Fundamentals of High Voltage Techniques

Skills:

- Be able to apply theories and laboratory experiments to describe generation and measurement of high AC, DC and impulse voltages for testing HV equipment
- Be able to apply theories and laboratory experiments to describe non-destructive test methods for evaluating the quality and lifetime of dielectrics
- Be able to analyze and model switch mode converters losses and derive transfer functions
- Be able to design filters and controllers for switch mode converters
- The student will further gain skills within the areas of:
  - *Fundamentals of High Voltage engineering*
    - *I*ntroduction to HV engineering
    - Generation, according to IEC standards, of high AC, DC and impulse voltages for testing purposes in the HV laboratory
    - Measurements, according to IEC standards, of high AC, DC and impulse voltages in the HV laboratory
    - Electrostatic field theory for simple insulation systems
    - Sphere gap measurements
    - Transfer function for impulse voltage dividers - response time
    - Impulse current generation and measurement for testing purposes in the HV laboratory

For EPSH, WPS & PED

- *Non-destructive test 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.
  - Partial discharge detection and measurement by means of PD-instruments
  - Partial discharges in windings of inverter-fed rotating machines

For EPSH, WPS & PED

2.Non-destructive test methods in HV engineering (as referred to above) will be covered by three lecture slots highlighting most interesting parts of the curri

Lecture plan for High Voltage Engineering

three

Lecture plan !

Lecture plan

1. Fundamentals of High Voltage Engineering part (as referred to above) will be covered by two lecture slots highlighting most interesting parts of the curriculum which, for this part is covered by [1], chapters 1, 2 and 3, pp. 1 – 199.
2. Non-destructive test methods in HV engineering (as referred to above) will be covered by three lecture slots highlighting most interesting parts of the curriculum which, for this part is covered by [1], chapter 7, pp. 395 – 459 + [2] and [3], which are papers to be found at the web.

Laboratory work

The High Voltage engineering part will include one mandatory demonstration of HV laboratory safety. Students should prepare by reading safety rules for HV http://www.et.aau.dk/digitalAssets/48/48085_rules_highvoltage_lab.pdfattend and attending the safety demonstration in the HV lab. After this one copy of the safety rules MUST be signed and returned to CLB before any work in HV lab is allowed.
A miniproject is offered for group HV lab training

Individual written exam!!

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

AALBORG UNIVERSITET

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.

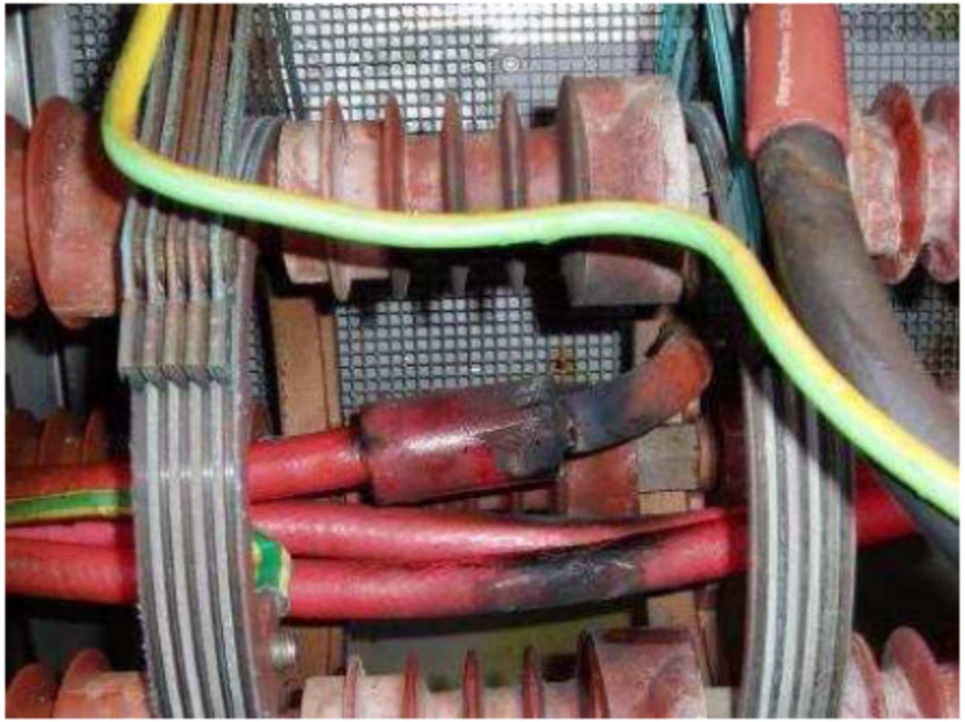
10 kV voltage transformer blown up !

BLACK – BURNED

No more isolation !

Figur 3.1: Sammenbrudt spændingstransformer.

Intermittent ground fault !!



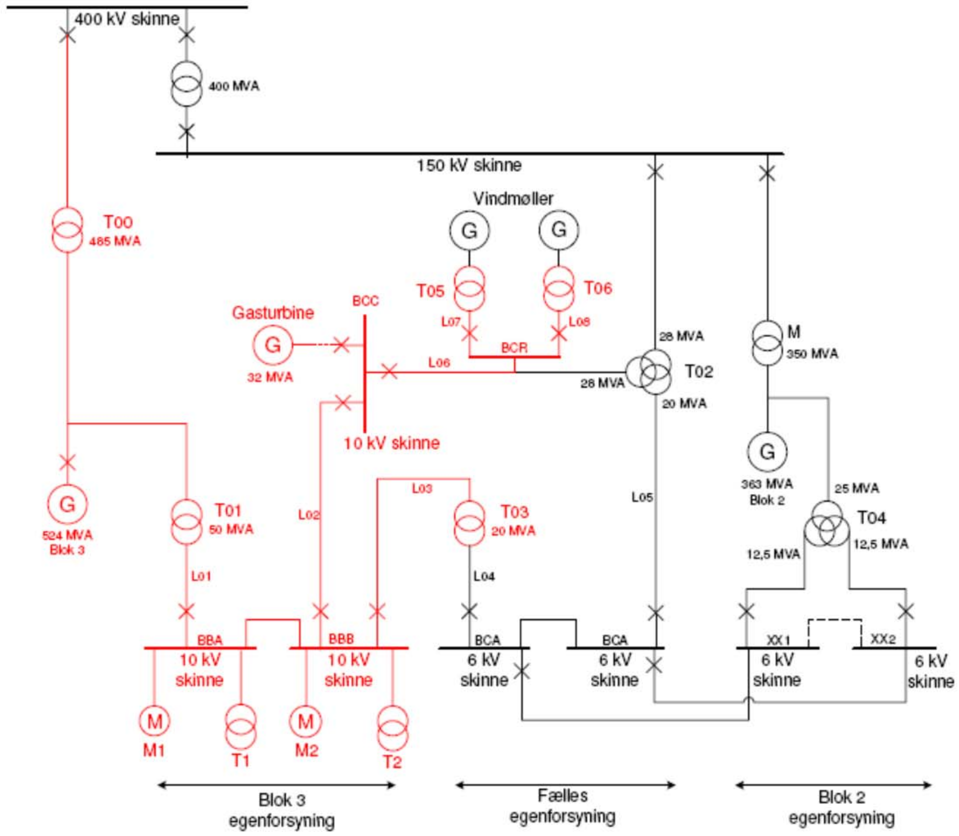
Figur 3.2: Intermitterende jordfejl mellem højspændingskabel og jord.

