Power Quality (PQ)

Power Quality (Standard EN 50160):

- frequency
- voltage level
- fast voltage fluctuation
- harmonic voltages
- unsymmetry
- signal voltages
- voltage dips
- interharmonic voltages
- operating frequency overvoltages
- transient overvoltages

Interruptions of supply

Frequency

Std 50160: limits for 10 second values:

- 95% in the band 50 Hz +/– 1% (49.5 … 50.5 Hz)
- all in the band 50 Hz +4/–6% (47 … 52 Hz)

In Nordic system usually between +/– 0.1 Hz

Voltage level

Std 50160: limits for 10 minute values
- 95% must be in the band U_n +/- 10%

Measurement for one complete week

In addition, all the 10 min values must be between -15 .. +10 %

In LV-system, according to association of utilities (sener):
- good quality: 10 min values between 220...240 V
- normal quality: 10 min values between 207...244 V
- standard quality: 10 min values between 207...253 V

In MV-system, according to association of utilities (sener):
- good quality: 10 min values between U_n +/- 4%
- normal quality: 10 min values between U_n +/- 10%
- standard quality: 10 min values between U_n +/- 10%

Voltage level is determined by voltage drop due to load current, on-load tap-changer, off-load tap-changer and compensation.

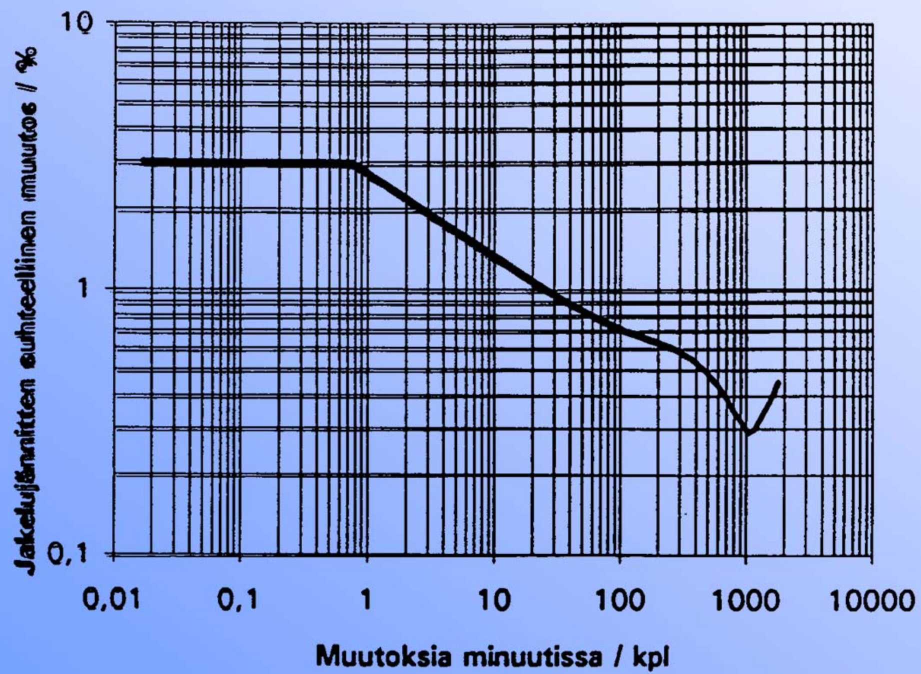
Fast voltage fluctuation (flicker)

Affects especially lighting and hence vision.
Also electronic equipment may be disturbed.

Fast voltage fluctuation is caused by,

- control of on-load tap-changer
- motor starting
- welding equipment

Limits according to CENELEC:



Voltage %-change / Changes per minute

Voltage unsymmetry

Std 50160: limits for 10 minute values:

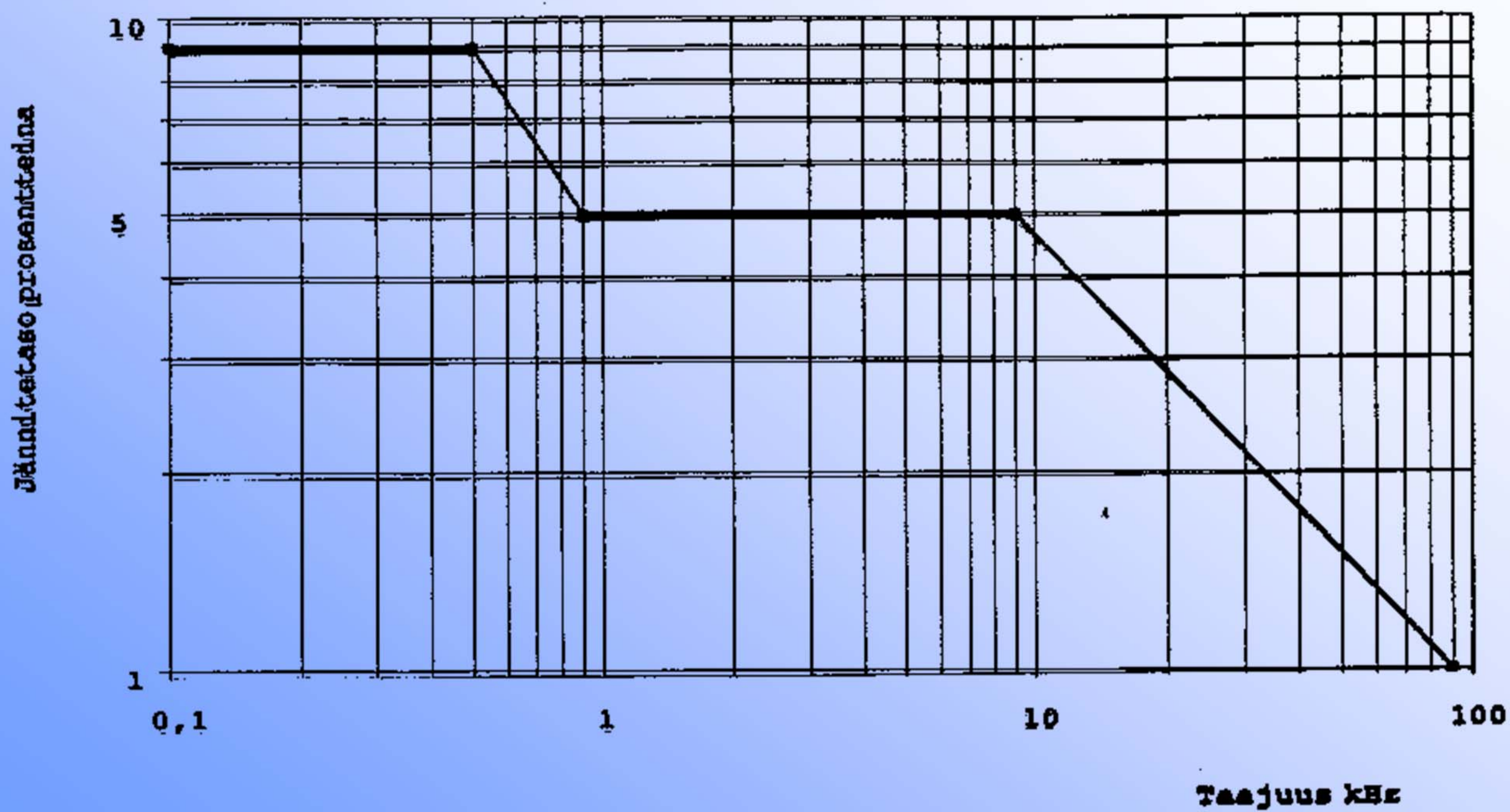
95% of the time the negative sequence component must be less than 2% of the positive sequence component.

Unsymmetry is caused by:

- uneven load between the three phases
- one-phase LV-faults (blown fuse)

Signal voltages

Std: Defined as 3 s values, measured in LV-connection point;
99% of the time the values must be equal or less than:



Signal voltages as % of nominal / Frequency kHz

Frequencies 95 kHz … 148.5 kHz may be used in customer installations

Voltage dips ($dU > 10\%$)

Mostly caused by faults. No limits given by standards.

