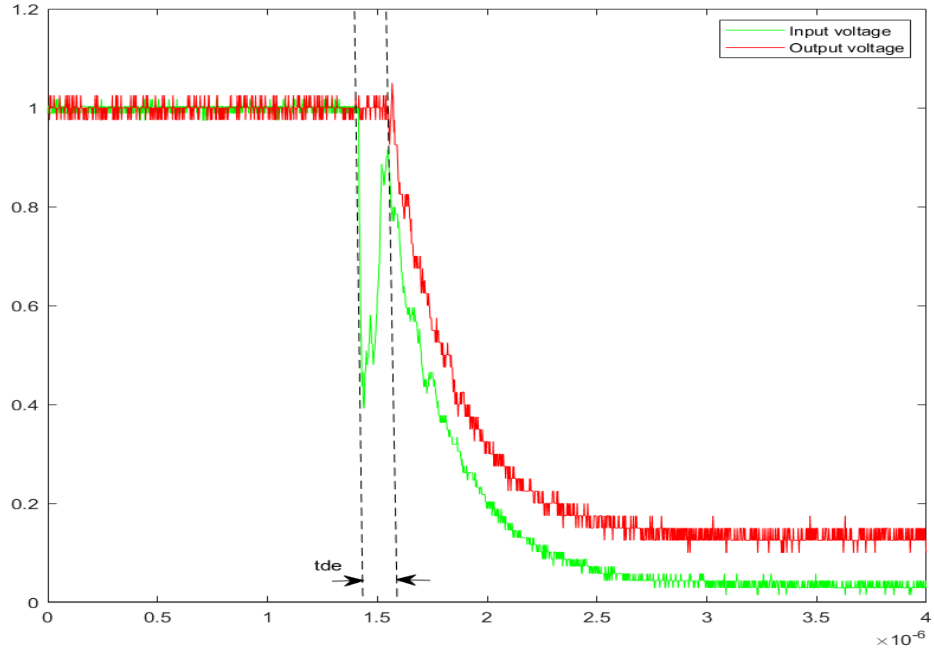
– Measure $u_1(t)$ and $u_2(t)$ with an oscilloscope, and comment the appearance of the curves. Then import the date files to eg. MATLAB to calculate the response time T.



From the scope the input voltage (5V amplitude) is the yellow curve and the voltage after the capacitive voltage divider is the red curve (25mV amplitude). If we compare both curves it can be validated the transfer ratio found previously:

5V /25mV = 200 = n

Moreover, the output voltage does not reach the final value of the input step voltage because of the capacitors of the voltage divider. In this case the value of Rd = 470 Ω which allows to damp the input voltage and that is why in the output voltage there is no overshoot.



The response time is calculated as stated in the following equations:

$$T^0 = \int_0^{\infty} [1 - g(\tau)]d\tau$$

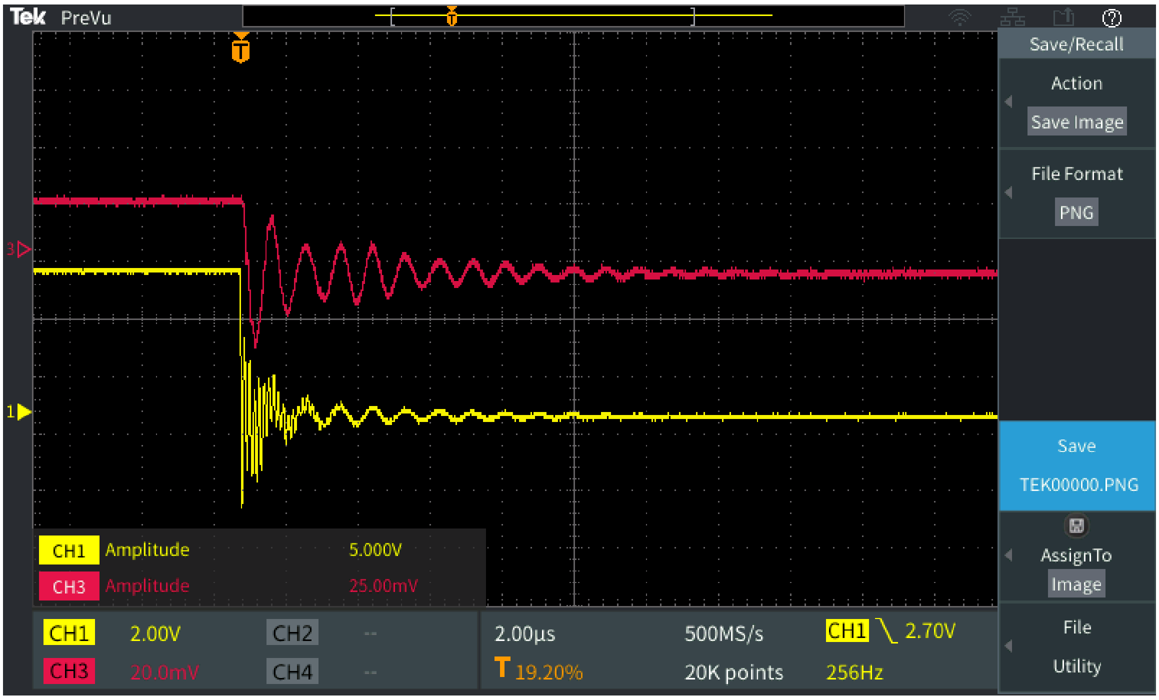
$$T = T^0 - \tau_{de} = \int_{\tau_{de}}^{\infty} [1 - g(\tau)]d\tau$$

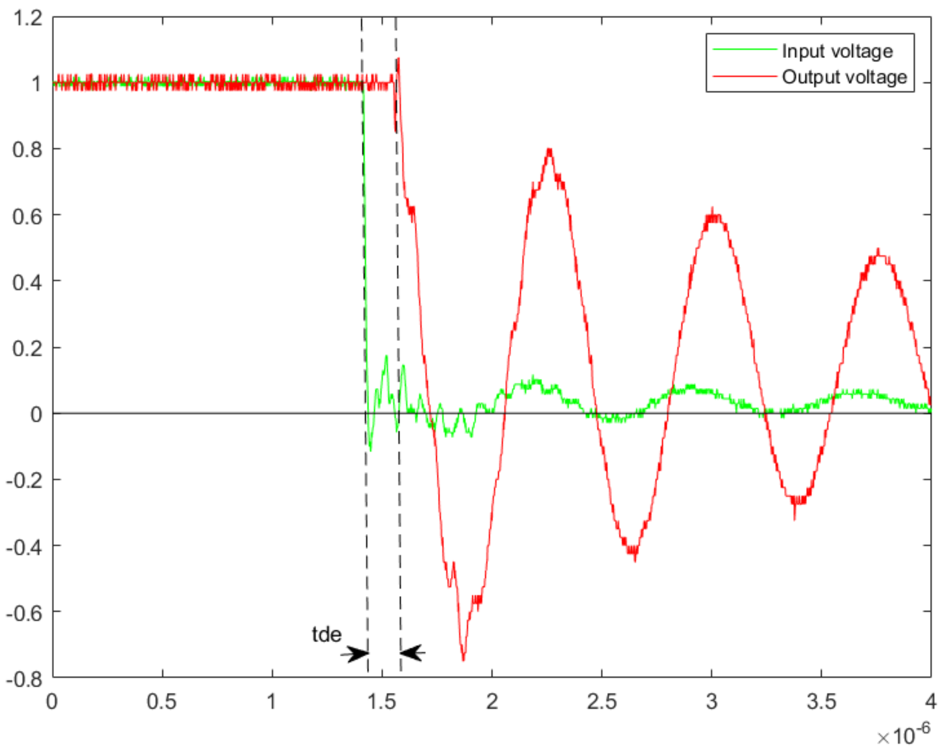
T = $\boldsymbol{T^0}$ – tde = 211.13 *ns*

