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Physical Aspects of Power Systems Control

Power and productivity
for a better world™

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Purpose of this Presentation
Describe how power systems are controlled

- (1) Fundamentals: Power system components, active and reactive power

- (2) Frequency and voltage control

- (3) Outlook: Impact of renewables?

- Focus is on the *interaction* of the components – the system aspect: why is the power system stable?

(1)

Fundamentals: Power System Components, Active and Reactive Power

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Power systems are made from four main components: Overhead lines, transformers, generators, breakers

High voltage overhead lines enable long distance power transmission with low losses

Transformers allow for adequate voltage levels for generation, transmission, distribution, and consumption
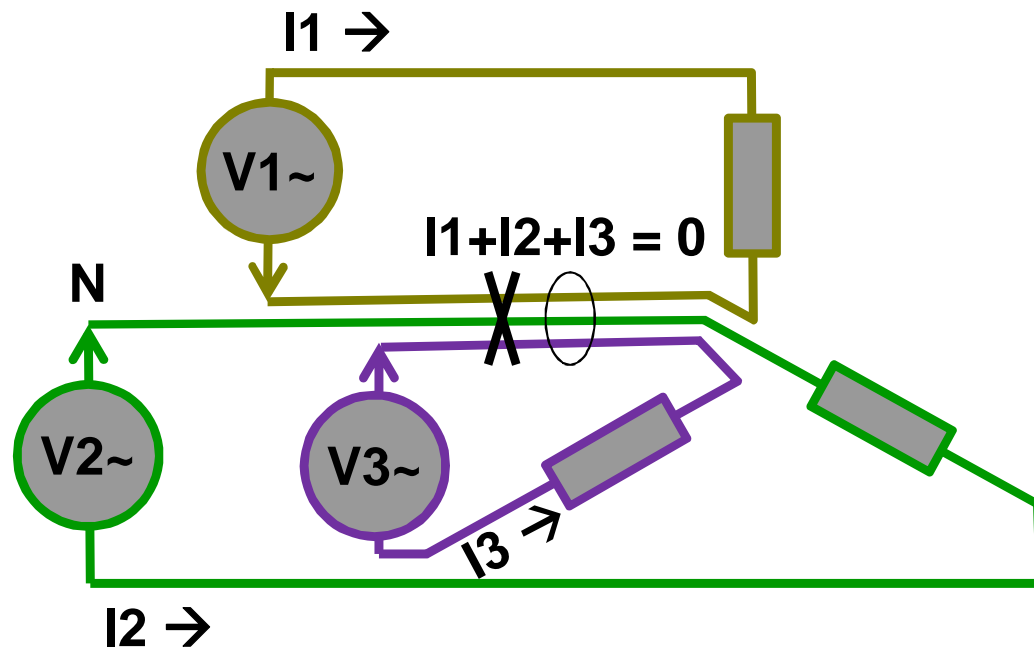

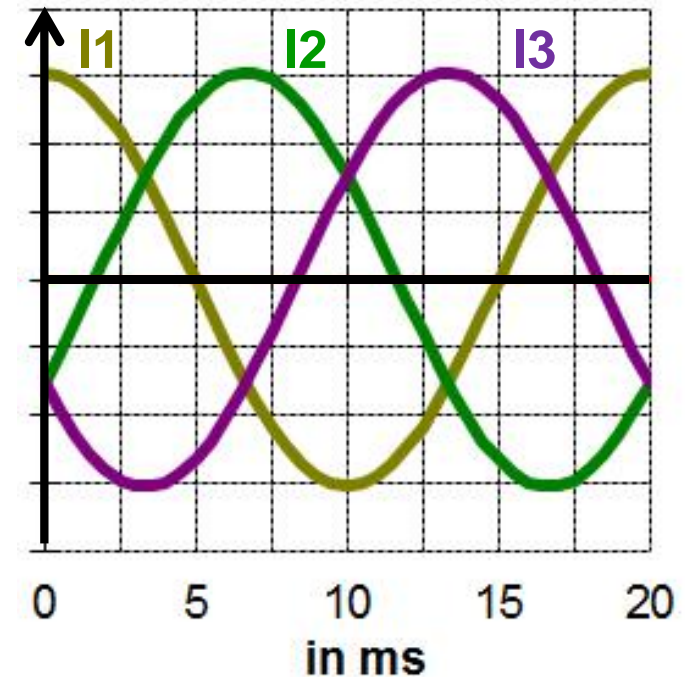Synchronous generators control real power and reactive power

Circuit breakers can interrupt short circuits and disconnect grid segments with a fault
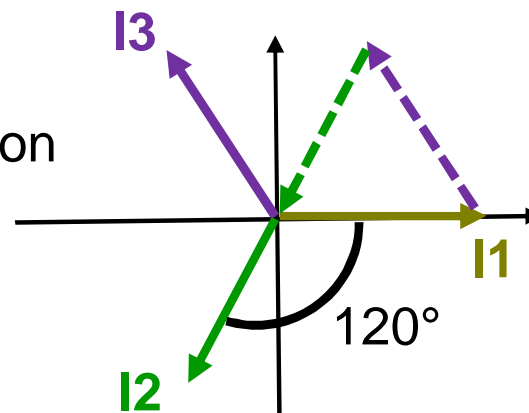
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Three symmetric phases provide steady power from alternating current and do not need return conductors

I1 →

V1~

I1+I2+I3 = 0

N

V2~   V3~

I3 →

I2 →

Current I

I1   I2   I3

0   5   10   15   20
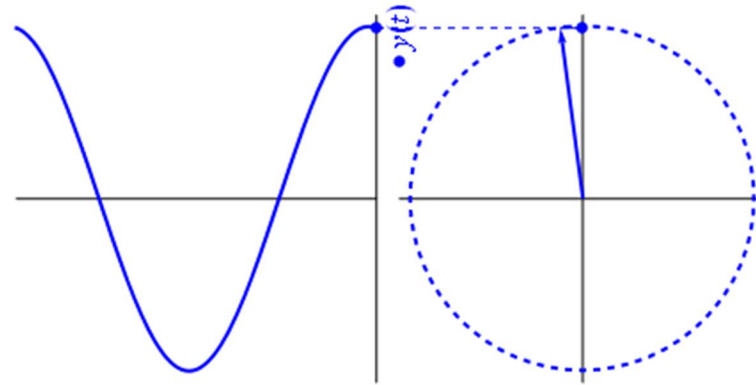
in ms

Phasor representation

I3

I1

I2

120°

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Review of Phasor Calculation

Time-domain

Phasor-domain
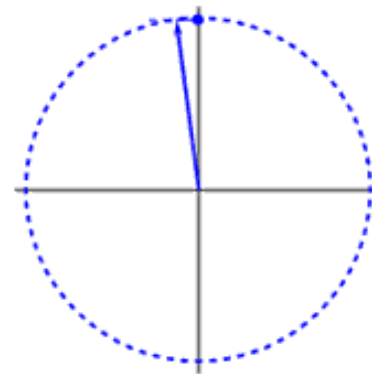
$$y(t) = A\sin(\omega t + \delta)$$