Interharmonic voltages

Levels are increasing due to semiconductor technology development. No limits given by standards.

Operating frequency overvoltages

Caused mostly by faults. General limits for voltage levels used.

Transient overvoltages

Caused by faults and switching actions.

Harmonic voltages

Std 50160: limits for 10 minute mean values.
total harmonic distortion THD 8% at maximum

$$THD = \sqrt{\sum_{h=2}^{40} (U_h)^2}$$

Other harmonics:

Maximum allowed harmonics as % of the nominal voltage in LV-connection point. Limits given up to the order 25.

odd harmonics				even harmonics	
not multiple of 3		multiple of 3			
order n	voltage %/Un	order n	voltage %/Un	order n	voltage %/UN
5	6 %	3	5 %	2	2 %
7	5 %	9	1,5 %	4	1 %
11	3,5 %	15	0,5 %	6…24	0,5 %
13	3 %	21	0,5 %		
17	2 %				
19	1,5 %				
23	1,5 %				
25	1,5 %				

Harmonic currents by diode rectifiers

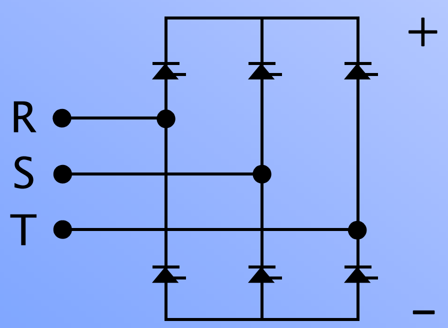
In an ideal case (a) the harmonics of the current are:

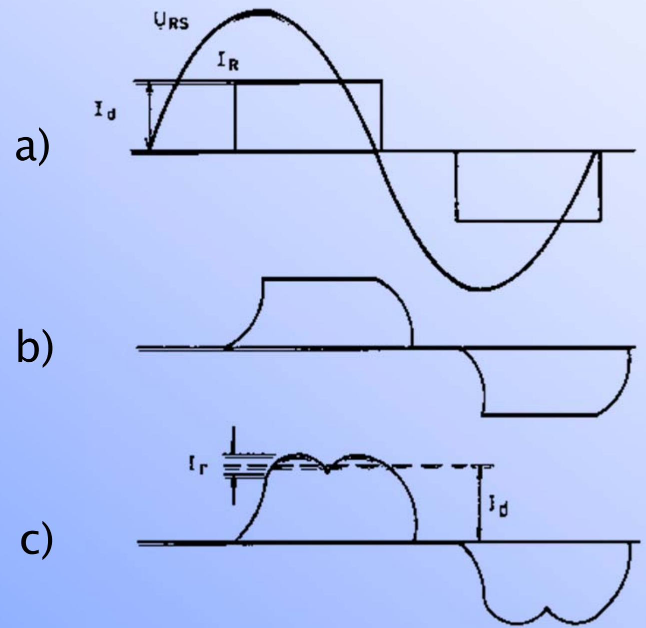
$I_n = I_1 / n$

n is the harmonic number

n = kp +/- 1 (k = 1,2,3,...), p is the pulse number

commutation (b) and ripple in DC-current (c) smooth the pulse edges, which makes the lower frequencies to increase and higher to decrease.





Maximum values for diode rectifiers

Harmonic order	I_n/I_1
5.	30%
7.	12%
11.	6%
13.	5%

For PWM-inverters, like solar and EV
switching frequency ≥ 2kHz ⇔
harmonics below 40 are minimal

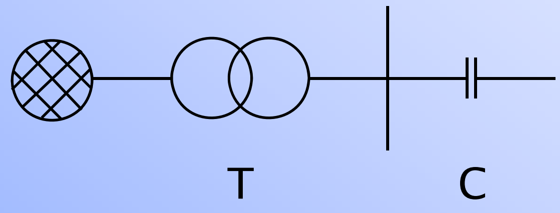
Other sources of harmonics:

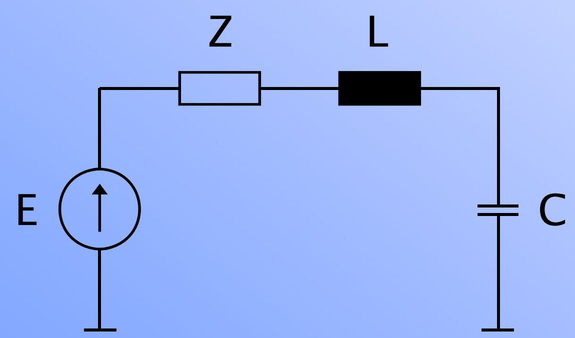
- discharge lamps
- power units of electronics

Harmonic series resonance

- Power system as a voltage source
- Transformer inductance and capacitor in series
- Low voltage distortion strongly amplified

Condition : $$2\pi f = \frac{1}{\sqrt{LC}}$$

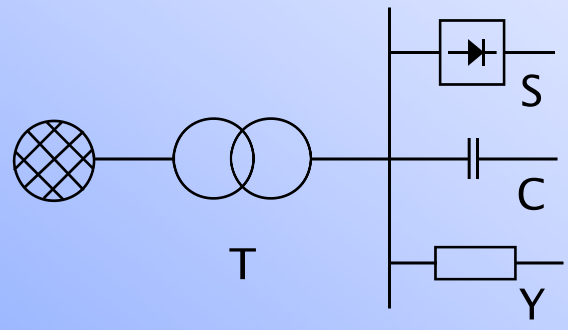


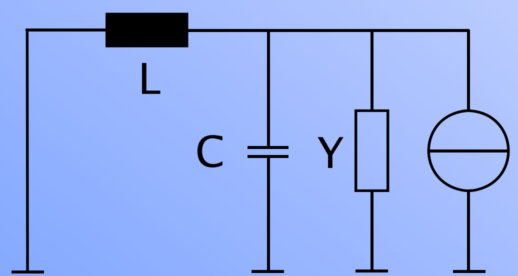


Harmonic parallel resonance

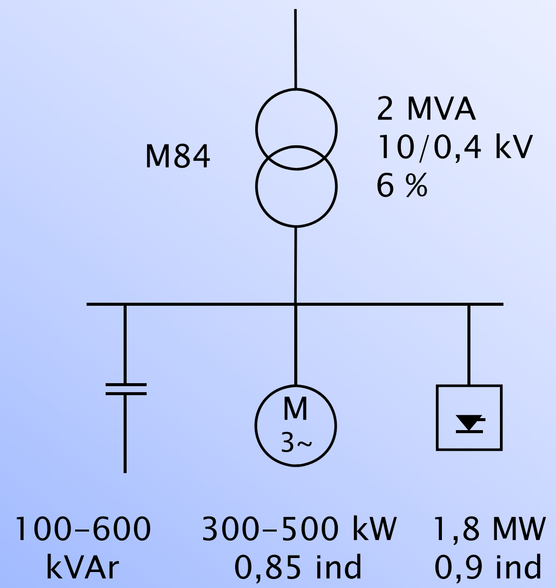
- More dangerous than series resonance
- Transformer load as harmonic current source
- Transformer inductance and capacitor in parallel
- Resistive load causes attenuation
- High risk of damage to the capacitor

