HIGH VOLTAGE ENGINEERING

MASTERS COURSE FOR INTRO, EPSH, WPS AND PED
BY
PROFESSOR CLAUS LETH BAK

DEPARTMENT OF ENERGY TECHNOLOGY
AALBORG UNIVERSITY

This is what the course
Is all about

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High Voltage Engineering – Fundamentals

Introduction to HV engineering.

Introductory stories and slides

The general layout of the transmission power system

Rated values p 493-494

Nameplate information, relevant design parameters for power systems

Nameplate examples, voltage transformer, circuit breaker, power transformer

Safety rules

Exercises

1) Explain the importance of name plate quantities

2) Read and discuss the safety rules – SIGN

High Voltage Engineering – Fundamentals

1. Introduction to HV engineering.
   - Introductory stories and slides
   - The general layout of the transmission power system
   - Rated values p 493-494
   - Nameplate information, relevant design parameters for power systems
   - Nameplate examples, voltage transformer, circuit breaker, power transformer
   - Safety rules
   - Exercises

     1) Explain the importance of name plate quantities

     2) Read and discuss the safety rules – SIGN

2. Study excursion to HVDC-HVAC substation Tjele to see both the DC switchyard, AC switchyard, valve halls for both VSC and LCC converters and synchronous condensers. Full day excursion! This trip will motivate for the students the need for understanding high voltage theories and experiments in order to be able to design the power network.

3. Generation of high voltages
   - The layout of a high voltage test setup
   - Generation of high AC voltages by means of transformers, cascades and series resonant circuits
   - Generation of high DC voltages by various rectifier circuits and cascade circuits
   - Exercises

     1) Safety going through of HV experimental setups

     2) Measurement of transfer ratio of VT by energizing with AC voltage equal to rated voltage

     3) Generation of DC voltage with measurement of ripple. Design of voltage divider.

4. Generation of high voltages
    - The impulse voltage generator, single stage and the Marx generator (multi-stage)
    - The sphere gap for measuring impulse voltages
    - The Volt-time characteristic of various gaps
    - Exercises

      1) Lightning impulse generator type b to be used in HV lab

      2) Measure volt-time characteristic for sphere gap and rod gap

5. Measurement of high impulse voltages
    - Voltage dividing systems for impulse voltage measurements
    - The concept of response time
    - Exercises

      1) The laundry wire experiment – to determine experimentally the response time

      2) Exercises

6. Electric Field stresses
    - Electrical field distribution and breakdown strength of insulating materials
    - Fields in homogeneous isotropic materials
    - Fields in multidielectric isotropic materials
    - Numerical methods
    - Exercises

      1) Simple field calculations

      2) Electrical onset for a coaxial cylindrical system

      3) FEM field calculation for an overhead line

7. Gaseous discharges
    - Classical gas laws
    - Ionization and decay
    - Townsends coefficients and mechanism
    - Cathode processes
    - Paschen's law
    - Breakdown in non-uniform field
    - Corona and polarity effects
    - Volt-time characteristic
    - Exercises

      1) Paschens law for air (experiment)

      2) Calculation of onset in a non-uniform field

8. Non-destructive insulation test methods
    - Dynamic properties of dielectrics
    - Dielectric loss and capacitance measurement
    - Exercises

      1) Measurement of dielectric loss angle for a) 100 pF capacitor, b) homemade capacitor and c) the 60 kV VT

      2) Dielectric frequency response with the DIRANA

9. Non-destructive insulation test methods
    - Definitions of internal and external partial discharges
    - Corona (make the deduction of parallel wire experiment)
    - Exercises

      1) Corona discharges in parallel wire experiment, compare with theoretical Eonset

      2) Corona cages and corona mill

10. Non-destructive insulation test methods
    - Definitions of internal and external partial discharges
    - Partial discharge detection circuits

- Partial discharges in PWM-inverter fed low-voltage induction motors
- HV practical study cases (incl Bjarni)
- Exercises 1) PD measurements in a) sphere gap, b) rod-plane, plane-rod, rod-rod gap, c) homemade capacitor and d) the 60 kV VT

11. Mini-seminar
    - Presentation in mini-conference of results obtained in mini-project

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Ideas for laboratory work:

To learn how to understand and perform most fundamental HV aspects:

- Safety in HV laboratory work
- Creating HV setups
- Voltage measurements with instruments and sphere gap
- Lightning and switching overvoltage test
- Loss angle measurement
- Partial discharge measurement

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HIGH VOLTAGE ENGINEERING

LABORATORY EXCERCISE INSTRUCTIONS FOR MINIPROJECT

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Why learn about High Voltage ???

MAJOR REASON !!!

ALL electrical engineering MUST rely on the ability to sustain electric potential difference !

Without potential difference, or say; voltage, NO current, NO power, NO work NO NOTHING !!!

Voltage (potential difference) can only be sustained if proper INSULATION exists!!

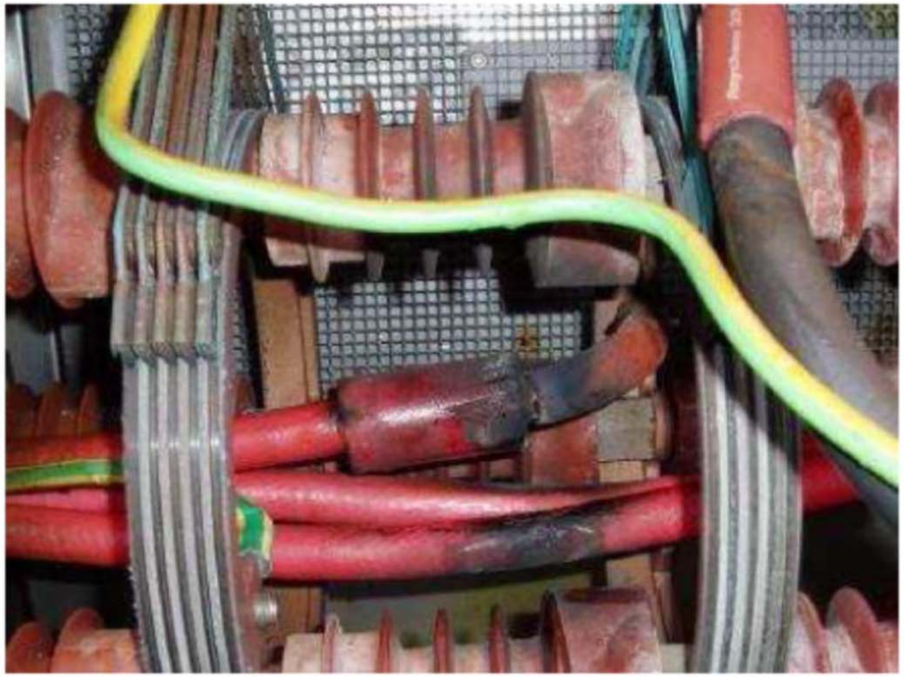
HV Engineering is about designing and keeping such insulation systems ALIVE for all voltage levels.

10 kV voltage transformer blown up !

BLACK – BURNED

No more isolation !

Intermittent ground fault !!



NO operation possible

Cables burned

Outage needed to repair

NORDJYLLANDSVÆRKET UNIT 3

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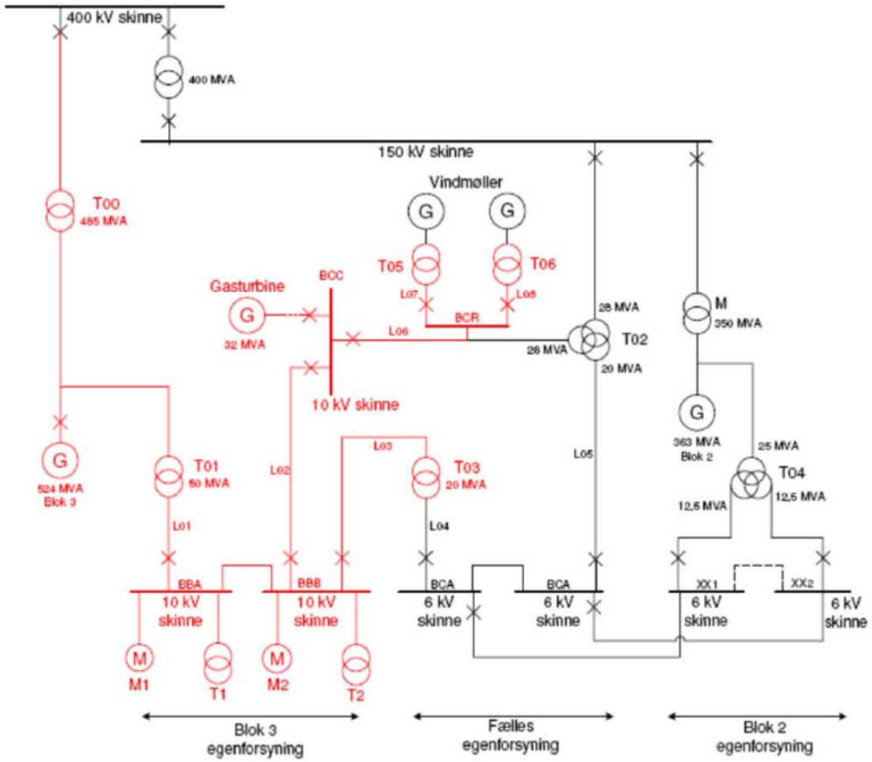
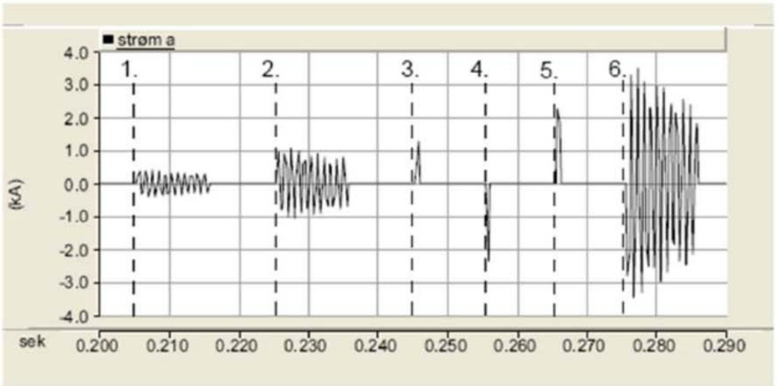
Medium voltage grid at Vattenfall power plant