NO operation possible

Cables burned

Outage needed to repair

Medium voltage grid at Vattenfall power plant

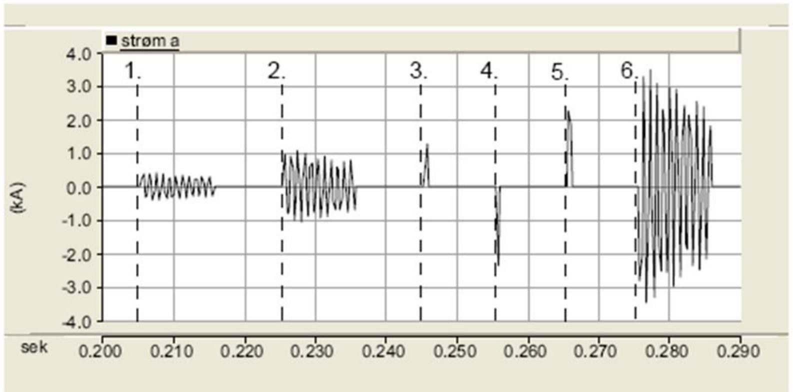


Figur 3.22: Model af mellemspændingsanlæg med størst netudstrækning.

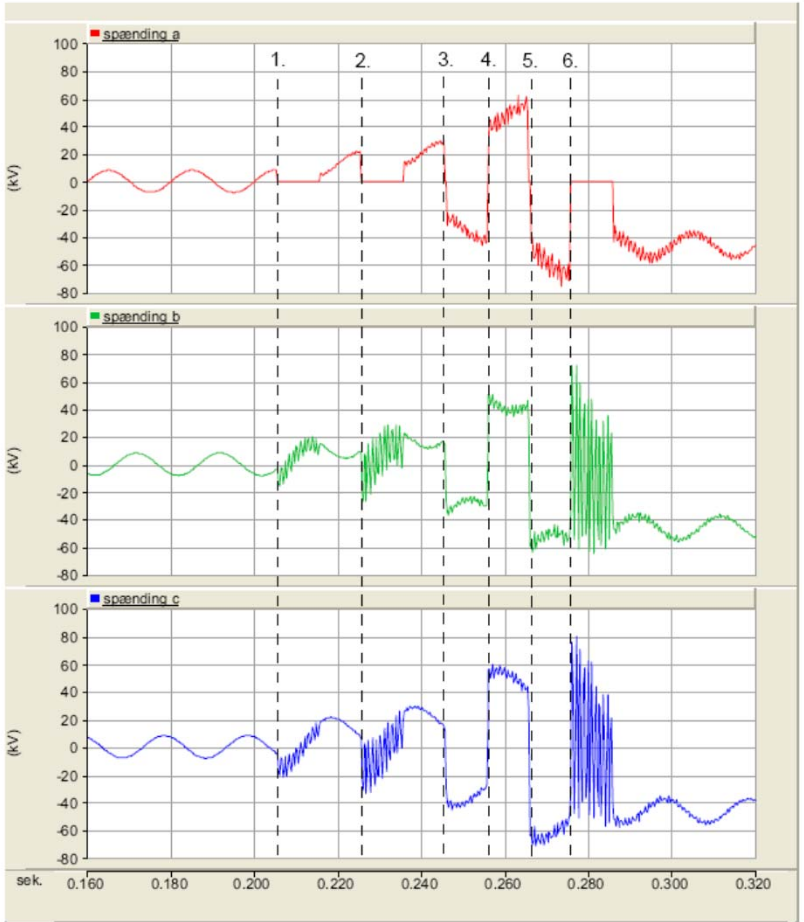
To be simulated in time domain in order to reveal possible max. overvoltages!

Current and voltage in faulted location.

Overvoltage by intermittent ground fault – dielectric BREAKDOWN !



Figur 4.30: Graf over fejlstrømmen ved seks fejl.



Figur 4.31: Graf over fasespændingerne i fejlstedet ved seks fejl.

400/150 kV Autotransformer

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

Very expensive

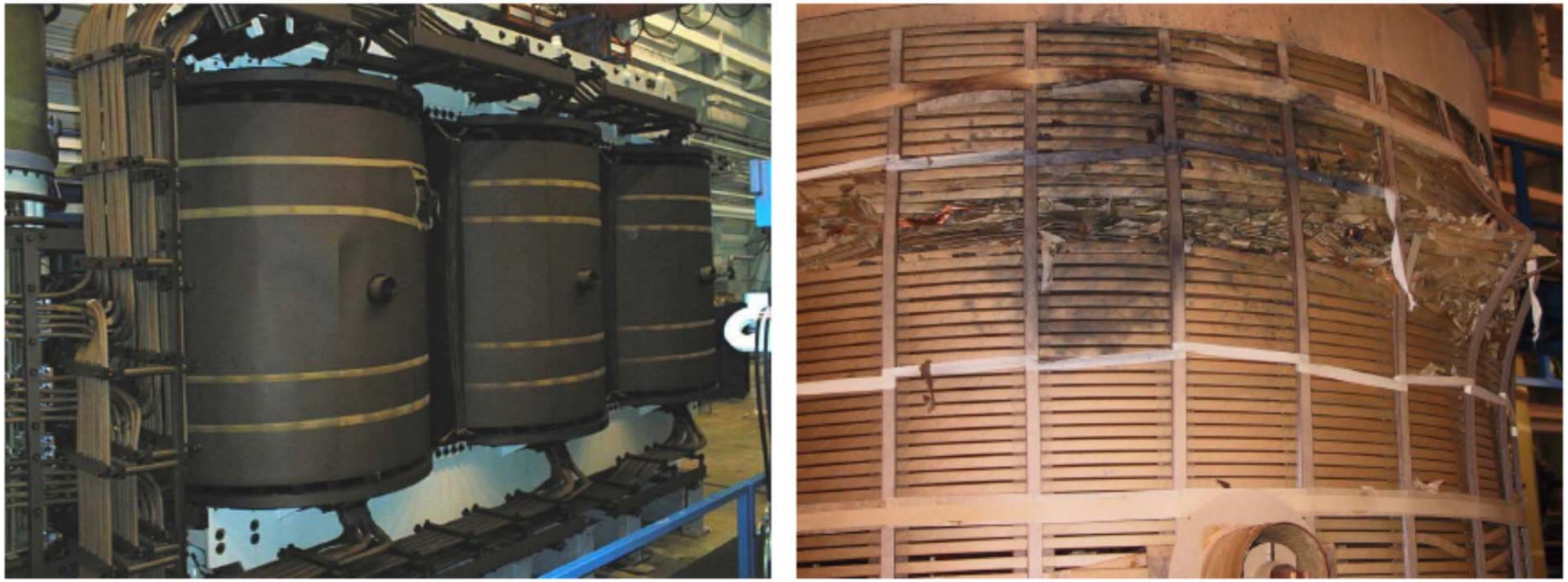
Indispensable

Long time of delivery

Repair expensive and prolonged

WE MUST PROTECT!