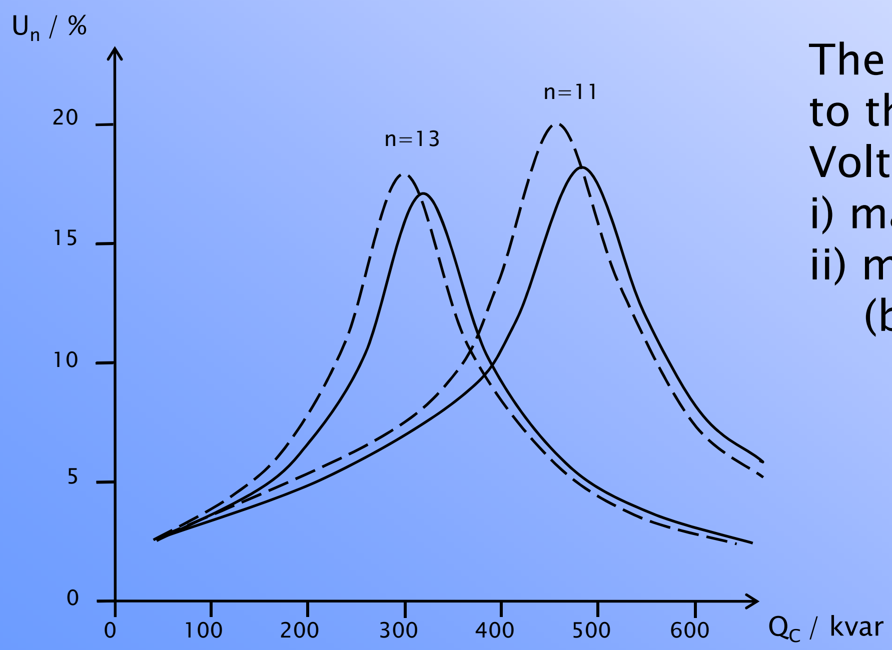
Condition : $2\pi f = \frac{1}{\sqrt{LC}}$





An example case: 0,4 kV
Motor control centre





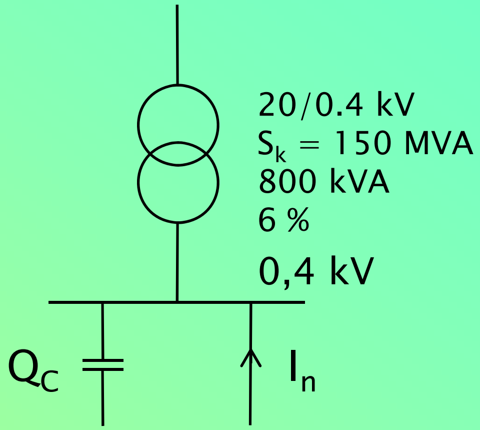
The effect of induction machine load to the 11. And 13. harmonic voltage. Voltages % of the rated voltage.
i) machine load 500 kW
ii) machine load 300 kW
(broken line)

Example: Parallel harmonic resonance and the dangerous ratings of a compensation capacitor in a secondary substation:

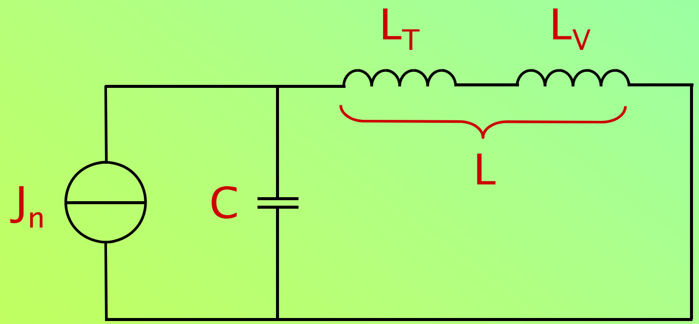
Harmonic currents I_n

$n = 5,7,11,13$

$Q_c = ?$ (resonance)



One-line diagram :



$$\omega_r = \frac{1}{\sqrt{LC}}$$

$$X_V = \omega\, L_V = \frac{U^2}{S_k} \quad \Rightarrow \quad L_V = \frac{U^2}{S_k \omega_1} = \frac{20^2}{150 \cdot 2\pi \cdot 50} H = 8{,}5\,\mathrm{mH}$$

$$X_T = \omega_1 L_T = u_x \frac{U^2}{S_N} \quad \Rightarrow \quad L_T = \frac{u_x U^2}{S_N \omega_1} = \frac{0{,}06 \cdot 20^2}{0{,}8 \cdot 2\pi \cdot 50} H = 95{,}5\,\mathrm{mH}$$

$$\Rightarrow \quad L = L_V + L_T = 104\,\mathrm{mH}\ \ (0.4/20)^2 = 41{,}6\,\mu H$$

→

Resonance condition : $\omega_r = \frac{1}{\sqrt{LC}}$

$$\Rightarrow \quad C = \frac{1}{\omega_r^2 \, L}$$

5. harmonic :

$$\omega_r = 5 \cdot 2\pi \cdot 50 \, \text{rad/s} = 1571 \, \text{rad/s}$$

$$\Rightarrow C = \frac{1}{1571^2 \cdot 0{,}0000416} \, \text{F} \approx \underline{\underline{9{,}74 \, m\text{F}}}$$

And the compensation rating Q_C :

$$\begin{cases} Q_C = 3 \, U_V \, I_C \\ I_C = U_V \, Y_C \end{cases}$$

$$\Rightarrow \quad Q_C = 3 \, U_V^2 \, Y_C = U_p^2 \, Y_C$$

$$= U_p^2 \omega_1 C$$

$$= 400^2 \cdot 2\pi \cdot 50 \cdot 9{,}74 \; 10^{-3} \; \text{VAr} = \underline{\underline{489 \; \text{kVAr}}}$$

→

Resonance point at different orders :

5. $C = 9{,}74\ m\mathrm{F} \qquad Q_C = 489\ \mathrm{kVAr}$

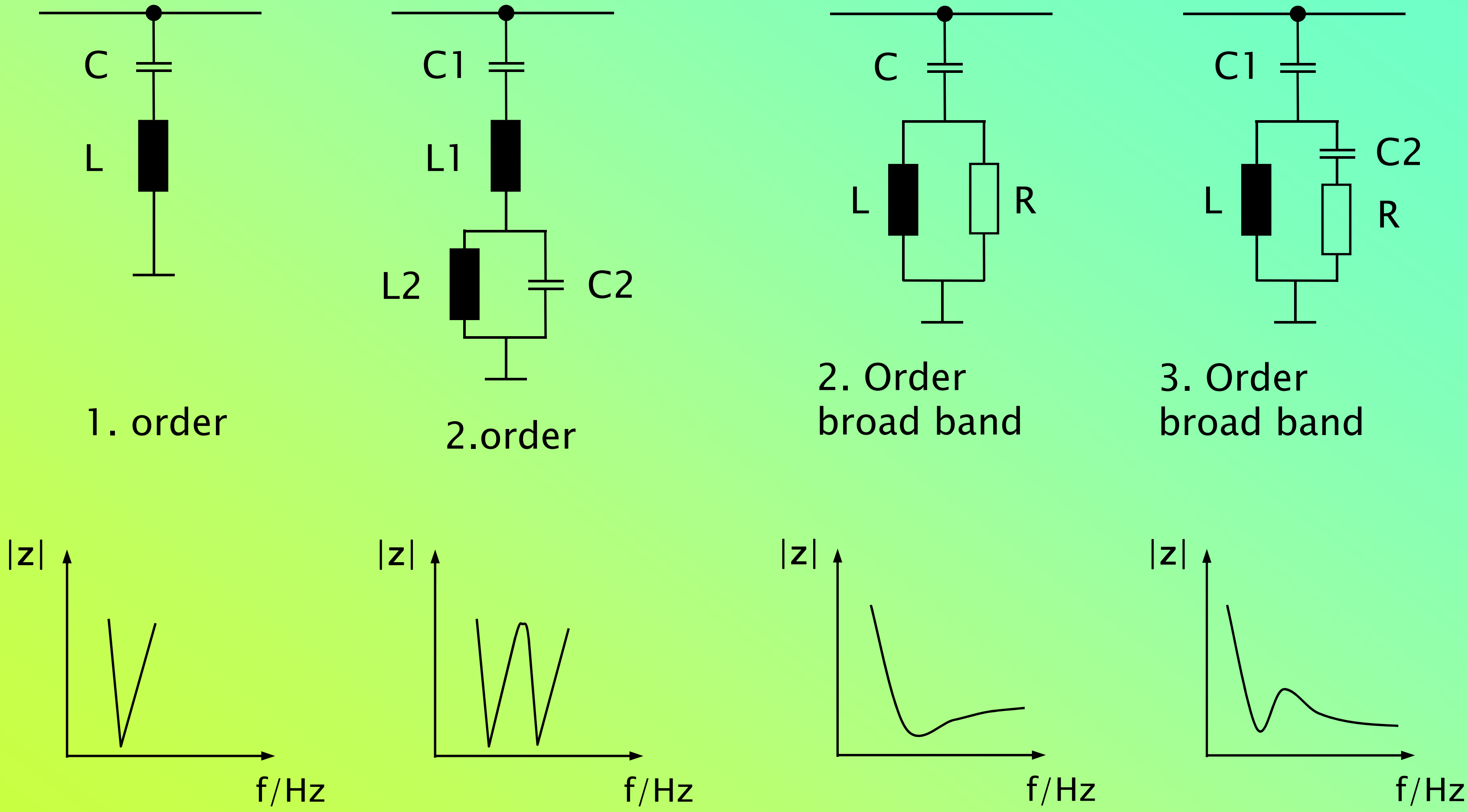
Other frequencies:

$$7.\quad C = \frac{1}{\omega_7{}^2\ L} = 4{,}96\ m\mathrm{F} \qquad Q_C = 250\ \mathrm{kVAr}$$

$$11.\quad C = \frac{1}{\omega_{11}{}^2\ L} = 2{,}01\ m\mathrm{F} \qquad Q_C = 101\ \mathrm{kVAr}$$

$$13.\quad C = \frac{1}{\omega_{13}{}^2\ L} = 1{,}44\ m\mathrm{F} \qquad Q_C = 72\ \mathrm{kVAr}$$

Different types of passive harmonic filters



Interruptions

- Planned interruptions vs. interruptions by faults
- Unexpected interruptions mostly by faults in MV-network
- In transmission, single fault causes no outage (n-1 criteria)
- Customers outage costs are a substantial factor

Typical Fault frequencies in Finnish transmission system

	Amount of faults (pcs / 100km,a)	Faults divided by cause (%)								
		Lightning	Other natural	External influence	Operation & maintenance	Technical equipment	Other	Unknown	1-phase faults	Permanent faults
400 kV lines	0.11	77.5	7.8	0.9	2.9	1.0	3.9	5.8	54.0	4.0
220 kV "	0.71	46.4	3.3	3.3	0.5	0.6	1.1	44.8	67.0	3.0
110 kV "	1.29	44.2	3.9	2.1	1.3	0.5	0.9	47.1	75.0	2.0

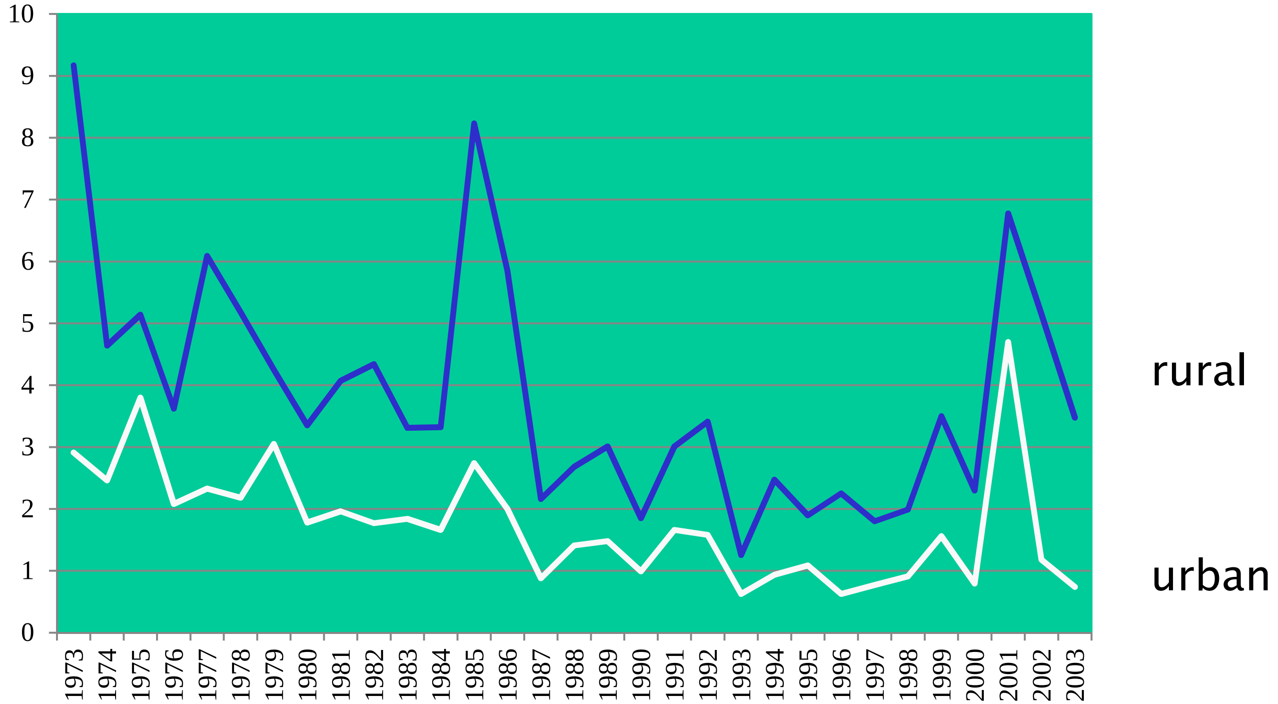
Reclosings

Fast reclosing	400 kV		220 kV		110 kV		sum	
	pcs	%	pcs	%	pcs	%	pcs	%
Succesful	13	87	5	83	177	82	195	81
Succesful in one end only	0	0	0	0	5	2	5	2
Failed due to a permanent fault	0	0	0	0	9	4	9	4
Failed due other reasons	2	13	1	17	27	12	30	13
Sum	15	100	6	100	218	100	239	100

Annual average outages if MV-distribution networks classified by fault reasons. Faults / 100 km of line

