Earth fault hazard voltages and their limitation

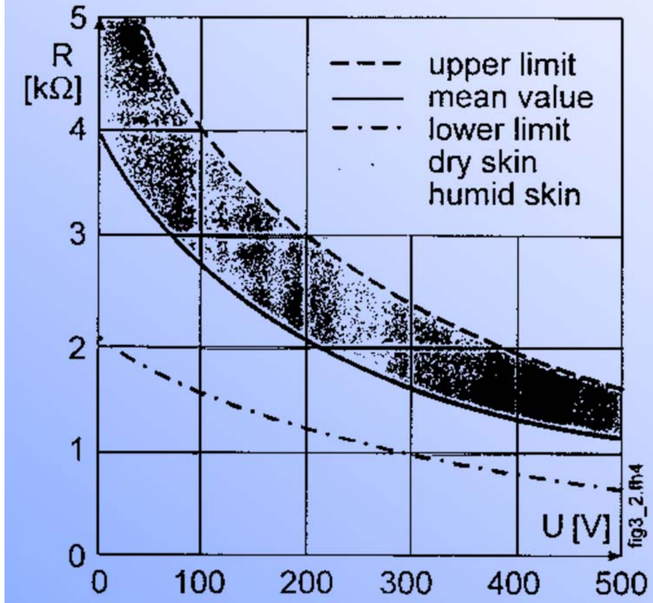
The effect of electricity on human body

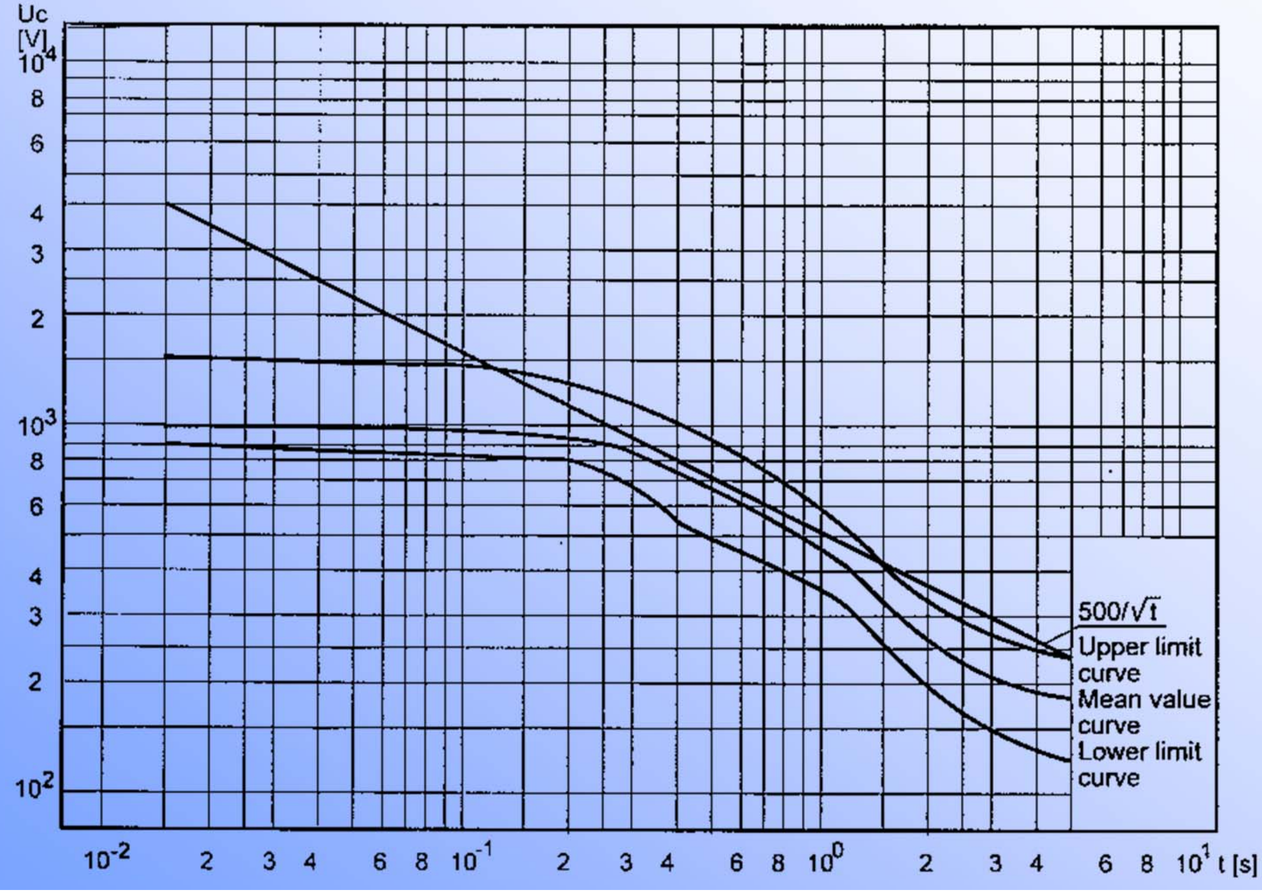
- combustion
- chemical changes in blood
- heart fibrillation

Currents corresponding to 10% and 1% probabilities of heart fibrillation, when the current coincides with the dangerous quarter of pumping cycle.