$$y(t) = A\,e^{\omega t + j\delta}$$

Use coordinate system rotating with speed ω rad/s

The phasor of a sinusoidal function (current, voltage, …) is a complex time-independent number with amplitude and «phase» angle
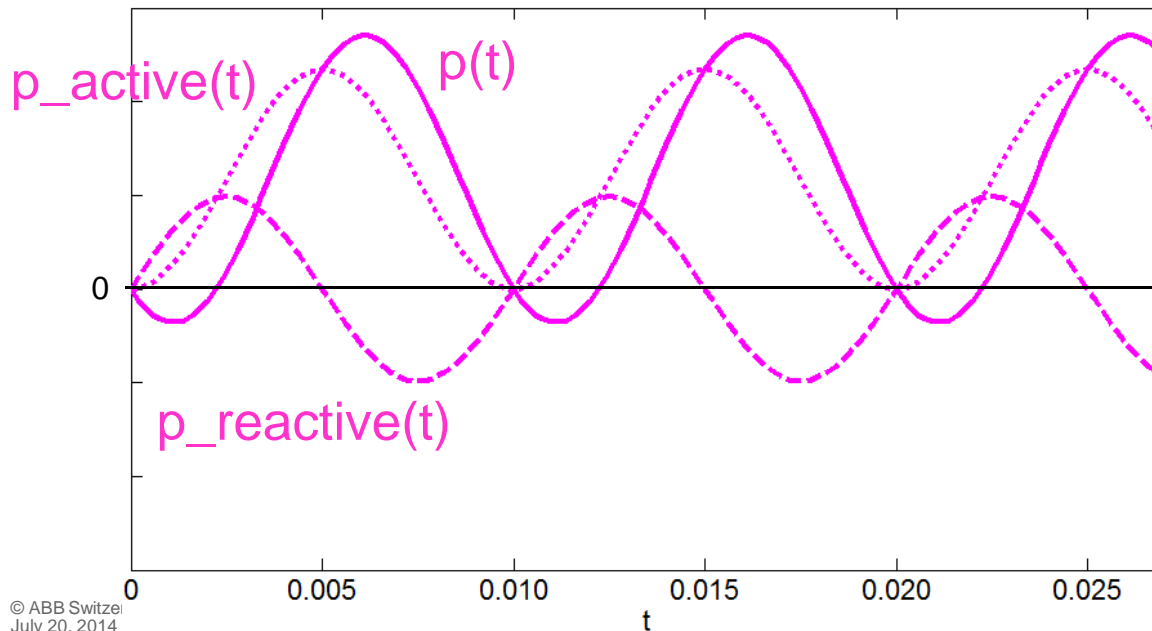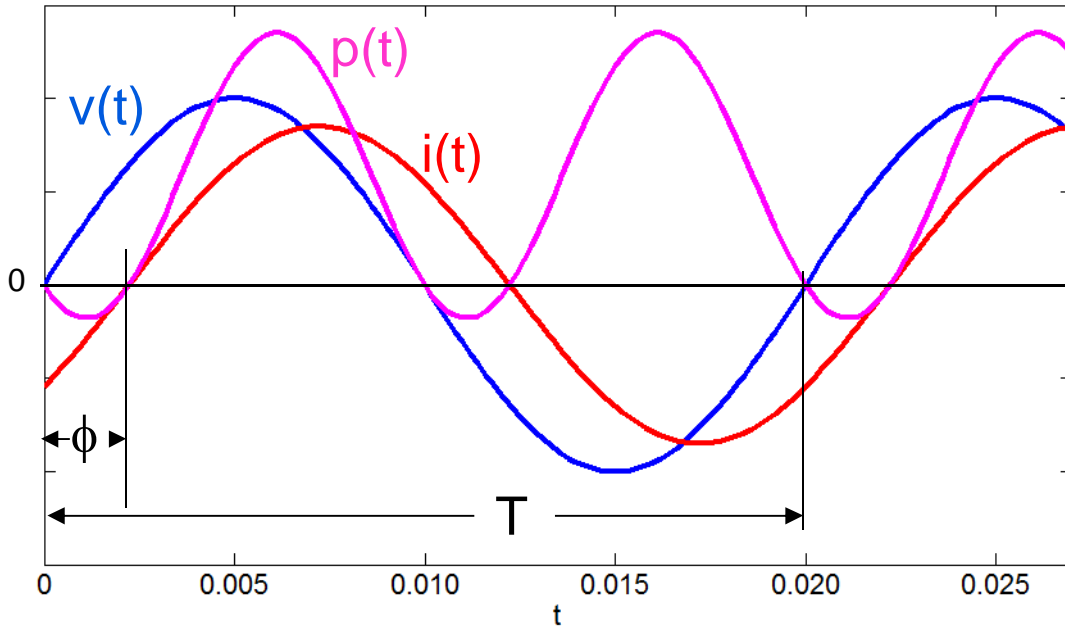
$$\bar{y} = A\,e^{j\delta} = A\angle\delta$$

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Why bother about active and reactive power?

- The balance of active power controls the frequency of the grid

- The balance of mainly the reactive power controls the voltage at every point of the grid

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Definition of Active and Reactive Power

p(t)

v(t)

i(t)

ϕ

T

0   0.005   0.010   0.015   0.020   0.025

t

p_active(t)

p(t)

0

p_reactive(t)

0   0.005   0.010   0.015   0.020   0.025

t

- For each single phase there is the instaneous power

  - $p(t) = v(t) * i(t)$

- Active (real) power

  $P_{active}(t) = P*(1-\cos(2\omega t))$ where

  $P = V_{eff}*I_{eff}*\cos(\phi)$

  $V_{eff} = V_{max}/\sqrt{2}$ etc. $, \omega = \frac{2\pi}{T}$

  ➜ Oscillates around P, is never negative
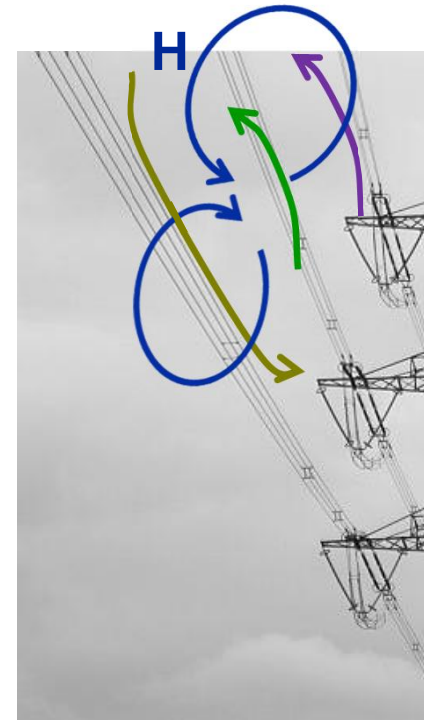
- Reactive power

  $P_{reactive}(t) = Q* \sin(2\omega t)$ where

  $Q = V_{eff}*I_{eff}*\sin(\phi)$

  ➜ Oscillates around zero

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Reactive power is the power flowing into and out of the magnetic field around the conductors

- Three phases

  - The sum of active power is time independent (doesn't oscillate)

  - The sum of reactive power is zero, but the redistribution of the magnetic field is the consequence of the oscillating reactive power in each phase

  ➔ Reactive power flow can <u>not</u> be neglected!

- Sign convention: inductors (lines, transformers, induction motors) *consume* reactive power, capacitors *generate* reactive power

Reactive power is the power flowing into and out of the magnetic field around the conductors (Animation)
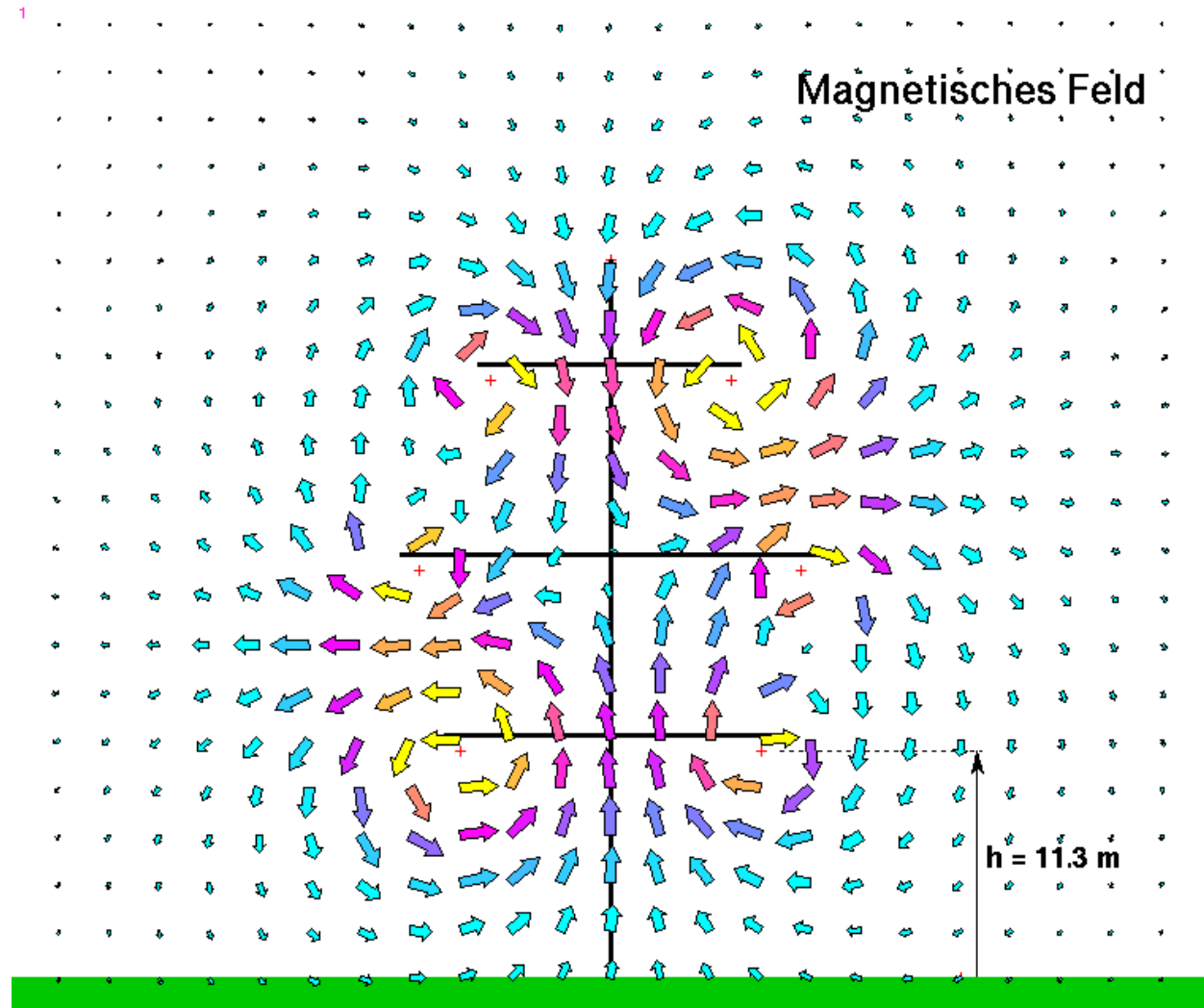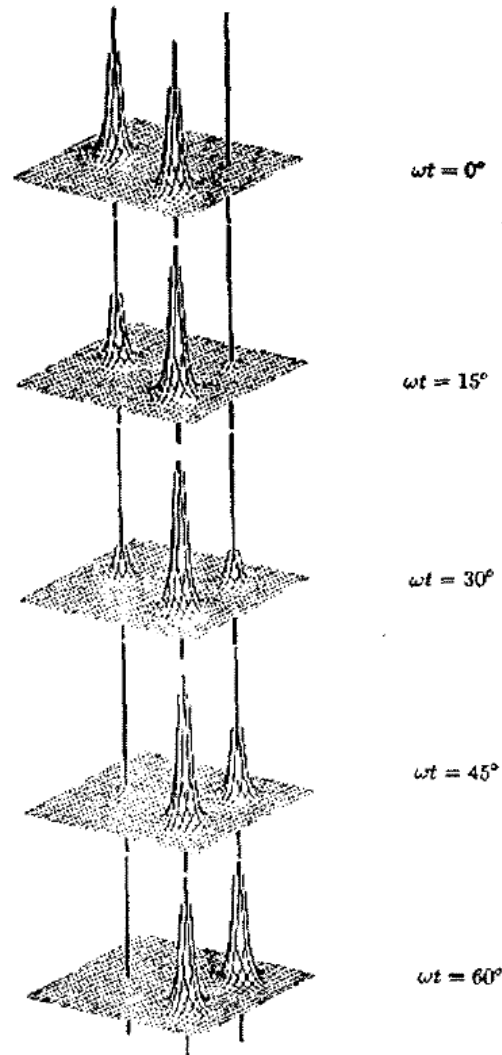