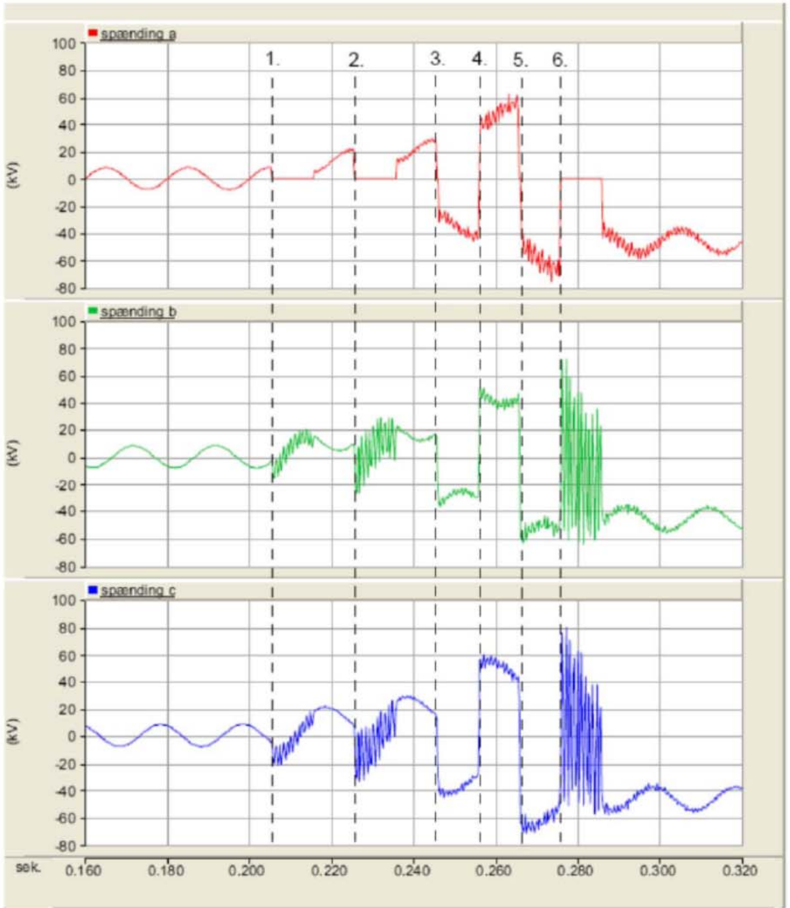


To be simulated in time domain in order to reveal possible max. overvoltages!

Current and voltage in faulted location.

Overvoltage by intermittent ground fault – dielectric BREAKDOWN !





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400/150 kV Autotransformer

Figure 2.4: A photograph of the 400/150 kV power transformer and its nearest surroundings.

Very expensive

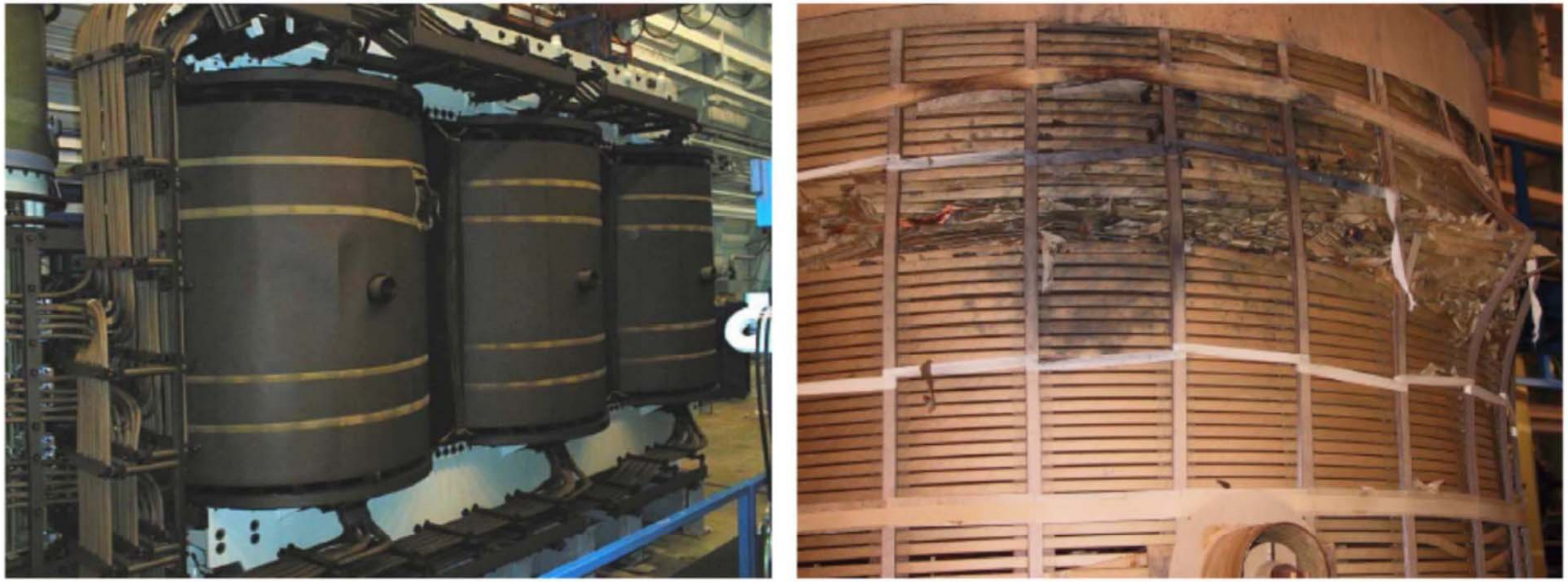
Indispensable

Long time of delivery

Repair expensive and prolonged

WE MUST PROTECT!

Transformer winding insulation failed $\Rightarrow$
Internal short circuit $\Rightarrow$
Transformer BROKEN !



(a) (b)

Figure 3.1: Photographs taken by ABB in Norway of the transformer. a) The three phases with the faulty phase furthest to the left. b) The faulty winding seen from the outside after various paper layers have been removed.

Simulation of the cause of overvoltage

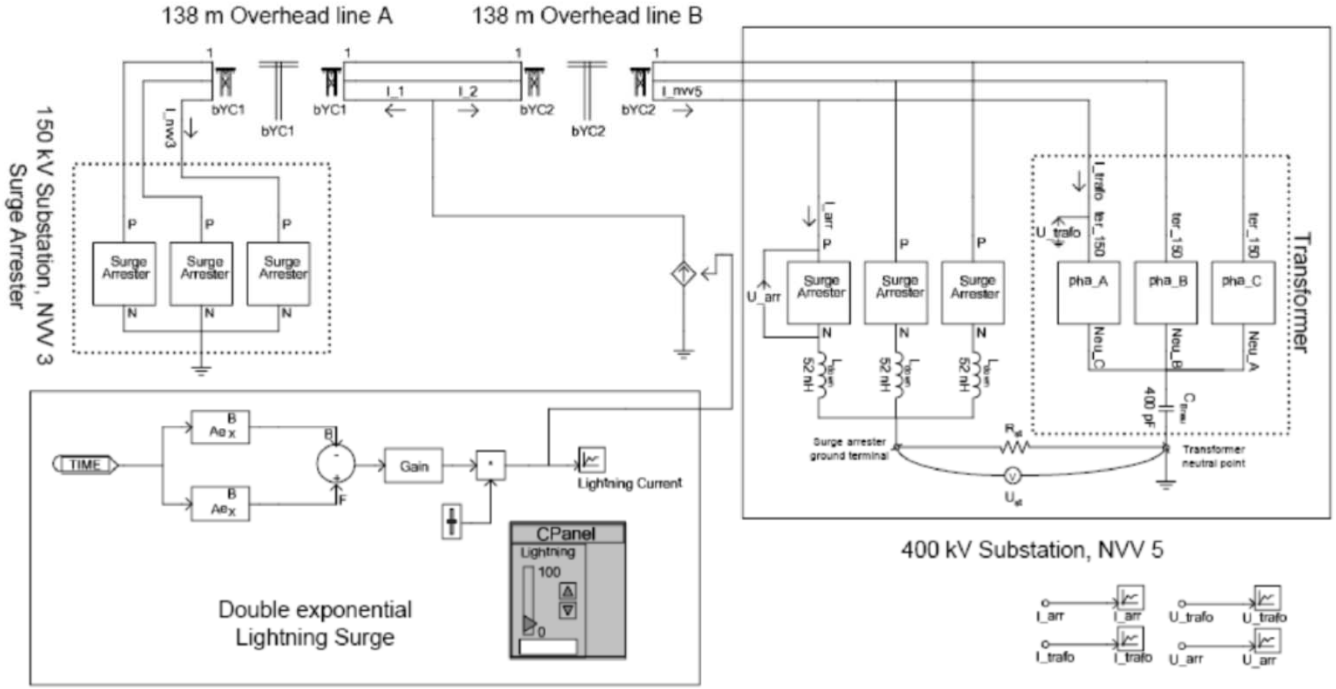


Figure E.1: A circuit diagram of the total system. The overhead lines between the 400 kV and the 150 kV substations are split up in two parts to make it possible to apply a lightning surge on the overhead line between the substations, and securing equal surge impedance on both sides. The overhead line at the 150 kV substation entrance are connected to 150 kV surge arresters.