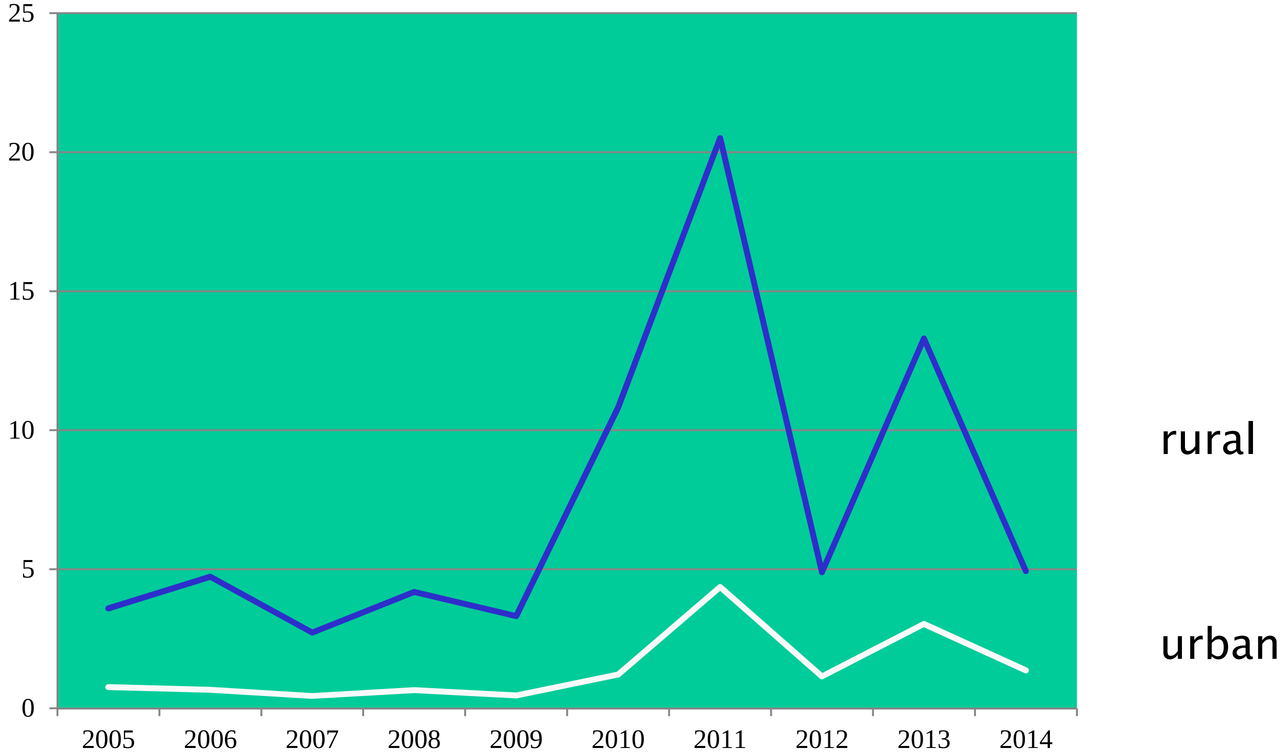
FAULT CAUSE	BARE CONDUCTOR OVERHEAD LINES	COVERED CONDUCTOR OVERHEAD LINES	AERIAL CABLES	GROUND CABLES
NATURE	3,39	0,24	0,07	0,10
- Wind and storm	2,38	0,19	0,07	0,01
- Snow and ice	0,53	0,05	0,05	0,00
- Lightnings	0,29	0,03	0,08	0,05
- Other weather	0,20	0,01	0,01	0,20
- animals	0,18	0,07	0,00	0,03
Technical cause	0,54	0,04	0,11	0,33
- Mechanical cause	0,39	0,03	0,12	0,24
- misoperation	0,19	0,03	0,02	0,15
others	0,84	0,04	0,02	0,38
- Public misbehavior	0,30	0,02	0,01	0,29
- unknown	0,51	0,02	0,04	0,13
SUM	4,77	0,32	0,36	0,81

Outage times in urban & rural network hrs/a in years 1973…2003



Energiateollisuus 2015

Outage times in urban & rural network hrs/a in years1973…2003
2005…2014



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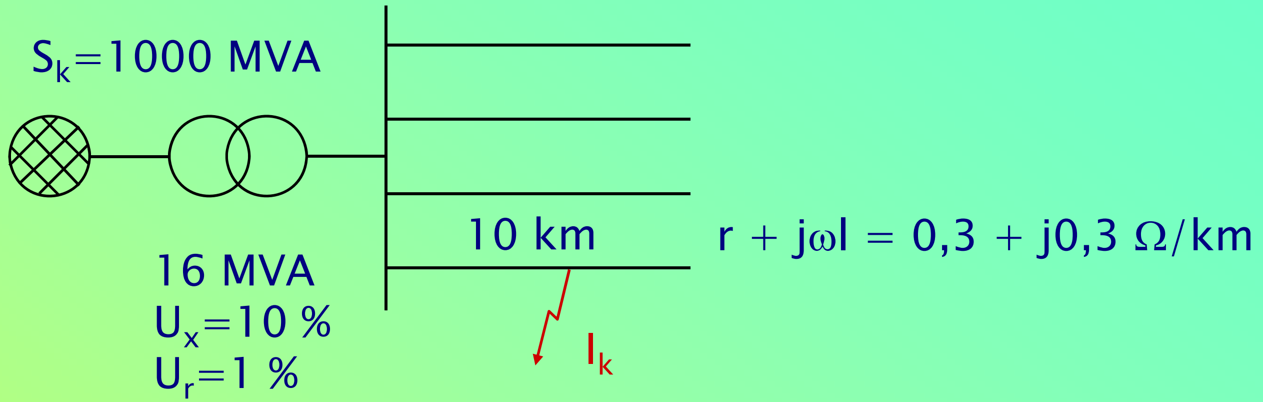
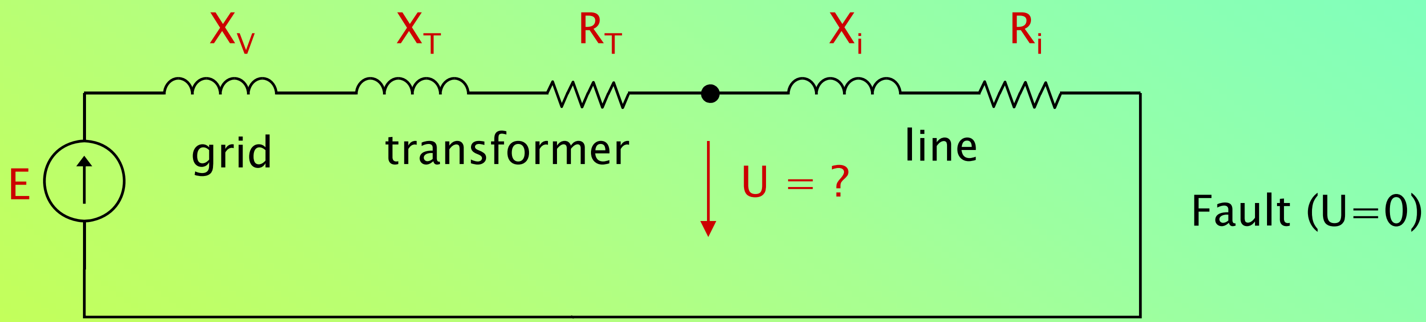
Example: voltage dip

3-phase short circuit at a MV-line 10 km from substation



ΔU in 20 kV busbar ?



$$X_V = \frac{U^2}{S_k} = 0{,}4\,\Omega$$

$$X_T = u_x \frac{U^2}{S_N} = 2{,}5\,\Omega \; ; \; R_T = u_r \frac{U^2}{S_N} = 0{,}25\,\Omega$$

$$X_j = 10\,\text{km} \cdot 0{,}3\,\Omega/\text{km} = 3\,\Omega \; ; \; R_j = 3\,\Omega$$

$$\underline{U} = \frac{R_j + jX_j}{(R_T + R_j) + j(X_V + X_T + X_j)} \underline{E} = \frac{3 + j3}{3{,}25 + j5{,}9} \underline{E}$$

$$\Rightarrow \quad U = 0{,}63\,E$$

$$\Delta U = 37\,\%$$

CUSTOMERS OUTAGE COSTS

IN DISTRIBUTION SYSTEMS

INQUIRY FORMS

- Four pages: Folded A3, with four A4 pages
  - page 1: Letter signed by the power company
  - page 2-4: questions to the customers
- Residential customers, Summer houses, Agriculture, Service sector, Public sector, Industry
- Network companies selected the customers included
- The forms were sent by mail: responses either by mail or Internet. Big customers (Service, Public, Industry) also by telephone interview

Inquiry Forms

- Background questions
  - For example: type of space heating, sector of business etc.
- Outage cost assessment
  - All customer categories: direct costing questions
    - Example: costs of an unexpected 1 hour outage, in winter time, ordinary week day, morning between 5 and 10 hrs ?.
    - Expected / unexpected outages
    - Outages in different times and seasons
    - Outages during / ouside working hours
  - For residential, summer house and agriculture, also WTA and WTP methods were user (willingness to accept / pay), for households also price-elasticity method
- Free comments

Results: Households €/kW

Outage length:	2min	1 hr	12hrs	36hrs
Direct costing:				
With electric heat	0.5	3.2	23.9	74.0
No electric heating	1.0	10.3	98.4	299.0
Average	0.7	6.5	54.9	163.7

