● Generation and measurement of high AC-voltages

High AC-voltages are used to experimental setups and testings (routinetesting and typetesting) of high voltage equipment, for instance a 170 kV circuit breaker.

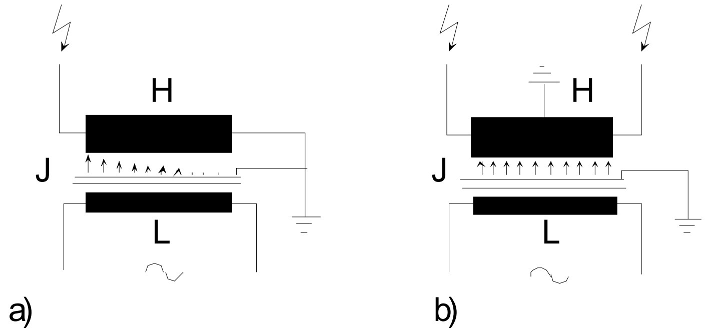
HV test transformers differs from “normal” power grid transformers in the following ways:

- Much greater transfer ratio, eg. 220/100000 V
- Much smaller rated power, eg. 5 kVA

Normally the size of the voltage (peak value, but sometimes also phase angle in comparison to a defined reference) is the most important measuring parameter of a high voltage experiment. Measuring is only possible at the HV level by different methods.

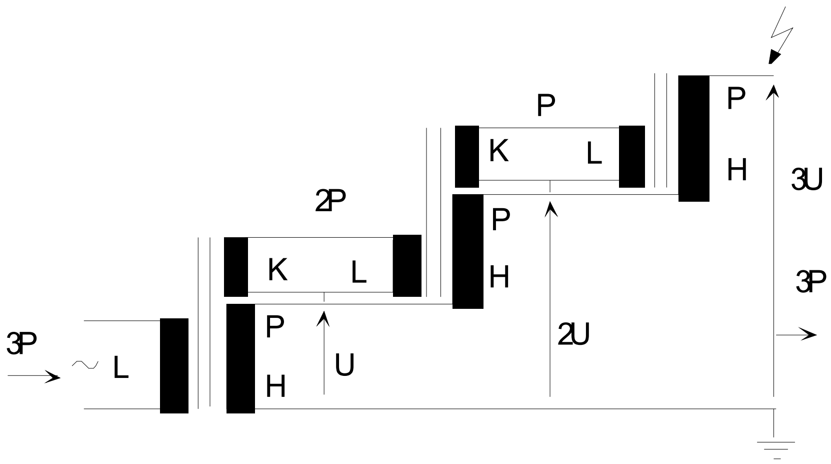
● Connection of HV test transformers

- Partially insulated (most power grid transformers) or fully insulated.



- Optional grounding of fully insulated HV transformer:
  - HV winding Terminal 1 (one side)
  - HV winding terminal 2 (the other side)
  - Mid point

- **Cascaded circuits for higher voltages**



Cascading is used to get higher HV voltages.
Auxilliary windings (K-L) to ”transport” power to higher stages not through HV winding

Fundamentals of High Voltage Techniques

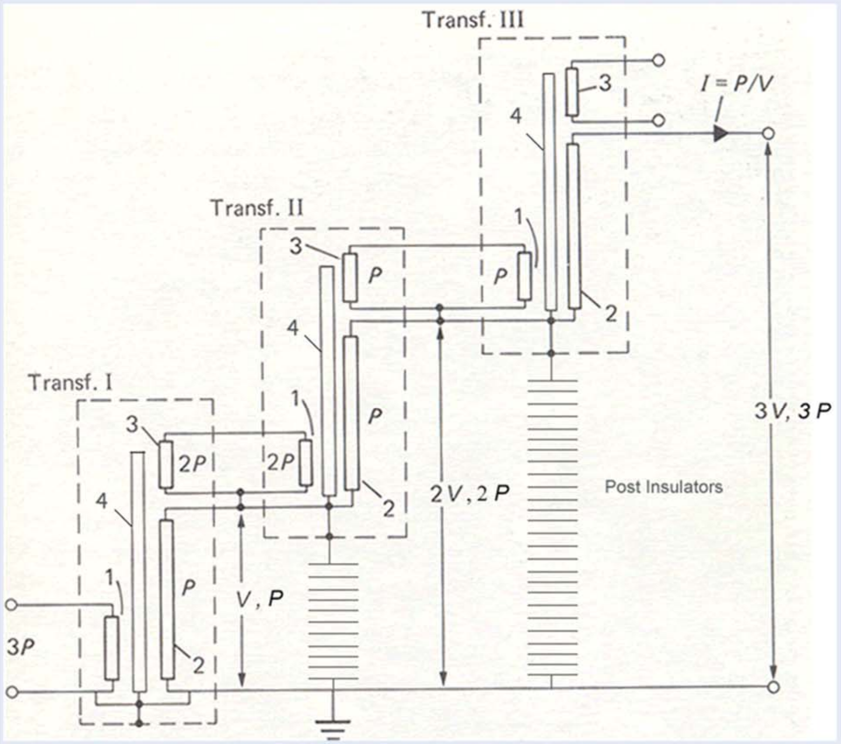
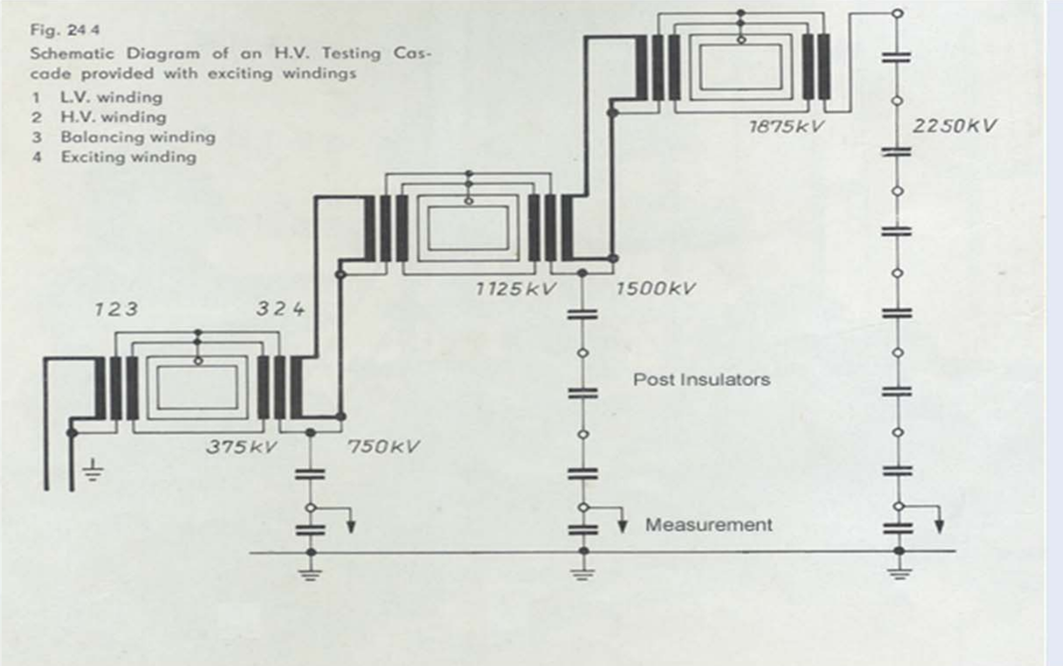