Cause found – dynamic impedance of grounding

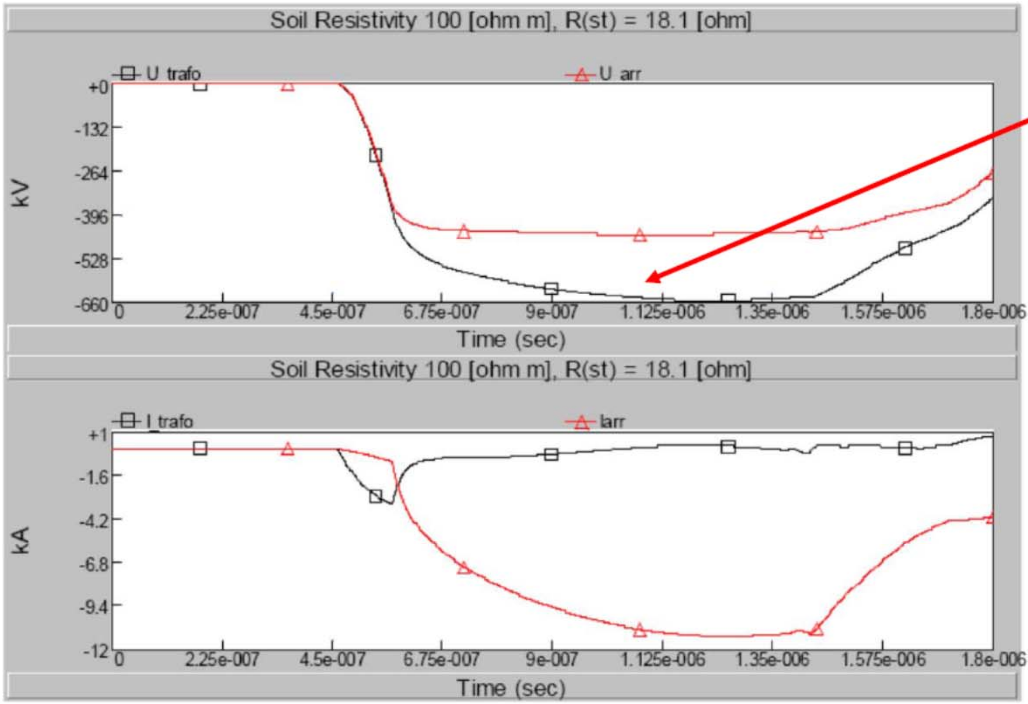


Figure 5.95: The simulation with a soil resistivity of 100 Ωm, relative soil permittivity of 10 F/m, and a front time of 1 μs. The resistance, R_{st}, was calculated in TEMP from the parameters of the soil and the front time. Upper: The voltage, U_{trafo}, at terminal c of the transformer and the voltage, U_{arr}, over the surge arrester. Lower: The current, I_{arr}, through the surge arrester and the current, I_{trafo}, at terminal c of the transformer.

Voltage higher than transfor-mer LIWL
LIWL for 170 kV is 565 kV

High Voltage Engineering

Fundamentals

Second edition

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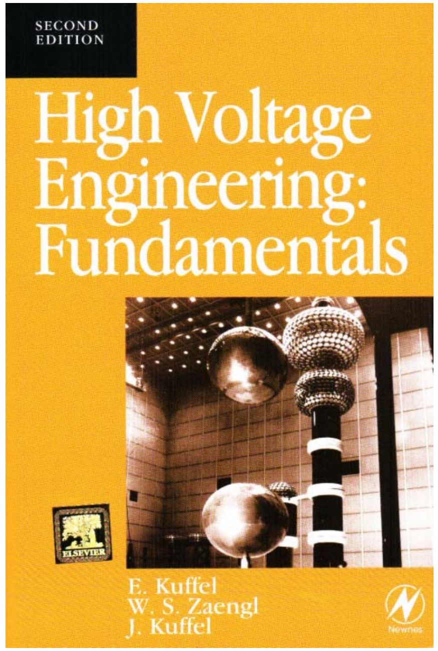

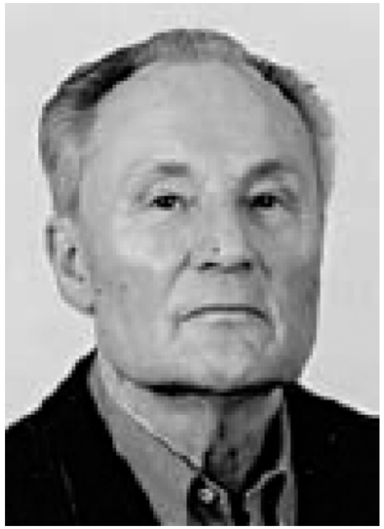

Newnes
OXFORD AUCKLAND BOSTON JOHANNESBURG MELBOURNE NEW DELHI

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Power transmission versus voltage level

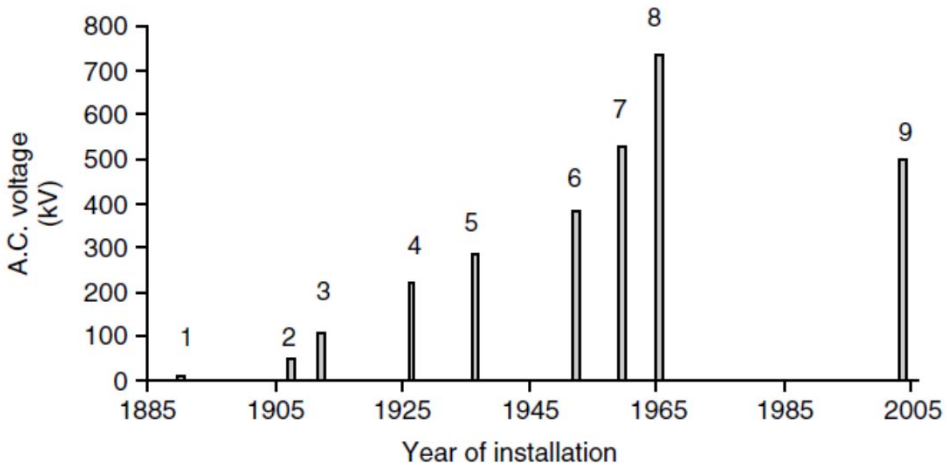
The electric power (P) transmitted on an overhead a.c. line increases approximately with the surge impedance loading or the square of the system's operating voltage. Thus for a transmission line of surge impedance Z_L ($\cong 250\,\Omega$) at an operating voltage V, the power transfer capability is approximately $P = V^2/Z_L$, which for an overhead a.c. system leads to the following results:

V (kV)	400	700	1000	1200	1500
P (MW)	640	2000	4000	5800	9000

How many amps ??

$\boxed{\text{170 kV is 116 MW}}$

AC voltage level versus time chronologically



1	1890	10 kV	Deptford
2	1907	50 kV	Stadtwerke München
3	1912	110 kV	Lauchhammer – Riesa
4	1926	220 kV	N. Pennsylvania
5	1936	287 kV	Boulder Dam
6	1952	380 kV	Harspränget – Hallsberg
7	1959	525 kV	USSR
8	1965	735 kV	Manicouagan – Montreal
9	2003 (Est)	500 kV	Three Gorges (China)

Figure 1.1 *Major a.c. systems in chronological order of their installations*

New issues 2017

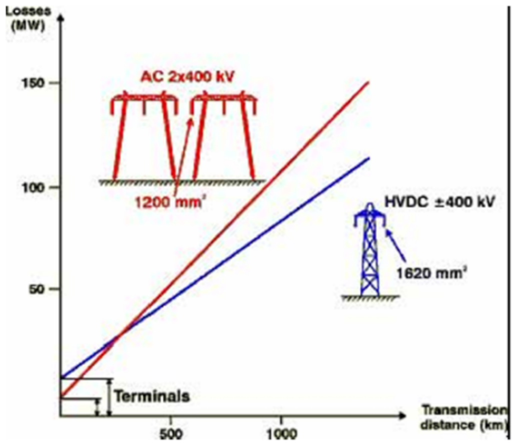
-UHV
-HVAC→HVDC
-HVDC – VSC
-Multiterminal HVDC
Offshore grid
-Changing trans-
mission grid
-Multi-circuits