WTA/1 hr: 10.1 €/kW

WTP/1hr: 1.0 €/kW

Price elasticity/1 hr: 2.1 €/kW

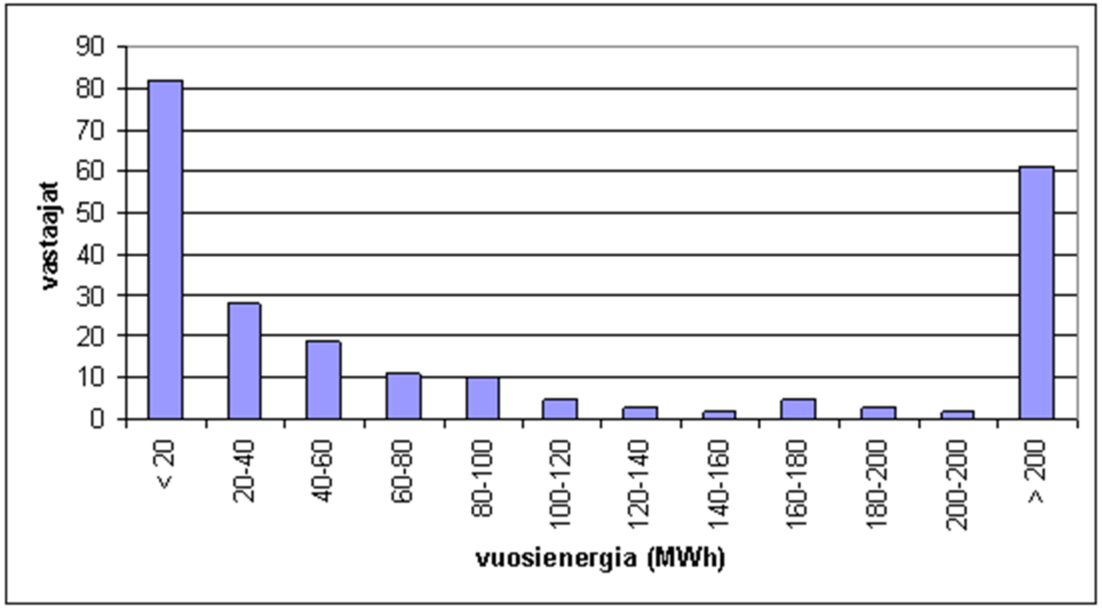
Results: Summer houses €/kW

Outage length:	2min	1 hr	12hrs	36hrs
Direct costing:				
With electric heat	0.3	33.9	91.5	297.1
No electric heating	8.6	25.3	49.4	74.6
Average	4.7	24.3	75.3	172.3

Agriculture €/kW

Outage length	2min	1hr	4hrs	12hrs	36hrs
Cornfields	1.0	14.0	33.5	121	299
Green houses	-	140	140	-	7384
Milk production	0.1	2.1	11.5	45.2	182
Beef production	3.0	154	143	182	131
Pig houses	0.0	135	130	301	2570

PUBLIC SECTOR:
Annual energies of the customers responded



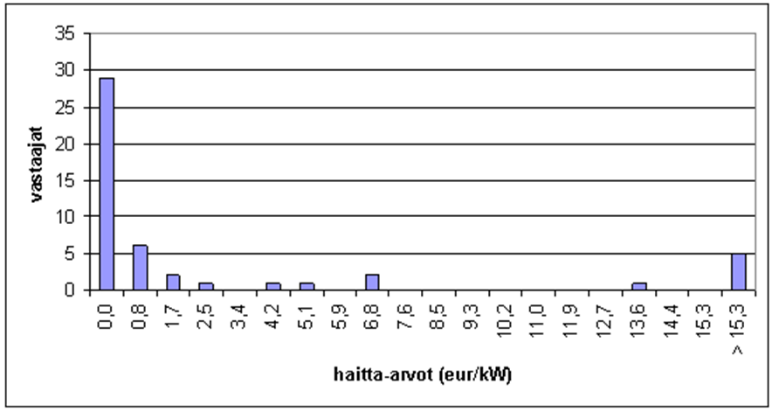
Horizontal axis: Annual energies - Vertical axis: number of customers

PUBLIC SECTOR
Direct costing results €/kW

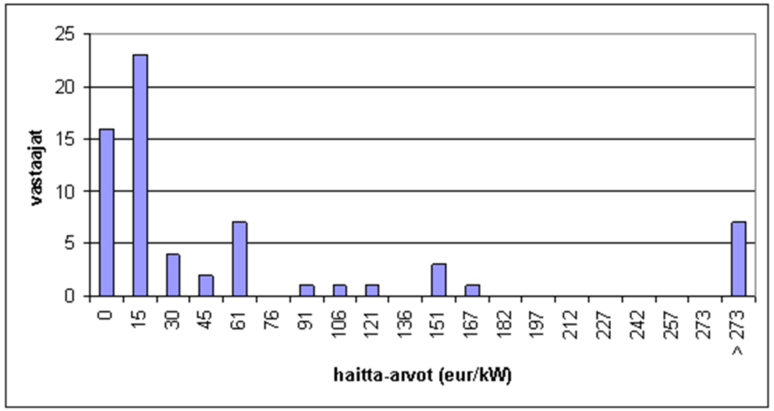
Outage length	2min	1hr	4hrs	12hrs	24hrs
Winter-mean	3.1	34.3	124	450	1050
Winter-median	0.0	5.5	21.9	72.3	150.6
Summer-mean	4.5	25.2	77.1	482	685
Summer-median	0.0	4.9	16.7	68.8	88.0

Public sector: direct costing results

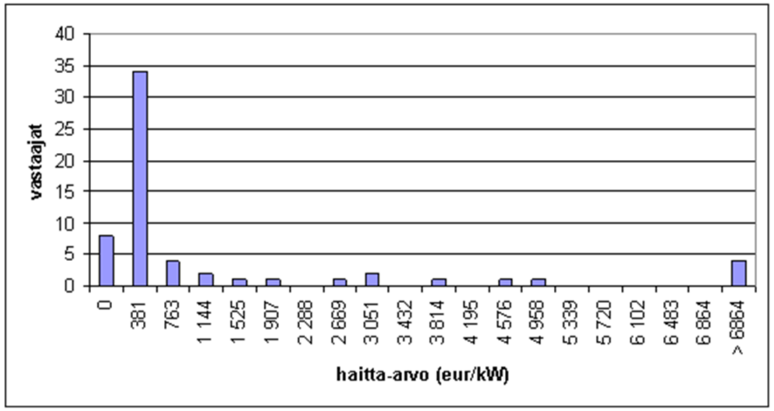
1 s



1 h

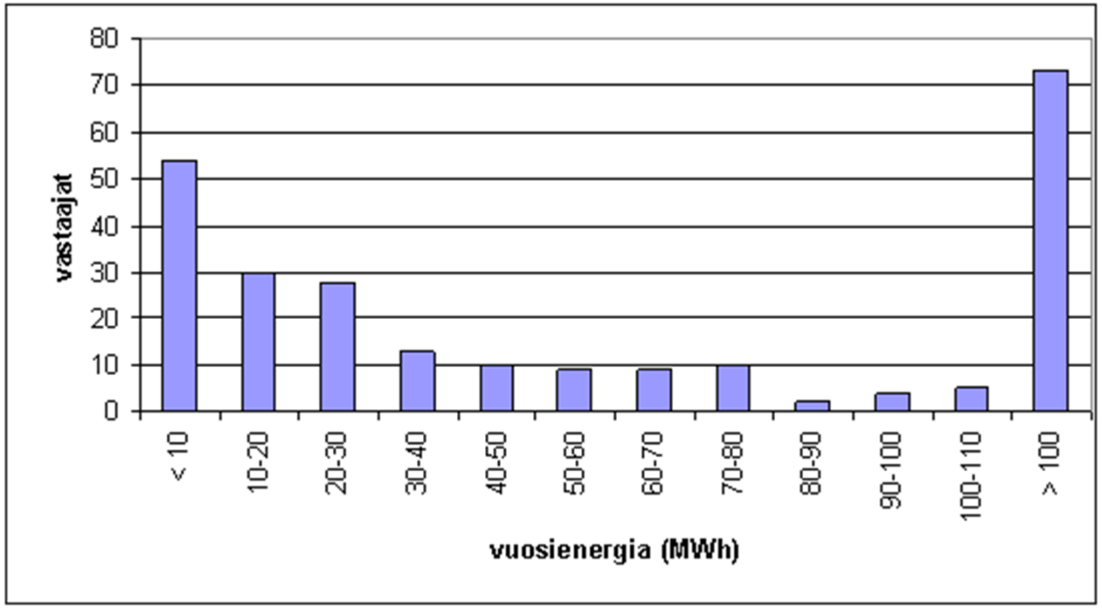


12 h



X-axis: cost estimate €/kW, y-axis number of cases, unexpexted outage in winter day