Where tde is the is the time delay at which the output voltage starts falling from 1 to 0.

– Short circuit R_d and measure $u_1(t)$ and $u_2(t)$ again. Calculate the response time T in this case.

If the value of Rd is 0 then the system will be undamped and therefore more oscillations will appear in the time response. The next figure reflects these oscillations and even though it seems that the response time in this case is higher than the damped system it is not. This is because when the output voltage gets lower than 0 it is necessary to subtract this time periods as: $T = T_1 - T_2 + T_3 - T_4 + T_5$ - ……





The response time is:

$$T = T1 - T2 + T3 - T4 + T5 - T6 + T7 - tde = 482.9\ ns$$

– Calculate the impulse voltage peak measuring error ΔV for the linearly rising impulse voltages with different front steepness S=2MV/μs, 200 kV/μs and 20 kV/μs.

$$\Delta V = S \cdot T$$

S = 2MV/μs:

T = 211.13 ns → ΔV = 422.7 kV

T = 482.9 ns → ΔV = 965.8 kV

S= 200 kV/μs

T = 211.13 ns → ΔV = 42.27 kV

T = 482.9 ns → ΔV = 96.58 kV

S= 20 kV/μs

T = 211.13 ns → ΔV = 4.226 kV

T = 482.9 ns → ΔV = 9.658 kV

5 Electrical onset for uniform field and coaxial cylindrical field and DC corona

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

5.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- Understand the concept of field utilization factor
- Be able to measure the breakdown voltage for uniform field in air.
- Be able to measure the onset/breakdown voltage for coaxial cylindrical field in air.
- Calculate onset E-fields for the above electrical onsets
- Visualize DC corona and polarity influence.

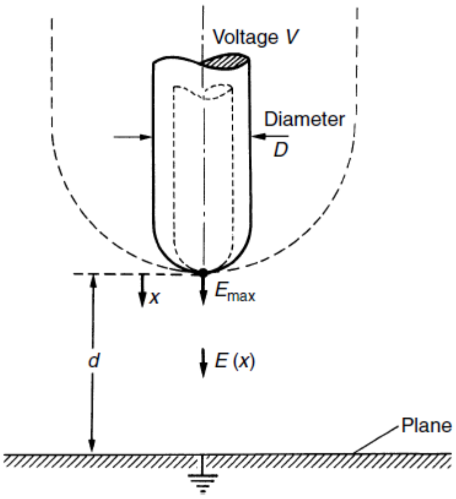
5.2 General description

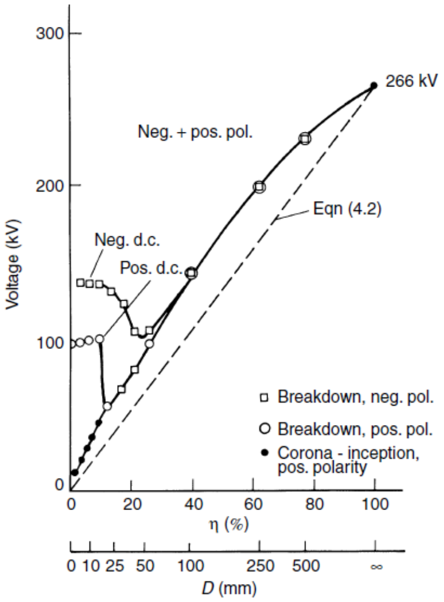
Electric fields govern every discharge process. Their strength delivers the force with which charged particles can act in a dielectric material.

The basic concept of calculating the "engineering relevant" quantity breakdown voltage (i.e. what a certain device can withstand) relies on the onset E-field being a constant.

$$\eta = \frac{E_{\text{mean}}}{E_{\text{max}}} = \frac{V}{dE_{\text{max}}}$$

Schwaigers equation gives the relation between E-field degree of uniformity, gap distance d, maximum E-field Emax and breakdown voltage V assuming Emax to be a constant value regardless of the degree of E-field uniformity. As we know from experimental work, see figure below:



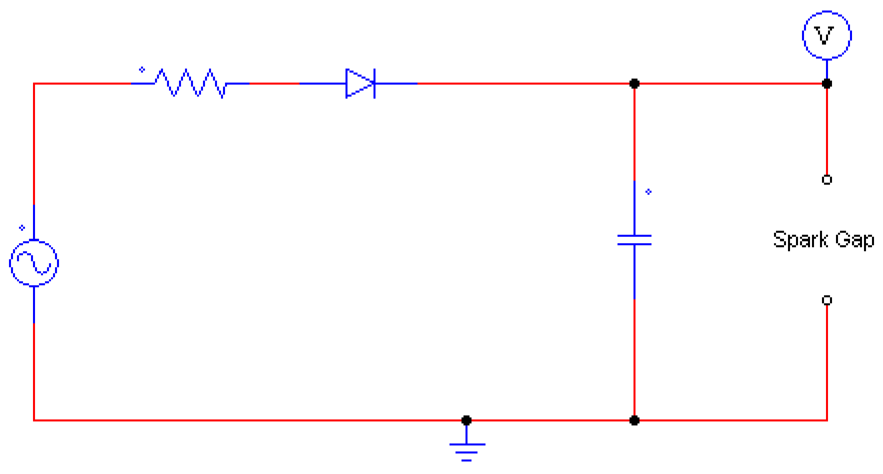


5.3 Laboratory work

The purpose of the laboratory work is to illustrate the different characteristics of uniform vs. non-uniform field discharges. This is accomplished by measuring the onset/breakdown voltage for a uniform gap and a non-uniform gap. Furthermore DC corona and its appearance will be illustrated and documented by photos/videos.

5.3.1 Setup

Please explain components in the circuit and how they work.