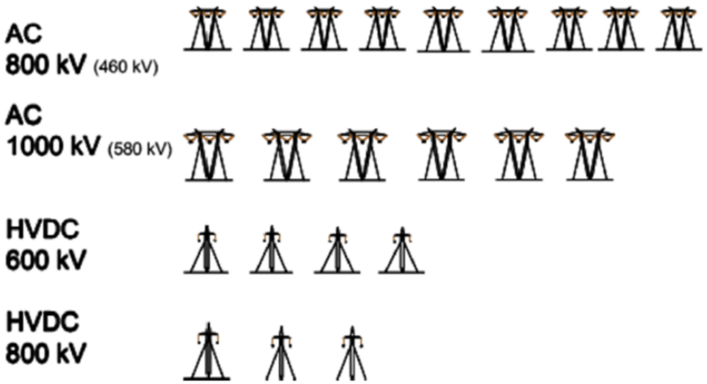
Voltage level increasing

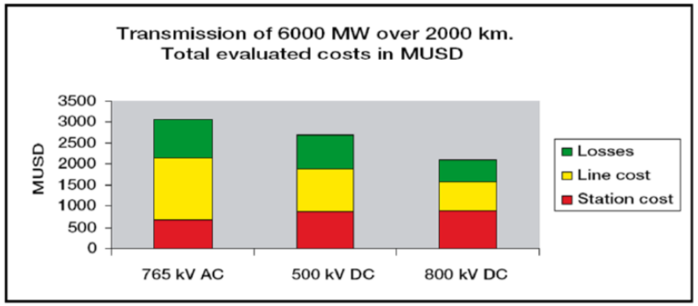
Insulation design challenge !

HVDC transmission – why?

HVDC transmission







www.iet.aau.dk

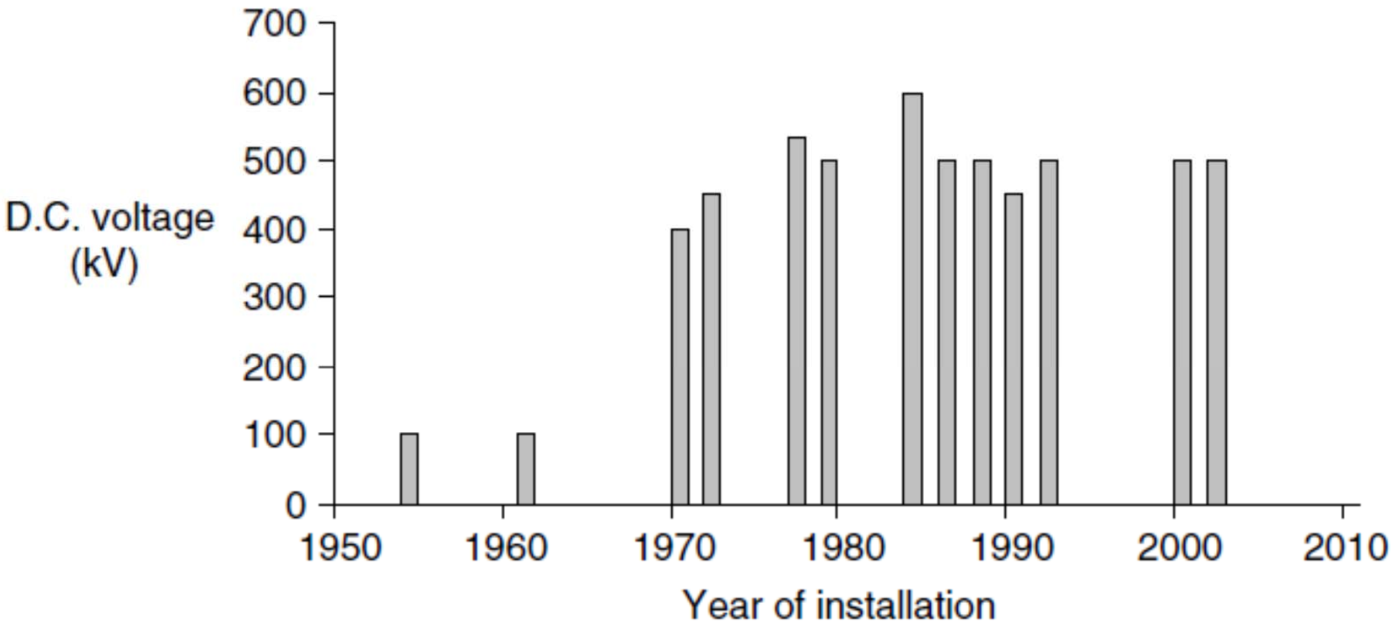


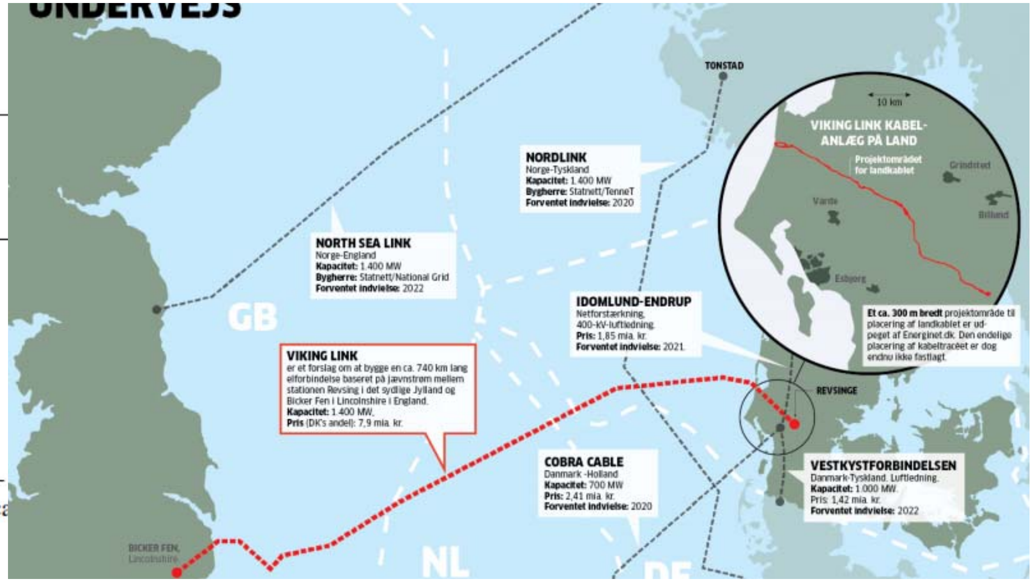
Figure 1.2 *Major d.c. systems in chronological order of their installations*

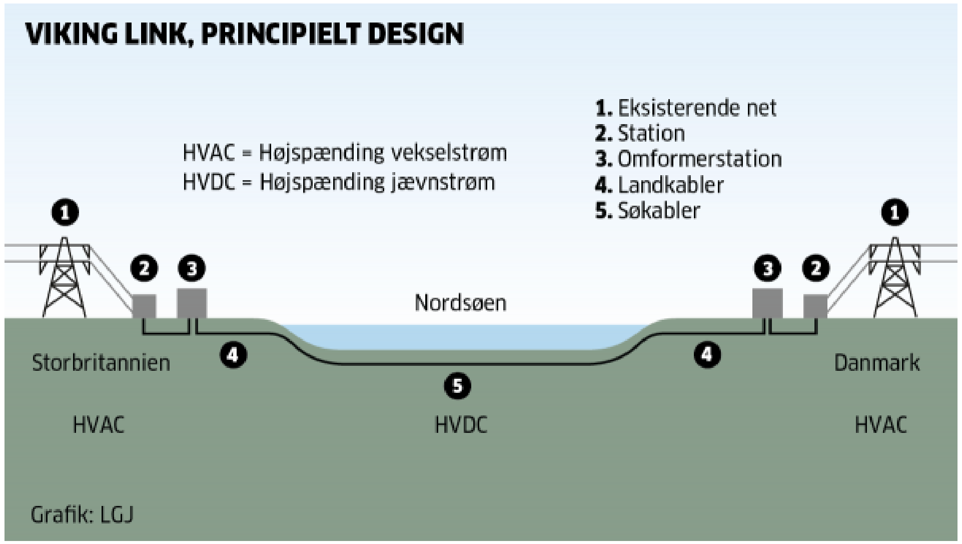
HVDC – VSC will gradually increase. Better grid support and less vulnerable to grid disturbances.

Table 1.1 *Major HVDC schemes*

Scheme	*Year*	*Power (MW)*	*D.C. voltage (kv)*	*Line or cable length (km)*	*Location*
Gottland 1	1954	20	±100	96	Sweden
English Channel	1961	160	±100	64	England–France
Pacific Intertie	1970	1440	±400	1362	USA
Nelson River 1	1972	1620	±450	892	Canada
Eel River	1972	320	2 × 80	Back to back	Canada
Cabora Bassa	1978	1920	±533	1414	Mozambique–South Africa
Nelson River 2	1978	900	±250	930	Canada
	1985	1800	±500		
Chateauguay	1984	1000	2 × 140	Back to back	Canada
Itaipu 1	1984	200	±300	785	Brazil
	1985	1575			
	1986	2383	±600		
Intermountain	1986	1920	±500	784	USA
Cross Channel	1986	2000	2 × ±270	72	England–France
Itaipu 2	1987	3150	±600	805	Brazil
Gezhouba–Shanghai	1989	600	500	1000	China
	1990	1200	±500		
Fenno-Skan	1989	500	400	200	Finland–Sweden
Rihand-Delhi	1991	1500	±500	910	India
Hydro Quebec–New England	1990	2000	±450	1500	Canada–USA
Baltic Cable	1994	600	450	250	Sweden–Germany
Tian Guang	2000 (est)	1800	±500	960	China
Three Gorges	2002 (est)	3000	±500	–	China

Source: HVDC Projects Listing, D.C. & Flexible A.C. Transmission Subcommittee of the IEEE Transmission and Distribution Committee, Working Group on HVDC, and Bibliography and Records, January 1998 Issue.