Fig 24.3 Three Transformers in cascade
(1) Primary windings,
(2) Secondary, HV, windings,
(3) Tertiary/excitation windings (4) Core



Fundamentals of High Voltage Techniques

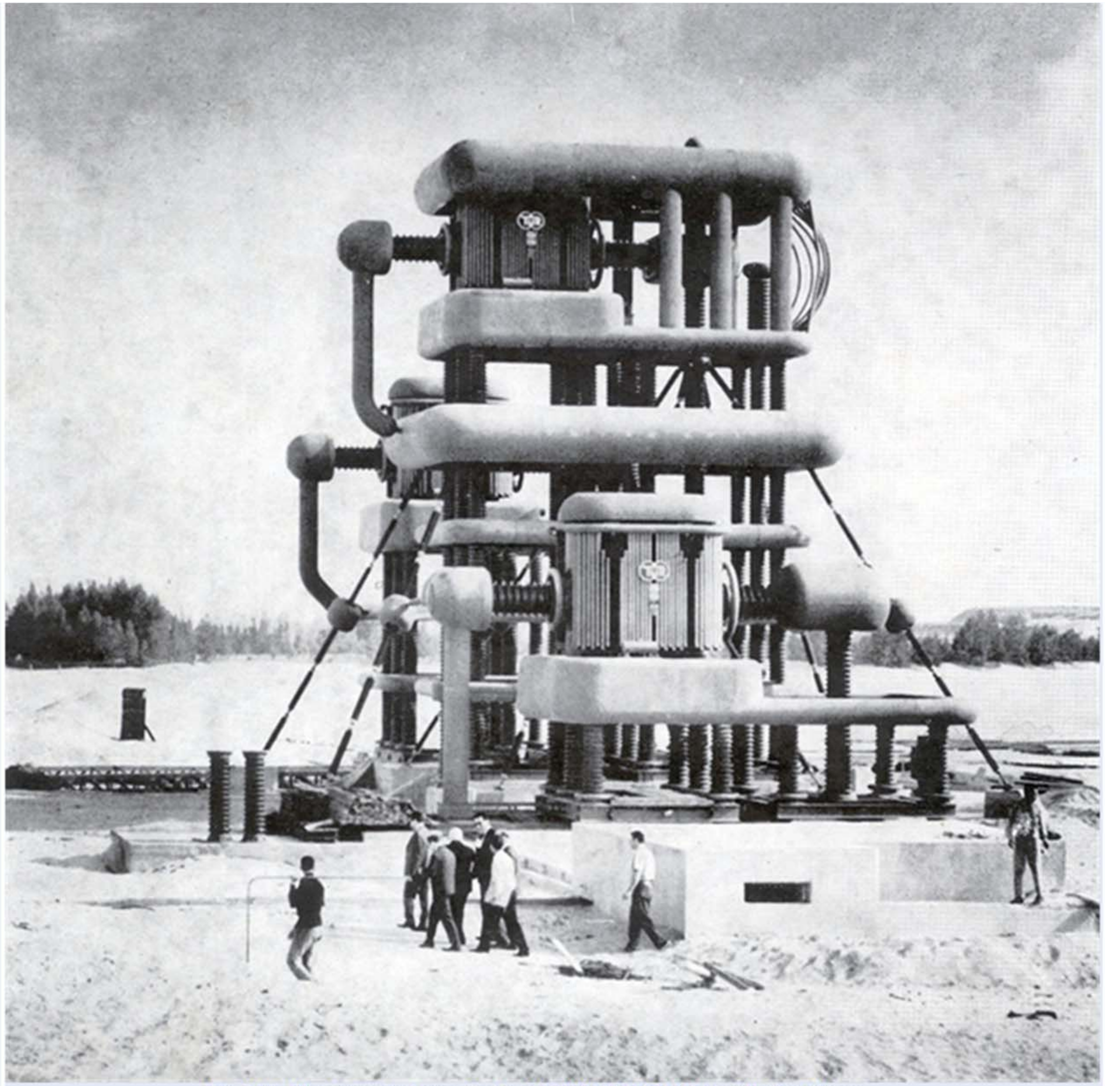
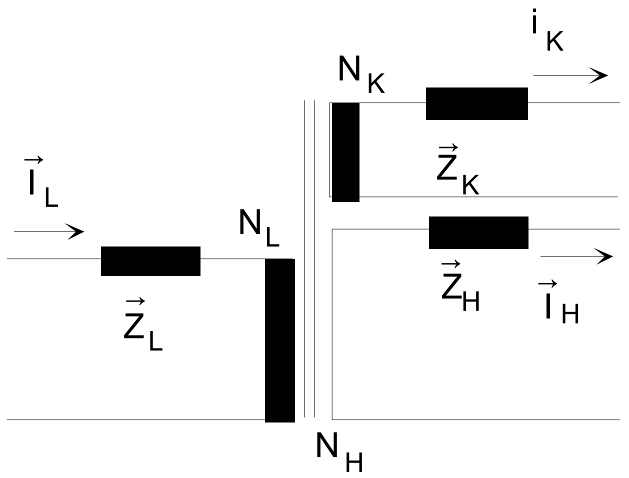