1

5.3.2 Measurements

- Measure the breakdown voltage for different E-field types
  a. Measure the positive and negative breakdown voltage for uniform field (the Bruce electrode profiles) for a gap distance $\boldsymbol{d} = 8\mathrm{mm}$. Convert to standard atmospheric conditions.
  b. Measure both the positive and negative onset/breakdown voltage for the coaxial cylindrical field using inner cylinder to be **2 mm**. Onset means the first time you can see the smallest signs of discharges on the inner cylinder – lab must be dark for this. Breakdown is when you see loudly flashes from inner cylinder to outer cylinder. Convert to standard atmospheric conditions.

Notice: When measuring breakdown voltage, the current measuring setup (see below) must be disconnected to the circuit!!!

E-field types	Onset/Breakdown voltage [kV]	
	Positive	Negative
Uniform	13.5	13.5
Non-uniform	Corona: 16.5 Breakdown: 26.5	Corona: 17.5 Breakdown: 28

- Measure the **negative** discharge current for the coaxial cylindrical field using inner cylinder to be 2 mm at three voltage levels being safely below the breakdown voltage. And calculate the corona losses at different voltage levels. Discuss what is causing this.
  Notice: For the following three voltage levels, the scale of the micro-ammeter should be adjusted to $100\mu A, 1000\mu A$ and $1000\mu A$ respectively!!! Always start the scale at 2000 μA and lower from that to the scales mentioned above.

Voltage [kV]	Current [μA]	Corona loss [W]
-25	160	4
-28	280	7.8
-30	360	10.8

- Take photos/videos of DC corona in positive and negative voltage in dark laboratory.

5.3.3 Analysis of results

- Calculate, on the basis of the measurement, the breakdown field strength $E_{max,uniform}$ for uniform field and compare to textbook value chapter 4.1. Comment.

The field was calculated following the formula:
E = V / d, being E = 13.5 kV / 8 mm = 16.87 kV/cm.

The value is significantly different to the textbook value, which is 26,6 kV/cm, the explanation might be due to COMPLETE, we considered that the difference might be due to imperfections in the structure but double check because according tok HV book page 217 figure 4.2, the efficiency is really small.

- Calculate, on the basis of the measurement, the onset/breakdown field strength $E_{max,coax}$ for coaxial cylindrical field with inner conductor negative and comment. The outer cylinder's diameter is 10cm.

  Using the formula E_max_cyl = V / (r1 * ln(r2/r1)), the result obatained is
  E_max_cyl_corona = 17.5 / (0.2 * ln(10/0.2)) = 22.37 kV/cm
  E_max_cyl_breakdown = 28 / (0.2 * ln(10/0.2)) = 35.79 kV/cm

- Calculate the onset/breakdown voltage using Schwaigers equation (4.2) for uniform field using the standard value for Emax from textbook page 203. Compare with the value you got in the measurement. Comment.

  Using the forementioned formula: V = E_max * d * n, assuming uniform field, n = 1.
  V = 26.6 * 0.8 = 21.28 kV.

  The value experimentally obtained is smaller than the theoretical one.

- Calculate the onset/breakdown voltage using Schwaigers equation (4.2) for coaxial cylindrical field using the standard value for Emax from textbook page 203. Compare with the value you got in the measurement. Comment.

  The efficiency is calculated with equation (4.1) eta = E_max_cyl_corona/E_max:
  eta = 22.37 / 26 = 0.86

  Now its possible to calculate the voltage with equation (4.2):
  Vb = Emax*d*eta = 26*0.8*0.86 = 17.90 kV

  The calculated voltage is lower than the measured, because of the lower efficieny

- Discuss the different appearances of DC corona for various voltage levels and polarities using the photos/videos you took with the lights out. **After the 7th lecture, explain why there are differences.**

  The corona effect with positive polarity started being a small and punctual glow. When the voltage was increased, the punctual glow vanished and the inner conductor started glowing homogeneously. When the voltage increased further, eventual breakdowns happened, leading to a bright and short current discharge. The main difference with the negative polarity experiment was that the corona effect appeared as many punctual glowings. The voltage which lead to corona effect and later to breakdown, was higher than in the positive polarity experiment.

6. Paschen's curve for atmospheric air

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

6.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- Determine the breakdown voltage for atmospheric air in a homogeneous field (Paschen's law) as a function of the product of gap length and pressure, V_b = f(pd) corrected to standard atmospheric conditions.
- Determine the constants $(E/p)_c$ og $\sqrt{K/C}$ (see page 338 in Kuffel) for atmospheric air.

6.2 General Description

For a homogeneous field, there is an unambiguous relation between the product of gap length, d and pressure, p and the breakdown voltage for a certain gas and a certain electrode material, due to the following relations:

$$\Delta W = e \cdot E \cdot \lambda$$

$$\lambda \propto \frac{1}{p}, E = \frac{V}{d}$$

$$\Delta W \propto e \cdot \frac{1}{p} \cdot \frac{U}{d}$$

For a certain gas and a certain electrode material, ΔW is a constant which stands for the energy needed to ionize the gas. Thus:

$$V = f(pd)$$

Fig.1 shows the curve which descripts V = f(pd), i.e. the Paschen's law.

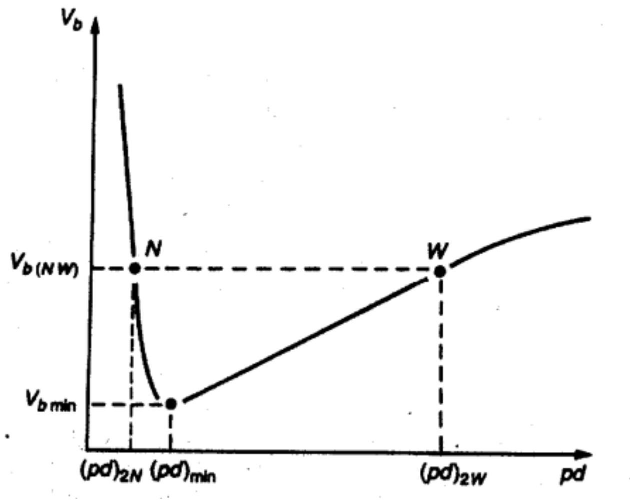


Fig.1 Paschen's law

It can be figured out that for each kind of gas, there is a minimum breakdown voltage V_{min} corresponding a minimum product of pressure and the gap length, $(pd)_{min}$. Table I shows the values of V_{min} and $(pd)_{min}$ of typical gases.

Table 1 Minimum breakdown voltage for various gases

Gas	$(pd)_{min}$ *torr cm*	$V_{b\,min}$ *volts*
Air	0.55	352
Nitrogen	0.65	240
Hydrogen	1.05	230
Oxygen	0.7	450
Sulphur hexafluoride	0.26	507
Carbon dioxide	0.57	420
Neon	4.0	245
Helium	4.0	155

6.3 Laboratory tasks

6.3.1 Test description

Create a setup in the HV laboratory as shown in Figure 2. It is important, that the sphere electrodes in the pressure vessel are cleaned (i.e. dust, greasy fingerprints etc.).