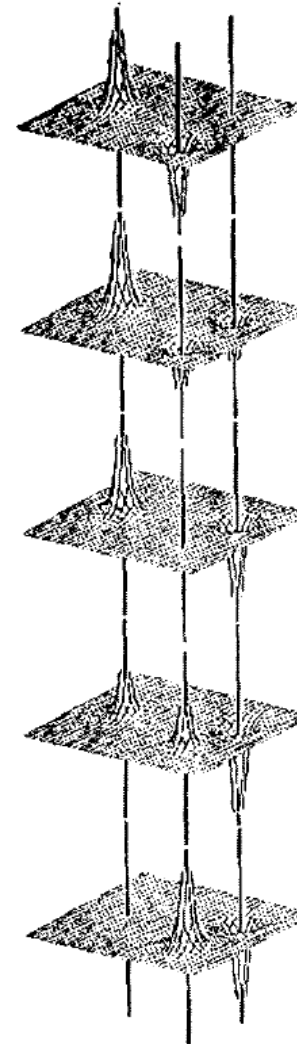Magnetic field around the six conductors of two 380 kV overhead circuits

Source: P. Leuchtmann, ETH Zurich, 2014.

Poynting vectors of active and reactive power flux show their physical character

Poynting vector envelopes of <u>active</u> power flux in a balanced three-phase overhead line

Poynting vector envelopes of <u>reactive</u> power flux in a balanced three-phase overhead line

$\omega t = 0°$

$\omega t = 15°$

$\omega t = 30°$

$\omega t = 45°$

$\omega t = 60°$

Source: Z. Cakareski, A. Emanuel, 1999.

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Summary 1 – A substantial part of the power is used for the electromagnetic fields around the conductors

- High voltage for low losses

- Alternating current in order to be able to transform the voltage and to interrupt

- In each phase, <u>reactive power</u> oscillates back and forth between the source and the sink at the frequency of the power system. Reactive power is the change of the energy stored in the electromagnetic fields of the components in operation.

(2)

Frequency and Voltage Control

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The power that a single generator feeds into the grid is a function of rotor angle (and hence torque, heat, fuel)

Governor valve

$\dot{W}_{pump}$

$\dot{Q}_{out}$

$\dot{Q}_{in}$

2

1

Source: Wikipedia

δ
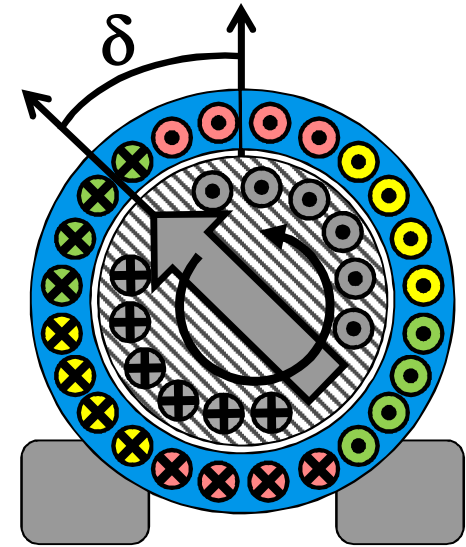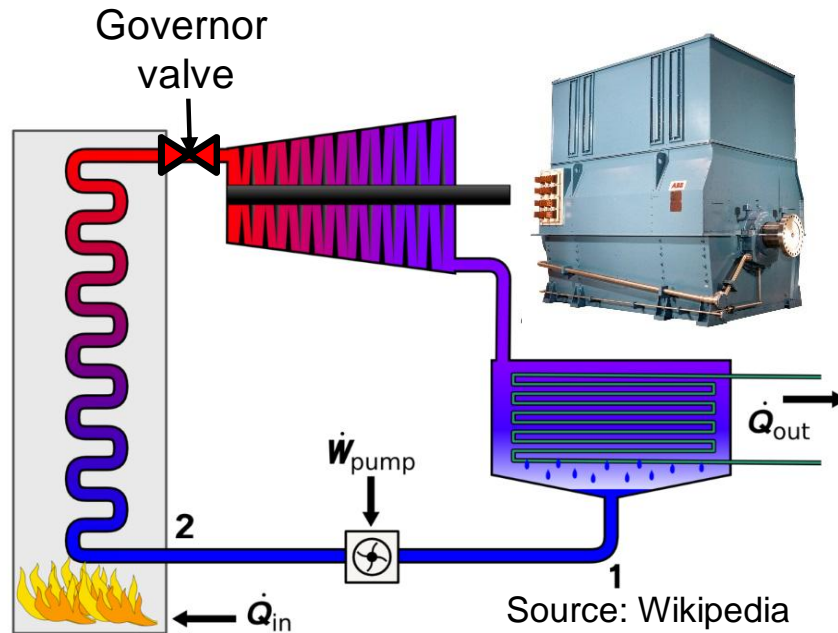
- Three phase stator connected to the power grid, stator field rotates with grid frequency

- Rotor of a synchronous generator and its DC field rotates with the same frequency