Duration t/s	$I_{10\%}$ / mA	$I_{1\%}$ / mA
> 5	60	40
5	80	50
2	150	80
1	400	150
0,75	500	200
0,5	700	300
0,3	1000	500
0,15	1150	650

The resistance of a human body

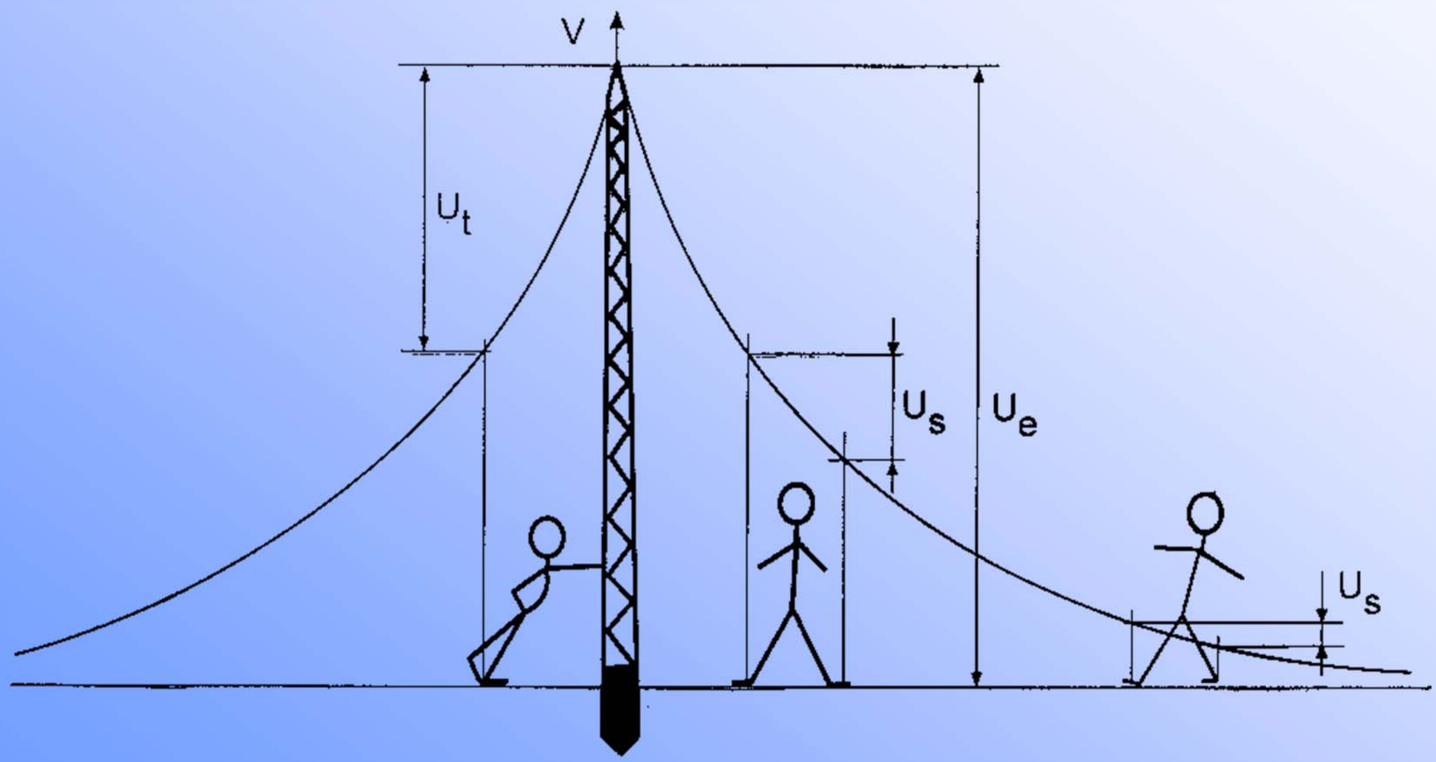




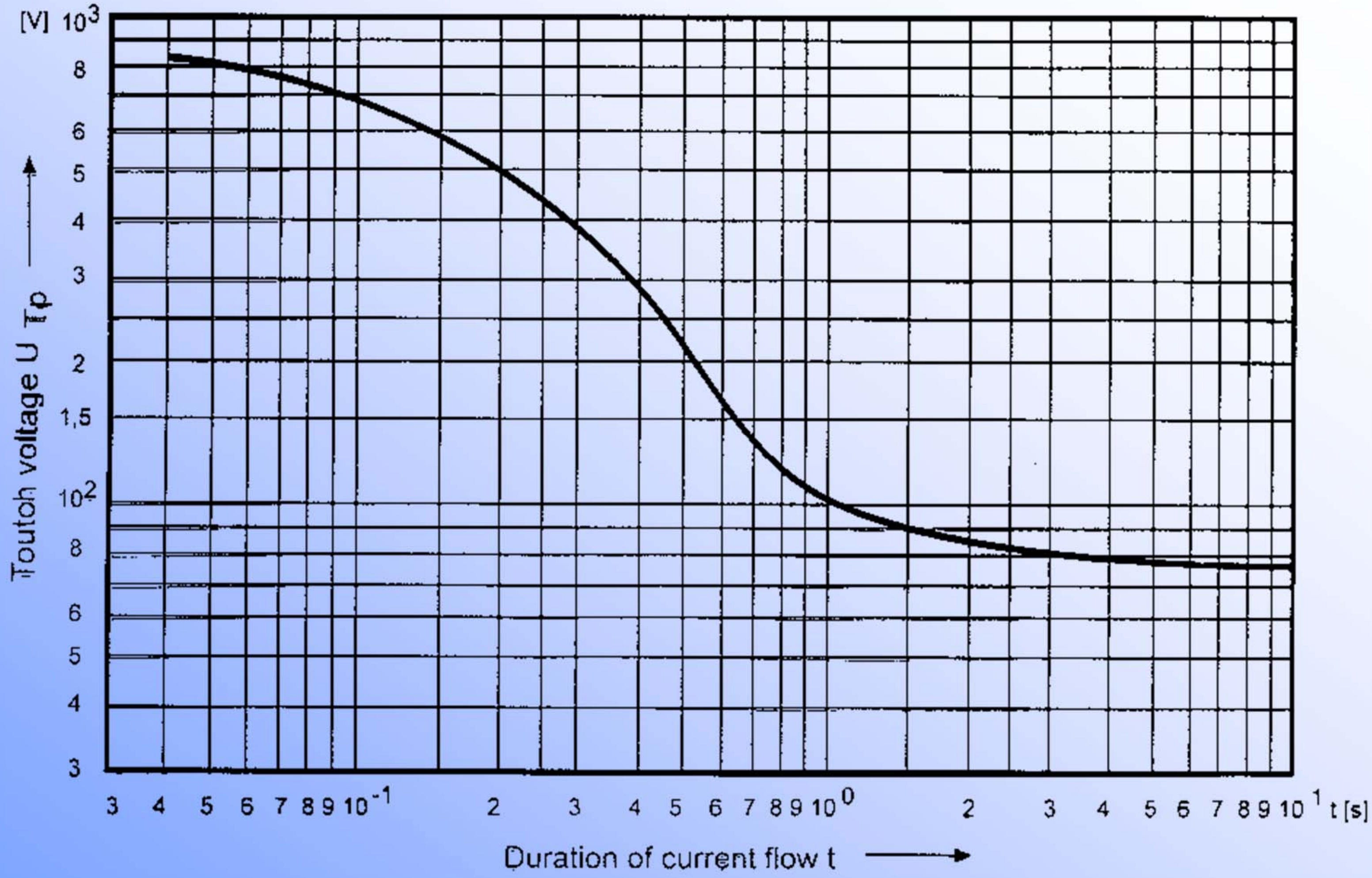
Voltages corresponding to the 10 % heart fibrillation probability as a function of stress duration.

Earth voltages versus touch voltages

- **touch voltage**
- **step voltage**
- only part of **earth voltage** is hazard voltage



Earth surface potential caused by an earth fault (V) and the corresponding touch voltage (U_t), and step voltage (U_s).



Maximum allowed touch voltages according to CENELEC

THE GROUNDING IS ACCEPTABLE, IF:

1) Global earth: city areas where grounding electrodes are connected
2) Earth voltage < 2 x maximum touch voltage
3) Earth voltage < 4 x maximum touch voltage & potential grading electrode
4) It is shown by measurements or calculations that the touch voltage limits are met

How to reduce touch voltages

Earth voltage:

$$\mathbf{U_e = I_{ef} R_e}$$

I_{ef} = earth fault current

R_e = grounding resistance

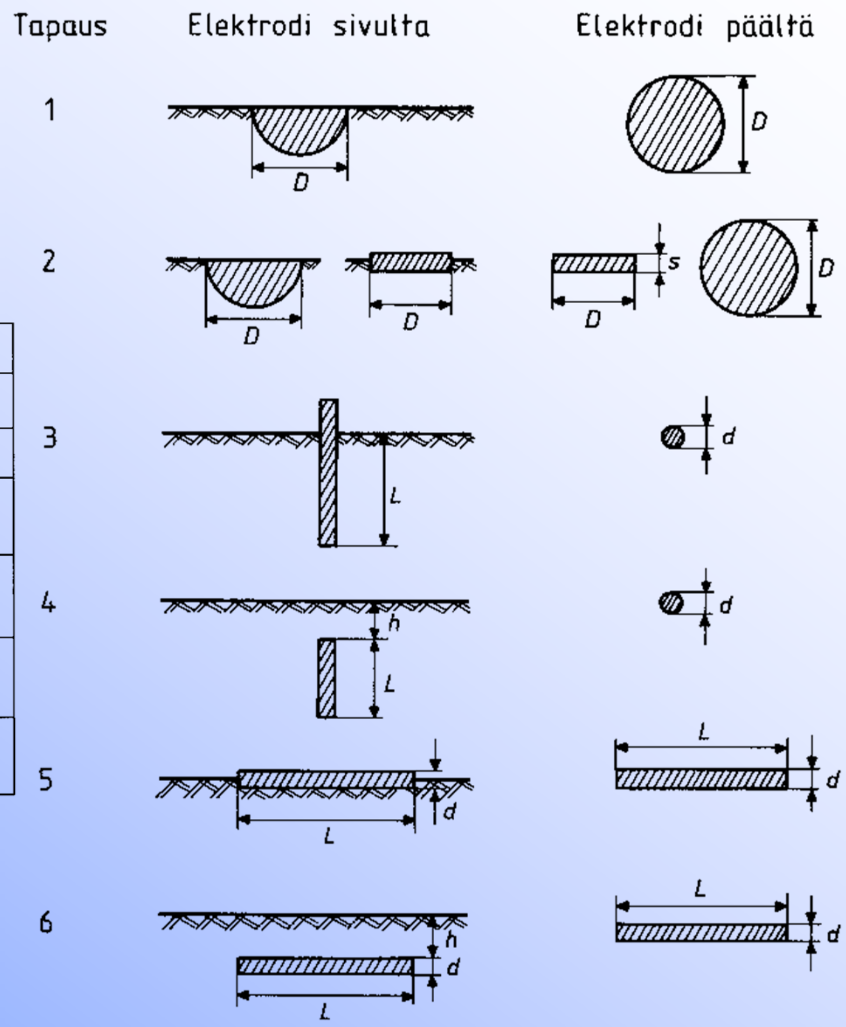
1) larger grounding electrodes (smaller Re)
2) reduction of the fault current
   - divide network into parts, compensation
3) reducing fault time by relay setting

Computation of the grounding resistance

- soil specific resistivity ρ
- typical value in Finland ρ = 2300 Ωm

Some earthing electrodes

N:o	Tapaus	Kaava	Huom.
1	Pallo pinnassa	$R = \rho / \pi D$	
2	Levy pinnassa	$R = \rho / 2\ D$	$s << D$
3	Pystysuora tanko tai putki pinnassa	$R = \frac{\rho}{2 \pi L} \ln \frac{4\ L}{1{,}36\ d}$	$d << L$
4	Pystysuora tanko tai putki upotettuna	$R = \frac{\rho}{2 \pi L} \ln \frac{4\ L}{1{,}36\ d} \cdot \frac{2\ h + L}{4\ h + L}$	$d << L$
5	Suora johdin pinnassa	$R = \frac{\rho}{\pi L} \ln \frac{2\ L}{1{,}36\ d}$	$d << L$
6	Suora johdin upotettuna	$R = \frac{\rho}{2 \pi L} \ln \frac{L^2}{1{,}85\ hd}$	$d << 4h$



Some earthing electrodes

Example: Earthing resistance of a 50 m rod

- straight conductor 50 m
- in 0,7 m depth
- soil resistivity ρ = 2300 Ωm
- 16° copper wire $\Rightarrow$ d $\approx$ 4,5 mm

$$R = \frac{\rho}{2\pi L} \ln \frac{L^2}{1{,}85hd}$$

$$= \frac{2300}{2\pi \cdot 50} \ln \frac{50^2}{1{,}85 \cdot 0{,}7 \cdot 0{,}0045} \ \Omega$$

$$= \underline{\underline{95\,\Omega}}$$

Example: Earth fault current = 20 A

earth voltage $U_e = I_{ef} R_e$ = 20 A· 95 Ω = 1900 V

base case: touch voltage = 1/2 U_m = 950 V $\Leftrightarrow$ not allowed !

with potential grading: touch voltage = 1/4 U_m

- U_T = 1/4 U_m = 475 V $\Leftrightarrow$ max. duration 0,2 s

If the CB operation takes 100 ms, the relay must trip in 0.1 s

Example

- MV substation with 300 km of 20 kV overhead line
  - $c_0 \approx 6$ nf / km
  - $\rho = 2300\ \Omega$/m
  - protection set to trip in 0,4 s
  - grounding electrode 16 mm^2 Cu in 0,7 m depth

How long electrode must be ?

Network earth capacitance $C_0 = c_0 \cdot l = 1{,}8\ \mu F$

Earth fault current in unearthed system case:

$$I_{ef} = \sqrt{3}\,U\omega C_0 \quad , \text{ when } R_f = 0\ \Omega$$

$$I_{ef} = \sqrt{3} \cdot 21 \cdot 10^3 \cdot 2\pi \cdot 50 \cdot 1{,}8 \cdot 10^{-6}\ A \cong \underline{\underline{20{,}6\ A}}$$

t = 0,4 s $\Leftrightarrow$ max allowed touch voltage $U_{Tp} \approx 280$ V

base case: max allowed earthing voltage:

$$U_m = 2 \cdot U_{Tp} = \underline{560\ V}$$

→

Example continued...

$$U_e = R_e\, I_{ef} \;\Rightarrow\; R_e = \frac{U_e}{I_{ef}} = \frac{560\ \text{V}}{20{,}6\ \text{A}} \cong 27\,\Omega$$