For each value of pd is recorded 5 meaurements. After this the pressure vessel must undergo a completely renewal of the air i.e. exchange the content of air to clean, new air. This can be done by opening the vessel and/or pumping by the vacuum pump. Explain why this step is important and include your explanation in the report. We need the clean air, to eliminate the ionized particles remaining in the air produced by the previous discharges

The experiments are performed with AC power frequency. Breakdown in a homogeneous field will be unaffected of the polarity of the applied voltage and will happen for the peak value of the AC-voltage.

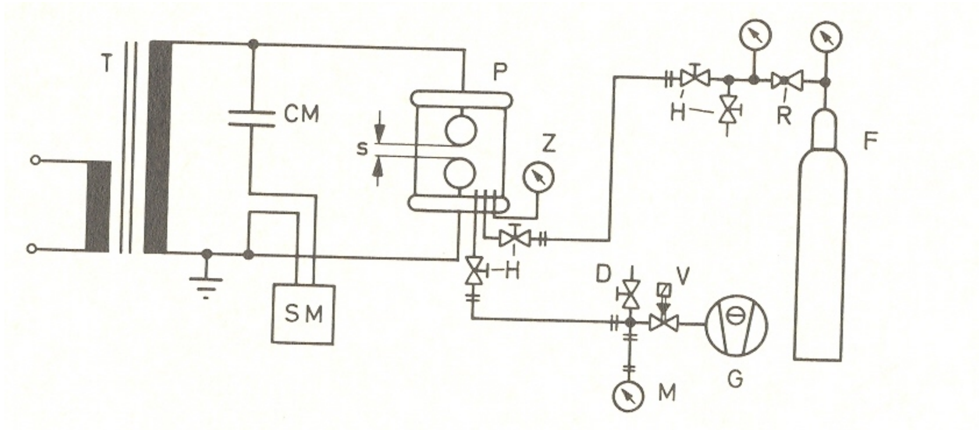


Fig. 2 The principle of the test setup for measuring the breakdown voltages for Paschen's law.

Furthermore, the processes of the gaseous discharge, are of so great rapidness, that the 50 Hz is acting as DC.

Pressures below 1 bar are established by means of the vacuum pump and pressures above 1 bar with the compressor. Take care no condensation water is present in the pressurized air.

The pressure vessel must not be pressurized to more than 3 bars!

6.3.2 Tests

Take 5 measuring points of the breakdown voltage for each value of pd for the gap lengths d=10 mm and d=20 mm, varying the pressure between 0,2 bar and 3 bar. The abscissa should be "covered" with app. 5 measuring points, which each are averages of 5 points for each gap length

Gap length d [mm]	Pressure [bar]	Average breakdown voltage [kV]					Standard deviation [kV]
10	0.2	8.9	7.9	6.9	5.9	5.9	1.3
	0.5	13.22	13.7	16.7	19.2	16.1	2.4
	1	23.1	26.5	28.4	33.8	29.9	3.95
	2	41	39.8	39.1	38.8	34.8	0.8
	3	50.4	55	55.4	51.4	53	2.8
Measurement		1	2	3	4	5	

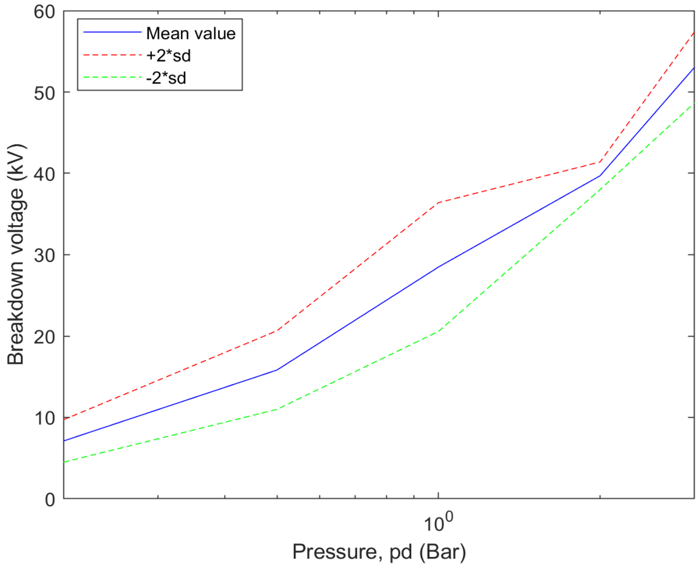
Note the sound and visual appearance of the breakdown phenomena at the varying pressures (lower the light of the lab.)

6.3.3 Calculation and curves

All breakdown voltages should be referred to standard atmospheric conditions, i.e. $p=p_0=1{,}013$ bar and $T=T_0=293$ K.

- Calculate the standard deviation for each measuring point and mark in a semilogarithmic graph as i.e. figure 5.23 in HVE pp. 338. Use the signature ”x” for d=10 mm and the signature ”o” for d=20 mm. The standard deviation is shown with horisontal bars around the measuring points. Draw the Paschen’s law curve below. Compare with figure 5.23 and table 3.3 pp. 83 –

Please draw the Paschen’s law curve.

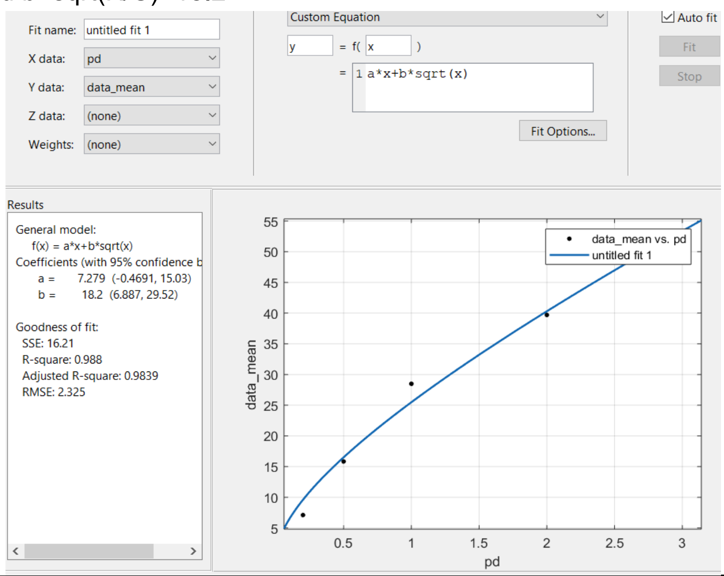


In comparison with the figure 5.23 from the book our measurements look similar in pressure below 1 bar but over that the breakdown voltage for figure 5.23 is higher. But our measurements is only a small