Transformer winding insulation failed ⇒
Internal short circuit ⇒
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

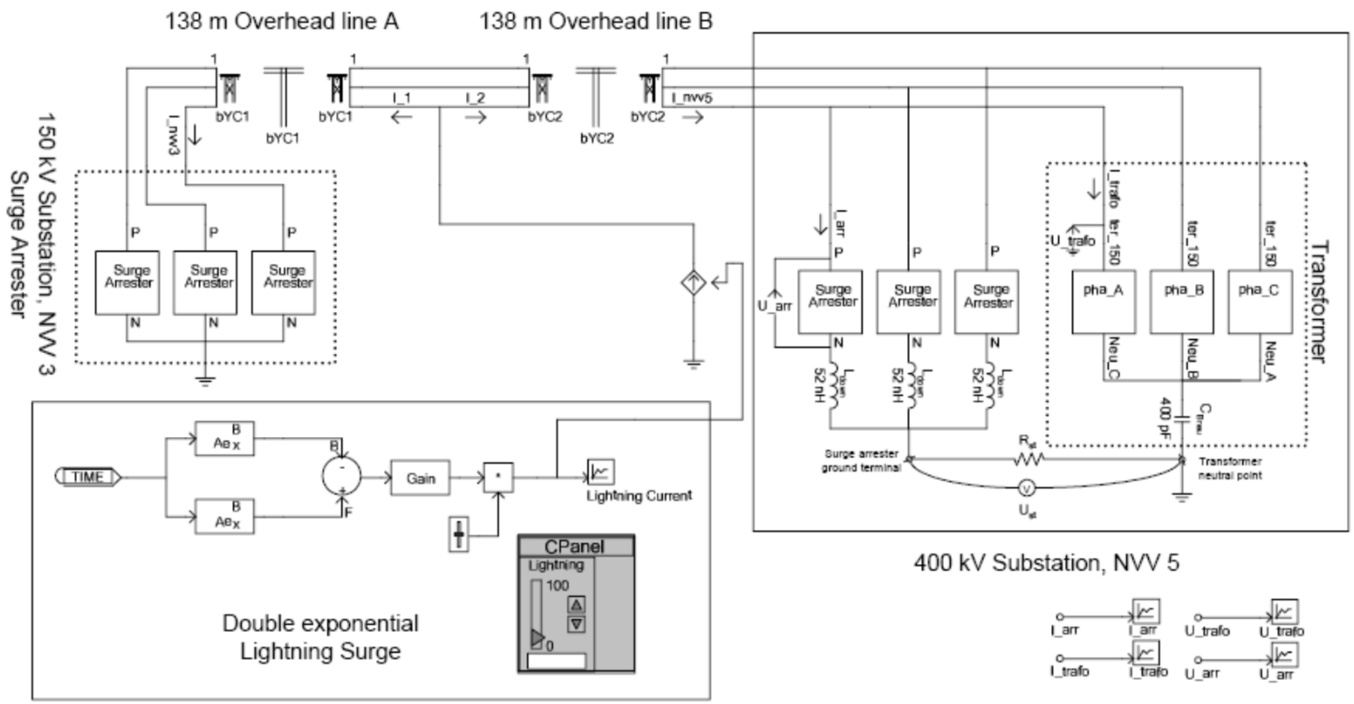
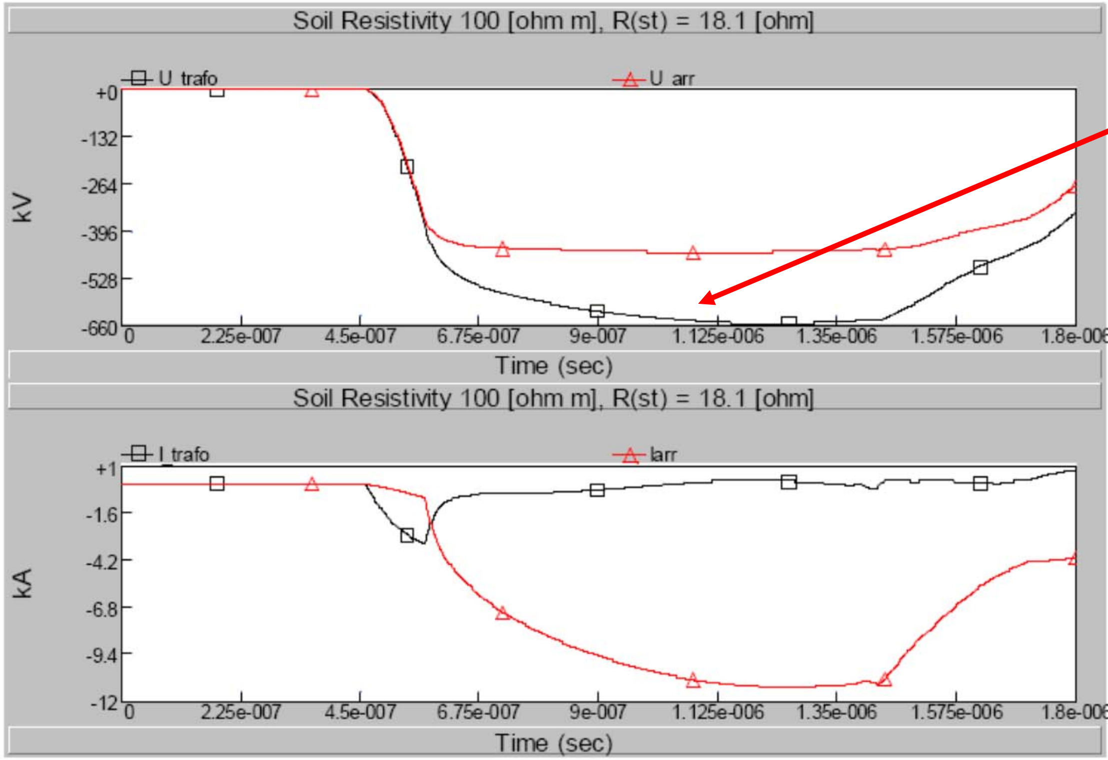


Figure E.1: A circuit diagram of the total system. The overhead lines between the 400 kV and the 150 kV substations are split up in two parts to make it possible to apply a lightning surge on the overhead line between the substations, and securing equal surge impedance on both sides. The overhead line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

Cause found – dynamic impedance of grounding



Voltage higher than transfor-mer LIWL

LIWL for 170 kV is 565 kV

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.

