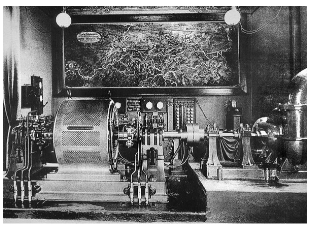
DAT300
The Electrical Power System

Stefan Lundberg
stefan.lundberg@chalmers.se

Department of Energy and Environment
Division of Electric Power Engineering
Chalmers University of technology

History of the power systems

AC transmission was first demonstrated at an exhibition in Frankfurt am Main 1891



170 kW transferred 175 km from Lauffen hydropower station to the exhibition area at 13000-14700 V

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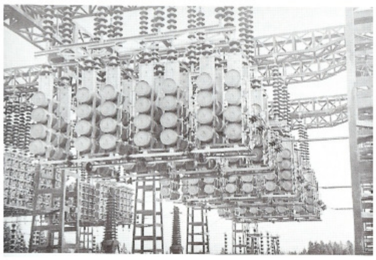
History of the power systems in Sweden

First 3-phase transmission system installed in Sweden between Hellsjön and Grängesberg 1893
voltage 9650 V, 70 Hz, 70 kW

First 400 kV system Harsprånget Hallsberg 1952

Series compensation introduced 1954



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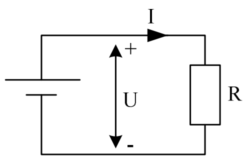
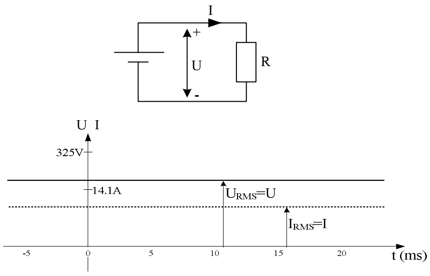
Fundamentals of Electric Power

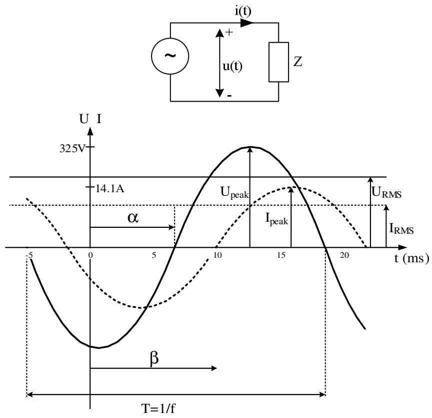
- Energy
  - Ability to perform work, [J], [Ws], [kWh] (1 kWh = 3.6 MJ)
- Voltage
  - Measured between two points [V], [kV]
  - Equivalent to pressure in a water pipe
- Current
  - Measure of rate of flow of charge through a conductor [A], [kA]
  - Equivalent to the rate of flow of water through a pipe.
  - Must have a closed circuit to have a current



Direct Current (DC) / Alternating Current (AC)



$$u(t) = U$$
$$i(t) = I$$



$$u(t) = U_{peak} \cos(\omega t - \alpha)$$
$$i(t) = I_{peak} \cos(\omega t - \beta)$$
$$\omega = 2\pi f$$

RMS = Root-Mean-Square

$$I_{RMS} = \sqrt{\frac{1}{T}\int_0^T i(t)^2\,dt} = \frac{I_{peak}}{\sqrt{2}}$$

Only for sinusoidal waveforms

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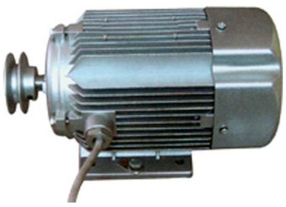
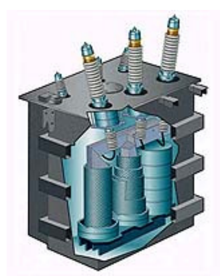
Why is AC used?

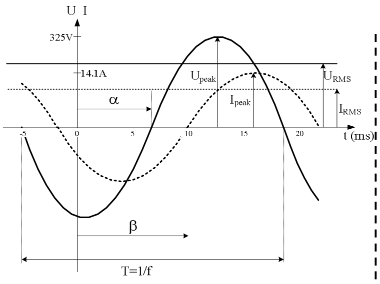
The two main factors that formed the power system

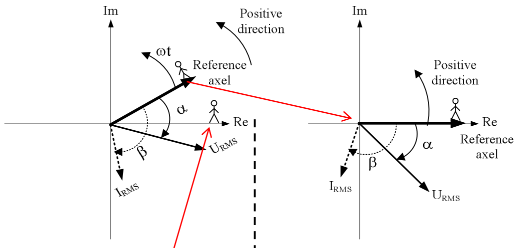
- Transformer (only works on AC)
- Robust and cheep motor (rotating flux)





Alternating Current (AC)





$$u(t) = U_{peak}\cos(\omega t - \alpha)$$
$$i(t) = I_{peak}\cos(\omega t - \beta)$$
$$\omega = 2\pi f$$

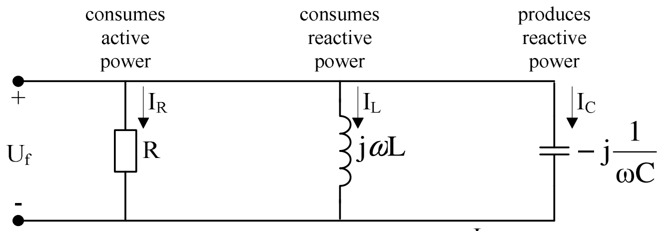
Express the sinusoidal voltage and current as complex rotating phasors and use RMS values for the amplitude