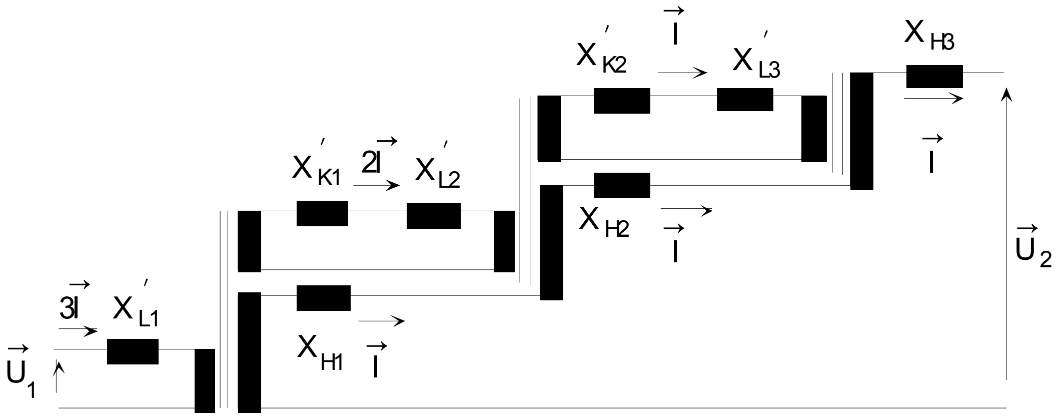
Fig. 24.5 Photograph of an ac test set of 2250 kV, 2250 kVA installed outdoors
People walking on the ground in this photograph gives an idea of the huge size of the test set.

Short circuit reactance for cascaded transformers



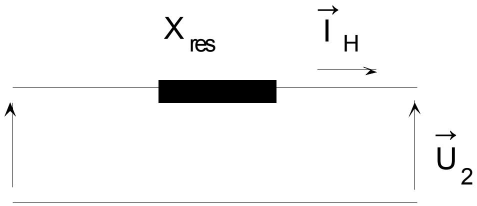
- The impedances Z_L, Z_H og Z_K are determined on the basis of 3 short circuit tests.
  - Assumed simplifications
    - Ampere turn balance with magnetizing current = 0
    - Active losses = 0
    - The same turns ratio (transfer ratio) for all stages of the cascade

a)



b)

$$\vec{U}_1' = 3\frac{N_H}{N_L}\vec{U}_1$$



In a simplified equivalent circuit of each transformer unit, which consists of a three-windings-type, we may define leakage or stray reactances X for each winding, the primary X_p, the h.t. winding X_h and the exciting winding X_e. Neglecting losses within the windings and magnetizing currents, the somewhat simplified calculation of the resultant reactance X_{res} of a cascade unit with n transformers having the individual reactances X_{pv}, X_{hv} and X_{ev} shows

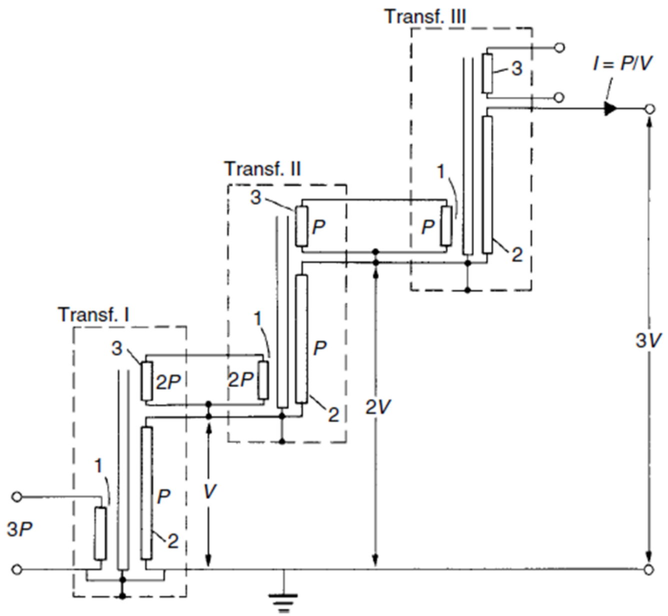
$$X_{res} = \sum_{v=1}^{n} [X_{hv} + (n-v)^2 X_{ev} + (n+1-v)^2 X_{pv}]. \tag{2.15}$$

(All reactances related to same voltage.)