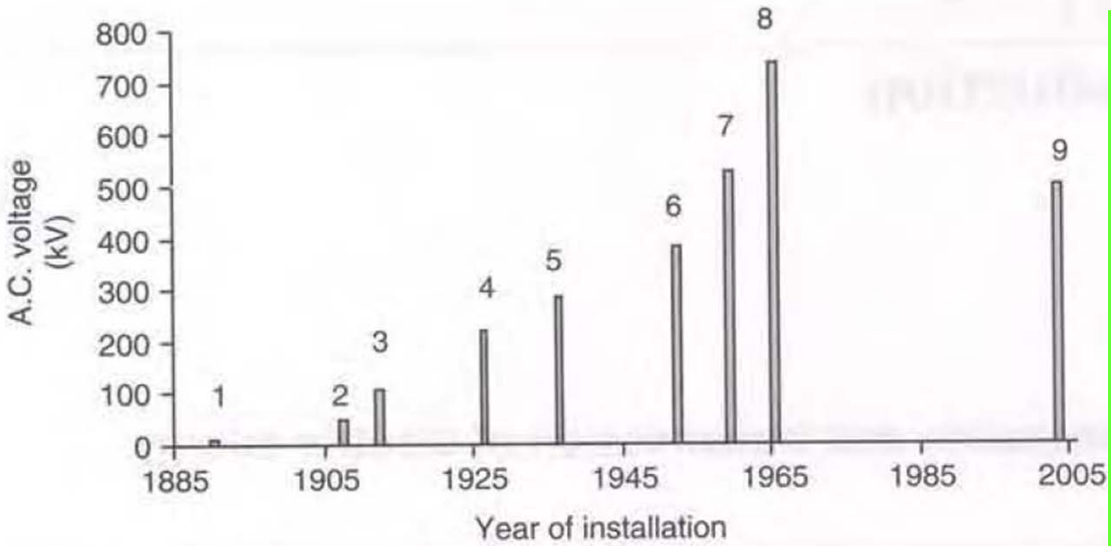
Power transmission vs. voltage level

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 Ω) 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

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

AC voltage level vs. 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*

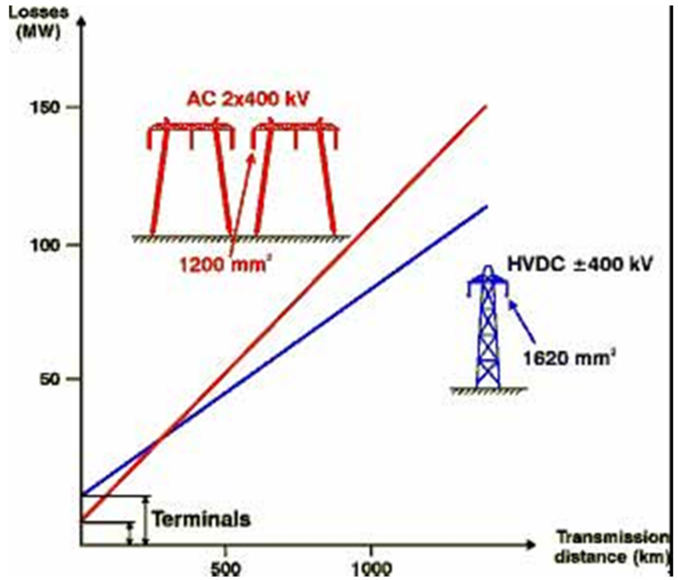
New issues 2016

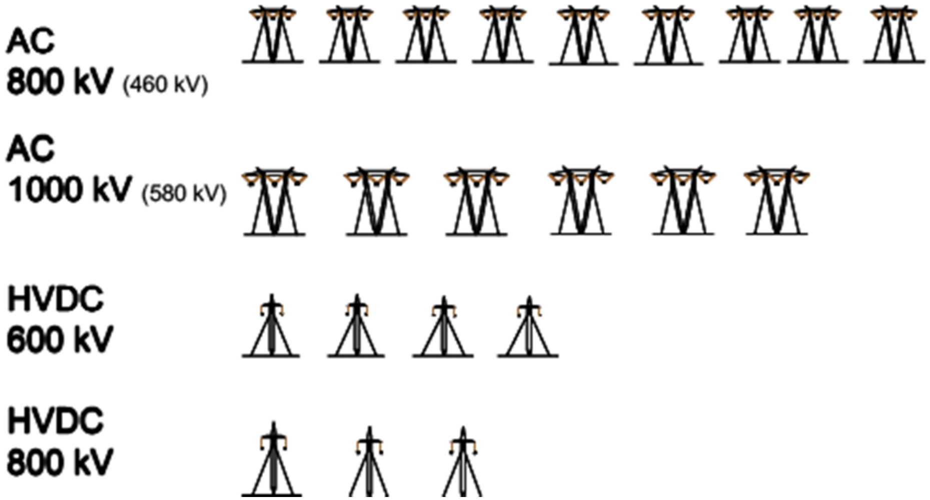
-UHV
-HVAC→HVDC
-HVDC – VSC
-Multiterminal HVDC
Offshore grid
-Changing trans-
mission grid
-Multi-circuits

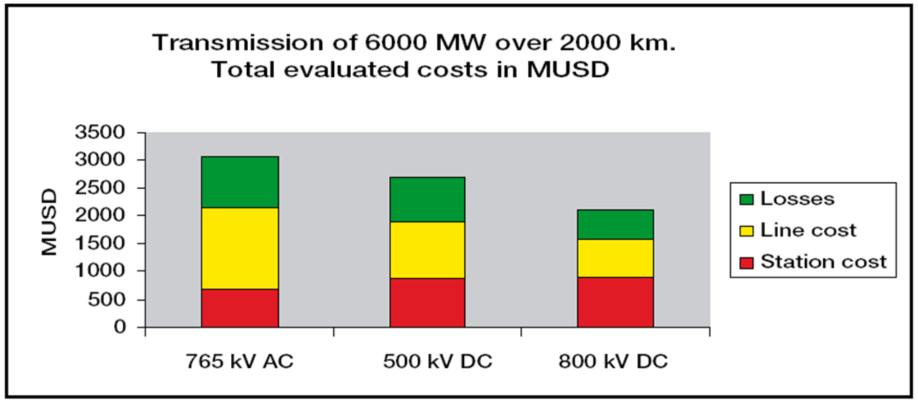
Voltage level increasing

Insulation design challenge !