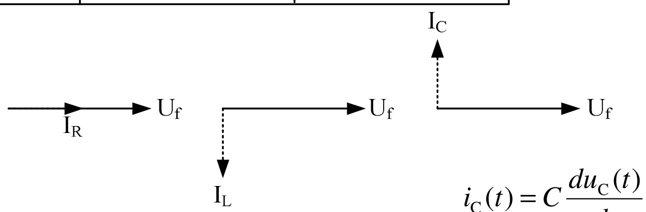
$$u(t) = \sqrt{2}\,\mathrm{Re}\{U_{RMS}e^{j(\omega t-\alpha)}\} \Rightarrow$$
$$u(t) = \sqrt{2}\,\mathrm{Re}\{\underbrace{U_{RMS}e^{j(-\alpha)}}_{\underline{U}}e^{j\omega t}\}$$
$$i(t) = \sqrt{2}\,\mathrm{Re}\{I_{RMS}e^{j(\omega t-\beta)}\} \Rightarrow$$
$$i(t) = \sqrt{2}\,\mathrm{Re}\{\underbrace{I_{RMS}e^{j(-\beta)}}_{\underline{I}}e^{j\omega t}\}$$

Since all phasors are rotating with the same speed, we select one as the reference and observe all others relative to this one. This gives that the rotation disappears and the voltage and currents can be expressed as complex number (constant)

$$\underline{U} = U_{RMS}\angle\alpha$$
$$\underline{I} = I_{RMS}\angle\beta$$

Impedance





$$u_R(t) = Ri_R(t)$$
$$\underline{U}_R = R\underline{I}_R$$

$$u_L(t) = L\frac{di_L(t)}{dt}$$
$$\underline{U}_L = j\omega L\underline{I}_L = jX_L\underline{I}_L$$
$$X_L = \omega L$$

$$i_C(t) = C\frac{du_C(t)}{dt}$$
$$\underline{U}_C = -j\frac{1}{\omega C}\underline{I}_C = -jX_C\underline{I}_L$$
$$X_C = \frac{1}{\omega C}$$

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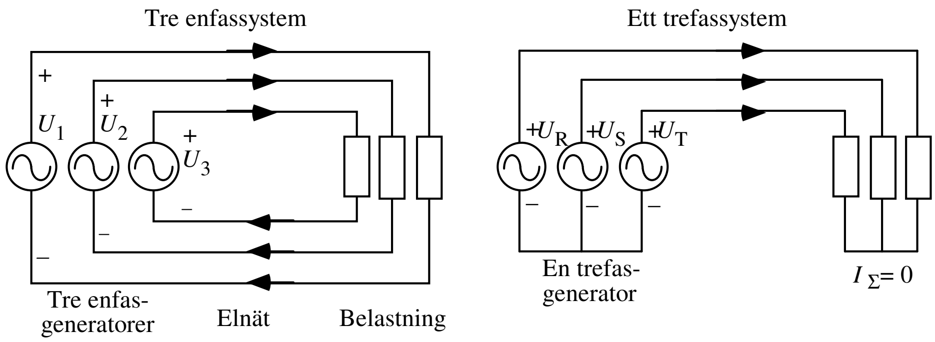
Why three phase system?



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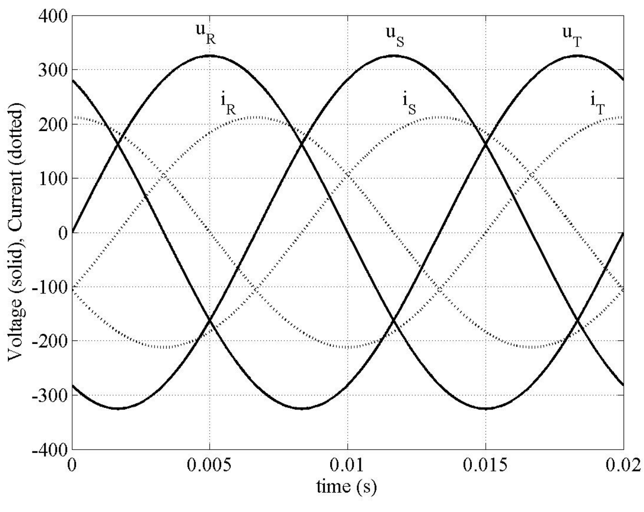
Three phase voltage and current