The resistance of the grounding electrode is computed as:

$$R_e = \frac{\rho}{2\pi L} \ln \frac{L^2}{1{,}85hd} \left\{ \begin{array}{lcl} \rho & = & 2300\ \Omega\text{m} \\ \text{h} & = & 0{,}7\ \text{m} \\ \text{d} & = & 0{,}0045\ \text{m}\ \ (16\ mm^2) \end{array} \right.$$

⇒

L/m	R_e/Ω
100	52,5
200	28,8
<u>215</u>	<u>27,05</u>

⇒ <u>215 m</u>

In the case of potential grading electrodes: :

$$\Rightarrow \max\ U_e = 4 \cdot U_{Tp} = 1120\ \text{V}$$

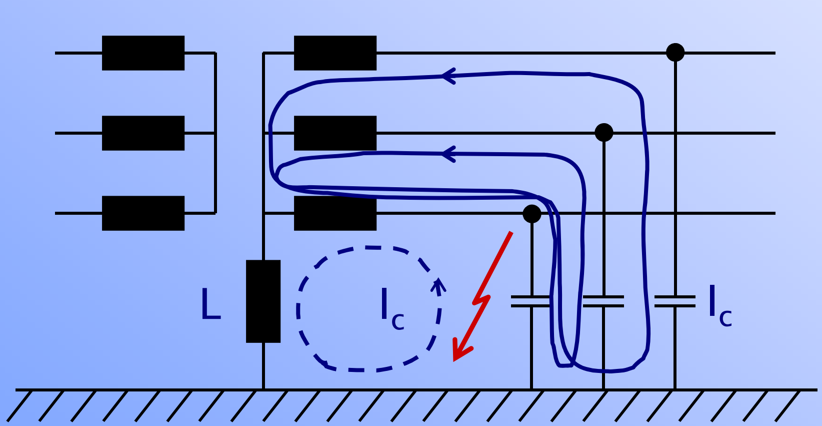
$$\Rightarrow R_e = \frac{U_e}{I_{ef}} \cong 54\,\Omega \quad \hat{=}\ \underline{\underline{97\ \text{m}}}$$

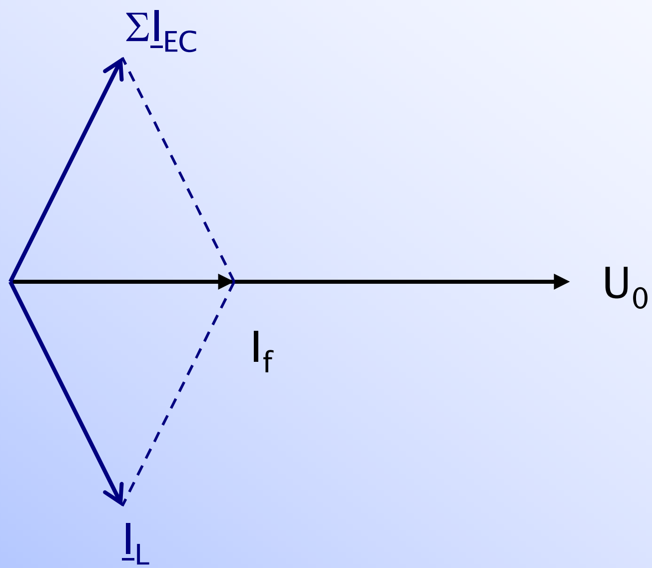
→

MEANS TO LIMIT THE TOUCH POTENTIALS

- reduction of grounding resistance
- reduction of earth fault current
    - dividing the network into parts
    - earth fault current compensation

Compensation :





- coil L is usually tuned so that its current is 95% of the capacitive current

- resistive leakage current is typically 5 - 8 % of the capacitive current

Example

Fault current of the previous example after compensation:

$$I_x = I_c\,(1 - 0{,}95) = 20{,}6 \cdot 0{,}05\,\mathrm{A} \cong 1{,}03\,\mathrm{A}$$

$$I_r = 8\,\% \;;\; I_r = 0{,}08 \cdot 20{,}6\,\mathrm{A} \cong 1{,}65\,\mathrm{A}$$

Total fault current:

$$I = \sqrt{I_r^{\,2} + I_x^{\,2}} \cong 1{,}94\,\mathrm{A}$$

Base case: U_e = 560 V

$\Rightarrow$ R_e = 288 Ω

$\Rightarrow$ L = 13 m ! (electrode length)

<u>Sustained operation of the network with an earth fault</u>

CENELEC : allowed, if $U_{Tp} \leq 75$ V

$\Rightarrow$ $U_e = 2 \cdot U_{Tp} = 150$ V (base case)

In compensated neutral case : $I_{ef} \approx 1.94$ A

$$\Rightarrow R_e = \frac{U_e}{I_{ef}} = \frac{150\,\mathrm{V}}{1.94\,\mathrm{A}} \cong 77.3\,\Omega$$

Earthings

System earthing

- a part of the power system is connected to earth
- e.g. the earthing of low voltage network neutral
- the aim is to limit the phase to earth voltages