Assuming three equal transformer units, the equation leads to a reactance of

$$X_{res} = 3X_h + 5X_e + 14X_p$$

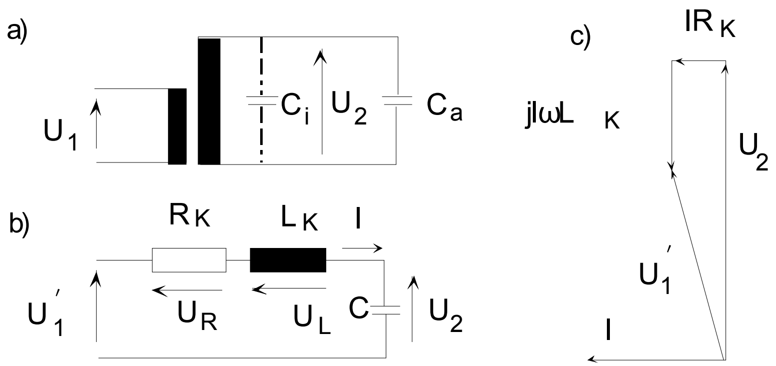
instead of only $3(X_h + X_e + X_p)$ which might be expected.



By assuming energy conservation of reactive power $I^2 * X$

● Operation of HV test transformers

Equivalent circuits for power grid transformers are unsuitable for HV test transformers, because the capacity of the HV winding Ci and the capacity of the test object determines the voltage drop. Putting the magnetizing current = 0 gives:



Assuming Zk = Rk + jXk mostly inductive gives arg(U1) ≈ arg(U2) ⇒

$$\boxed{U_2 \simeq U_1' \frac{1/\omega C}{1/\omega C - \omega L_K} = U_1' \frac{1}{1-\omega^2 L_K C} \quad V}$$

Series resonant voltage rise during nominal operation, Un·ω·C=In

$$u_K = \frac{U_K}{U_n} = \frac{I_n \cdot \omega L_K}{U_n} = \frac{I_n \cdot \omega L_K}{\frac{I_n}{\omega C}} = \omega^2 L_K C$$

Example: uk=20 % and nominal load gives:

$$U_2 \simeq U_1^{/} \frac{1}{1-u_K} = U_1^{/} \frac{1}{1-0{,}20} = U_1^{/} \cdot 1{,}25$$

This voltage rise renders LV measuring of the HV voltage impossible.

So we must use directly HV connected instruments to measure the actual HV voltage !

● Measurement of high AC-voltages

● Peak voltage measurement with sphere gaps

- Quasi-homogeneous field gives rise to breakdown time delays in therange of ns to µs.
- Breakdown for the peak of the voltage for:
  - "Normal" 50 Hz AC-voltage
  - Impulse voltages up to approximately 500 kHz.

- Sphere gaps can be designed so that the breakdown voltage is very well-defined

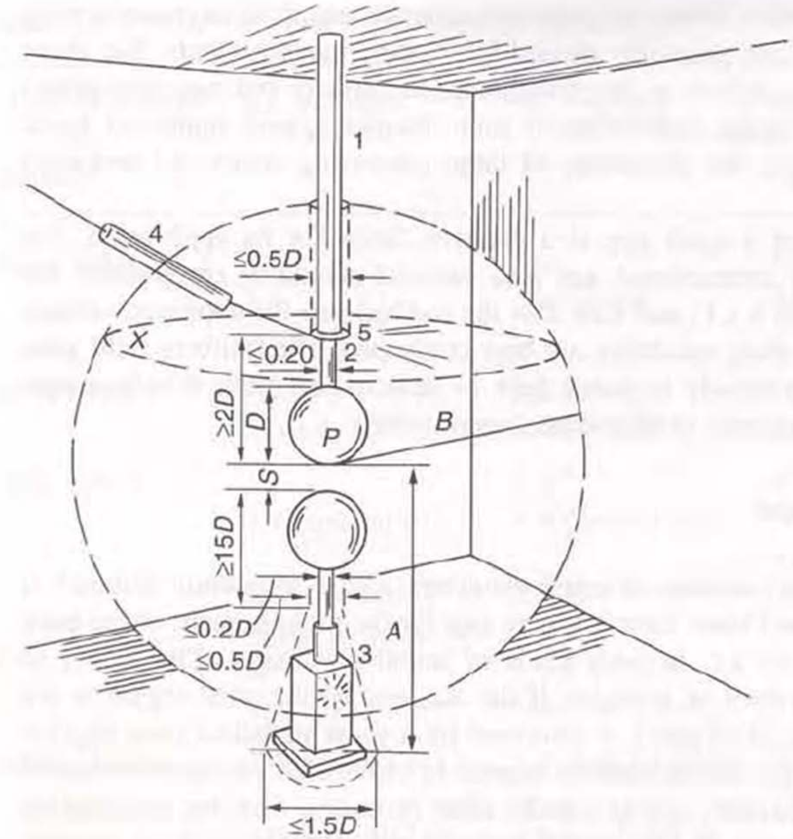


Figure 3.1 *Vertical sphere gap. 1. Insulating support. 2. Sphere shank. 3. Operating gear, showing maximum dimensions. 4. High-voltage connection with series resistor. 5. Stress distributor, showing maximum dimensions. P. Sparking point of h.v. sphere. A. Height of P above ground plane. B. Radius of space free from external structures. X. Item 4 not to pass through this plane within a distance B from P. Note: The figure is drawn to scale for a 100-cm sphere gap at radius spacing. (Reproduced from ref. 5)*

Vertical sphere gap

MUST fulfill demands of chapter 3.1.1

Table 3.2 *Clearance around the spheres*

Sphere diameter D (mm)	*Minimum value of A*	*Maximum value of A*	*Minimum Value of B*
62.5	7D	9D	14S
125	6	8	12
250	5	7	10
500	4	6	8
750	4	6	8
1000	3.5	5	7
1500	3	4	6
2000	3	4	6