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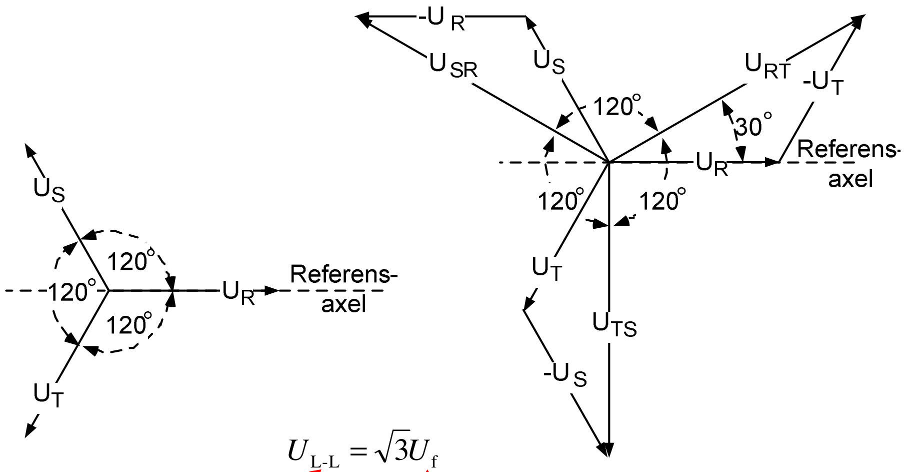
Line-to-line phasors for the voltages



$$U_{\text{L-L}} = \sqrt{3}U_{\text{f}}$$

Line to Line — Phase (to ground)

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Power – Rate of energy flow [W]

$$u(t) = \sqrt{2}U_{RMS}\cos(\omega t)$$
$$i(t) = \sqrt{2}I_{RMS}\cos(\omega t - \varphi)$$

Angle between voltage and current

$$\varphi = \beta - \alpha$$

Single phase	Three phase
$p(t) = u(t)i(t)dt$ ← Instantaneous power →	$p(t) = u_R(t)i_R(t) + u_S(t)i_S(t) + u_T(t)i_T(t)$
$P = \frac{1}{T}\int_0^T u(t)i(t)dt$ ← average →	$P = \frac{1}{T}\int_0^T \{u_R(t)i_R(t) + u_S(t)i_S(t) + u_T(t)i_T(t)\}dt$
Apparent power $S = \underline{U}_{RMS}\underline{I}_{RMS}{}^{*} = P + jQ$ [VA]	$S = 3\underline{U}_{RMS}\underline{I}_{RMS}{}^{*} = \sqrt{3}\underline{U}_{L-L,RMS}\underline{I}_{RMS}{}^{*} = P + jQ$
Active power $P = \lvert\underline{U}_{RMS}\rvert\lvert\underline{I}_{RMS}\rvert\cos\varphi$ [W]	$P = 3\lvert\underline{U}_{RMS}\rvert\lvert\underline{I}_{RMS}\rvert\cos\varphi = \sqrt{3}\lvert\underline{U}_{L-L,RMS}\rvert\lvert\underline{I}_{RMS}\rvert\cos\varphi$
Reactive power $Q = \lvert\underline{U}_{RMS}\rvert\lvert\underline{I}_{RMS}\rvert\sin\varphi$ [VAr]	$Q = 3\lvert\underline{U}_{RMS}\rvert\lvert\underline{I}_{RMS}\rvert\sin\varphi = \sqrt{3}\lvert\underline{U}_{L-L,RMS}\rvert\lvert\underline{I}_{RMS}\rvert\sin\varphi$

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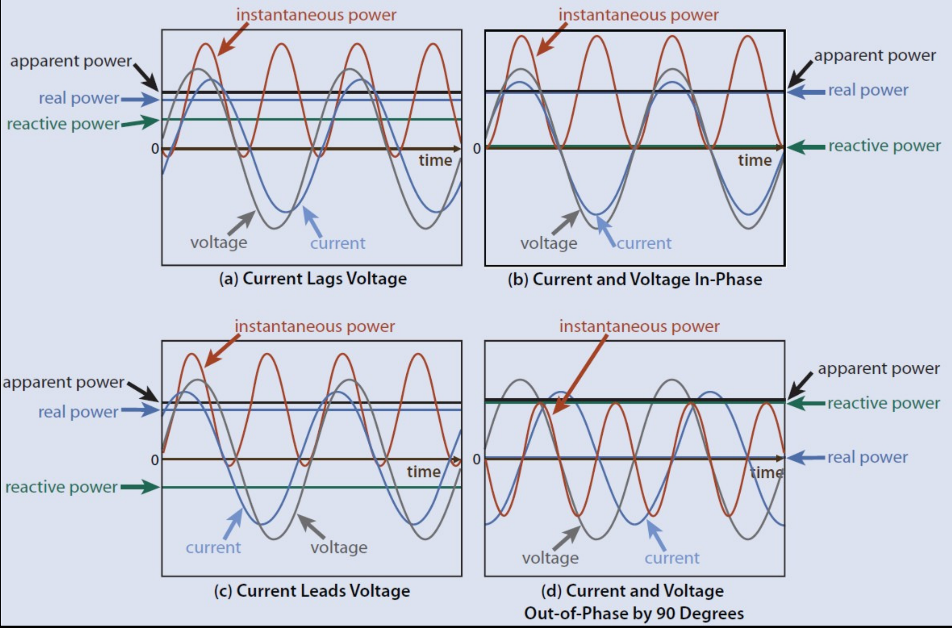
Power – Rate of energy flow [W]