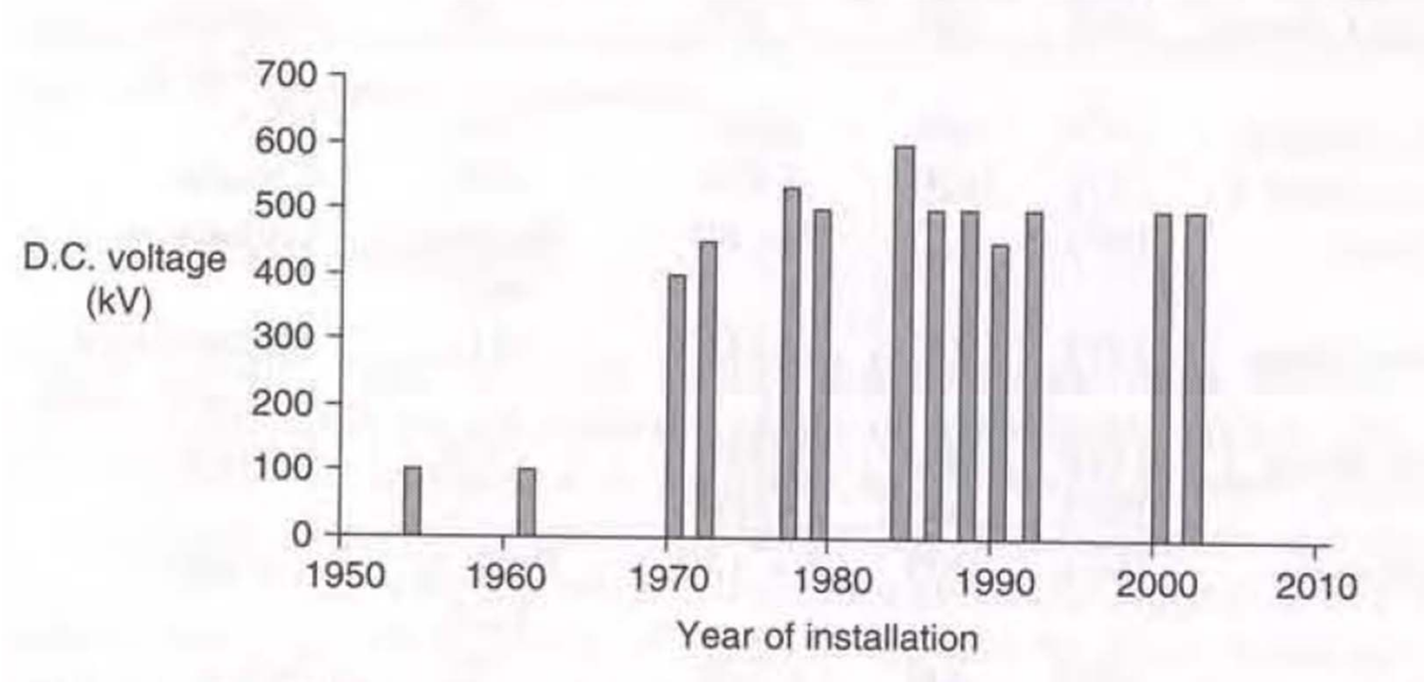
HVDC transmission







HVDC voltage level development



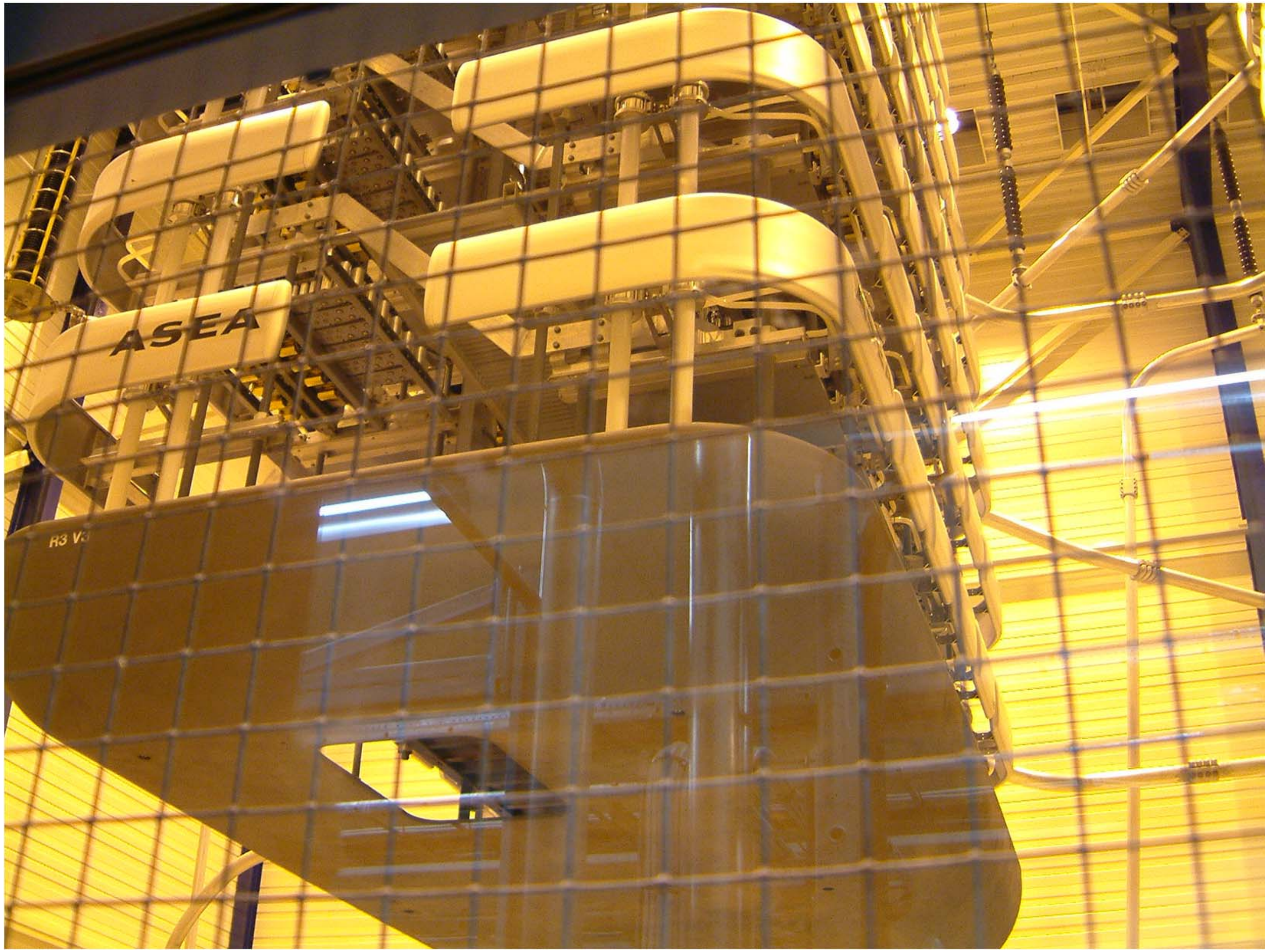
HVDC – VSC will gradually increase. Better grid support and less vulnerable to grid disturbances.