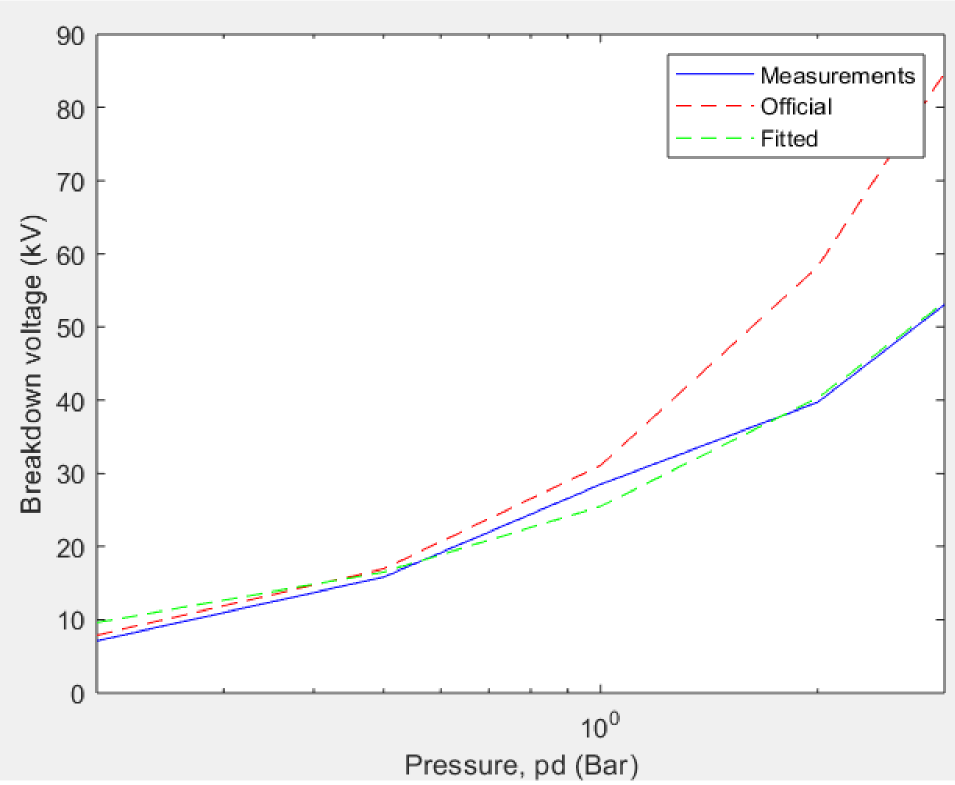
COMMENT ! part of the figure. From 0.2 to 3bar.

- By means of MATLAB and the routine FMINS you should determine the optimum values of (E/p)c and $\sqrt{K/C}$, see eq. 5.102 and 5.103 in HVE pp. 338. These should be compared with the standard values for air; (E/p)c = 24,36 kV/cm and $\sqrt{K/C}$= 6,72 kV/cm½ .The fitted curve based on 5.102 with your own values for (E/p)c and $\sqrt{K/C}$ should be drawn in the same graph as the measurements together with the ”official” one from figure 5.23 – COMMENTS PLEASE !

To do this optimization the "curve fitting tool" has been used from matlab. As it can be seen on the picture below the equation from 5.102 has been inserted and the X data is our pd values while the y data is the mean of the breakdown voltages from each pd value. From this we get that a=(E/p)c=7.279 and b=sqrt(K/C)=18.2



The fitted curve from above is drawn in the graph below together with the official one from figure 5.23 and from the measurements based on the test values



It can be seen that the fitted curve is very similar to the measurements which it should because the same values have been used. The difference is that the measurement line has obviously 5 points while the fitted is more smooth. In comparison with the official from the figure in the book, all three are very similar in pressure below 1 bar. After this value the official ones breakdown voltage is way higher than the measured.

7. Dielectric Spectroscopy Test

SAFETY MEASURES: Interlocks are **not** provided to prevent high voltage to be switched on while the gates/ doors are open. Therefore only one student is allowed to be inside the high-voltage cage, taking special care of high-voltage equipment. Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

7.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- Discuss the aim for conducting dielectric response measurements and describe the theoretical approach.
- Describe the dielectric spectroscopy equipment.
- Evaluate and understand the basics of the loss angle frequency dependence and the concept of the complex permittivity.
- Measure the moisture content and oil conductivity of the inductive voltage transformer.

7.2 Why dielectric spectroscopy?

The goal is to evaluate the condition (e.g., amount of degradation) of the inductive voltage transformer insulation, which can be obtained by means of dielectric frequency response tests. The effects of moisture and ionic contamination lead to the degradation of the oil-paper and therefore accelerate the insulation aging. There are three dangerous situations: i) it decreases the dielectric withstand strength, ii) accelerates cellulose aging, and, iii) causes the emission of gas bubbles at high temperatures.

In order to measure the moisture content and the oil conductivity, the DIRANA device from OMICRON will be used. DIRANA derives the moisture content in paper or pressboard from properties such as polarization current, complex capacitance, and dissipation factor. Each of these parameters is strongly affected by moisture. The dissipation factor plotted together with the frequency range can give information about the moisture content as shown in Figure 1.

- **Frequency range: 10 Hz – 1000 Hz.** Dominated by the cellulose insulation, cables and connection techniques.

- **Frequency range: 0.01 Hz – 1 Hz.** Dominated by the oil conductivity.

- **Frequency: 0.003 Hz.** Dominated by insulation geometry.

- **Frequencies bellow 0.0005 Hz.** Dominated by the cellulose insulation.

Moisture will be determined basically by this low frequency range.

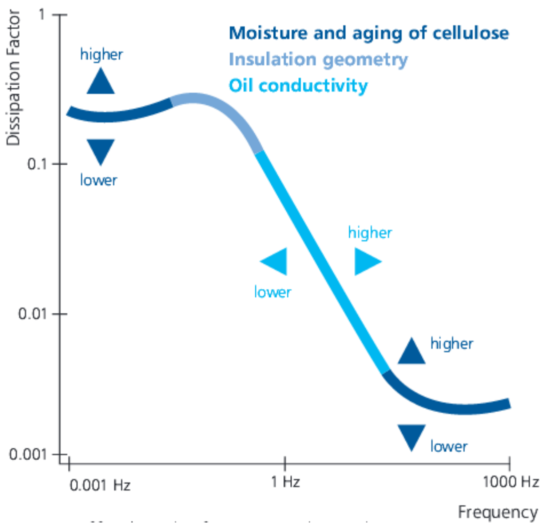


Figure 1. Factors affecting the frequency-dependent dissipation factor.

On this basis, the **student** must describe how the previous curve shifts in case of:

A. Different moisture content.
B. Different aging conditions.

7.3 Test setup

Figure 2 illustrates the setup containing DIRANA device and the test object: ABB inductive voltage transformer. The student should provide a description of the electrical connections between DIRANA and the test object.