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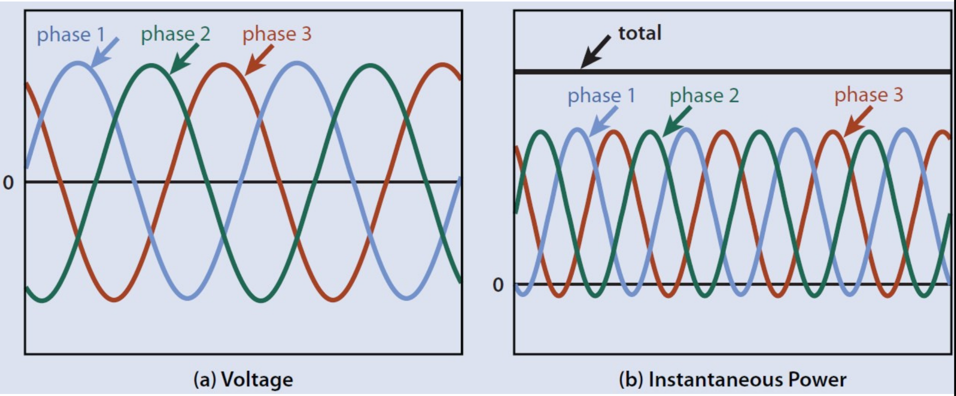
Power – Rate of energy flow [W]

3-phase Power [W]



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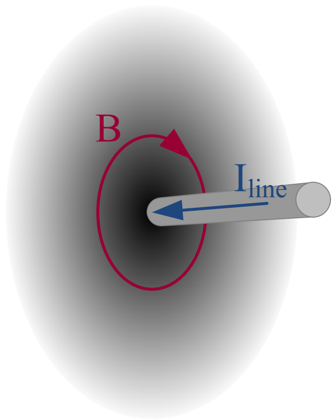
Reactive power flow – What is reactive power?

Consider an alternating current I_{line} flowing in a line

- The current causes a magnetic field around the conductor
- The field strength is highest close to the conductor surface
- The field energy density is proportional to the square of the field strenght
- The field is built up and eleminated with the double of the network frequency in each phase



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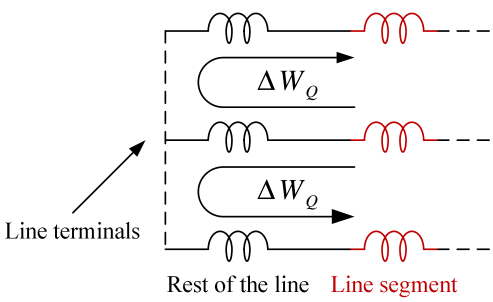
Reactive power flow – What is reactive power?

Consider a line segment of, for example, 100 km in a long transmission line



- The distance between the phases is about 10 m.
- It is not possible to transfer the energy directly between the neighboring phases.
- The energy must be transported to some place where the conductors are connected (a generator or a transformer).

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Reactive power flow – What is reactive power?

How much energy is involved?

Consider a line segment of 100 km and a current of 1 kA (rms value); the energy at the current peak is

$$W_Q = \frac{1}{2} L \hat{i}_{line}^2 = \frac{1}{2} 0.1(1000\sqrt{2})^2 = 100kJ$$

It is the same energy needed to lift a 1500 kg car up to 7 meters.

This is done each 10 ms, in each phase.

7 m

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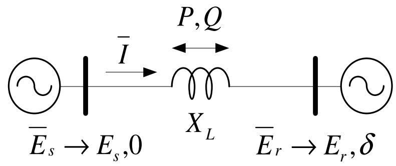
Reactive power flow – What is reactive power?

Due to the presence of the reactive power, the system cannot be used up to its thermal limit

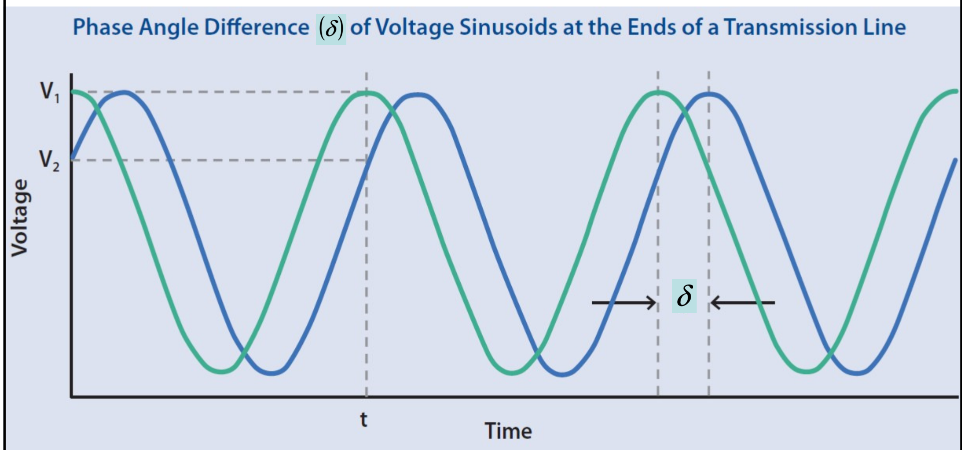
Need for reactive power compensation for better utilization of the system

Power flow



Active/reactive power at sending end E_s	Active/reactive power at receiving end E_r
$P_s = \mathrm{real}\left(\bar{E}_s \bar{I}^*\right) = E_s I_p = \dfrac{E_s E_r \sin\delta}{X_L}$	$P_r = \mathrm{real}\left(\bar{E}_r \bar{I}^*\right) = \dfrac{E_r E_s \sin\delta}{X_L}$
$Q_s = \mathrm{imag}\left(\bar{E}_s \bar{I}^*\right) = E_s I_q = \dfrac{E_s(E_s - E_r \cos\delta)}{X_L}$	$Q_r = \mathrm{imag}\left(\bar{E}_r \bar{I}^*\right) = -\dfrac{E_r(E_r - E_s \cos\delta)}{X_L}$