KONTISCAN 1 – mercury arc valves

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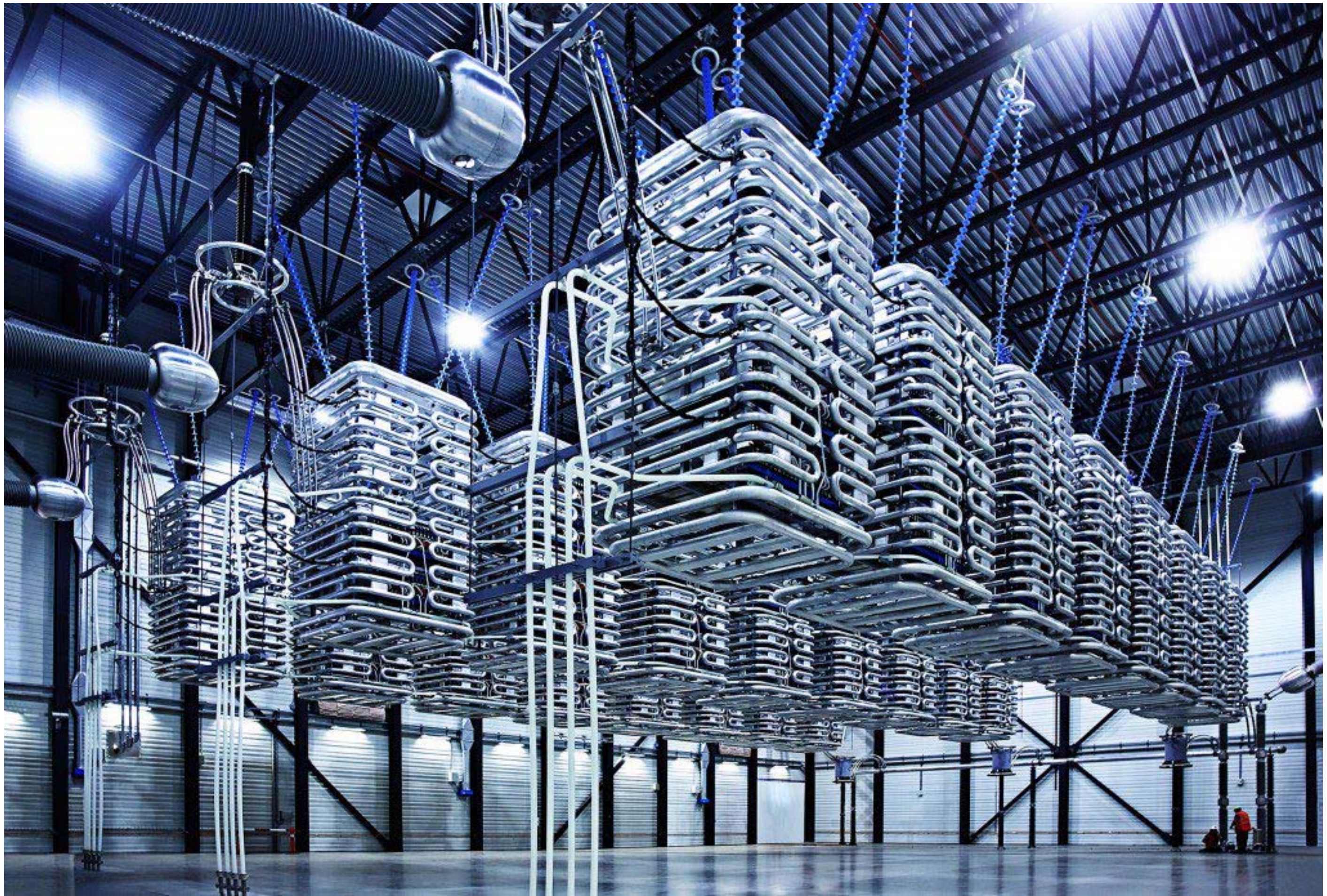
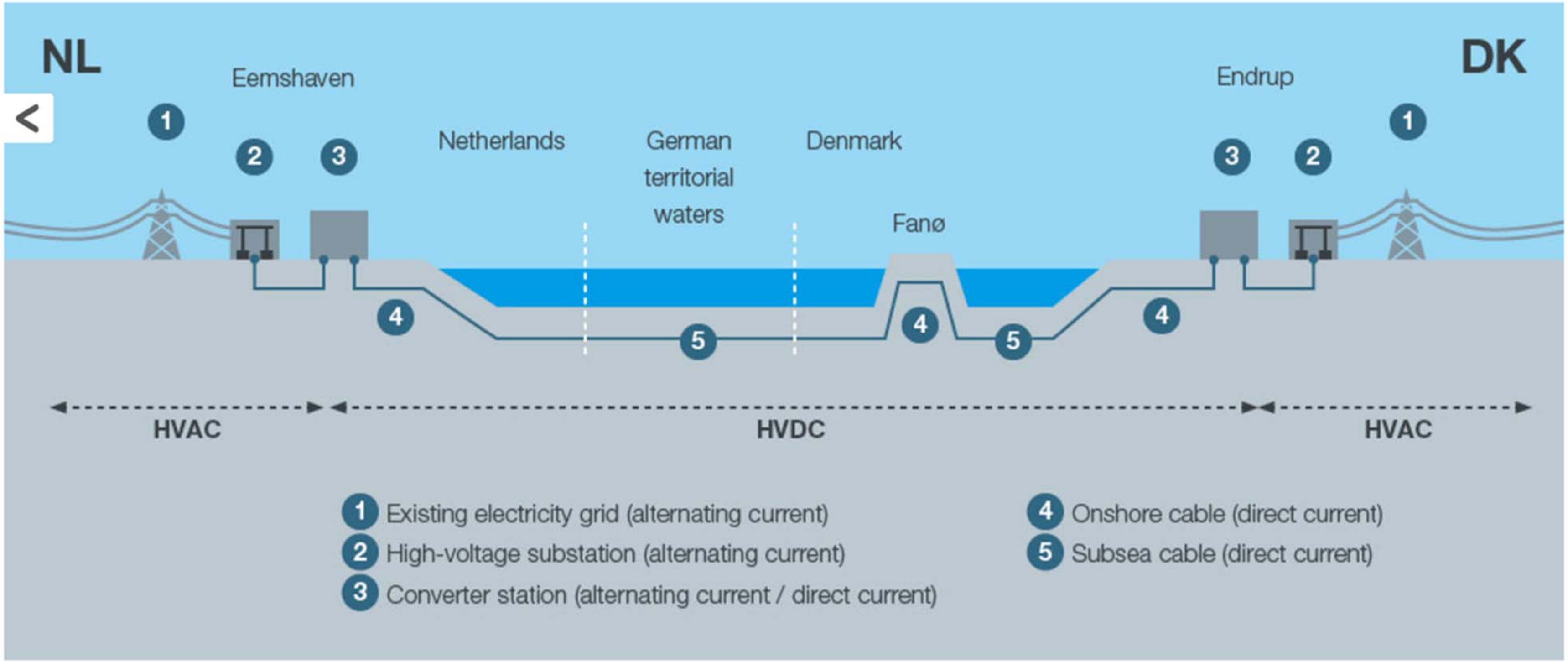
LCC Thyristor based HVDC