Figure 2. Dielectric spectroscopy laboratory setup.

Please draw the schematic of the dielectric spectroscopy test setup.

7.4 Experimental results: moisture content and conductivity.

DIRANA is used to conduct dielectric spectroscopy test to analyze the properties of insulation systems across a wide frequency range (e.g., 1000 Hz to 0.0001 Hz).

The student will be able to measure:

- Dissipation factor for a wide frequency range.
- Moisture content of the solid insulation.
- Oil conductivity.

At the end of the experimental test, the student must be able to:

- Define the moisture category. Is it necessary to apply any dry methods?
- Discuss the results and give an assessment of the condition of the voltage transformer.

Moisture Categories	Value
Dry	< 2.2 %
Moderately wet	>2,2 % and < 3.7 %
Wet	>3.7 % and < 4.8 %
Extremely wet	>4.8 %

Lab exercise 7: Dielectric Spectroscopy Test

7.2 Why dielectric spectroscopy?

How the previous curve shifts in case of:

A. Different moisture content.

B. Different aging conditions.

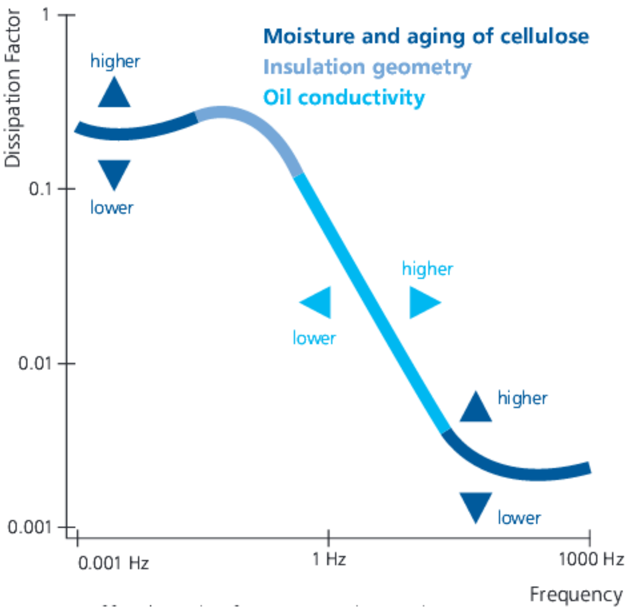


Figure 7.1: Factors affecting the frequency-dependent dissipation factor[1].

A: For a high moisture content (4%) the dissipation factor will increase in low and high frequency range as you can see in figure 7.1. In this two ranges the moisture content a high impact to shift the curve. Low moisture content shifts the curve to lower dissipation factor in low and high frequency range.

B. If the aging process is advanced on the insulator, the curve will shift to the right. This means that the dissipation factor for the medium frequency range (1 Hz) will increase compared to an isolator that does not show aging yet. In low frequency range the dissipation factor will have the same value. For high frequency range (1000 Hz) the dissipation factor will increase because of the shift to the right of the curve.

7.3 Test setup

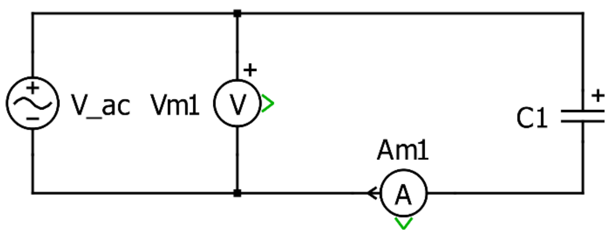


Figure 7.2: Schematic of the dielectric spectroscopy test setup.

For the dielectric spectroscopy test an insulator is used instead of a transformer. This is shown in the diagram as a capacitor, see Figure 7.2. For the power supply the DIRANA device is used, which also serves as an analyzer. The DIRANA can generate voltage at different frequencies. For the dielectric spectroscopy test the isolator is supplied with voltage in the frequency range from 1mHz to 5kHz. Since DIRANA is also an analyzer, the voltage and the current can be measured simultaneously. From 100 mHz, the supply is switched from 100 V AC to 100 V DC to accelerate the process. In addition, the calculation method changes from FDS to PDC. PDC measures the polarization current and the depolarization current and transfers the currents to the frequency domain to obtain the dissipation factor.

7.4 Experimental results: moisture content and conductivity

Define the moisture category. Is it necessary to apply any dry methods?

The Transformer belongs to the moisture category extremely wet (m. c.: over 4.8%). The figure 1 shows the measurement curve from the transformer (blue) comparing a simulate curve for a moisture content over 5.2% (red). The blue curve is located in large parts above the red curve. Based on these observations it can be concluded that the transformer has a moisture content of over 4.8 % and therefore belongs to the extremely wet category. Therefore it is necessary to use some dry methods to reduce the moisture content.

Discuss the results and give an assessment of the condition of the voltage transformer

In lower frequency you can see that the value of the dissipation factor from the transformer is higher than the red reference curve, as you can see in figure 7.3. The aging process in cellulose is well advanced. In the frequency domain 0.1 to 1 the red and the blue curve quit similar behavior.1 Hz and higher the dissipation factor from the transformer is higher than the dissipation factor from the simulation curve. This means that the oil conductivity from the transformer is higher than the simulation one.

The transformer is in not so good condition. If you compare the curve with a reference curve for a moisture content 5.2 %, the transformer dissipation factor is almost every frequency higher or equal to the reference value(red curve). The transformer should be subjected to a drying method so that it can continue to be used in the future.