Table 1.1 *Major HVDC schemes*

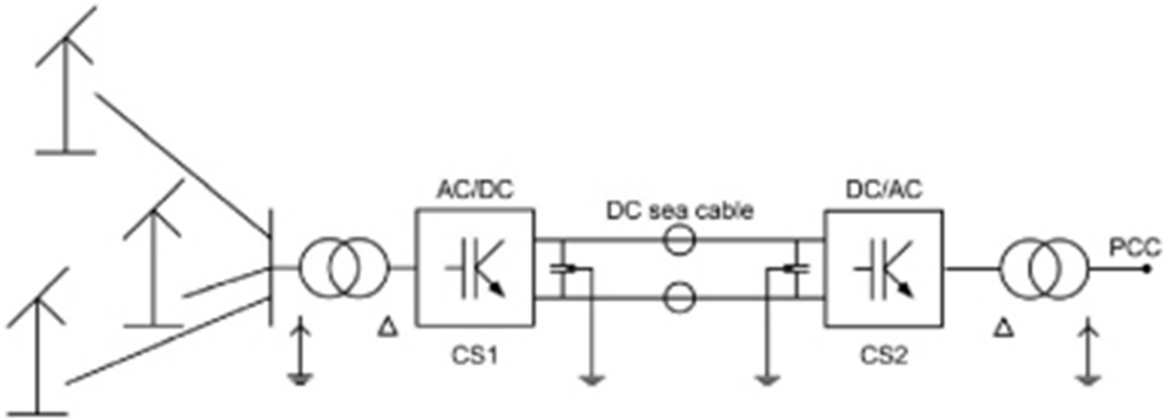
Scheme	*Year*	*Power (MW)*	*D.C. voltage (kv)*	*Line or cable length (km)*	*Location*
Gottland 1	1954	20	±100	96	Sweden
English Channel	1961	160	±100	64	England–France
Pacific Intertie	1970	1440	±400	1362	USA
Nelson River 1	1972	1620	±450	892	Canada
Eel River	1972	320	2 × 80	Back to back	Canada
Cabora 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

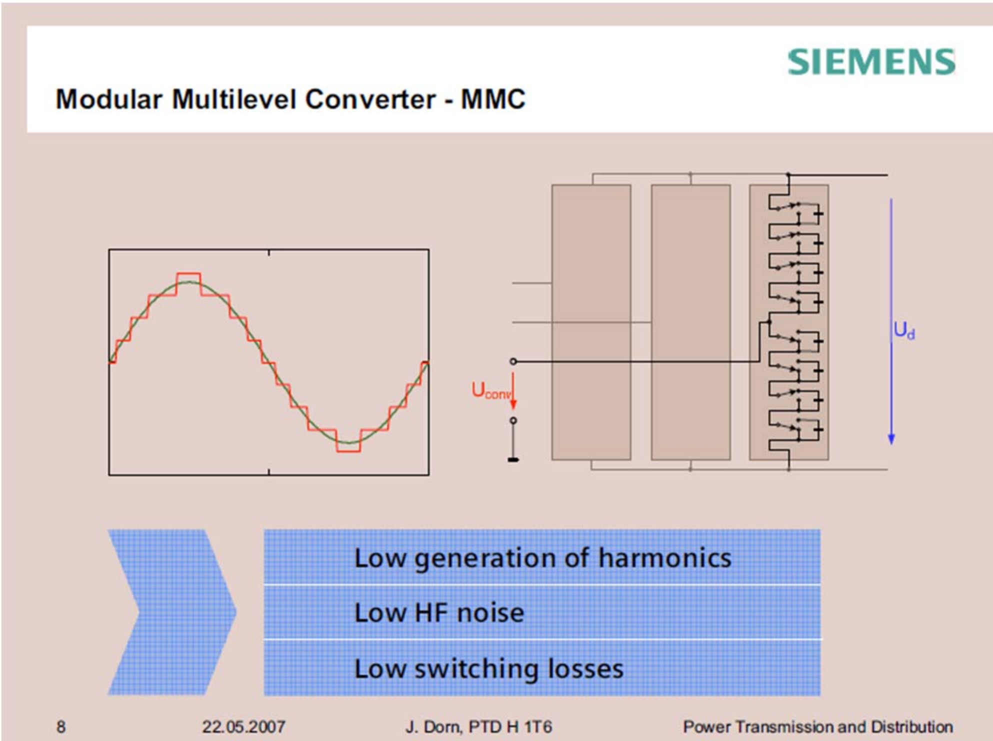
HVDC voltage levels for various HVDC projects through time