- The more torque the turbine provides to the generator shaft, the larger will be the angle between rotor and stator field
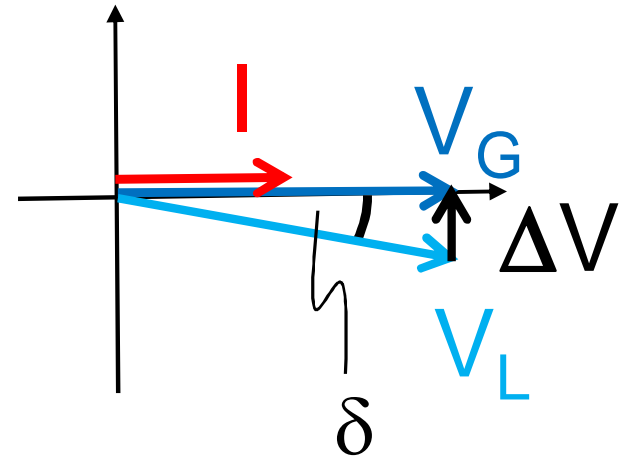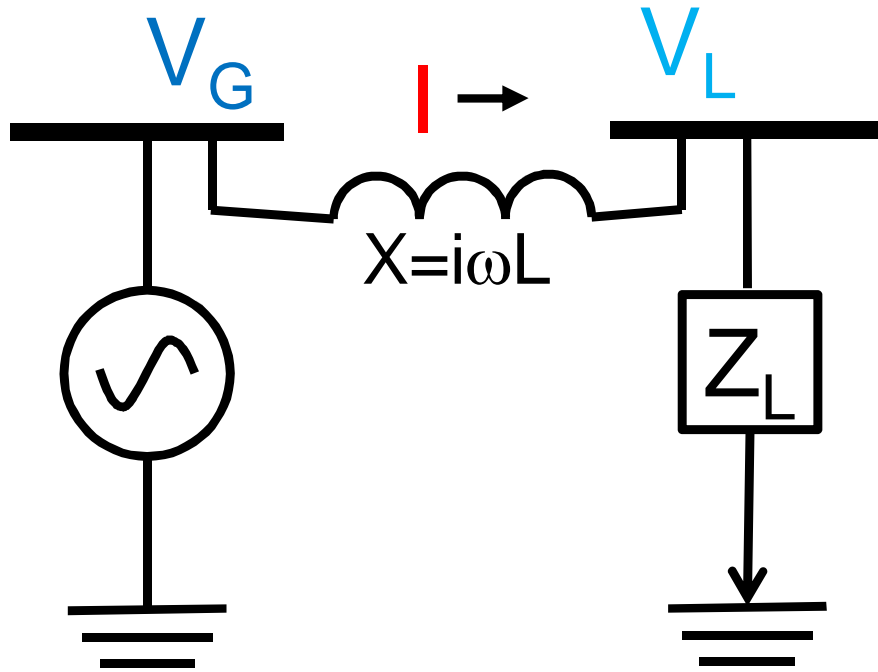
# Operation avoids coming close to the maximum torque where the generator looses synchronization

- $P(\delta) = P_{max} * \sin(\delta)$
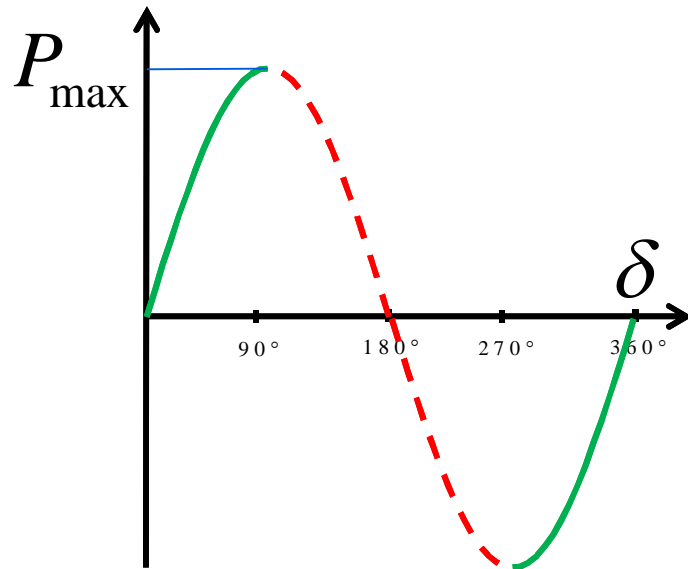
- Stable against small disturbances in mechanical torque or grid voltage for $\delta < 90°$

- Realistic operation point with sufficient safety margin is 45°

The phase angle of the voltage determines the amount of active power transferred by a transmission line

$$P(\delta) = \frac{V_G * V_L}{X} * \sin(\delta)$$

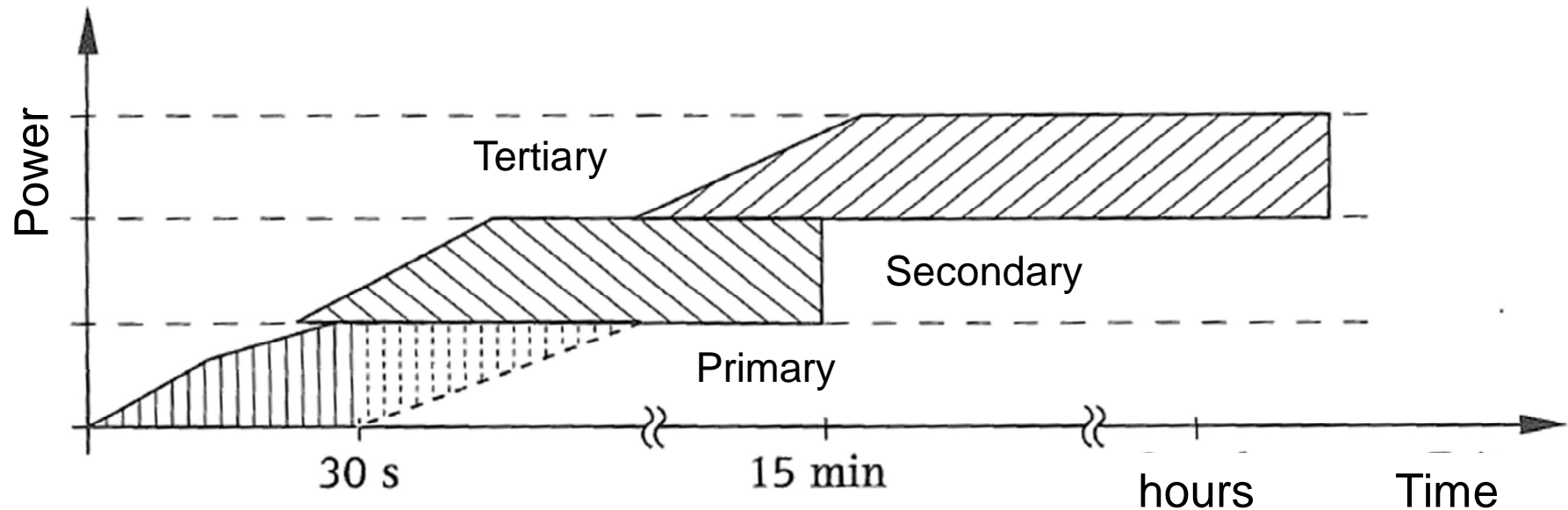# In the interconnected power system thousands of generators operate synchronously
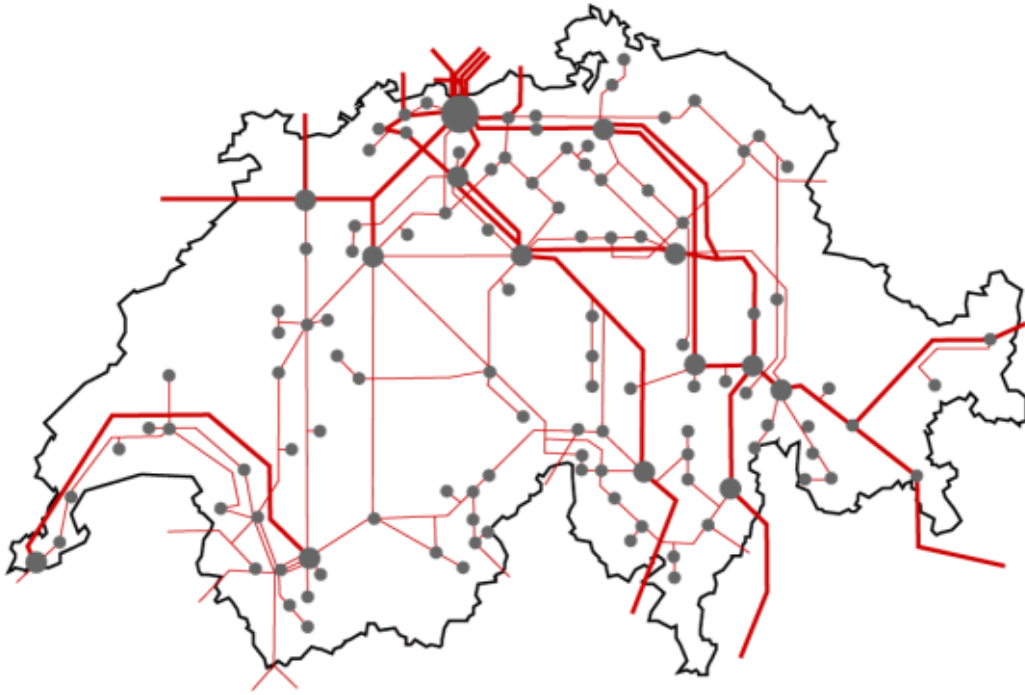
Map of the Swiss transmission grid with major power plants (1.5% of European ENTSO-E grid)

The bicycle equivalent- but think rubberbands instead of rigid chains

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Some power plants contract part of their output for primary, secondary, tertiary reserve (frequency control)


- The power plants contracted for primary frequency control act as a proportional controler