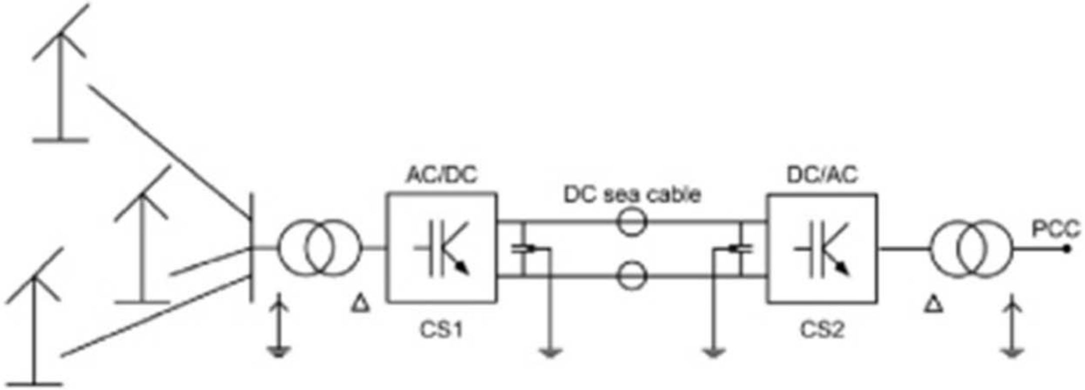
HVDC-VSC – read more

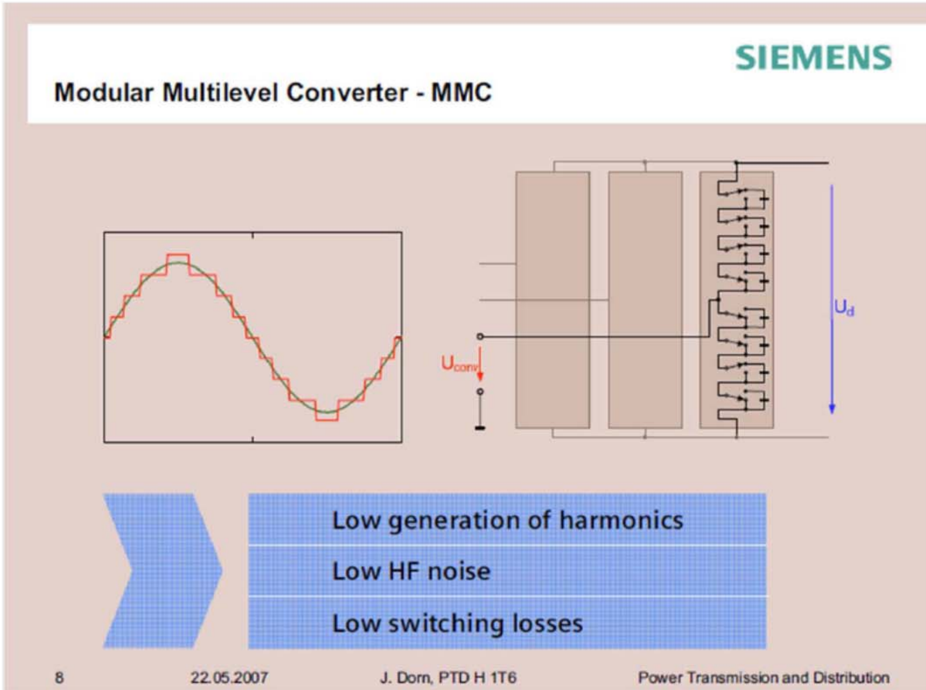
http://new.abb.com/grid/projects/skagerrak-hvdc-link



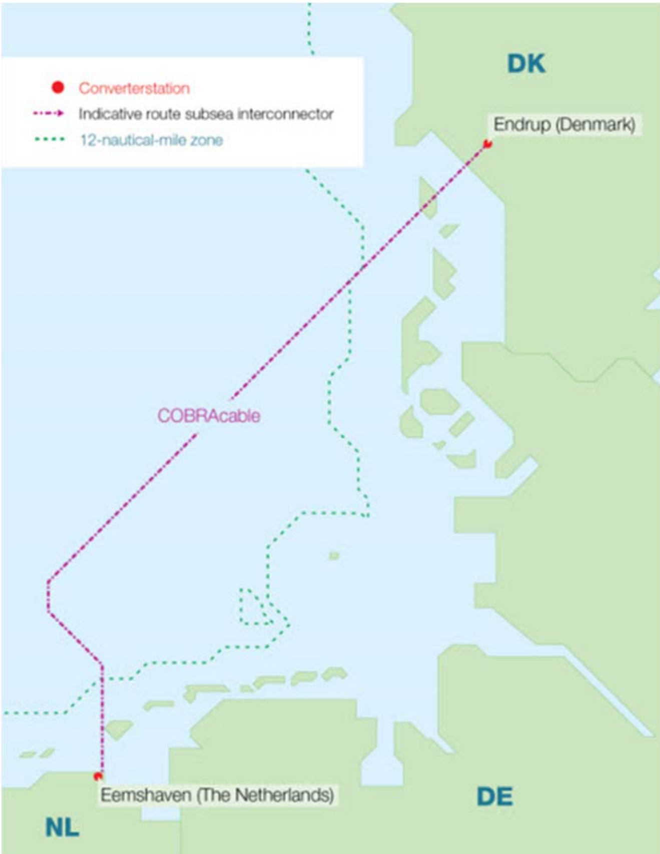
COBRACABLE

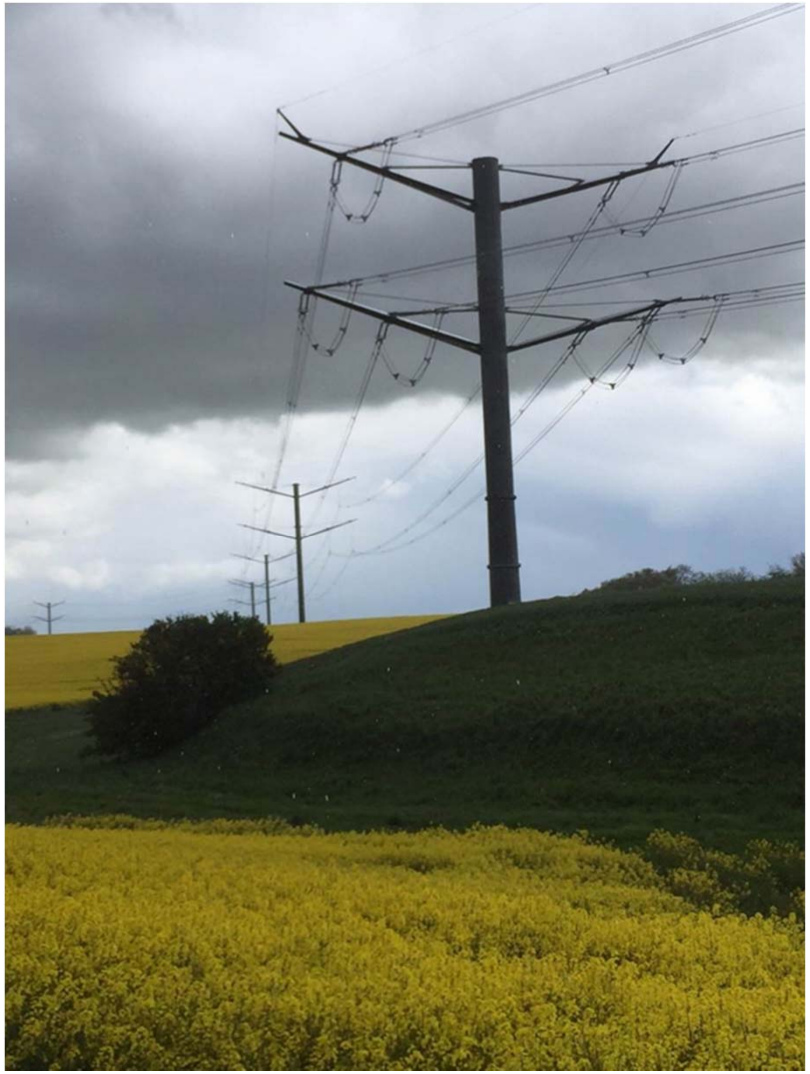

NL
DK
Eemshaven
Endrup
Netherlands
German territorial waters
Denmark
Fanø
HVAC
HVDC
HVAC
1 Existing electricity grid (alternating current)
2 High-voltage substation (alternating current)
3 Converter station (alternating current / direct current)
4 Onshore cable (direct current)
5 Subsea cable (direct current)


AC/DC
DC sea cable
DC/AC
PCC
CS1
CS2


SIEMENS
Modular Multilevel Converter - MMC
Low generation of harmonics
Low HF noise
Low switching losses
8
22.05.2007
J. Dorn, PTD H 1T6
Power Transmission and Distribution

COBRACABLE


Converterstation
Indicative route subsea interconnector
12-nautical-mile zone
DK
Endrup (Denmark)
COBRAcable
Eemshaven (The Netherlands)
DE
NL



1.2 Voltage stresses

Normal operating voltage does not severely stress the power system's insulation and only in special circumstances, for example under pollution conditions, may operating voltages cause problems to external insulation. Nevertheless, the operating voltage determines the dimensions of the insulation which forms part of the generation, transmission and distribution equipment. The voltage stresses on power systems arise from various overvoltages. These may be of external or internal origin. External overvoltages are associated with lightning discharges and are not dependent on the voltage of the system. As a result, the importance of stresses produced by lightning decreases as the operating voltage increases. Internal overvoltages are generated by changes in the operating conditions of the system such as switching operations, a fault on the system or fluctuations in the load or generations.

Their magnitude depends on the rated voltage, the instance at which a change in operating conditions occurs, the complexity of the system and so on. Since the change in the system's conditions is usually associated with switching operations, these overvoltages are generally referred to as switching overvoltages.

In designing the system's insulation the two areas of specific importance are:

(i) determination of the voltage stresses which the insulation must withstand, and
(ii) determination of the response of the insulation when subjected to these voltage stresses.

The balance between the electric stresses on the insulation and the dielectric strength of this insulation falls within the framework of insulation coordination and will be discussed in Chapter 8.

Testing – why HV engineering MUST be experimental !