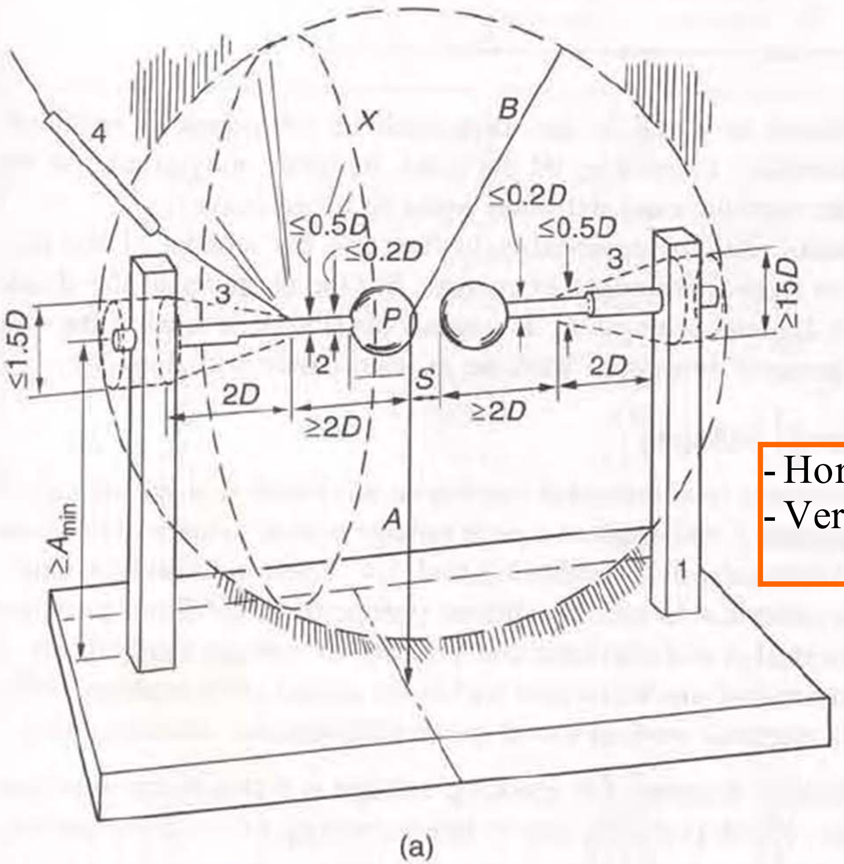


Figure 3.2 *(a) Horizontal sphere gap. 1. Insulating support. 2. Sphere shank. 3. Operating gear, showing maximum dimensions. 4. High-voltage connection with series resistor. P. Sparking point of h.v. sphere. A. Height of P above ground plane. B. Radius of space free from external structures. X. Item 4 not to pass through this plane within a distance B from P. Note: The figure is drawn to scale for a 25-cm sphere gap at a radius spacing. (Reproduced from ref. 5).*

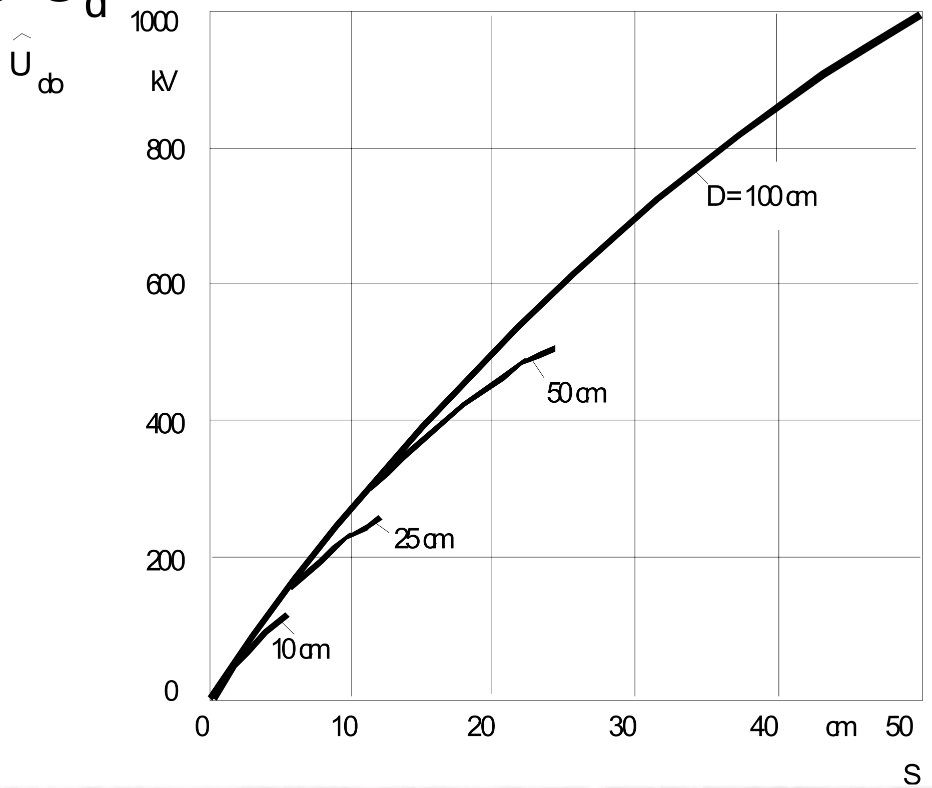
- Horizontal for D < 50 cm
- Vertical also for D > 50 cm, measurements against ground

- **Standard: IEC 52**
- Voltage measurements are converted to standard atmospheric conditions, p=1013 mbar og T=20°C, air humidity has no effect when the E-field is quasi-homogeneous.

$$\hat{U}_d \simeq d\,\hat{U}_{do} = \frac{p}{1013}\,\frac{273+20}{273+\theta}\,\hat{U}_{do} = 0{,}289\,\frac{p}{273+\theta}\,\hat{U}_{do} \qquad [V]$$

- Rule of thumb: D in [mm] ≥ Û in [kV] and s/D ≤ 1/2
- The measuring accuracy of sphere gaps according to IEC 52 is better than 3 %

Relation between gap length s and breakdown voltage U_d



Note. For every sphere diameter the sparking voltage is a non-linear function of the gap distance, which is mainly due to the increasing field inhomogeneity and only less to the physics of breakdown. All table values could well be simulated by polynominals of order 6 or even less. Note also, that many table values are the result of only linear interpolation between points which have been the result of actual measurements.