- The power plants contracted for secondary reserve act as an integral controler

- If the tertiary reserve is insufficient, the final option is load shedding ☹
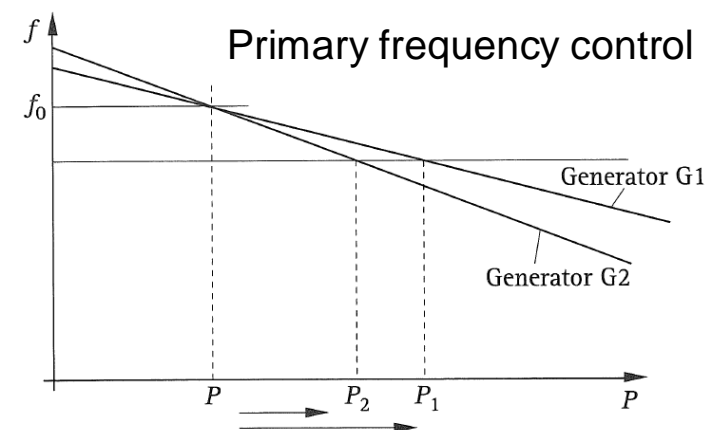
# Tripping of a nuclear power plant in Hamburg on June 28, 2007 measured in Zurich
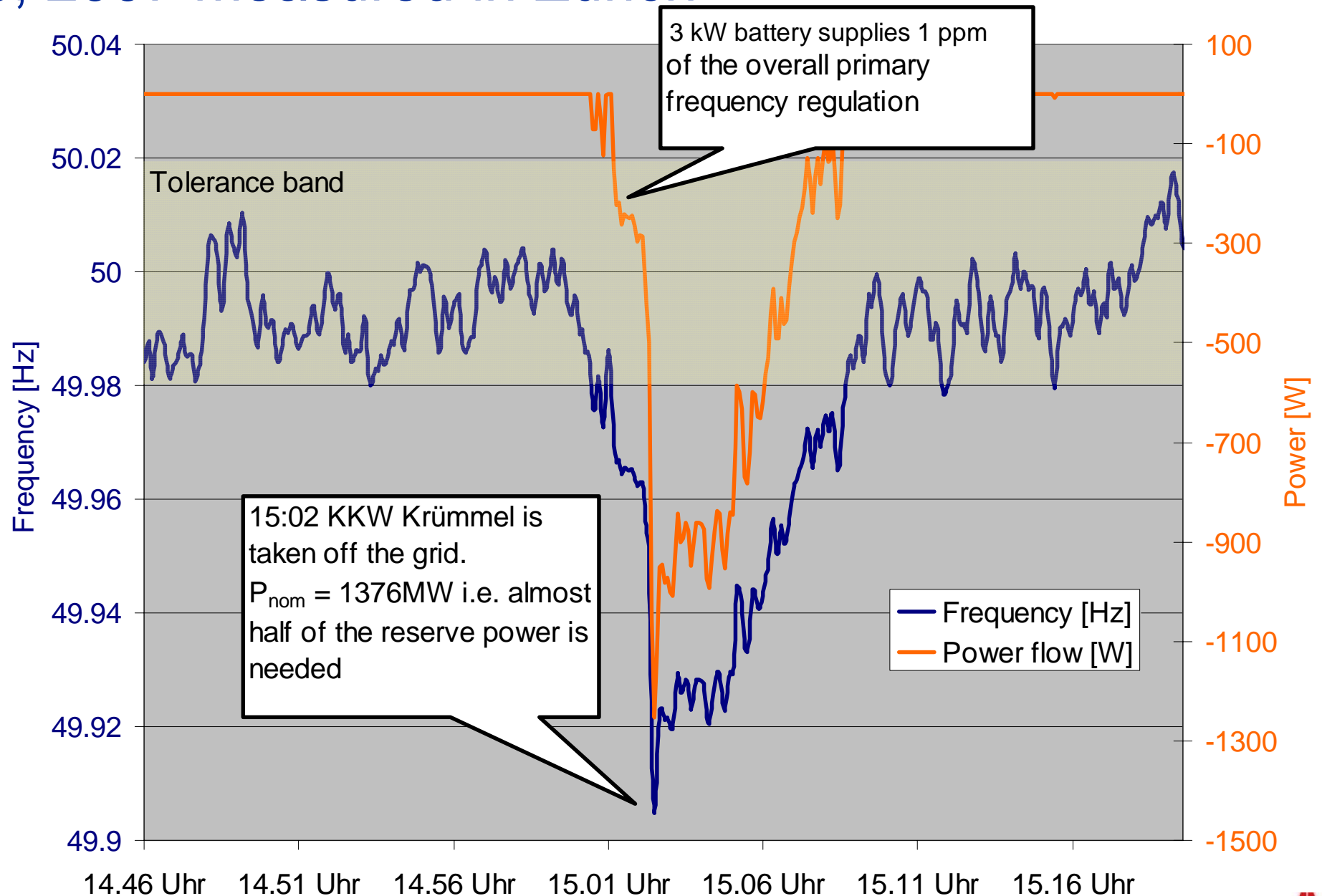
Overhead lines and cables have an impedance, hence the receiving end voltage depends on the load.
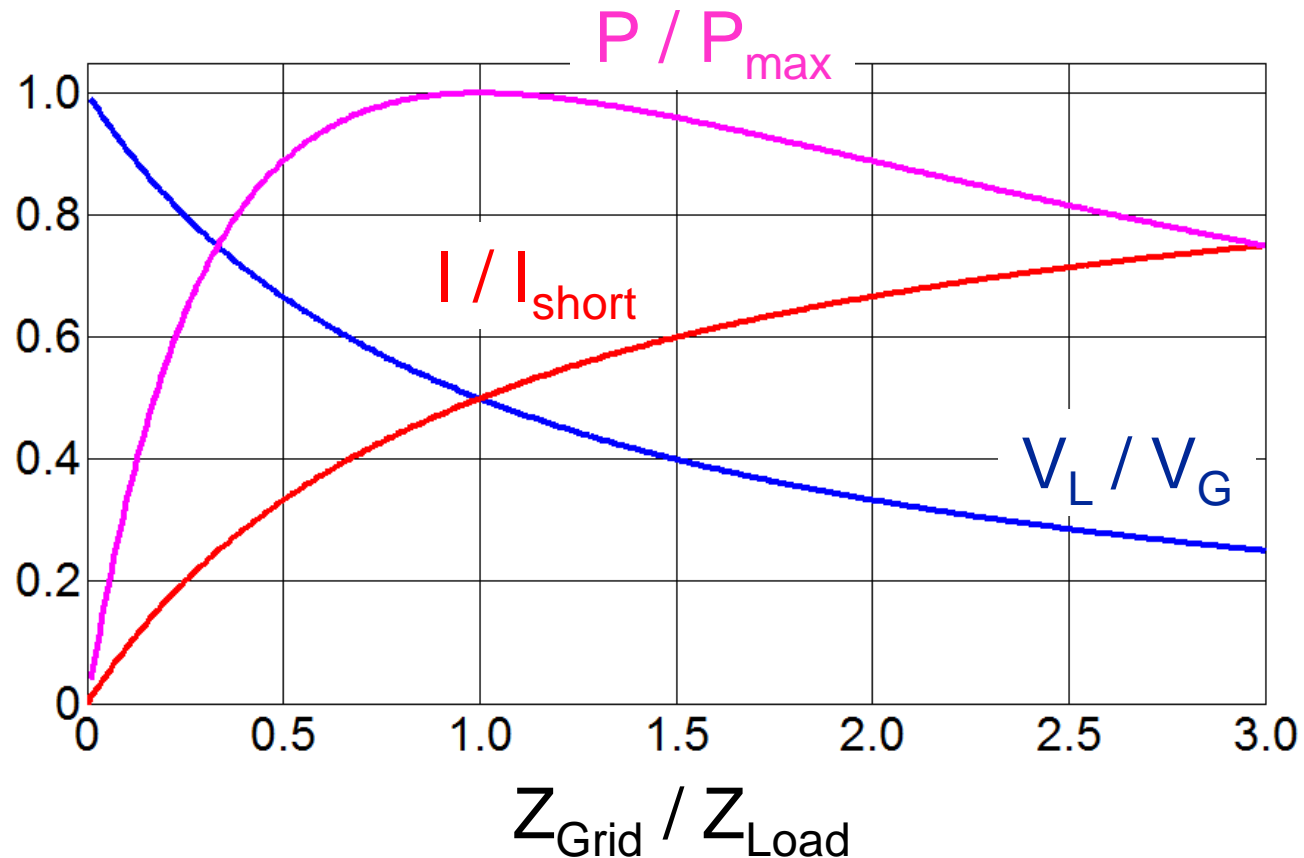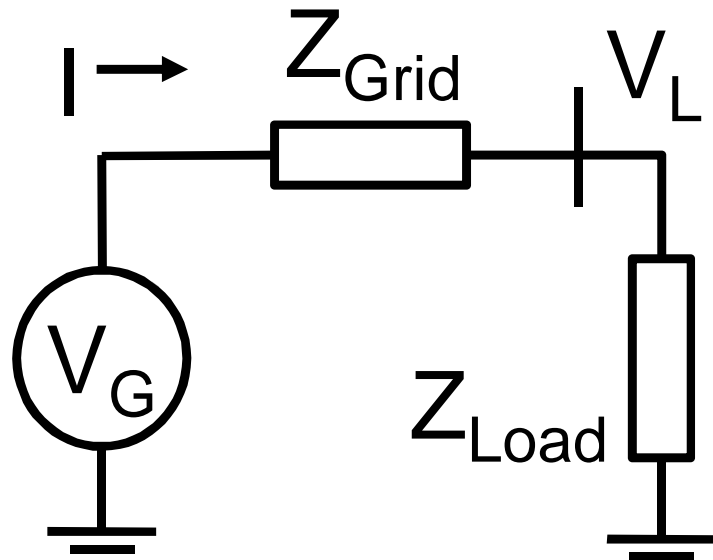
- In this (unrealistic) example Z(Grid) and Z(Load) are both pure resistances and the voltage at maximum power transfer is 50% of the sending voltage.
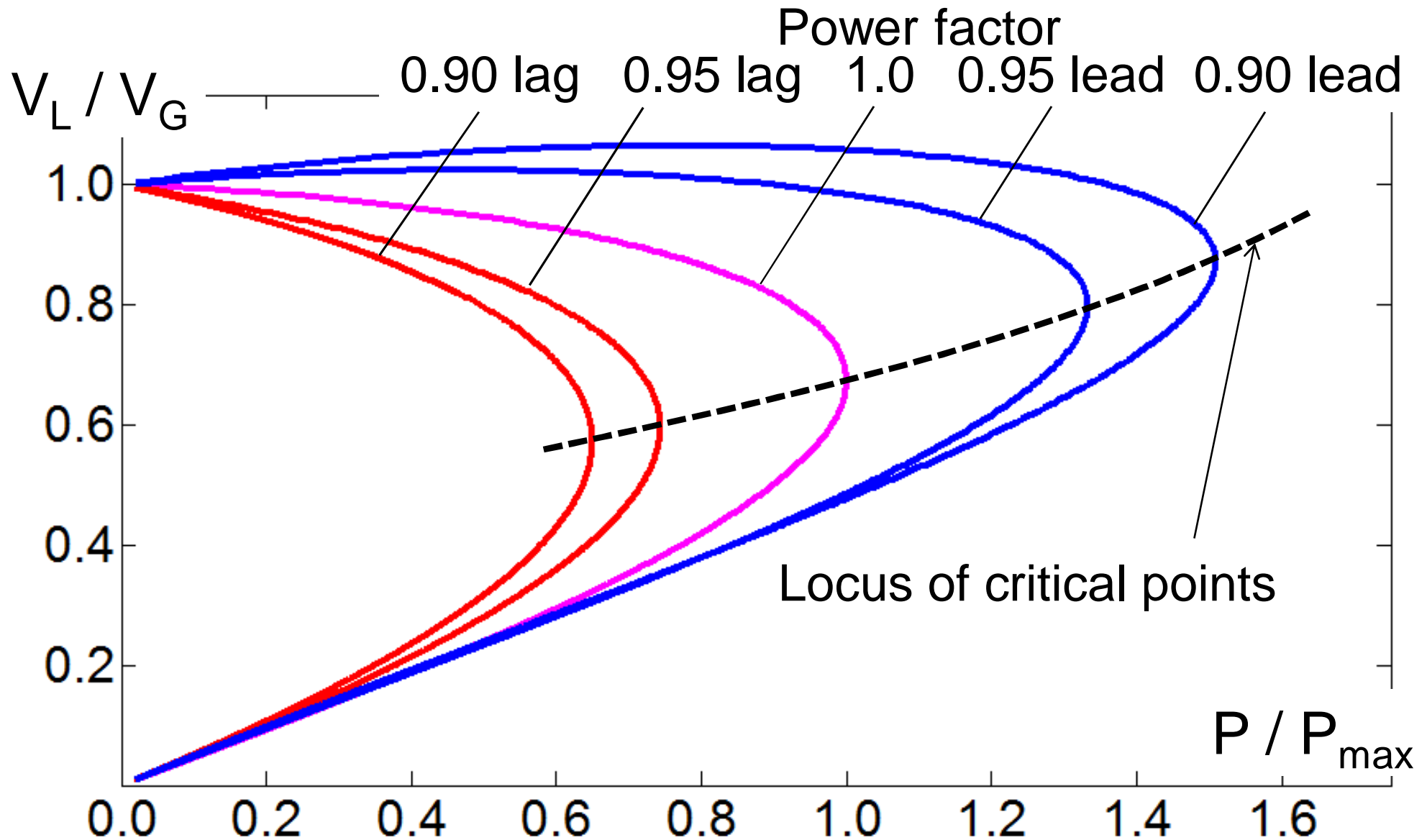
The voltage drop across a transmission line is mainly caused by the reactive power transferred
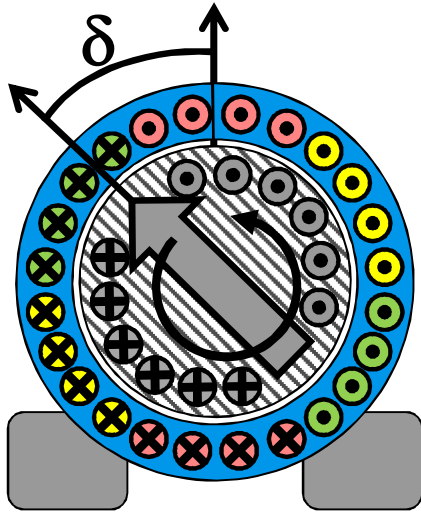
V_G $I \rightarrow$ V_L