Equipment (or protective) earthing

- a normally dead metallic part is connected to earth
- e.g. metallic body of a piece of electrical equipment
- the aim is to prevent hazardous touch voltages

Temporary earthing

- protective earthing used when working on power system components

Connection of the MV equipment earth and the LV system earth

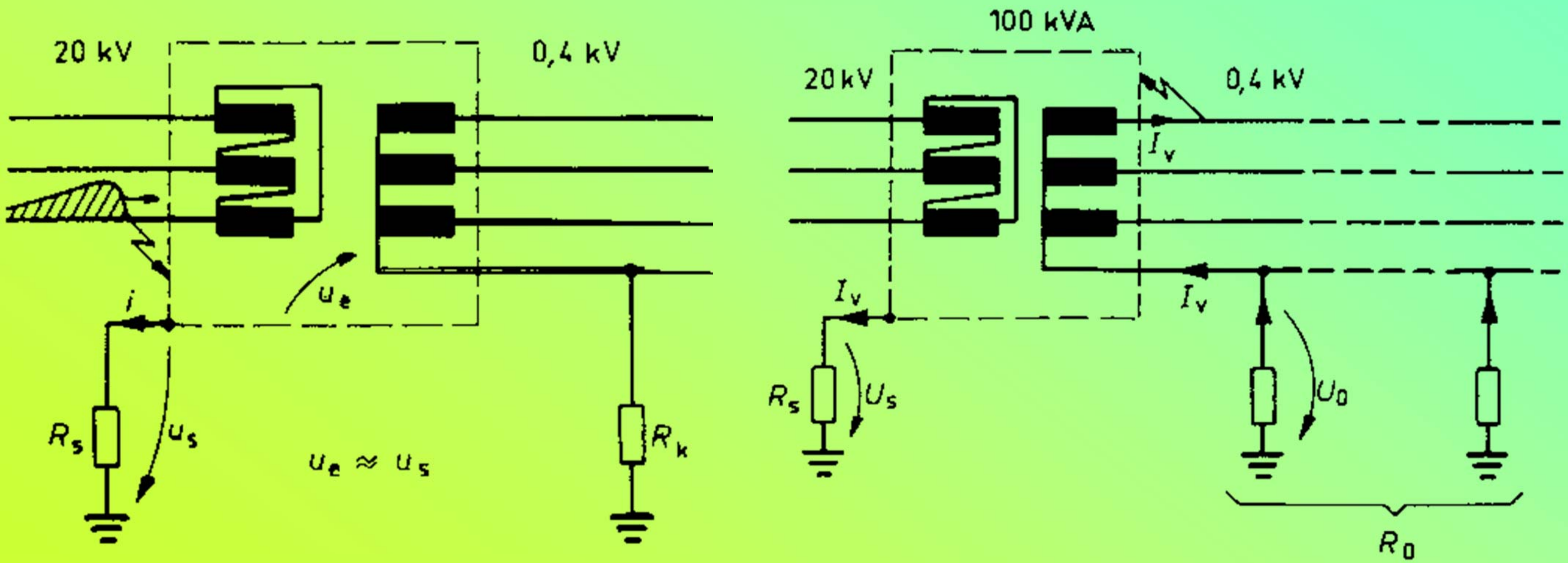
Separate earthings :

- a MV fault causes high stress between tank and LV-winding
- a fault between LV winding and tank causes a hazardous voltage (> 110 V)

Connected earthings:

- the voltage of MV faults spreads in LV system over the 0-conductor

The earthings must be connected if it is difficult to make sure that they will remain isolated from each other (urban areas).



Earthings in tower footings

- the aim is to reduce the lightning voltages in the tower and shielding wires $\Rightarrow$ number of back flashovers reduced
- the decrease in earthing resistances increases earth fault currents and improves the sensitivity of earth fault protection

Compare distance relay: $X = 0{,}3 - 0{,}4\ \Omega/\text{km}$

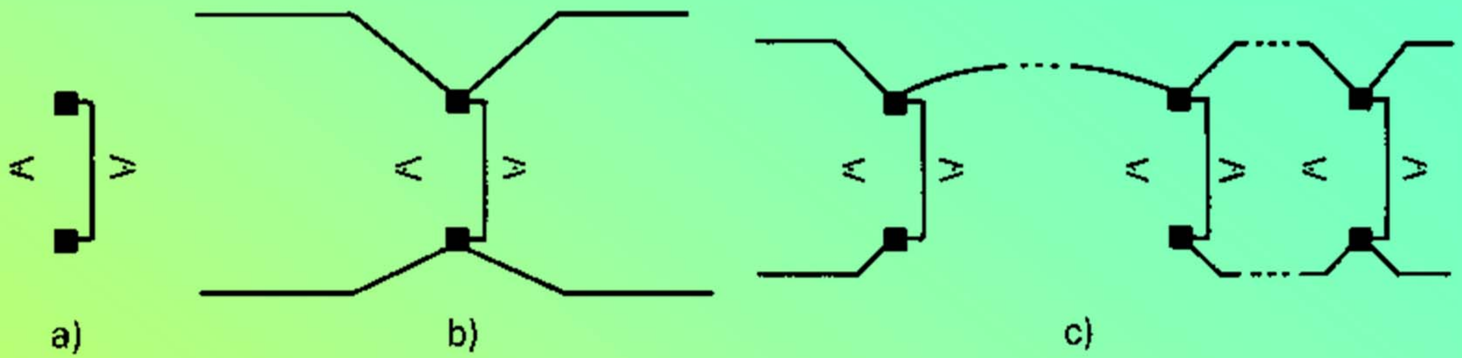
- an important goal also is to reduce the touch potentials of towers