RK
ASEA
SA
ASEA

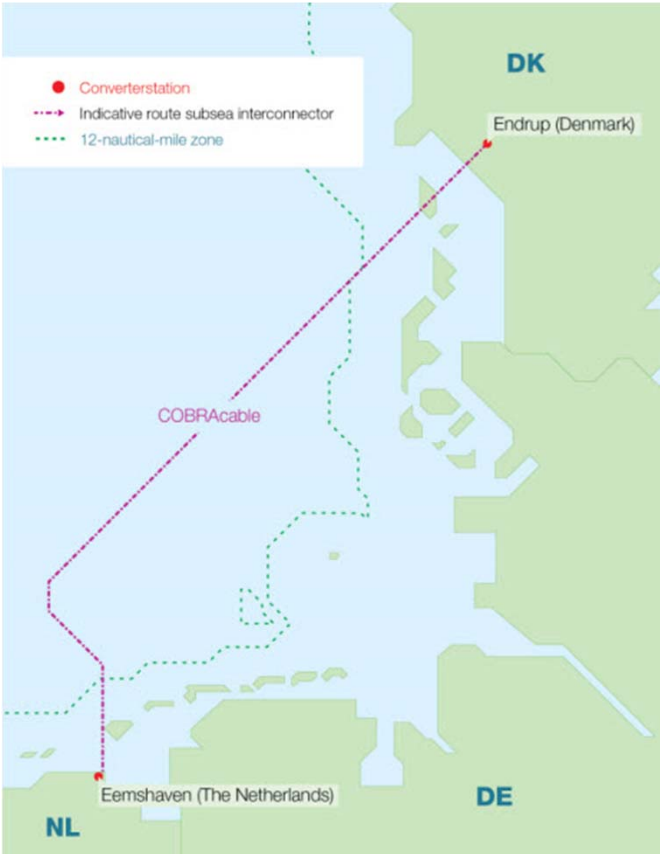

ASEA
R3 V3

HVDC - VSC

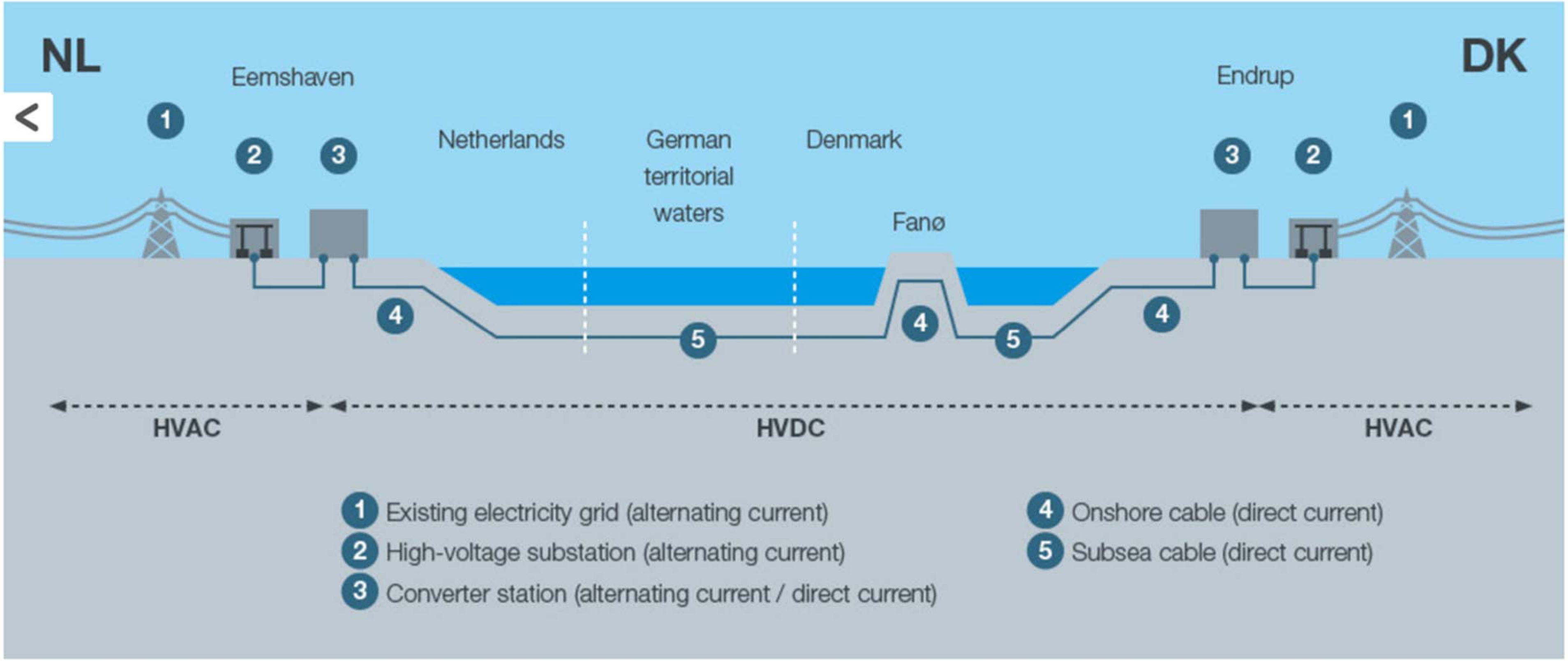

AC/DC
DC sea cable
DC/AC
PCC
CS1
CS2


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

New challenges



COBRA cable


NL
Eemshaven
Netherlands
German territorial waters
Denmark
Fanø
Endrup
DK
1
2
3
4
5
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)

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.

Insulation design basic principle

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 !

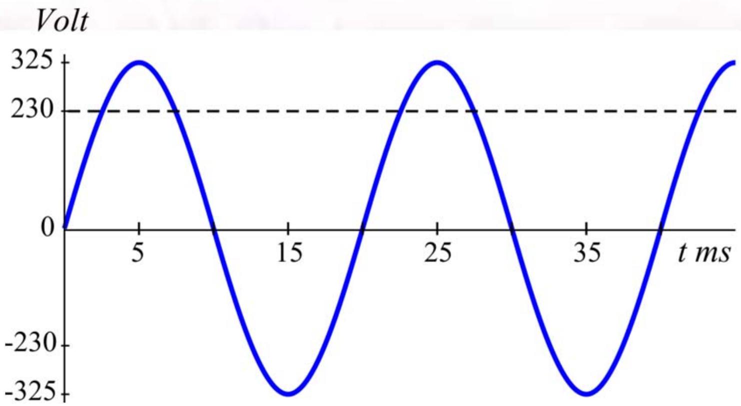
1.3 Testing voltages

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.

Power frequency test

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.



Lightning impulse voltage test

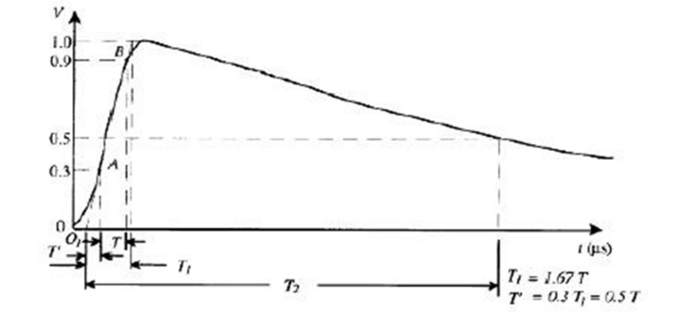


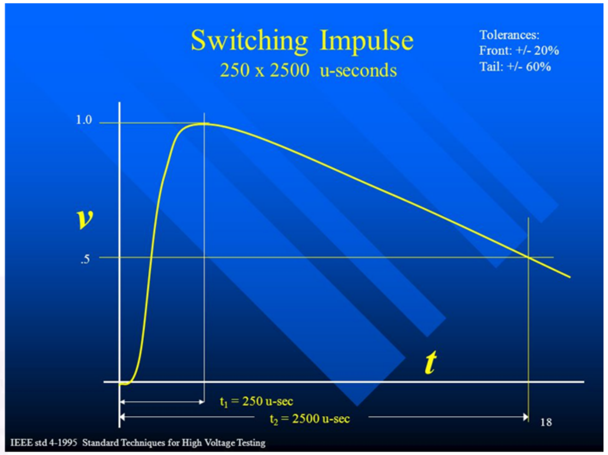
Fig. 3. LI 1.2/50 μs (IEC 60060-1) standard with T1-T2 time parameters

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.

In addition to testing equipment, impulse voltages are extensively used in research laboratories in the fundamental studies of electrical discharge mechanisms, notably when the time to breakdown is of interest.

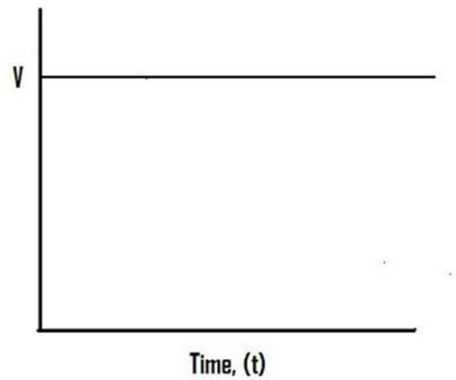
Switching impulse voltage test



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, oscillating switching impulse voltages are recommended for obtaining higher efficiency of the impulse voltage generator Full details relating to generation, measurements and test procedures in testing with switching surge voltages will be found in Chapters 2, 3 and 8.