$X = i\omega L$

Z_L

V_L V_G

I

ΔV

$$Q(\Delta V) = \frac{V_L}{X} * \Delta V \quad (\text{for } \delta = 0)$$

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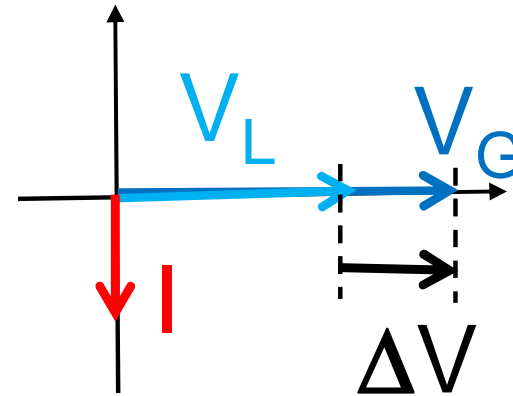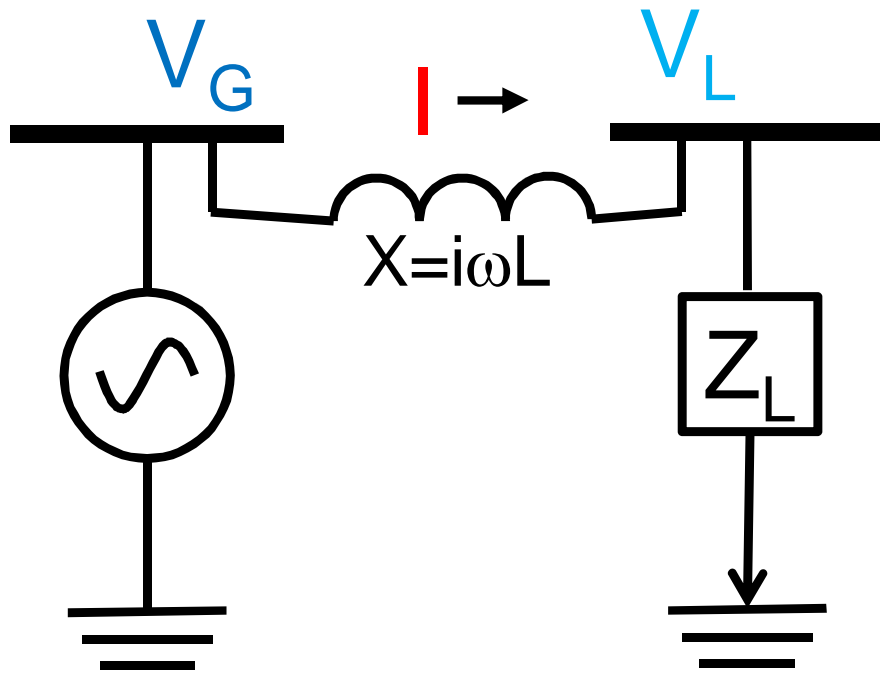
The maximum real power transfer capability is strongly dependent on the power factor of the load

Power factor

V_L / V_G · 0.90 lag · 0.95 lag · 1.0 · 0.95 lead · 0.90 lead

Locus of critical points

P / P_max

Source: After Kundur (1994)