Example: a 110 kV line

- 60 Ω tower footing earthing ; $U_m \approx 50$ kV
- with shield wires & additional earth electrodes

  $\Rightarrow R_m < 1\ \Omega \Rightarrow U_m$ in accepted limits
- Note: the screening effect of earth wires: the earth fault current in soil is reduced by about 50-60 %

Tower basic and additional earthing



a) basic, b) radial earthing, c) continuous counterpouse

Examples of a 110 kV transmission line earthings

shield wires	ρ Ωm	z_u Ω/km	no additional earth. [1]		additional earthing	
			R_p/Ω	Z_e/Ω	R_p/Ω	Z_e/Ω
2 x 35 St	500	3,3	60	3,1	15	1,6
	2300	3,3	200	5,7	32	2,3
	10000	3,3	550	9,5	50	2,9
2 x Imatra	500	0,60	60	1,3	15	0,7
	2300	0,65	200	2,5	32	1,0
	10000	0,70	550	4,4	50	1,3

Z_u = impedance of the shielding wire
R_p = footing earthings solely
Z_e = the effect of shielding wires included

Tower basic and additional earthing

The chain of tower footings and shielding wires

$$Z_k = \sqrt{R_p \cdot Z_u} \qquad (1)$$

R_p = the resistance of tower footing Ω

Z_u = the impedance of shielding wire (2-3 Ω/km)

(the length between two towers)

In the middle of the line $Z_e = 0{,}5\ Z_k$ (2 directions)

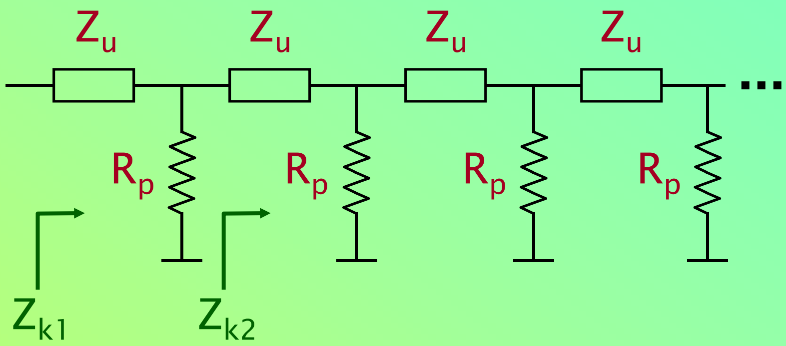
Example: $R_p = 60\ \Omega$ & $Z_u = 0{,}6\ \Omega$

$\Rightarrow$ $Z_k = 6\ \Omega$

$Z_e = 3\ \Omega$

Tower basic and additional earthing

The derivation of equation (1):



$$Z_k = \sqrt{R_p\, Z_u} \quad ?$$

An infinite chain : $Z_{k1} = Z_{k2} = Z_k$

$$\Rightarrow \quad Z_{k1} = Z_u + \frac{R_p \cdot Z_{k2}}{R_p + Z_{k2}}$$

$$\Rightarrow \quad Z_k = Z_u + \frac{R_p \cdot Z_k}{R_p + Z_k} \quad \Big| \cdot (R_p + Z_k)$$

$$\Rightarrow \quad Z_k (R_p + Z_k) = Z_u (R_p + Z_k) + R_p \cdot Z_k$$

$$\Rightarrow \quad \cancel{Z_k R_p} + Z_k^{\,2} = Z_u R_p + Z_u Z_k + \cancel{R_p Z_k}$$

$$\Rightarrow \quad Z_k^{\,2} = Z_u R_p + Z_u Z_k \approx Z_u R_p \quad (R_p >> Z_k)$$

$$\Rightarrow \quad \underline{\underline{Z_k = \sqrt{Z_u R_p}}}$$

Electrical injuries

<u>The number of deaths due to electrical accidents in Nordic countries in average</u>

90´s	0,6 - 0,9 / mill.people, yr
80´s	1,0 - 1,5 / - -
70´s	1,6 - 2,1 / - -
60´s	2,3 - 3,3 / - -

The number of deaths due to electricity 1994-1997

Year	Number of deaths (persons)	Deaths because of faulty equipment (persons)	The use of electricity (GWh)
1994	2	1(0)	68258
1995	4	0(1)	68946
1996	4	1(1)	70018
1997	3	0(1)	73536
sum	13	2(3)	