Voltages at the ends of a transmission line (same phase)



s = 1 (sending end)
r = 2 (receiving end)

s = 1 (sending end)
r = 2 (receiving end)

Power flow

$$\bar{I} = \frac{\bar{E}_1 - \bar{E}_2}{jX} = \frac{E_1 \sin\delta}{X} + \mathrm{j}\frac{E_2 - E_1\cos\delta}{X} = I_{p2} - \mathrm{j}I_{q2}$$

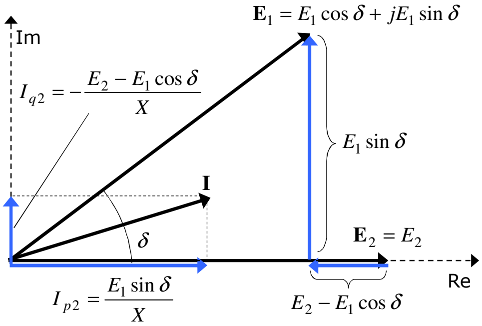
Complex power to E_2:

$$\bar{S}_2 = \bar{E}_2 \bar{I}^* = E_2(I_{p2} + \mathrm{j}I_{q2}) = P_2 + \mathrm{j}Q_2$$

Active/reactive power to E_2:

$$P_2 = E_2 I_{p2} = \frac{E_2 E_1 \sin\delta}{X}$$

$$Q_2 = E_2 I_{q2} = -\frac{E_2(E_2 - E_1\cos\delta)}{X}$$



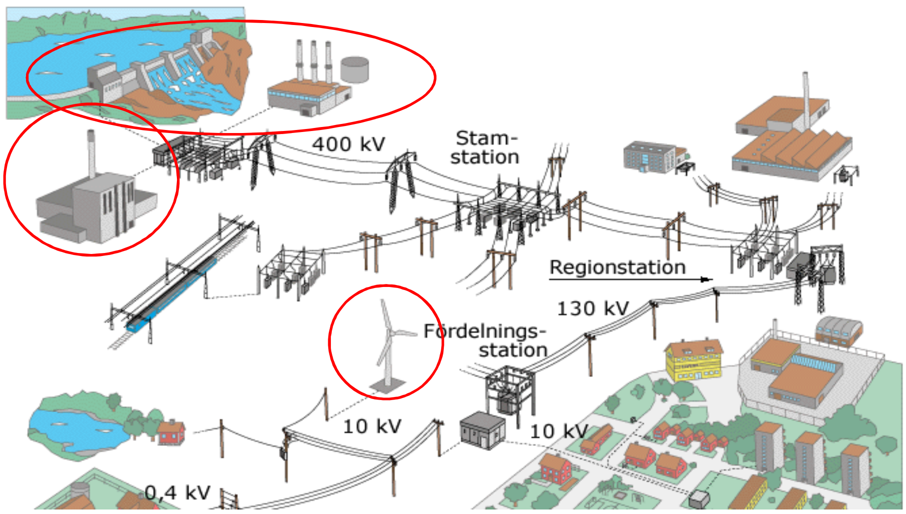
Active power from E_1 to E_2 :

$$P = P_1 = P_2 = \frac{E_2 E_1 \sin\delta}{X}$$

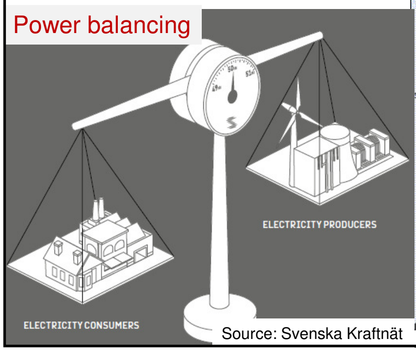
Reactive power consumption of the transmission line:

$$\Delta Q = Q_1 - Q_2 = \frac{1}{X}\left(E_1^2 + E_2^2 - 2E_1E_2\cos\delta\right) = \frac{E_L^2}{X}$$

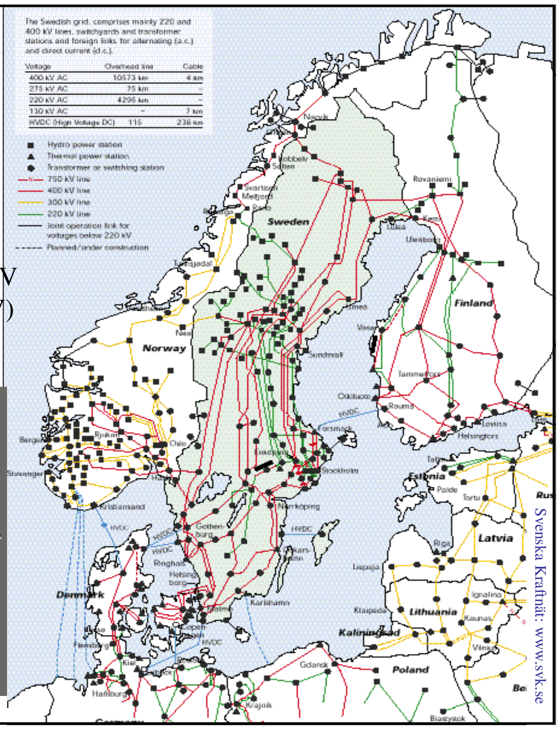
Structure of the Electric Power System



- Transmission 400, 220 kV
- Regionalnät 130 kV
- Distributionsnät *70*, 40, *30*, 20,10 kV
- Kunder 400 V (Industri 10-130 kV)