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The rotor excitation of synchronous generators controls the voltage at that grid location

Overexcitation

Capacitive current

Inductive current
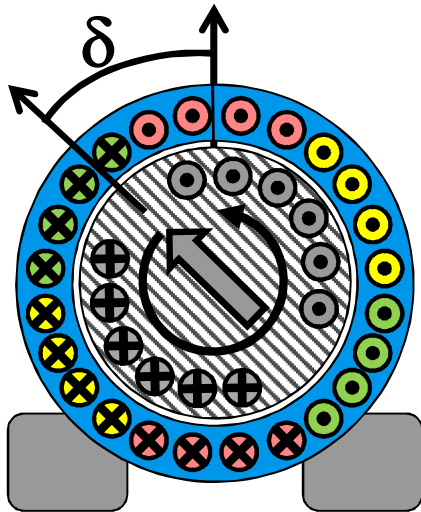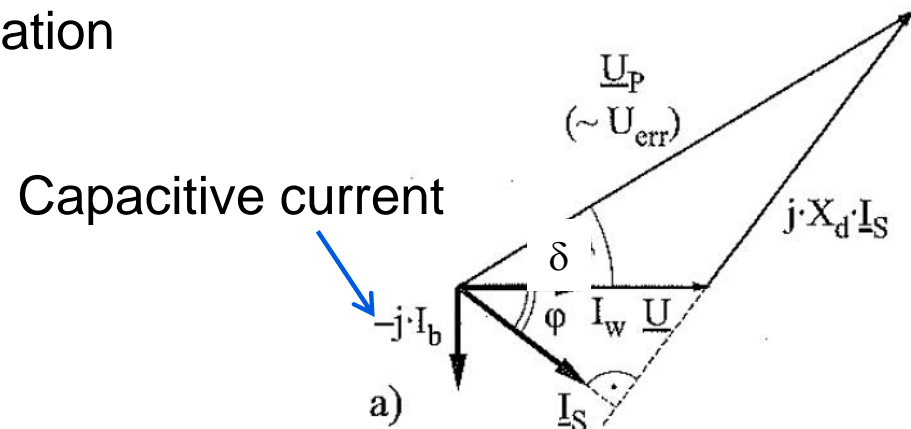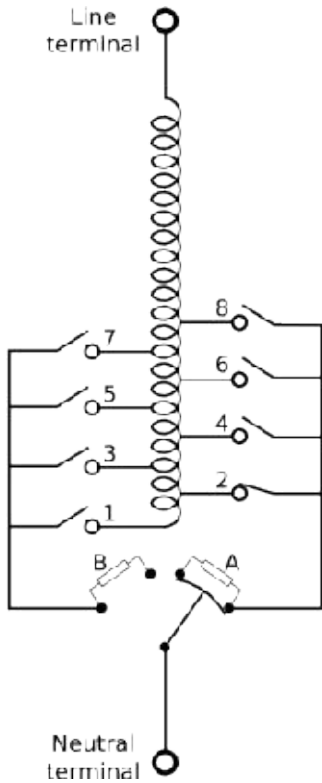
Underexcitation

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A variety of equipment types contributes to the local voltage control by injecting or absorbing reactive power

Shunt capacitor

Shunt reactor

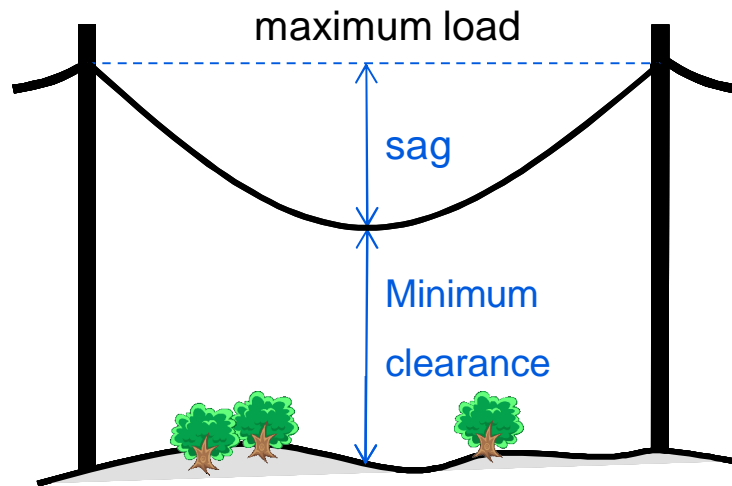Series compensation

On-load tap changers

(in Transformers)

Synchronous condenser (machine without turbine)

Static Var Control

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The elongation due to resistive losses causes a sag of overhead lines

maximum load

sag

Minimum

clearance

- Resistive losses heats up conductor

- Heating causes elongation

- Elongation causes sag

- Sag reduces clearance

- Severe overtemperature causes annealing

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Short lines can be loaded to the thermal limit, longer lines are limited by voltage drop and angle stability
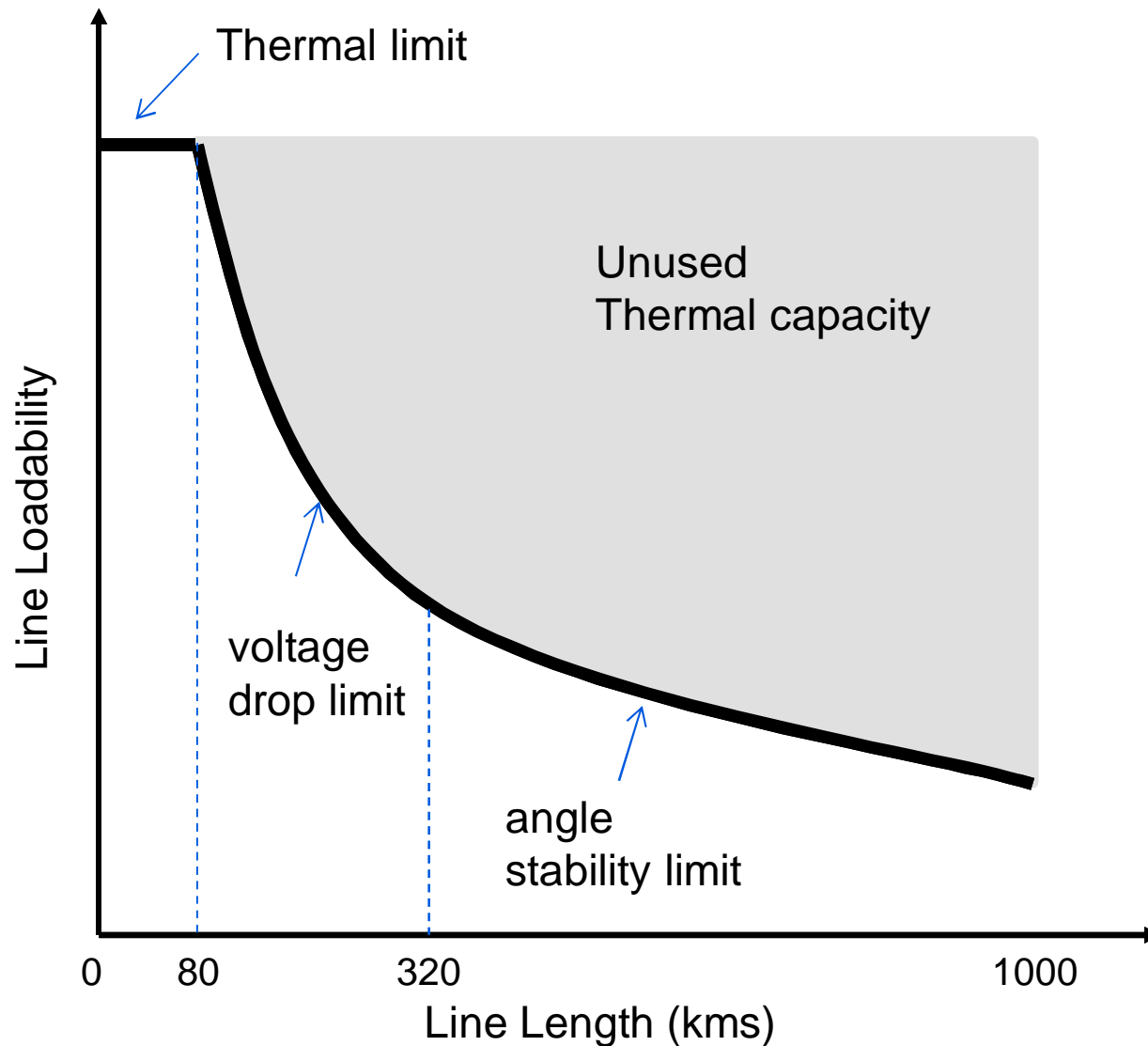
Summary 2 – Stable frequency indicates global equilibrium of active power, stable voltage needs local control of reacive power
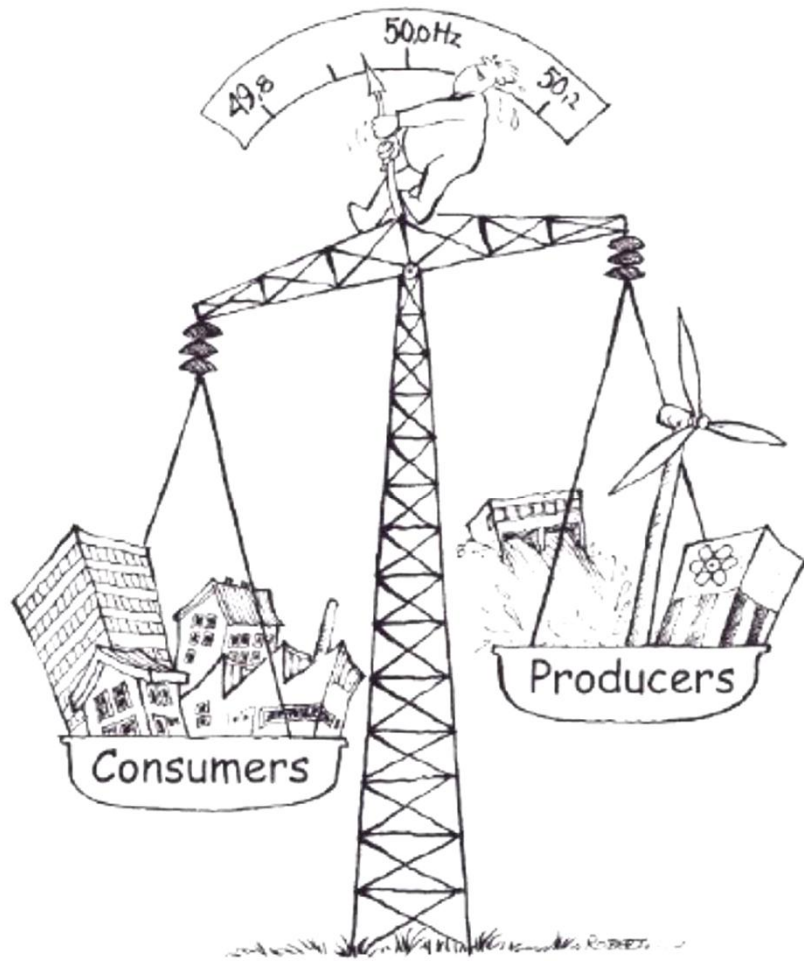