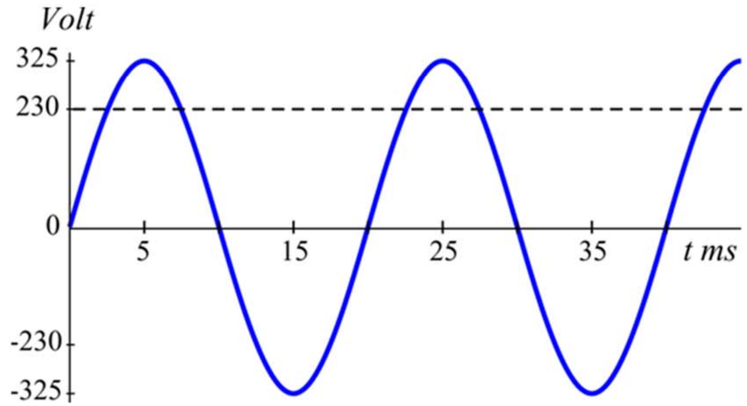
1.3 Testing voltages

Power systems equipment must withstand not only the rated voltage (V_m), which corresponds to the highest voltage of a particular system, but also overvoltages. Accordingly, it is necessary to test h.v. equipment during its development stage and prior to commissioning. The magnitude and type of test voltage varies with the rated voltage of a particular apparatus. The standard methods of measurement of high-voltage and the basic techniques for application to all types of apparatus for alternating voltages, direct voltages, switching impulse voltages and lightning impulse voltages are laid down in the relevant national and international standards.

HVAC power frequency testing

1.3.1 Testing with power frequency voltages

To assess the ability of the apparatus's insulation withstand under the system's power frequency voltage the apparatus is subjected to the 1-minute test under 50 Hz or 60 Hz depending upon the country. The test voltage is set at a level higher than the expected working voltage in order to be able to simulate the stresses likely to be encountered over the years of service. For indoor installations the equipment tests are carried out under dry conditions only. For outdoor equipment tests may be required under conditions of standard rain as prescribed in the appropriate standards.



Lightnbing impulse voltage test

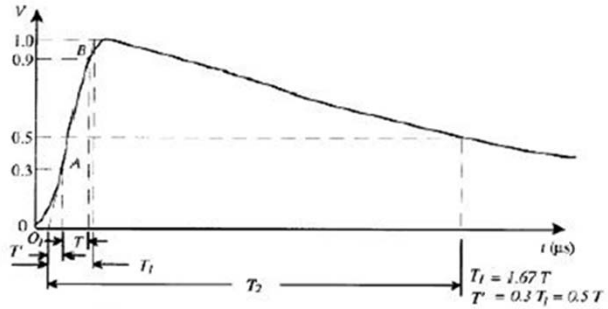
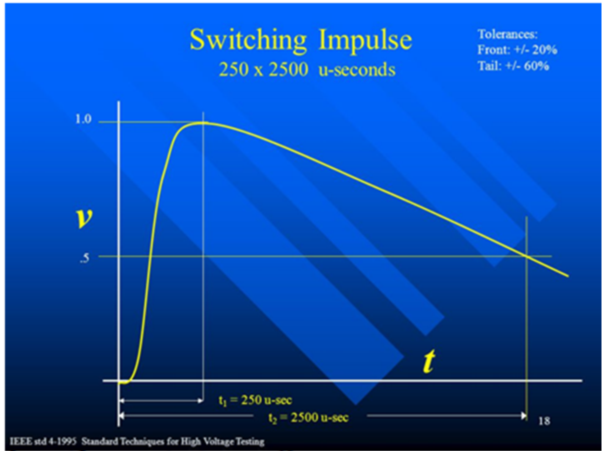


Fig. 3. LI 1.2/50 μs (IEC 60060-1) standard with T1-T2 time parameters

1.3.2 Testing with lightning impulse voltages

Lightning strokes terminating on transmission lines will induce steep rising voltages in the line and set up travelling waves along the line and may damage the system's insulation. The magnitude of these overvoltages may reach several thousand kilovolts, depending upon the insulation. Exhaustive measurements and long experience have shown that lightning overvoltages are characterized by short front duration, ranging from a fraction of a microsecond to several tens of microseconds and then slowly decreasing to zero. The standard impulse voltage has been accepted as an aperiodic impulse that reaches its peak value in 1.2 µsec and then decreases slowly (in about 50 µsec) to half its peak value. Full details of the waveshape of the standard impulse voltage together with the permitted tolerances are presented in Chapter 2, and the prescribed test procedures are discussed in Chapter 8.

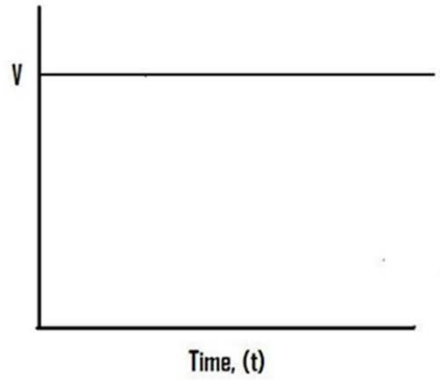
Switching impulse voltage test



1.3.3 Testing with switching impulses

Transient overvoltages accompanying sudden changes in the state of power systems, e.g. switching operations or faults, are known as switching impulse voltages. It has become generally recognized that switching impulse voltages are usually the dominant factor affecting the design of insulation in h.v. power systems for rated voltages of about 300 kV and above. Accordingly, the various international standards recommend that equipment designed for voltages above 300 kV be tested for switching impulses. Although the waveshape of switching overvoltages occurring in the system may vary widely, experience has shown that for flashover distances in atmospheric air of practical interest the lowest withstand values are obtained with surges with front times between 100 and 300 µsec. Hence, the recommended switching surge voltage has been designated to have a front time of about 250 µsec and half-value time of 2500 µsec. For GIS (gas-insulated switchgear) on-site testing,

DC voltage test



1.3.4 D.C. voltages

In the past d.c. voltages have been chiefly used for purely scientific research work. Industrial applications were mainly limited to testing cables with relatively large capacitance, which take a very large current when tested with a.c. voltages, and in testing insulations in which internal discharges may lead to degradation of the insulation under testing conditions. In recent years, with the rapidly growing interest in HVDC transmission, an increasing number of industrial laboratories are being equipped with sources for producing d.c. high voltages. Because of the diversity in the application of d.c. high voltages, ranging from basic physics experiments to industrial applications, the requirements on the output voltage will vary accordingly. Detailed description of the various main types of HVDC generators is given in Chapter 2.

SO – THIS is what HV Engineering is all about ☺

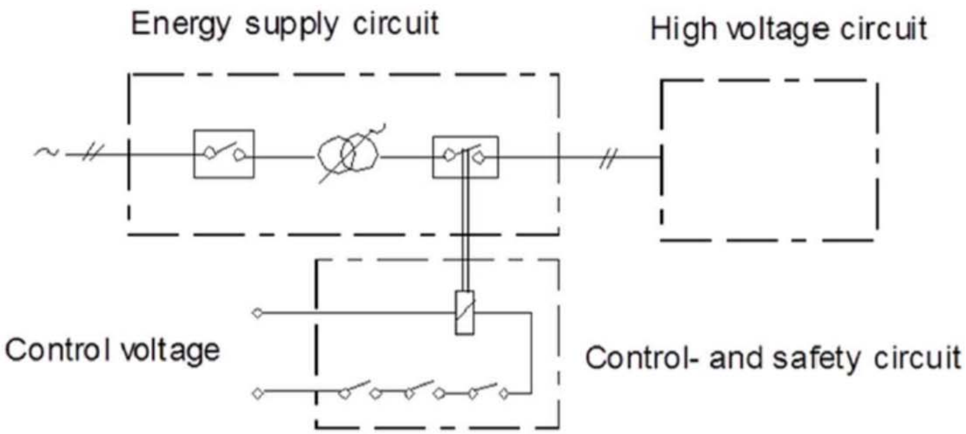
HV testing needs – motivation!

High Voltage test fields are used for testing real power system equipment such as:

- Circuit breakers
- GIS/GIL (Gas Insulated)
- Instrument transformers
- Surge arresters
- Power transformers