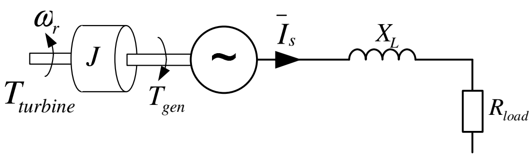


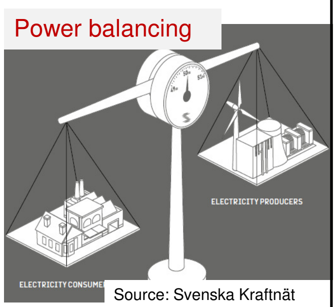
Source: Svenska Kraftnät



Svenska Kraftnät: www.svk.se

What happens if the turbine power does not match the load power?





Source: Svenska Kraftnät

$$\left.\begin{aligned} J\frac{d\omega_r}{dt} &= T_{turbine} - T_{gen} \\ P_{turbine} &= \omega_r T_{turbine} \\ P_{gen} &= \omega_r T_{gen} \\ P_{load} &\approx P_{gen} \\ \omega_r &= \frac{2\pi f_{grid}}{n_p} \end{aligned}\right\} \Rightarrow J\frac{4\pi^2}{n_p^2}\frac{df_{grid}}{dt} = \frac{P_{turbine} - P_{gen}}{f_{grid}}$$

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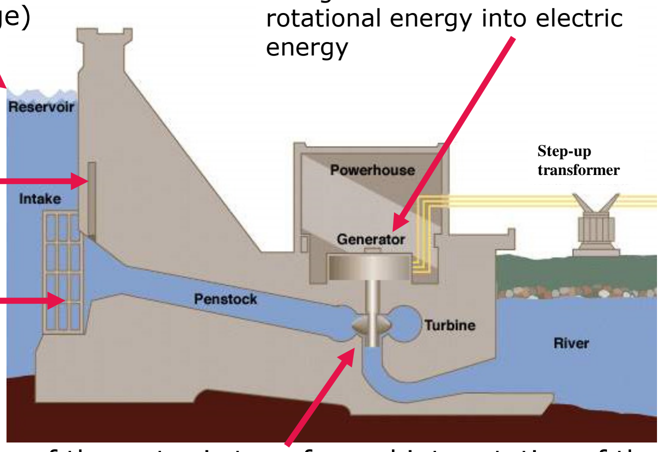
Hydro Power Station

Reservoir (energy storage)

The generator transforms the rotational energy into electric energy

Control gate

Screen



The kinetic energy of the water is transformed into rotation of the generator shaft (rotational kinetic energy)

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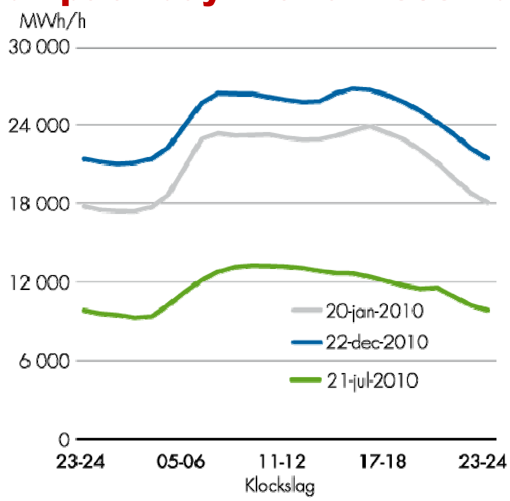
Profile over the electric energy consumption in Sweden for a typical summer day, winter day and the highest consumption day 22th of December 2010

On the 23rd of February 2011 Sweden used 26 000 MW between 08-09



Elåret 2010

Källa: Svenska Kraftnät och Svensk Energi

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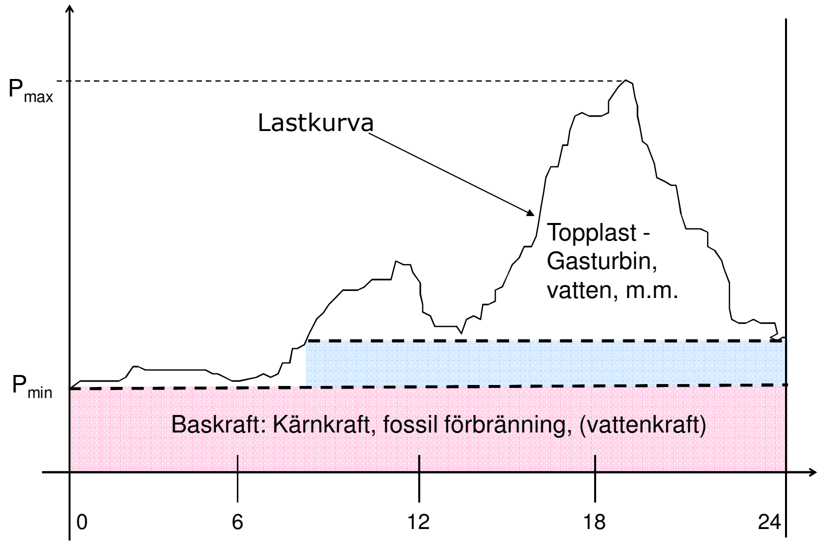
Production planing