© Svenska Kraftnät 2001

- *If frequency is too low – more power needed*

- Power plants are throttled to be able to ramp power up or down immediately if required

- Tap changing transformers and switched capacitors are the traditional way to achieve voltage stability

(3)

Renewables Integration

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The power electronic converter lets the solar cell look like a synchronous generator
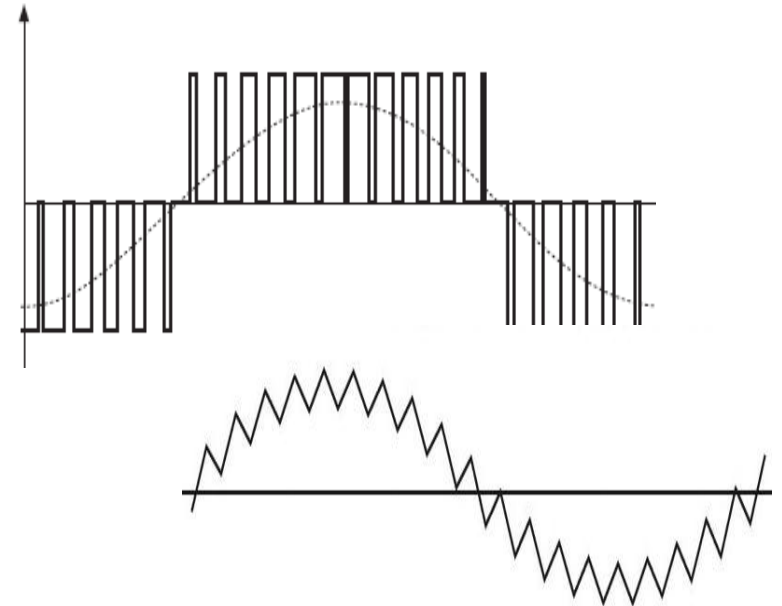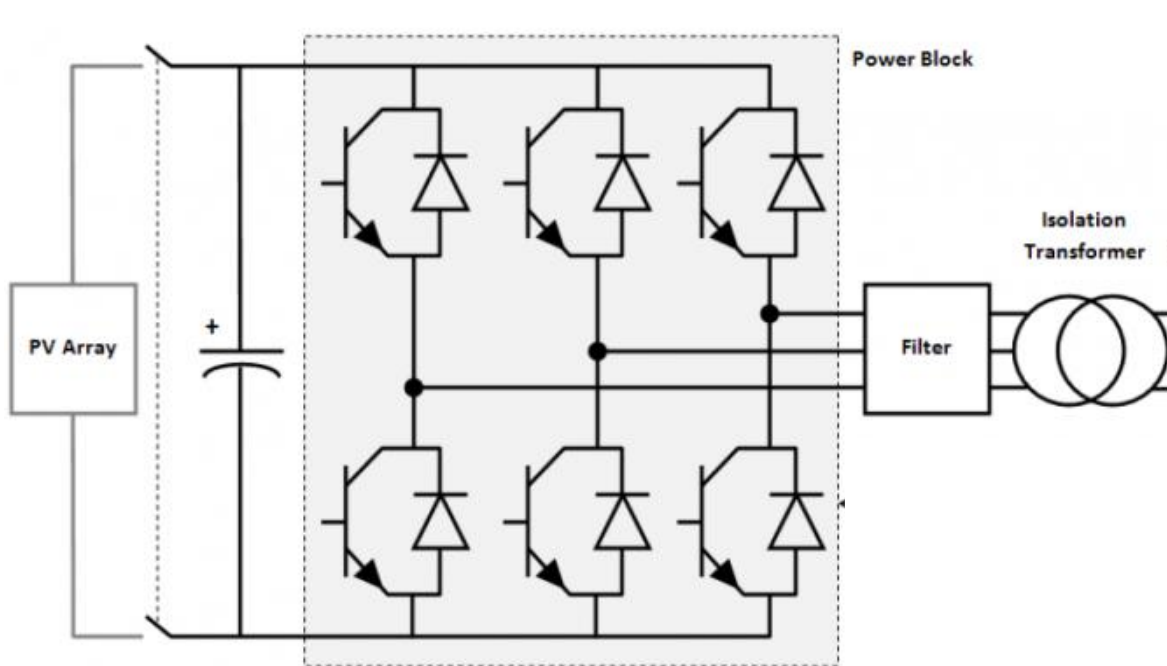
- Power semiconductors switch on/off with high frequency
- Output is smoothened with low pass filters
- Power converters can
  - Maximize the output power of the solar cell
  - While generating or consuming reactive power

Integration of power from wind and sun into the power system is a challenge, but can be done

- New location for feeding power into the grid

  → Grid upgrades and voltage control with power electronic converters

- Larger reserve requirements (prediction error)

  → Renewables can also take the role of reserve (trade-off with energy yield)

- Wind and sun are contingent, statistical energy sources → Need to give economic incentive to

  - grid upgrades

  - complementary power plant technology with fast ramp rate, capacity credits

  - energy storage
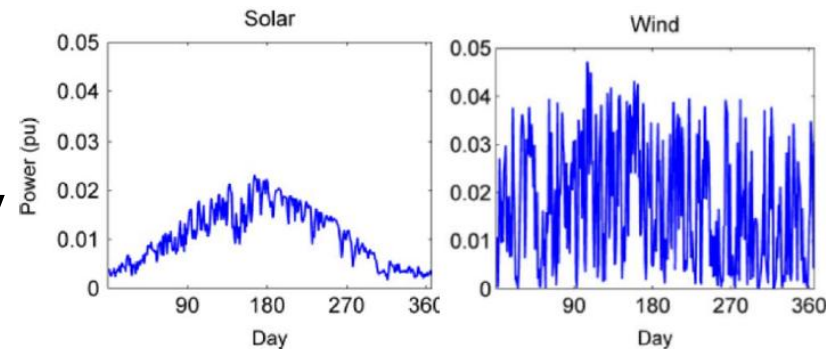
Summary of this Presentation
Physical Aspects of Power Systems Control

(1) High voltage alternating current for low losses. → We have to deal with reactive power.

(2) Frequency low. → More active power needed. Voltage depends on local reactive power balance.

(3) PV and wind power can contribute to voltage control (and frequency control), but their intermittent statistical nature increases the frequency reserve requirements. And they are contingent and statistical by nature.

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Photo: Michael Ploss

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