SERVICE SECTOR:
Annual energies of the customers responded



Horizontal axis: Annual energies - Vertical axis: number of customers

Service sector:

Broken equipment due to short interruptions

- Number of equipment breaks 50 (20%)
- Average costs per failure 1105 €
- Maximum cost per failure 10000€

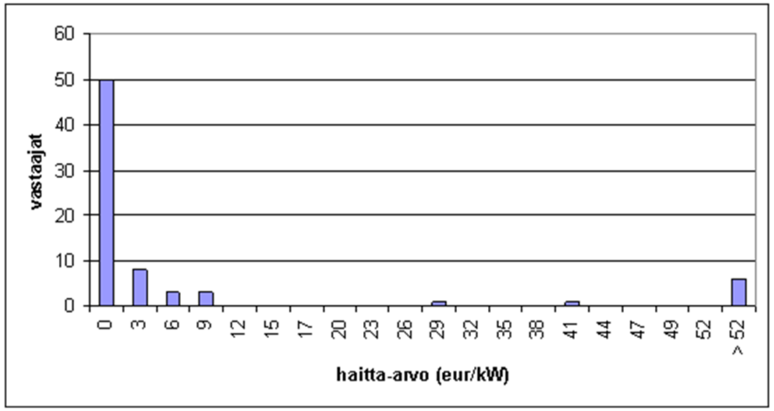
Service sector

Direct costs €/kW

Outage length	2min	1hr	4hrs	12hrs	24hrs
Winter-mean	5.2	48.1	139	282	337
Winter-median	-	19.6	69.7	165	189
Summer-mean	6.0	42.7	130	287	358
Summer-median	-	18.8	67.4	143	197

Service sector: Direct costs €/kW

1 s



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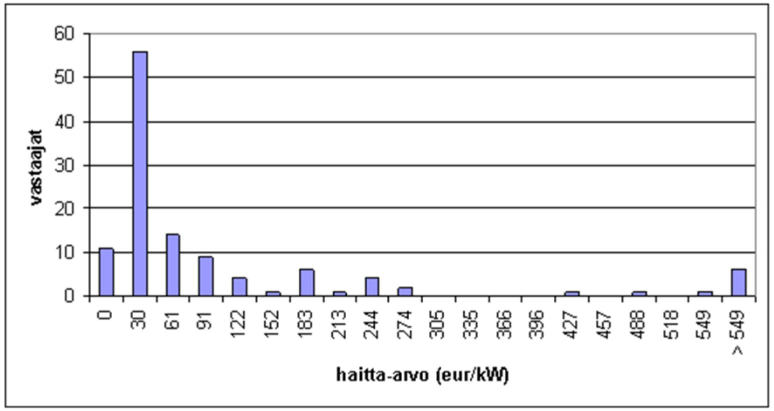

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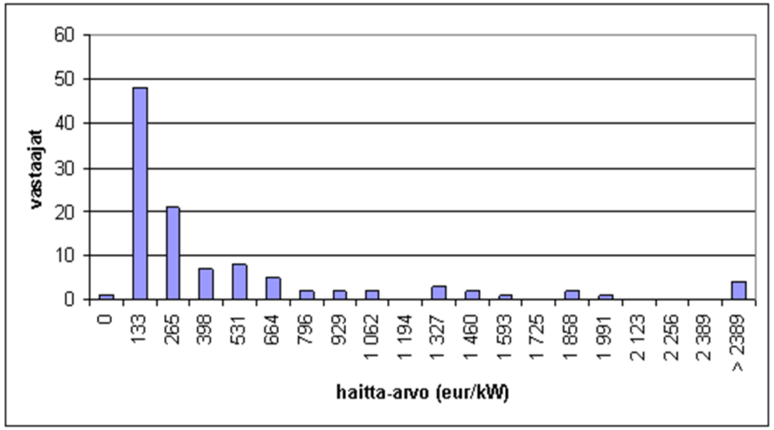
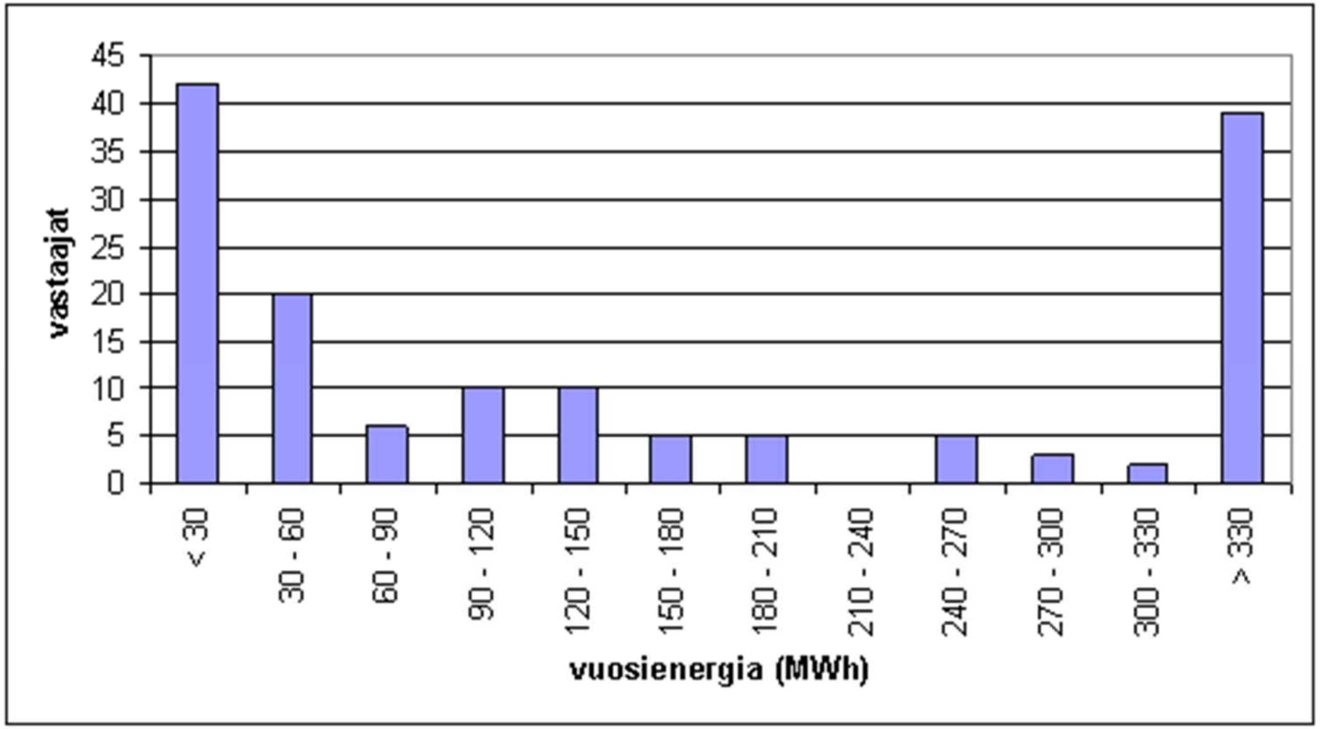


X-axis: cost estimate €/kW, y-axis number of cases, unexpexted outage in winter day