DC voltage test



1.3.4 D.C. voltages

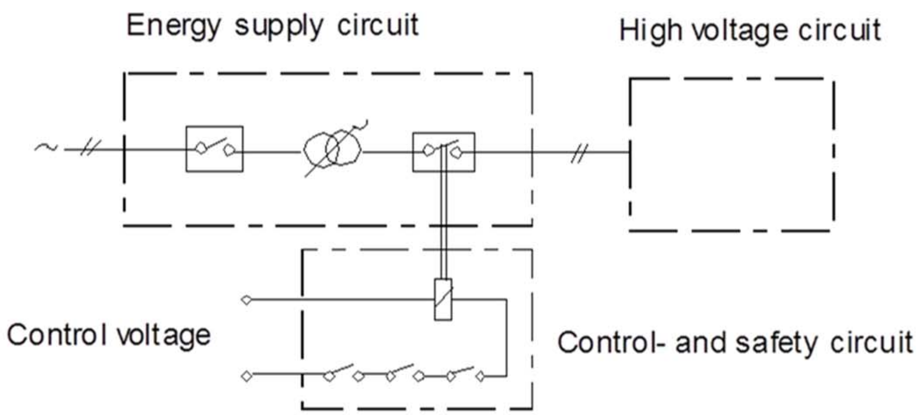
In the past d.c. voltages have been chiefly used for purely scientific research work. Industrial applications were mainly limited to testing cables with relatively large capacitance, which take a very large current when tested with a.c. voltages, and in testing insulations in which internal discharges 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 also what's HV engineering is about!

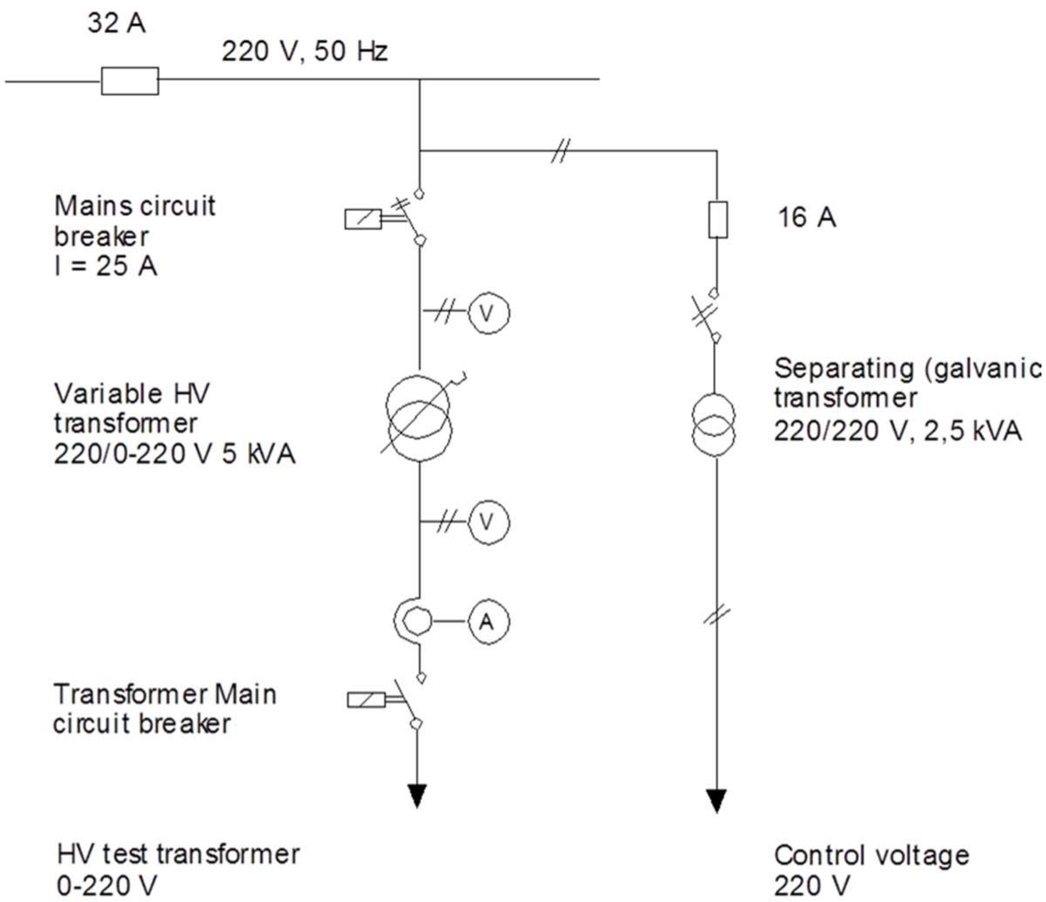
High Voltage test fields are used for testing real power system equipment such as:

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

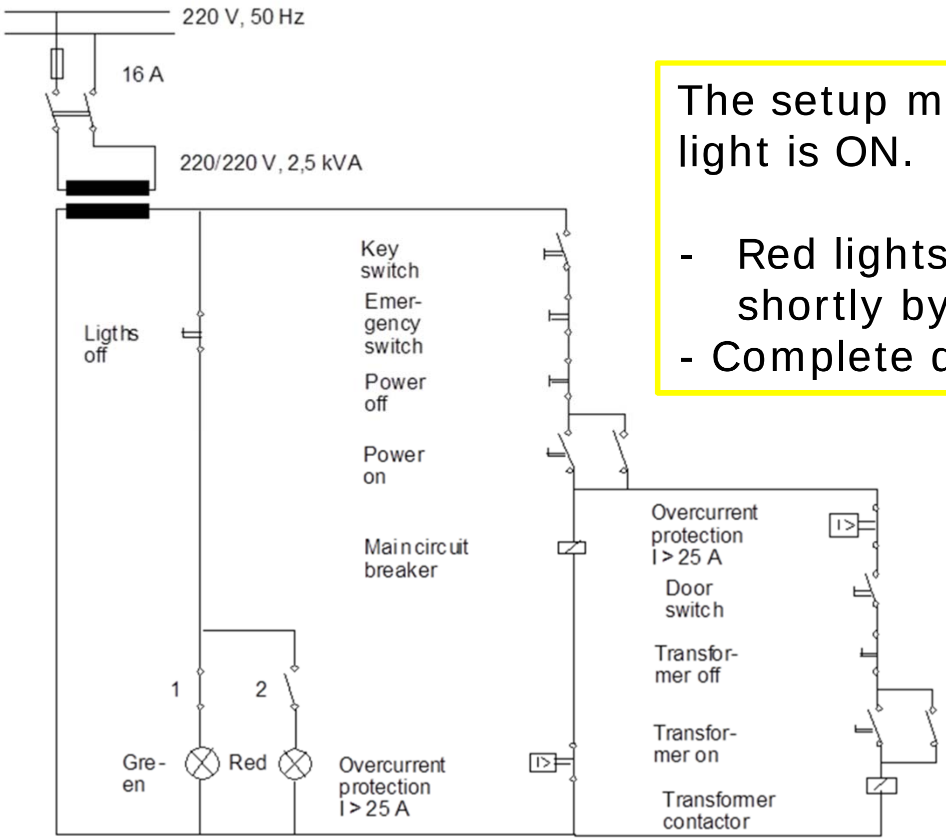
Fundamental safe layout of electrical supply for HV test setup



Main circuit for HV test setup



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


60 W
10 MΩ
8 W
500 kΩ
5 mA
140 kV
140 kV
5 mA
500 kΩ
8 W
60 W
416 Ω


10000 pF
140 kV =
140 W
140 MΩ
60 W
9500 Ω
140 kV =
1200 pF
140 kV =
6000 pF


100 pF
100 kV ~

Control desk II


HIGH VOLT
5 mA
8 W
10000 pF

Impulse current experiment – 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 !!!