Table 3.3

(PART 1) Sphere gap with one sphere grounded

Peak values of disruptive discharge voltages (50% for impulse tests) are valid for:

- alternating voltages,
- negative lightning impulse voltages,
- negative switching impulse voltages,
- direct voltages of either polarity.

Atmospheric reference conditions: 20°C and 101.3 kPa

Sphere gap spacing (mm)	*Voltage, kV peak*		
	Sphere diameter (cm)		
	6.25	*12.5*	*25*
5	17.2	16.8	
10	31.9	31.7	
15	45.5	45.5	
20	58.5	59.0	
25	69.5	72.5	72.5
30	79.5	85.0	86
35	(87.5)	97.0	99
40	(95.0)	108	112
45	(101)	119	125
50	(107)	129	137
55	(112)	138	149
60	(116)	146	161
65		154	173
70		(161)	184
80		(174)	206
90		(185)	226
100		(195)	244
110		(203)	261
120		(212)	275
125		(214)	282
150			(314)
175			(342)
200			(366)
225			(385)
250			(400)

(continued overleaf)

Table 3.3 *(continued)*

(PART 2) Sphere gap with one sphere grounded

Sphere gap spacing (mm)	*Voltage, kV peak*				
	Sphere diameter (cm)				
	50	*75*	*100*	*150*	*200*
50	138	138	138	138	
75	202	203	203	203	203
100	263	265	266	266	266
125	320	327	330	330	330
150	373	387	390	390	390
175	420	443	443	450	450
200	460	492	510	510	510
250	530	585	615	630	630
300	(585)	665	710	745	750
350	(630)	735	800	850	855
400	(670)	(800)	875	955	975
450	(700)	(850)	945	1050	1080
500	(730)	(895)	1010	1130	1180
600		(970)	(1110)	1280	1340
700		(1025)	(1200)	1390	1480
750		(1040)	(1230)	1440	1540
800			(1260)	(1490)	1600
900			(1320)	(1580)	1720
1000			(1360)	(1660)	1840
1100				(1730)	(1940)
1200				(1800)	(2020)
1300				(1870)	(2100)
1400				(1920)	(2180)
1500				(1960)	(2250)
1600					(2320)
					(2320)
1700					(2370)
1800					(2410)
1900					(2460)
2000					(2490)

Note. The figures in parentheses, which are for spacing of more than $0.5D$, will be within ±5 per cent if the maximum clearances in Table 3.2 are met. On errors for direct voltages, see text.

Table 3.4

(PART 1) Sphere gap with one sphere grounded

Peak values of disruptive discharge voltages (50% values) are valid for:

- positive lightning impulses,
- positive switching impulses,
- direct voltages of either polarity.

Atmospheric reference conditions: 20°C and 101.3 kPa

Sphere gap spacing (mm)	*Voltage, kV peak* — *Sphere diameter (cm)* 6.25	12.5	25
5	17.2	16.8	–
10	31.9	31.7	31.7
15	45.9	45.5	45.5
20	59	59	59
25	71.0	72.5	72.7
30	82.0	85.5	86
35	(91.5)	98.0	99
40	(101)	110	112
45	(108)	122	125
50	(115)	134	138
55	(122)	145	151
60	(127)	155	163
65		(164)	175
70		(173)	187
80		(189)	211
90		(203)	233
100		(215)	254
110		(229)	273
120		(234)	291
125		(239)	299
150			(337)
175			(368)
200			(395)
225			(416)
250			(433)

(continued overleaf)

Table 3.4 *(continued)*

(PART 2) Sphere gap with one sphere grounded

Sphere gap spacing (mm)	*Voltage, kV peak* — *Sphere diameter (cm)* 50	75	100	150	200
50	138	138	138	138	138
75	203	202	203	203	203
100	263	265	266	266	266
125	323	327	330	330	330
150	380	387	390	390	390
175	432	447	450	450	450
200	480	505	510	510	510
250	555	605	620	630	630
300	(620)	695	725	745	750
350	(670)	770	815	858	860
400	(715)	(835)	900	965	980
450	(745)	(890)	980	1060	1090
500	(775)	(940)	1040	1150	1190
600		(1020)	(1150)	1310	1380
700		(1070)	(1240)	(1430)	1550
750		(1090)	(1280)	(1480)	1620
800			(1310)	(1530)	1690
900			(1370)	(1630)	1820
1000			(1410)	(1720)	1930
1100				(1790)	(2030)
1200				(1860)	(2120)
1300				(1930)	(2200)
1400				(1980)	(2280)
1500				(2020)	(2350)
1600					(2410)
1700					(2470)
1800					(2510)
1900					(2550)
2000					(2590)

Note. The figures in parentheses, which are for spacing of more than 0.5*D*, will be within ±5 per cent if the maximum clearances in Table 3.2 are met.