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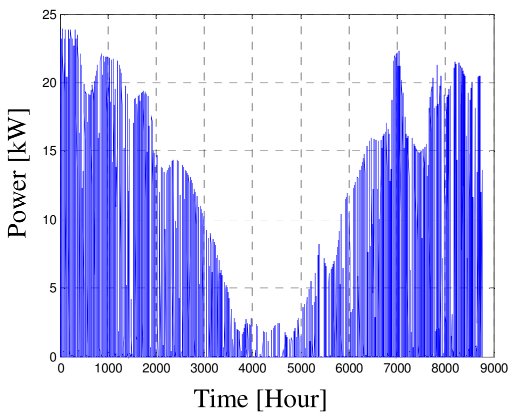
Solar Plant

<u>Göteborg</u>
Latitude 57.7 °
200 m^2 of solar cells
Statistical cloudiness
Sun tracking

<u>Efficiency</u>:

MPP	0.95
Power electronics	0.95
Solar cells	0.15



Integrated power during 1 year
24 000 kWh

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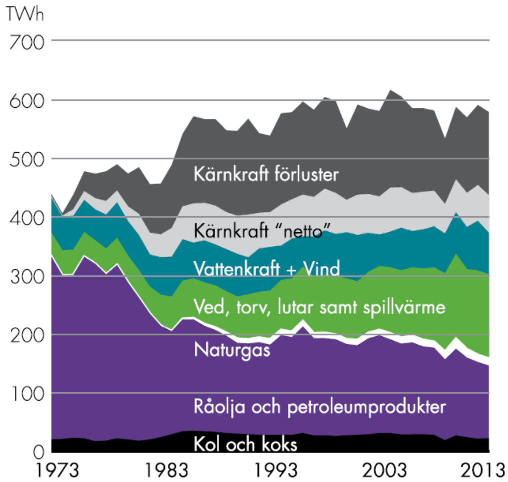
Total input energy to Sweden 1973–2013



Källa: SCB

Elåret 2013

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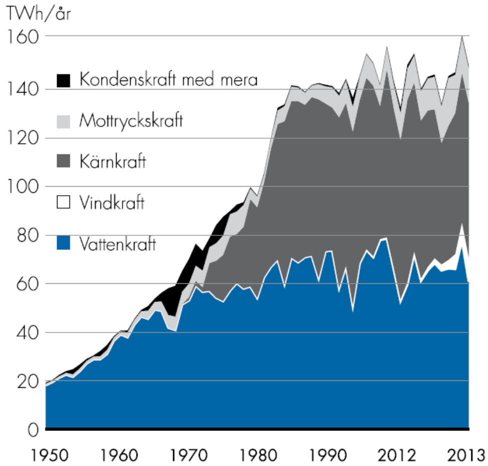
Electric energy production and ussage in Sweden for 1950–2013, TWh/week



Källa: Svensk Energi

Elåret 2013

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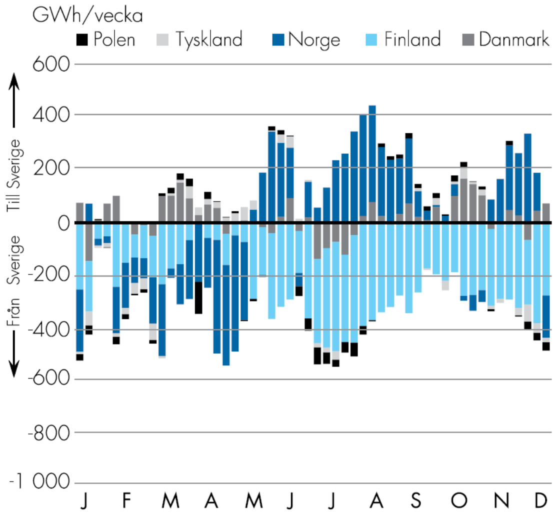
Electric energy flow to and from Sweden 2013, GWh/week



Källa: Svenska Kraftnät och Svensk Energi

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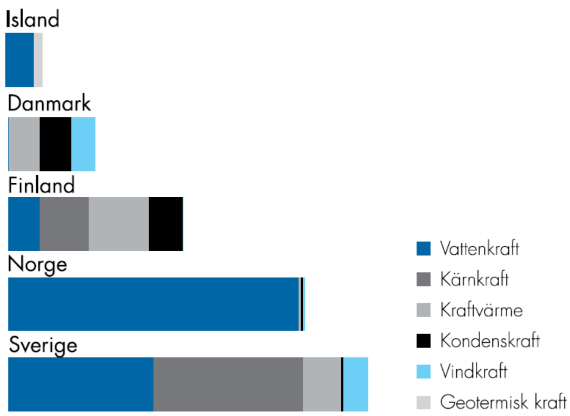
Normalized electric production mix for the Nordic countries



Källa: Svensk Energi

Elåret 2013

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Electric energy production in Sweden:

145,0 TWh år **2007** **(v 65,5; k 64,3)**

146,0 TWh år **2008** **(v 68,6; k 61,3; v 2,0)**

133,7 TWh år **2009** **(v 65,3; k 50,0; v 2,5)**

144,9 TWh år **2010** **(v 66,8; k 55,6; v 3,5)**

146,9 TWh år **2011** **(v 66,0; k 58,0; v 6,1)**

162,4 TWh år **2012** **(v 78,4; k 61,4; v 7,2)**

149,5 TWh år **2013** **(v 60,8; k 63,6; v 9,9)**

v=Hydro power

v=Wind power

k=nuclear power

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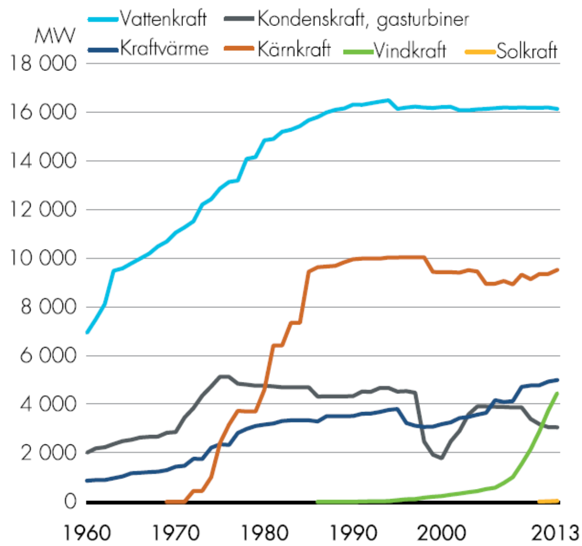
Installed peak power in Sweden, MWel



Elåret 2013

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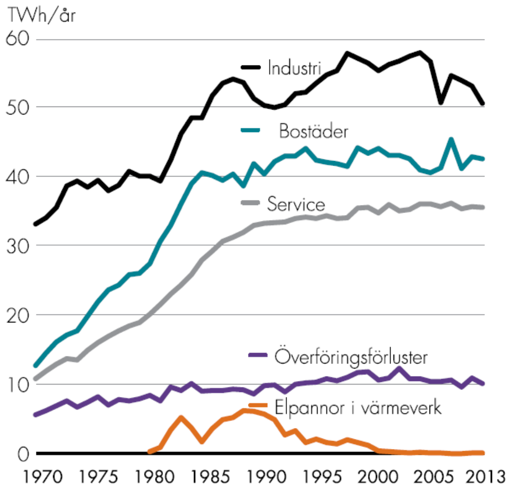
Electric energy consumption in Sweden divided on different consumers 1970–2013



Källa: SCB

Elåret 2013

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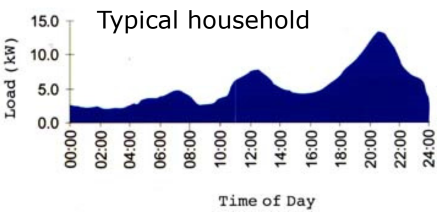
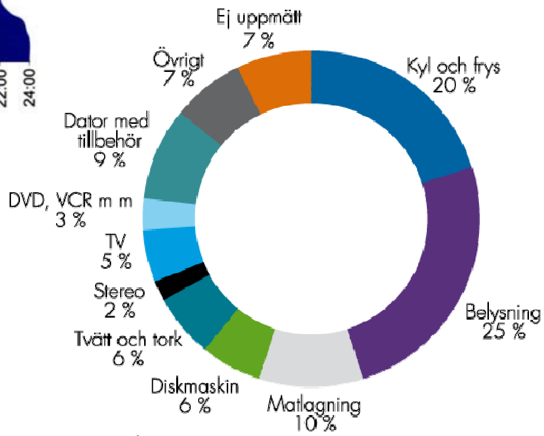
Electric energy consumption for households in Sweden (investigated 2007)



The consumption is higher in winter time in the Nordic countries, but in warm countries it is opposite



Elåret 2010

Källa: Energimyndigheten

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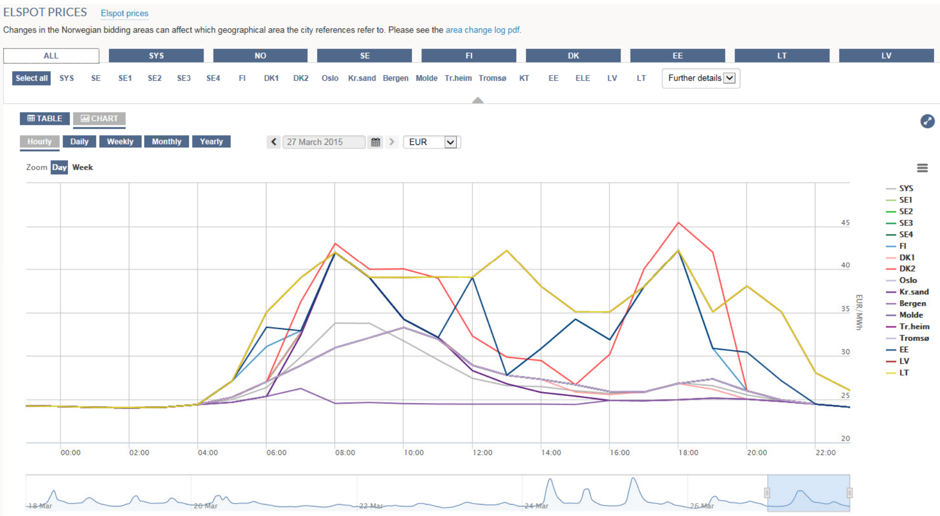
Spot market price for 2015-03-27



The End

Do you have any questions?