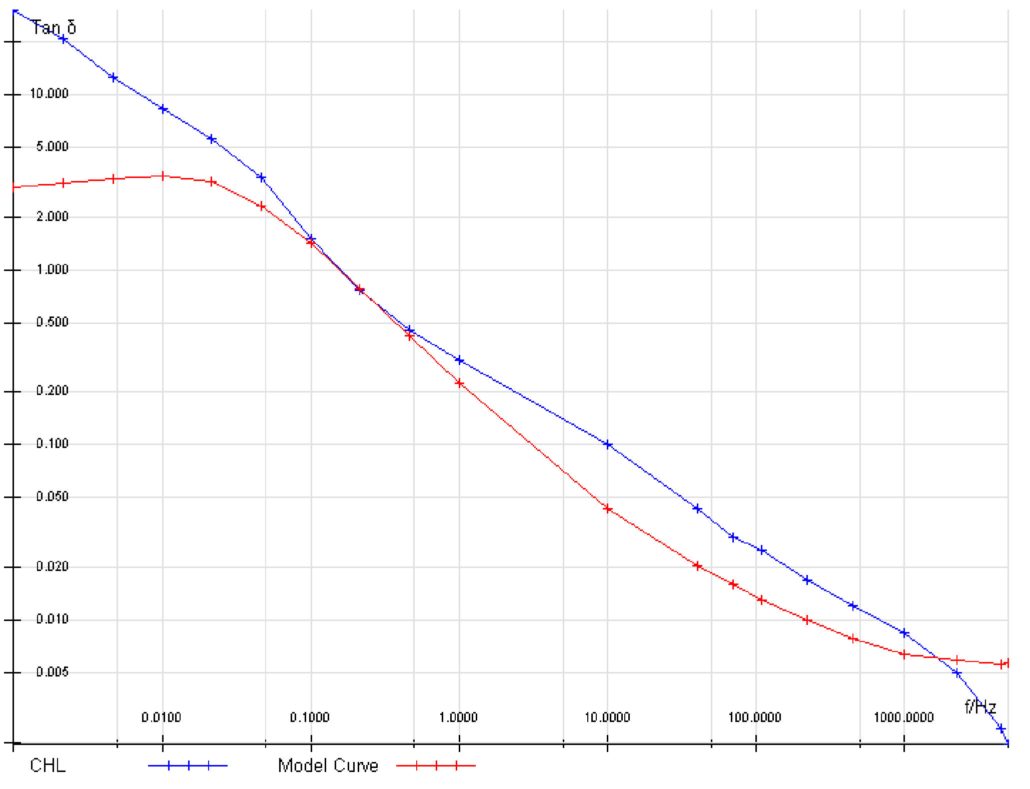


Figure 7.3: Result of the test.

Bibliography

[1]	Lab exercise introduction 7

8. Dielectric Loss Angle

SAFETY MEASURES: Interlocks are provided to prevent high voltage to be switched on while the gates/ doors are open. Despite these measures it is necessary to connect the safety earth stick to the HV parts before touching. (There could be some charge left on the capacitors). Special safety rules for the High Voltage laboratory must be read, understood, signed and always followed to every detail!

8.1 Objectives

The student must gain the following knowledge and comprehension in the following topics:

- General description of the non-destructive high voltage test method: Schering-bridge.
- Assessment of the capacitance, C_x, and the dissipation factor, *tan* δ_x: ABB inductive voltage transformer.
- Assessment of the capacitance, C_x, and the dissipation factor, *tan* δ_x: ideal homemade capacitor.

8.2 General Description: Schering-bridge

The loss factor or dissipation factor, *tan* δ, is an indicator of the quality of solid or liquid dielectrics. In order to measure the capacitance and dissipation factor, *tan* δ, a non-destructive test is performed with the high voltage Schering-bridge, which schematic is shown in Figure 1 and the test equipment is shown in Figure 2. Such tests are usually carried out at different voltage levels in order to ensure that **both capacitance and dissipation factor are constant,** i.e., linear with respect to voltage. The Schering-bridge adjusts the resistance and capacitance values automatically. In case that some deviations are observed when measuring the loss angle at different applied voltage levels; two possible explanations can be given: i) non linearity of the system (please explain this with the polarization processes as being non-linear), ii) indication of partial discharges.

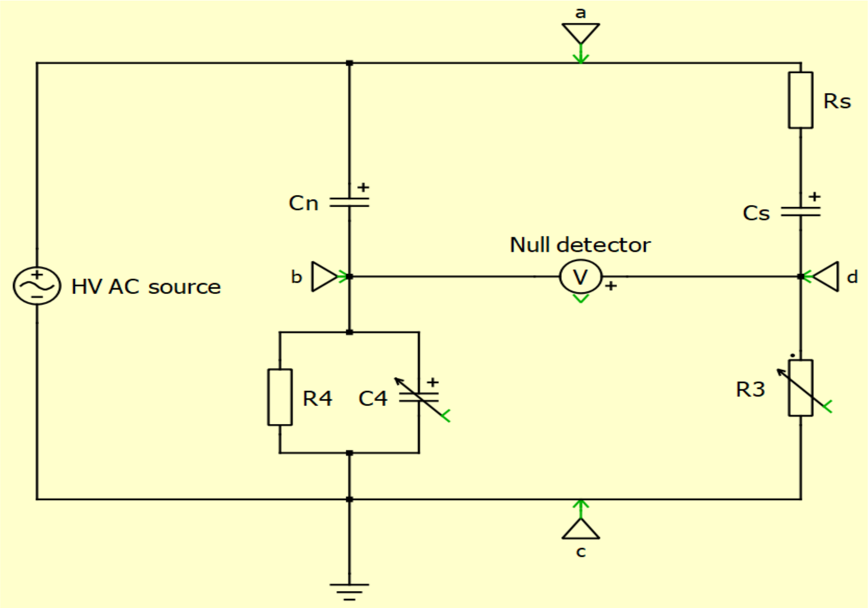
The Schering-bridge is based on the fact that whenever there is the same voltage across the two mid-points of the bridge (this is Vb = Vd), the loads can be related following the next equation:

$\frac{Zab}{Zbc} = \frac{Zad}{Zdc}$ where $Zad = Rs + {}^{1}/_{jwCs}; Zab = {}^{1}/_{jwCn}; Zbc = \frac{1}{{}^{1}/_{R4} + jwC4}; Zdc = R3$

With this information, it is also possible to obtain $Cs = Cn * \frac{R4}{R3}$ and $Rs = R3 * \frac{C4}{Cn}$.

Finally since both the active and reactive loads are known, we can calculate tan δ as:
$\tan\delta = w * Rs * Cs = w * R4 * C4$ and also $\mathrm{P} = \tan\delta * Q$

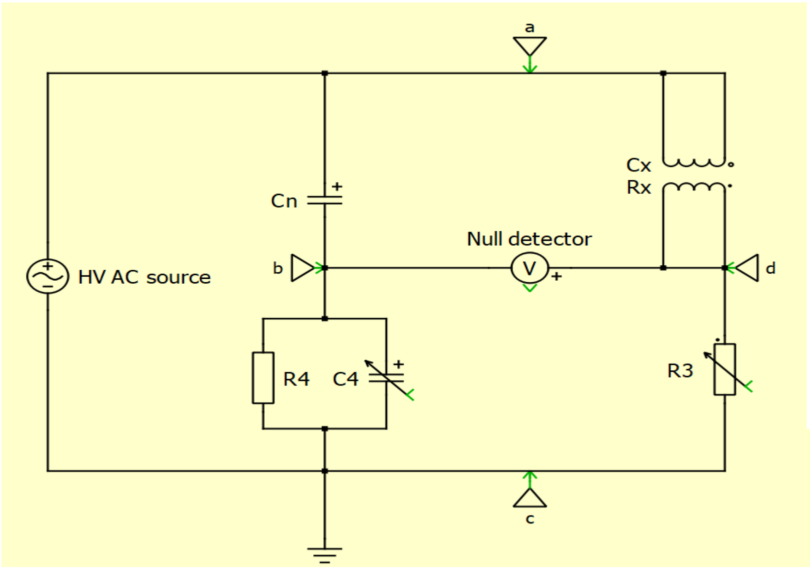
The
two
equa
$\frac{Zab}{Zbc}$
With
Fina



8.3 ABB Inductive Voltage Transformer

8.3.1 Setup Description

During the first experiment, the capacitance and the loss angle of the 60 kV ABB inductive voltage transformer EMF (EMF 52-170) will be measured. The test object is connected between the **primary terminals** (High Voltage side, point (a) from Figure 1) and the **secondary terminal** (point (d) from Figure 1). The normal capacitor, C_N, consists of a pressurized gas capacitor which represents an ideal capacitor, therefore it can be assumed that $\varphi_N = 0$. The low voltage branch is included inside the measuring equipment (capacitance and *tan* δ measuring bridge).