HVDC Three Gorges

Main data	
Commissioning year:	2004
Power rating:	3 000 MW
No. of poles:	2
AC voltage:	500 kV (both ends)
DC voltage:	±500 kV
Length of overhead DC line:	940 km
Main reason for choosing HVDC:	Long distance, network stability, low losses, environmental concerns

Single stage rectification

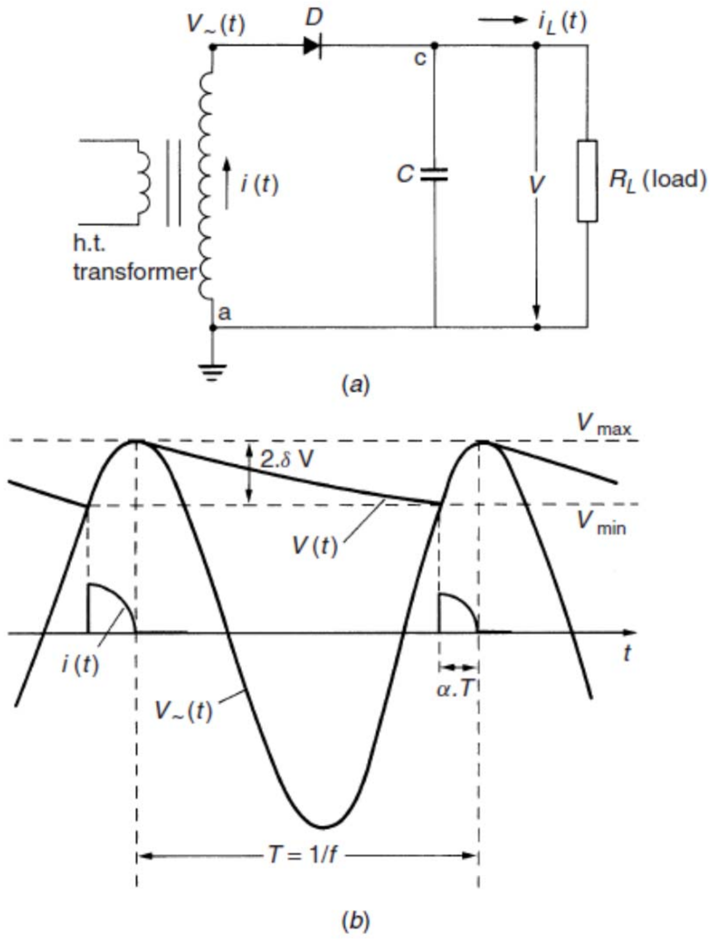


Figure 2.1 *Single-phase half-wave rectifier with reservoir capacitance C. (a) Circuit. (b) Voltages and currents with load R_L*

$$Q = \int_T i_L(t)\,\mathrm{d}t = \frac{1}{R_L}\int_T V(t)\,\mathrm{d}t = IT = \frac{I}{f}.$$