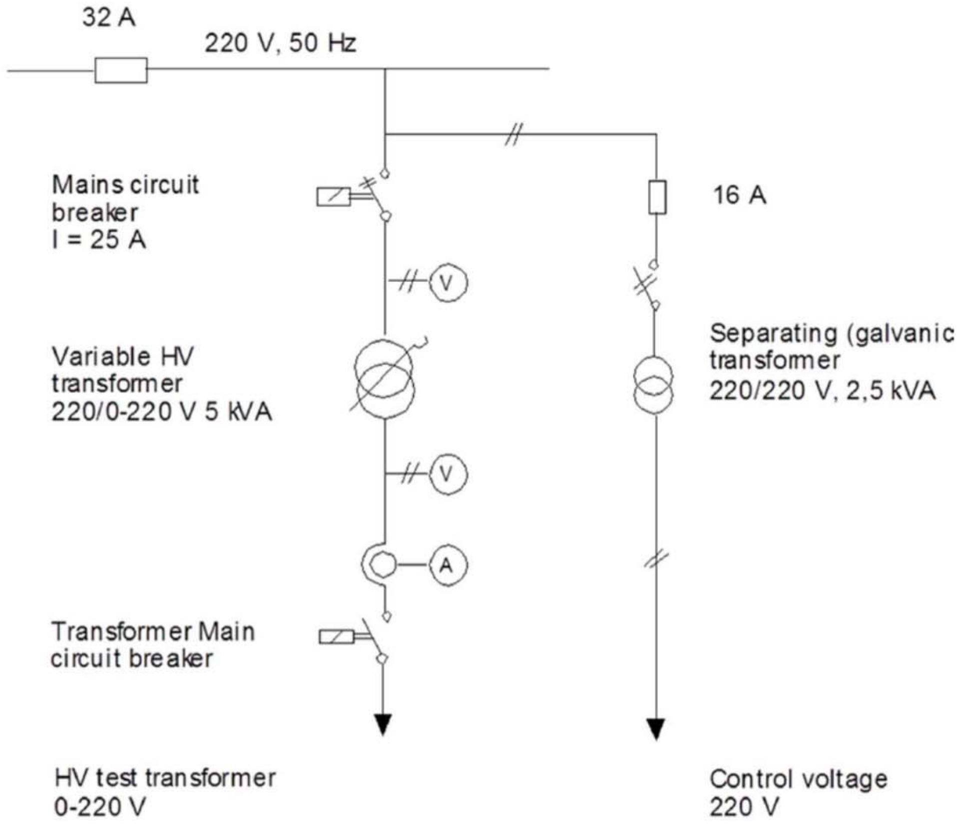
HV test setups

Fundamental safe layout of electrical supply for HV test setup



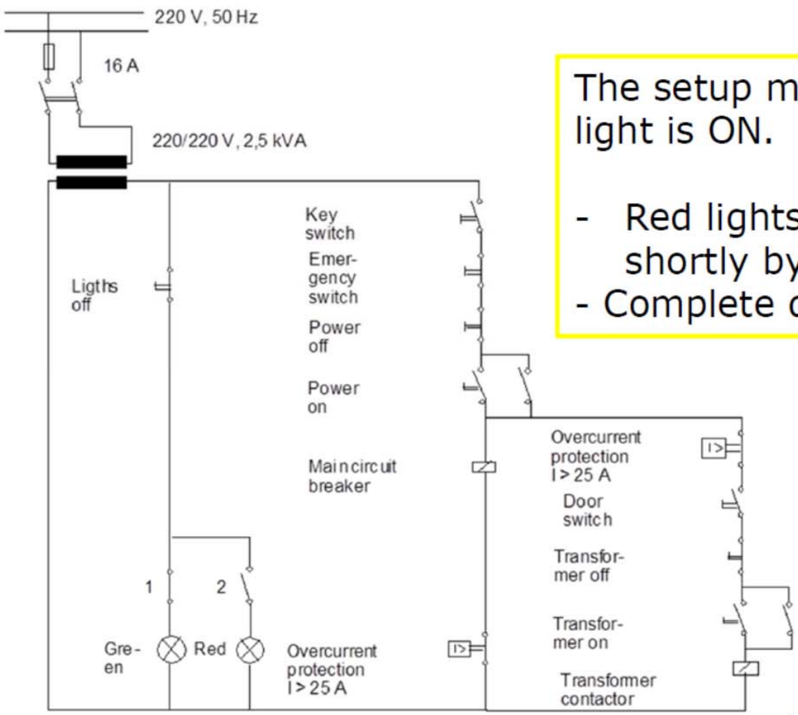
Safe supply of main HV test setup

Main circuit for HV test setup



Safety interlockings

Fundamental control circiuit for an HV setup including interlockings



The setup must only be accessed when the green light is ON.

- Red lights indicate ”DANGER”. Can be switched off shortly by ”lights out” pushbutton.
- Complete darkness using black out curtains

MWB standard test set – 40 years – still going strong ☺

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Typical HV experiment setup

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Lightning impulse generator

HV experiments are FUN – beer can crushing

Safety during high voltage experiments - Fundamental rules !!!

- **The people**
  - At least 2 persons
  - One and only one responsible
  - Everybody confident with the setup
- **The setup**
  - Mechanical closing and signposting
  - Safety distance AT LEAST 50 cm, remember 50 cm per 100 kV.
  - Electrical interlocking
  - Warning lamps
  - Groundings, automatic and manual
  - Capacitors short circuited
  - Read and understand manuals
- **Voltage supply**
  - AT LEAST 2 series connected switches
  - The super visor MUST approve the setup BEFORE the voltage is switched on.
  - Switch OFF and GROUND EVERY time ANYTHING in the setup is changed.

THINK BEFORE YOU ACT !!!

Safety rules

http://www.et.aau.dk/digitalAssets/87/87113_guidelines-and-rules-energy-technology-aau.pdf

Safety rules for work in laboratories at

The Department of Energy Technology, Aalborg University

The rules are applicable to laboratories in and around Pontoppidanstræde

Safety rules can also be found at http://www.et.aau.dk/safety-information/

PAGE 1-16 PENDING APPROVAL

PAGE 17-18 APPROVED

PURPOSE

The purpose of the safety rules are to make the laboratories a safe place to work, and to prevent accidents.

LABORATORY TYPES, WORKSHOPS AND ACCESS

The laboratories are divided into two categories:

- Standard laboratories which are open to students who have completed an approved safety course and have signed a work place permission form (APT), see Appendix 1.

- Specialised laboratories which are open to students who have obtained special permission and instruction from the laboratory supervisor and/or have completed a special safety course and have signed an APT, see Appendix 1.

DEPARTMENT OF ENERGY TECHNOLOGY

AALBORG UNIVERSITY

Appendix 2
Safety rules for
work with high voltages

These safety rules are valid for work with voltages above 1000Vrms ac-voltages or 1500Vdc-voltages from systems capable of supplying currents above 5 mA or systems which include capacities with energy higher than 10 Ws.

1. When working with high voltages, two persons must always be present. All persons, who take part in the test, must be confident with the used test system and should be capable of closing down the systems. From a practical point of view, a person working close to the test set-up can be considered a member of the test (a so-called help guard). This person should be aware that he or she is a test member and should be confident with the test system, the used test set-up and these safety rules.

2. In arrangement with the head of the laboratory or his substitute the person, is making the high voltage test has the full responsibility for the technical as well as the safety part of the test. In case of several test members, one of the members only, is responsible and the other members must obey this persons authority.

   The responsible person must control the following:

   - That the test set-up, the safety grid and the test are made in agreement with these safety rules
   - That all test members are confident with the used test set-up
   - That all test members are aware of these safety rules

Furthermore, the responsible person of the test must take care that continuous information is given to the other test members, such as:

- Removal of grounding sticks and closing of the safety grid
- Connection of the power supply
- Decoupling of the power supply
- Opening of the safety grid and grounding of the test set-up

If a help guard is used during the test, the responsible person of the test must inform the help guard of starting up and closing down the test.

NB! A safety guard must only be entered with permission from the responsible person of the test in this area.

3. If one of the test members is leaving the test, this information must be given to the responsible person of the test

4. The voltage supply to the test system must take place via two series connected switches which both must be in switched-off position when working on the test set-up.

5. During set-up of test systems all parts, which can be supplied with high voltage, should be placed with a secure distance to the measuring equipment and the controlling parts to secure that these parts are not being injected with high voltages at unwanted flashovers. The distance from the equipment carrying high voltages to walls and other building parts should be at least 1m per 400 kV impulse voltages and at least 1m per 200 kV alternating voltages, yet at least 0.5m

6. The test system is to be secured with a mechanical and an electrical barrier. On the barrier (safety grid) warning signs must be set up. When the test system is not being used the door in the safety grid must be left open. The distance from the safety grid to the voltage carrying parts must be at least 0.5m or the distances mentioned in rule number 5.

7. In every test set-up such a number of grounding sticks (at least one) must be used so that all necessary parts of the set up can be grounded permanently after opening the safety grid.

   NB! Removal of the grounding stick(s) is(are) the last thing to be done before the safety grid is closed, and the grounding sticks are the first thing to be put on after the safety grid has been reopened.

8. After the grounding sticks (rule number 7) has been removed from the test set-up the safety grid is closed. When the safety grid is closed, no one must be inside the test area as well as no one must set foot on the test area without opening the safety grid. When the safety grid is closed, the test set-up is regarded as supplied by voltage. This means that the test set-up is not to be left.

   NB! During long term tests, an agreement with the head of the laboratory or his substitute must be made since special rules have to be used for long term tests.

9. As energized capacitors can lead to dangerous voltages, the capacitors in the test set-up must be efficiently grounded before working on the test set-up. It is not enough just to short circuit the capacitors with the grounding stick as dielectrical repercussions can lead to new high voltages on the capacitors. Therefore, the capacitors in the circuit must be permanently grounded when the test area is opened. Series coupled capacitors are only made without voltages by short circuiting the terminals if all capacitors have the same time constant. Before series coupled capacitors are touched they must therefore be efficiently grounded separately. Capacitors, which are not used in a test set-up, should normally be short circuited.

10. The test set-up must be grounded with regard to safety, measuring and service as bad or missing earthing connections may lead to dangerous voltages, for instance on the measuring circuit. All earth connections must be properly made (screwed together, soldered or made by another approved connection) and they should be placed with uninsulated leads so that they are visible.

11. The operation procedure for the different test set-ups must be obeyed.

For students working in the High Voltage Laboratory the following must also be obeyed:

12. Students, working in the laboratory must unconditionally follow the directions given by the personal in the laboratory who has the supervision of the test.

13. During test one of the students (rule number 2) has the responsibility for the whole test team. Before voltage is connected to the system, the test set-up and the safety grid must be approved by the supervisor who also must approve and supervise the test until the test set-up with capacitors is made without voltage and grounded efficiently. The test set-up must not be touched until permission is given by the supervisor.

No dispensation is given to these safety rules without agreement from the head of the laboratory or his substitute in each case.

I understand and agree on the above safety rules

Date:__________________ Name:____