8.3.2. Results and discussions

1

The 60 kV inductive voltage transformer must be tested at different voltage levels in a range between $0\,kV - \frac{60}{\sqrt{3}}$ kV.

V [kV]	C_x [pF]	$\tan\delta_x$	δ_x [º]	I [μA]
1.5	686	0.021	1.203	337
2.0	686	0.021	1.203	440
2.5	686	0.021	1.203	559
3.0	686	0.0214	1.226	670
4.0	686	0.0215	1.232	885
4.5	686	0.0218	1.249	993
5.0	687	0.0219	1.255	1102

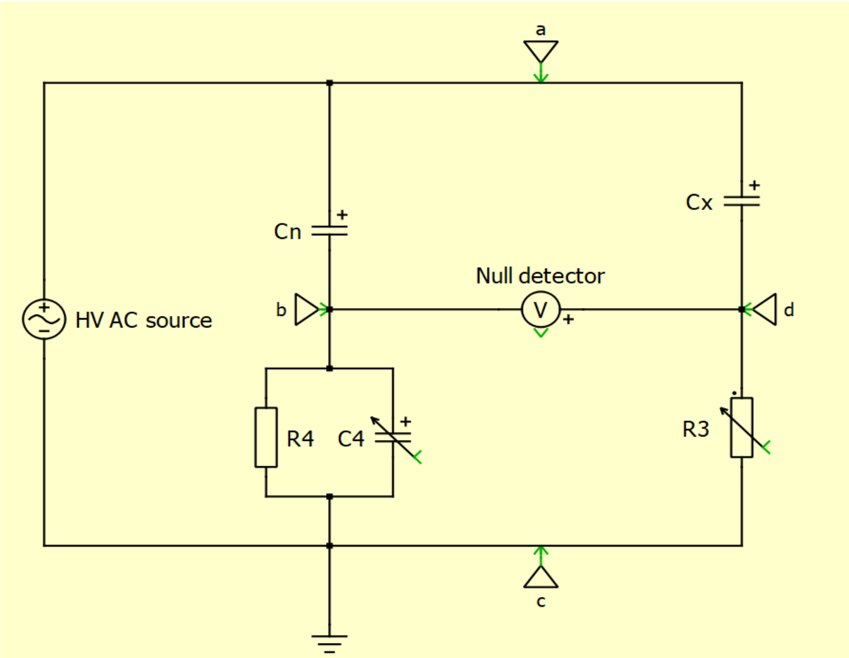
The results obtained are according to the expected since constant values are obtained. Voltage difference should not make a difference in the capacitance obtained as well as in $\tan\delta$.

It is clearly shown how the capacitance is constant (less than 0.15% change) as well as the losses ($\tan\delta$ is also almost constant).

8.4 Homemade Capacitor

8.4.1 Setup Description

During the third experiment, the inductive voltage transformer will be replaced with a homemade capacitor which is purely capacitive. The purpose is to conclude with a clearer idea of the experimental setup and understand the fundamental principle of the Schering-bridge.



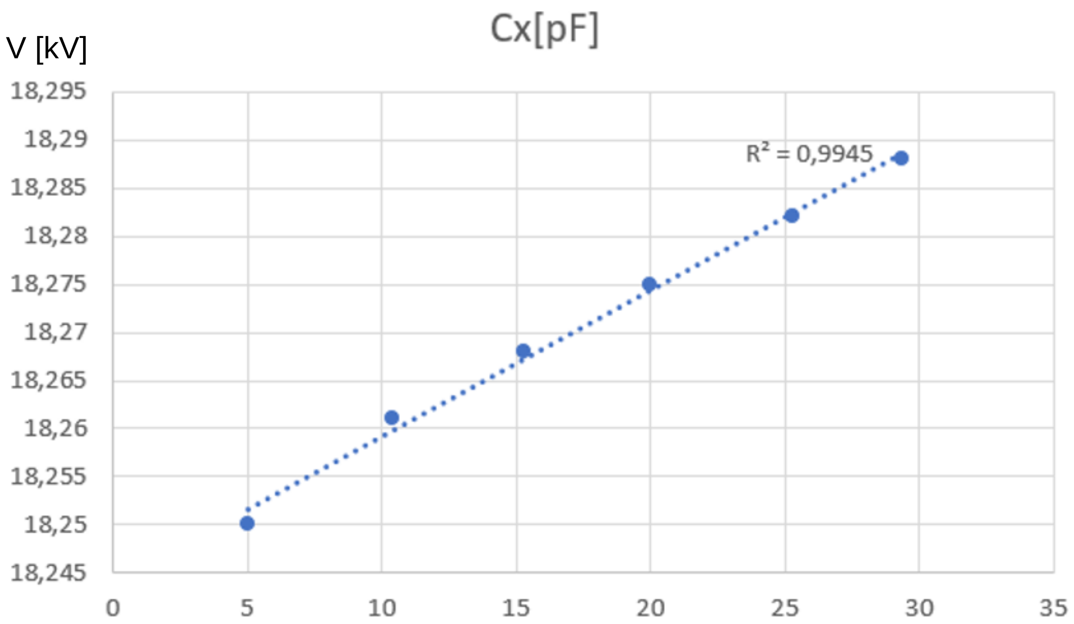
8.4.2 Results and Discussions

2

The homemade capacitor must be tested at different voltage levels, in a range between 0 kV – 25 kV.

V [kV]	C_x [pF]	$\tan\delta_x$	δ_x [º]	I [µA]
5.0	18.25	0.0323	1.850	29.8
10.4	18.261	0.0336	1.924	59.9
15.32	18.268	0.0345	1.976	88.1
20.28	18.275	0.0354	2.027	115.1
25.28	18.282	0.0362	2.073	145.4
29.35	18.288	0.0365	2.090	168.6

We can also see that the results obtained with the home-made capacitor are quite similar although not as similar as those obtained in the previous experiment. We can also see the behavior of the insulation material with respect to the voltage applied in the following graph.



It is clearly shown how the capacitance of the home-made capacitor is linear with an almost perfect fit. If this capacitor was replaced with a normal capacitor, its capacitance should not show dependence on the voltage applied.