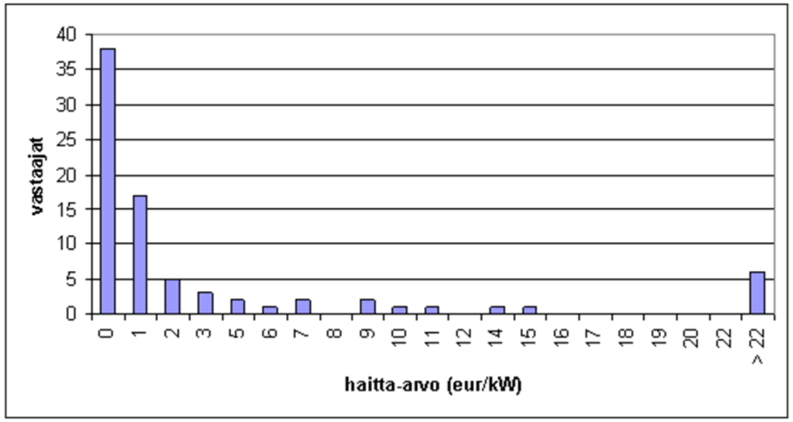
INDUSTRIAL SECTOR:
Responses & annual energies



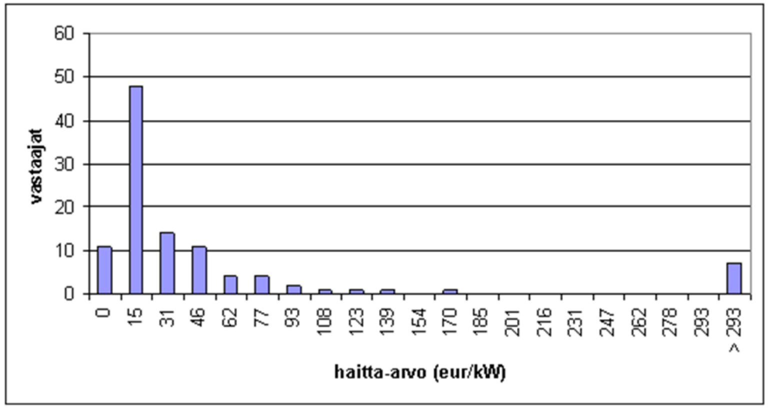
Horizontal axis: Annual energies - Vertical axis: number of customers

INDUSTRIAL SECTOR:
Direct costs €/kW

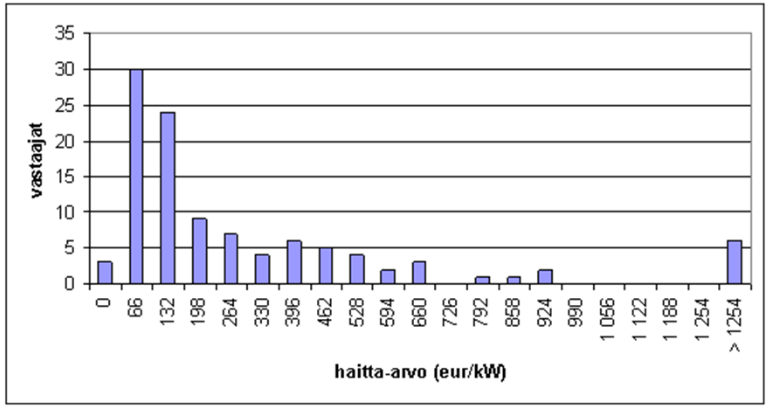
1 s



1 h



12 h

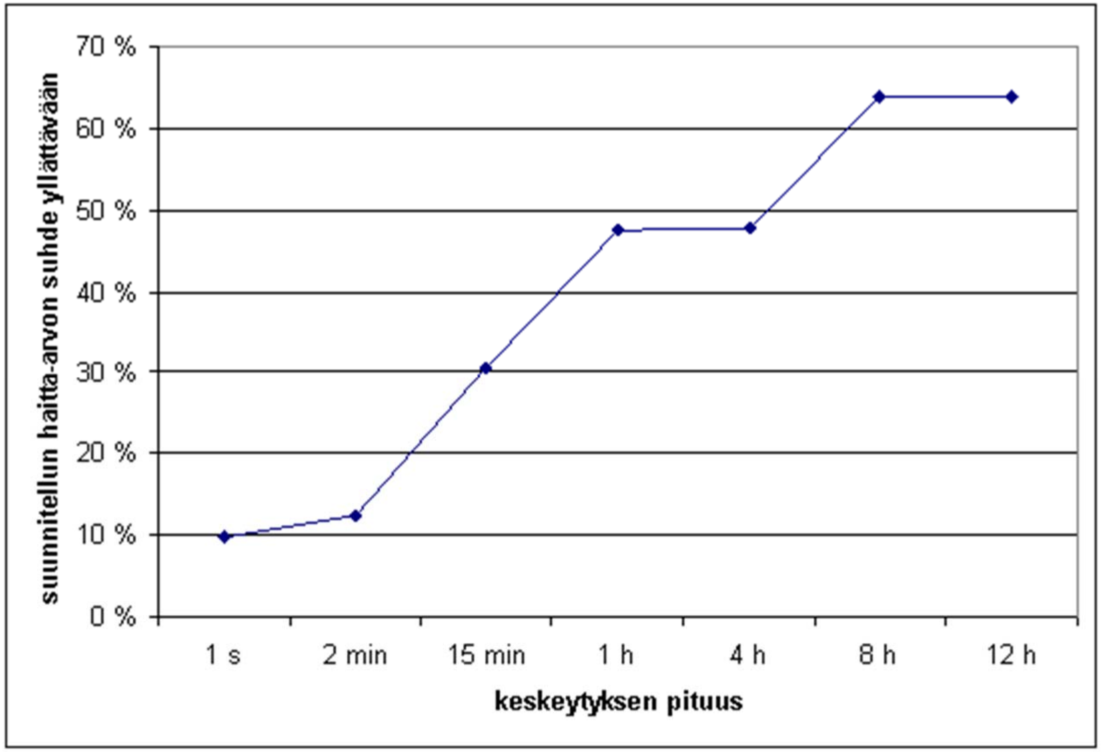


X-axis: cost estimate €/kW, y-axis number of cases, unexpexted outage in winter day

Industrial sector: Direct costs €/kW

Outage length	2min	1hr	4hrs	8hrs	24hrs
Unexpexted in working hrs	2.4	21.6	76.2	141	190
Planned in working hrs	0.3	10.3	36.4	90.0	121
Unexpected outside work hrs	-	2.4	-	33.3	-

INDUSTRIAL CUSTOMERS:
planned / unexpected outages



X-axis: outage duration - Y-axis: cost of planned outage / cost of unexpected outage

CONCLUSIONS

- Outage costs vary largely depending on
  - time of outage
  - length of outage
  - customer class and subclass
  - between different customers in same category
- The distribution of outage costs is skew
  - the difference between mean and median values is big

CONCLUSIONS

Typical total outage costs €/kW and marginal costs €/kWh

Customer group	Total cost		Marginal costs	
	1hr	12hrs	1 hr	12hrs
Households	3-10	25-60	3-7	2-5
Summer houses	2-20	48-81	2-17	4-7
Argiculture	3-16	50-120	3-13	5-11
Service	4-60	25-270	4-47	2-25
Public	5-35	60-450	5-30	5-41
Industry	7-22	50-190	7-20	4-15

STANDARD COMPENSATION

For longer outages, DSO has to compensate to the customers as follows:

- 12-24 h ⇔ 10% of annual transmission fee
- 24-72 h ⇔ 25% of annual transmission fee
- 72-120 h ⇔ 50% of annual transmission fee
- 120-192 h ⇔ 100% of annual transmission fee
- 192-288 h ⇔ 150% of annual transmission fee
- Over 288 h ⇔ 200% of annual transmission fee

Max payment is 2000 EUR