$$Q = 2\delta V C = IT; \quad \delta V = \frac{IT}{2C} = \frac{I}{2fC}.$$

Ripple voltage depends from loading, frequency and capacitance

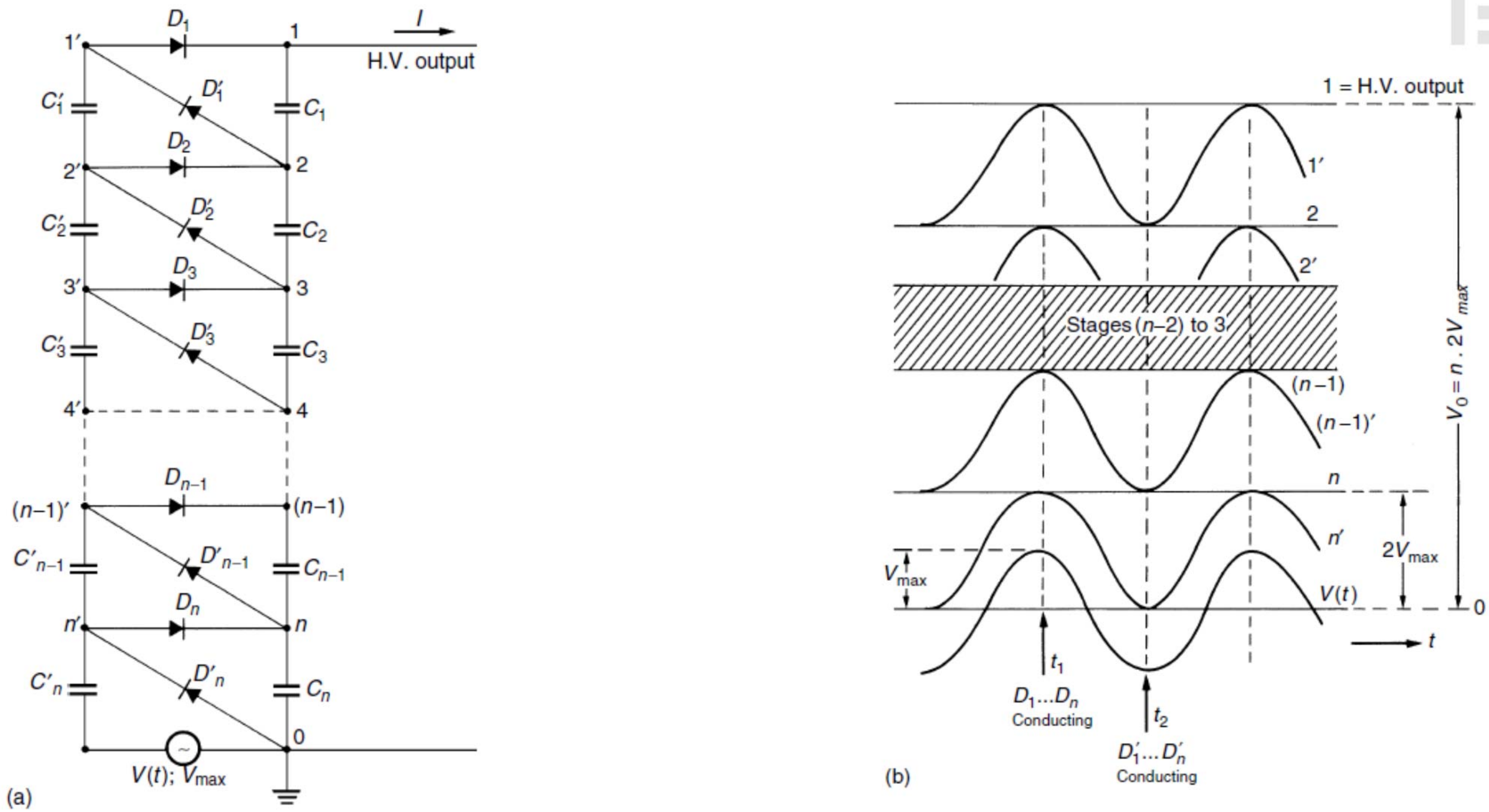


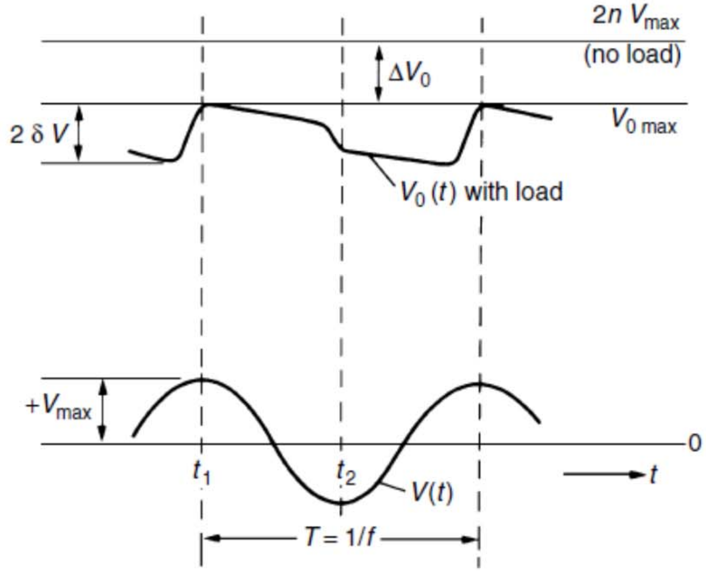
Figure 2.3 *(a) Cascade circuit according to Cockroft–Walton or Greinacher. (b) Waveform of potentials at the nodes, no load*

- the potentials at the nodes $1', 2' \ldots n'$ are oscillating due to the voltage oscillation of $V(t)$;
- the potentials at the nodes $1, 2 \ldots n$ remain constant with reference to ground potential;
- the voltages across all capacitors are of d.c. type, the magnitude of which is $2V_{\max}$ across each capacitor stage, except the capacitor C'_n which is stressed with $V_{\max}$ only;
- every rectifier $D_1, D'_1 \ldots D_n, D'_n$ is stressed with $2V_{\max}$ or twice a.c. peak voltage; and
- the h.v. output will reach a maximum voltage of $2nV_{\max}$.

$$\delta V = \frac{I}{fC} \times \frac{n(n+1)}{4}.$$

$$n_{\text{opt}} = \sqrt{\frac{V_{\max} f C}{I}}$$

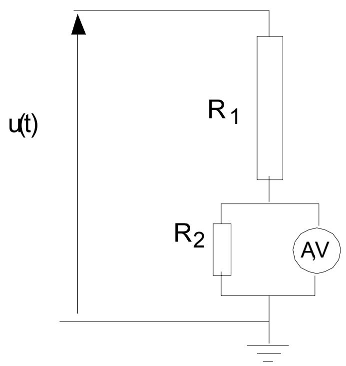
$$\Delta V_0 = \frac{1}{fC}\left(\frac{2n^3}{3} - \frac{n}{6}\right)$$



Current I ☺

Measurement of high DC-voltages

Measurement with HV-resistors



- Problems
    - Loading of the voltage source
    - Heating of the HV measuring resistor ⇒ temperature variation
    - Therefore; measuring current app. 1 mA ⇒ bad signal to noise ratio

    - R2 is used to change the measuring range
    - Useable instruments:
    - Sensitive moving coil instrument for current measurement.
    - Voltmeter with large internal impedance, which measures the voltage across R2 or oscilloscope.

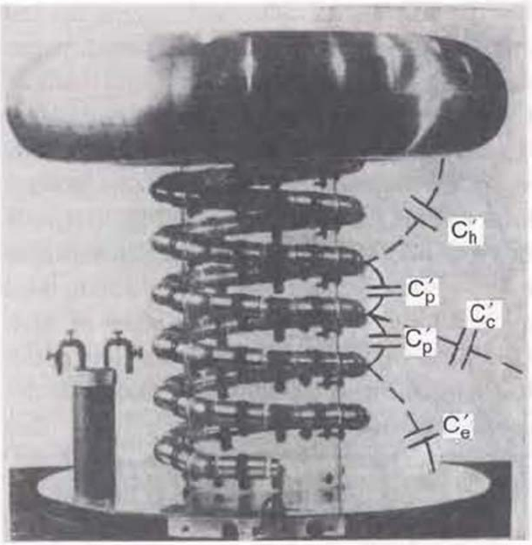


Figure 3.5 *100-MΩ, 100-kV standard resistor according to Park*[32]

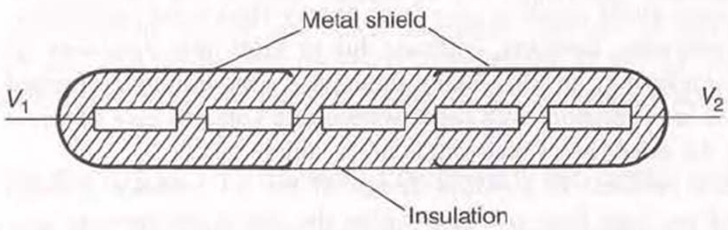


Figure 3.6 *Sketch of cross-section of an h.v. resistor element*

Very accurate control of electric potential distribution achieved by use of HV resistor elements in a helix-wound shape.

Corona should be avoided because of leakage current