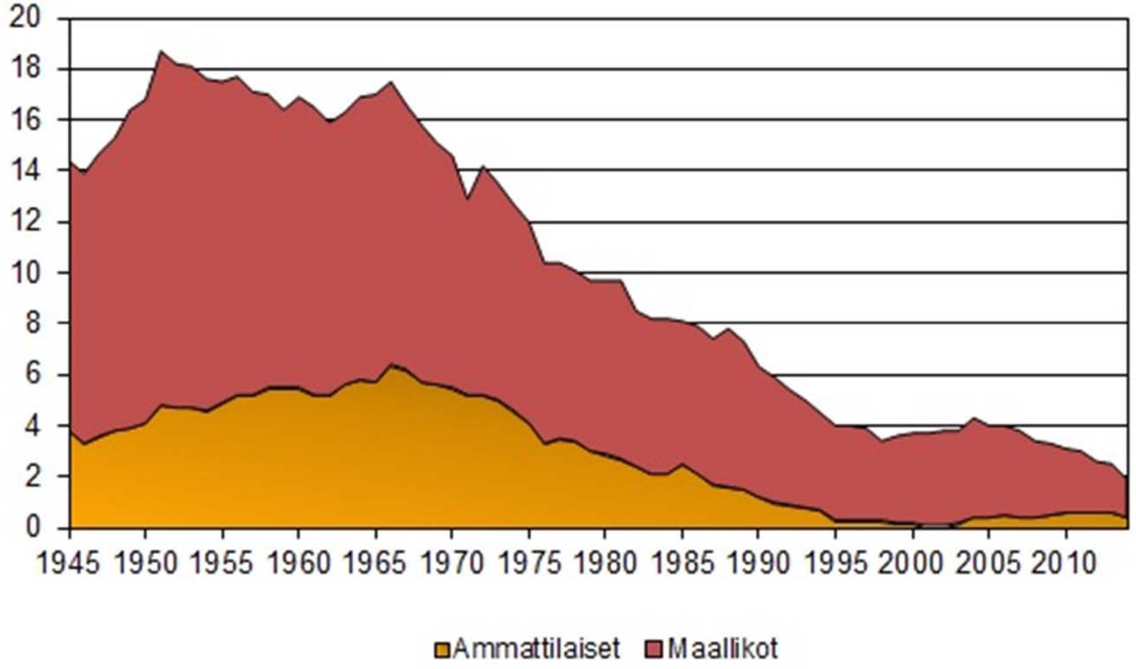
The number of deaths in electrical injuries in Finland 1980-1986

	80	81	82	83	84	85	86
High voltage	2	3	4	3	3	7	1
Low voltage	12	4	5	5	4	2	3
Electrical technician	3	3	1	1	1	4	0
Trainee or student	1	0	0	3	0	0	1
Common people	10	4	8	4	6	5	1
Equipment not allowed by security code	6	1	4	2	2	1	1
Faulty equipment or installation	0	2	0	0	0	0	0
The cause of victim 1)	8	1	3	5	4	8	2
Other cause 2)	0	3	2	1	1	0	1
SUM	14	7	9	8	7	9	4

1) uncarefulness, play, public disobeyance

2) inadequate guidance, third party, unknown

Number of deaths in electrical injuries in 1945-2014



Professionals and commoners

Electrical injuries in Finland 2011-2015

Year	2011	2012	2013	2014	2015
Electric shock					
- Professionals - Commoners	28 47	41 42	28 56	27 48	39 64
Electric arc					
- Professionals - Commoners	9 4	13 5	9 2	5 3	8 4
Injuries	88	101	95	82	115
Deaths	2	1	3	3	3

Fires caused by electrical phenomena

Causes :

- misuse of electrical equipment

- short circuit and earth fault

- loose connections

- overload

- static electricity

- lightning

About 40 % of fires are caused by electricity !

Fires caused by electricity in Sweden in years 1974-1982

CAUSE	number	
	pcs	%
flash over, short circuit	383	13,2
Faulty component	351	12,1
misuse of heating equipment	219	7,6
mechanical, chemical or thermal fault	205	7,1
covering the heating equipment	180	6,2
Loose contact	117	4,0
erroneous operation or use	59	2,0
spark igniting gas	55	1,9
spike in cable	49	1,7
overload, oversized fuses	39	1,3
other causes	265	9,3
not known	979	33,8
sum	2901	100,0

Electrical fires and deaths in Finland 2011-2015

Year	**2011**	**2012**	**2013**	**2014**	**2015**
Electric fires	592	570	530	562	497
Deaths in Electric fires	15	11	11	24	16
All deaths in fires	58	78	47	87	78

Electrical fires and causes in Finland 2011-2015

Year	2011	2012	2013	2014	2015
KITCHEN OVEN	1026	1020	1056	846	959
LAMP	162	190	233	213	238
SAUNA STOVE	35	75	156	79	132
ELECTRIC CENTER	104	93	128	91	89
WASHING MACHINE	108	109	95	100	63
ELECTRIC WIRES	113	116	83	106	88
MICROWAVE OVEN	81	73	69	75	73
OTHER ELECTRIC NTWK	87	78	67	75	71
PROCESS EQUIPMENT	143	135	66	151	128
COLD EQUIPMENT	82	55	64	61	56