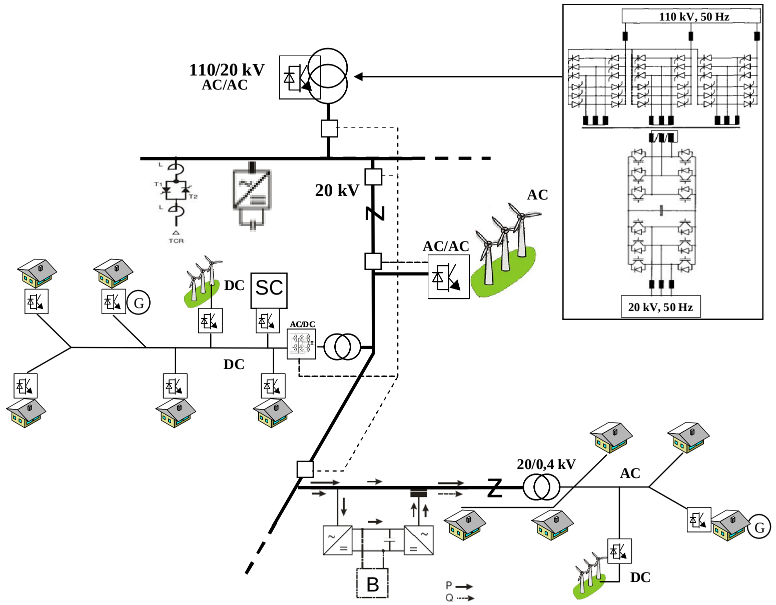
Revolutionary Electricity Distribution System Based on Power Electronics

Power Electronics in Electricity Distribution



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Background

- Hyphothesis:

  “Radical changes are expected in technology, business models and the functionality of electricity distribution. Based on innovative technical solutions and new business models, there are opportunities to develop active electricity distribution systems that tolerate disturbances, are safe, and have positive impacts on the electricity market development.”

- Objective:

  “To develop concepts, methods and algorithms for analysis, simulation and verification of intelligent power electronics-based distribution networks including an interactive customer interface to be applied in the European electricity energy market”

SmartGrids is “reinventing the grid” -Per Hallberg, Eurelectric

Vision

- Characteristics of intelligent electricity distribution system:
  - Market oriented demand and small scale power production control
  - System oriented demand and small scale power production control
  - Energy services motivating for efficient use of energy
  - Improved energy efficiency of whole electricity system
  - On-line management and control of quality of supply
  - On-line network condition monitoring and highly automated control
  - Easy-to-manage network interface for DG and power storages
  - Support intended islanding and operation as independent microgrid
  - Cost efficient network infrastructures
  - Improve reliability and security of electricity distribution
  - Both AC and DC power delivery for optimal grid connections

Research Topics

Questions:

- Technology concepts
- Energy efficiency
- Life cycle cost minimisation
- Material questions
- Component structures
- System integration
- Physical modelling
- Techno-economic modelling
- System management and control
- Risk management
- Safety issues
- Planning methods
- Business models

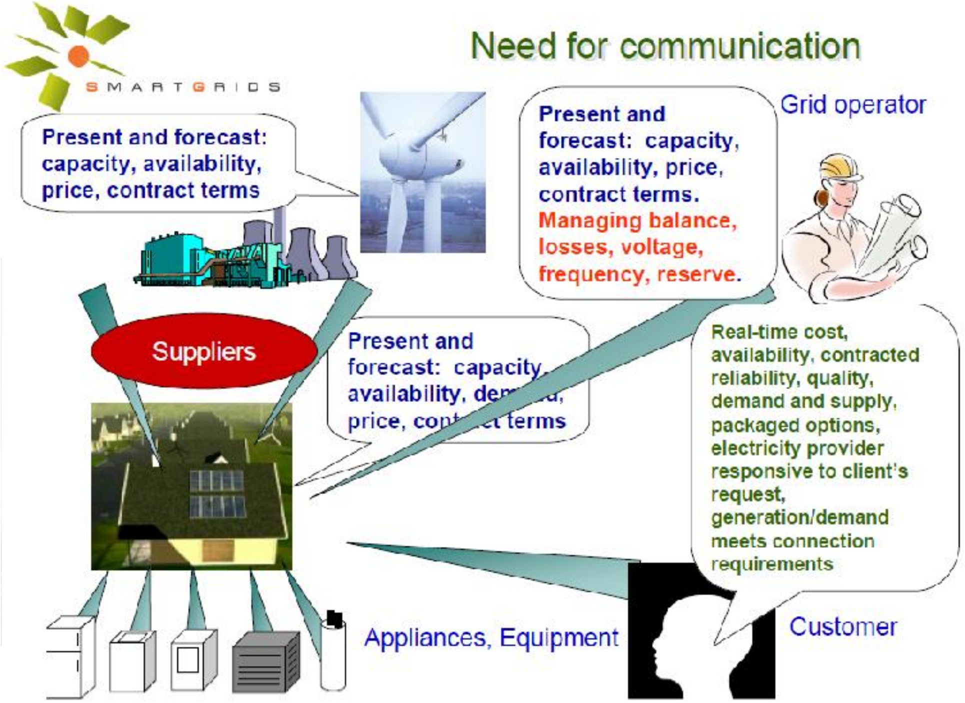
Technologies

- Cabling concepts
- Network topology and structures redesign
- Fault locating
- Automated switching pattern
- Power electronic converters
- LVDC-distribution
- Energy storages and DG
- Intelligent metering and DSM
- Network information systems and optimisation algorithms
- Communication and IT

Goal:

Improvement of energy and cost efficiency of entire electric energy chain by developing both primary technological solutions of electricity distribution networks and intelligent grid connection interfaces for generation, consumption and power storages

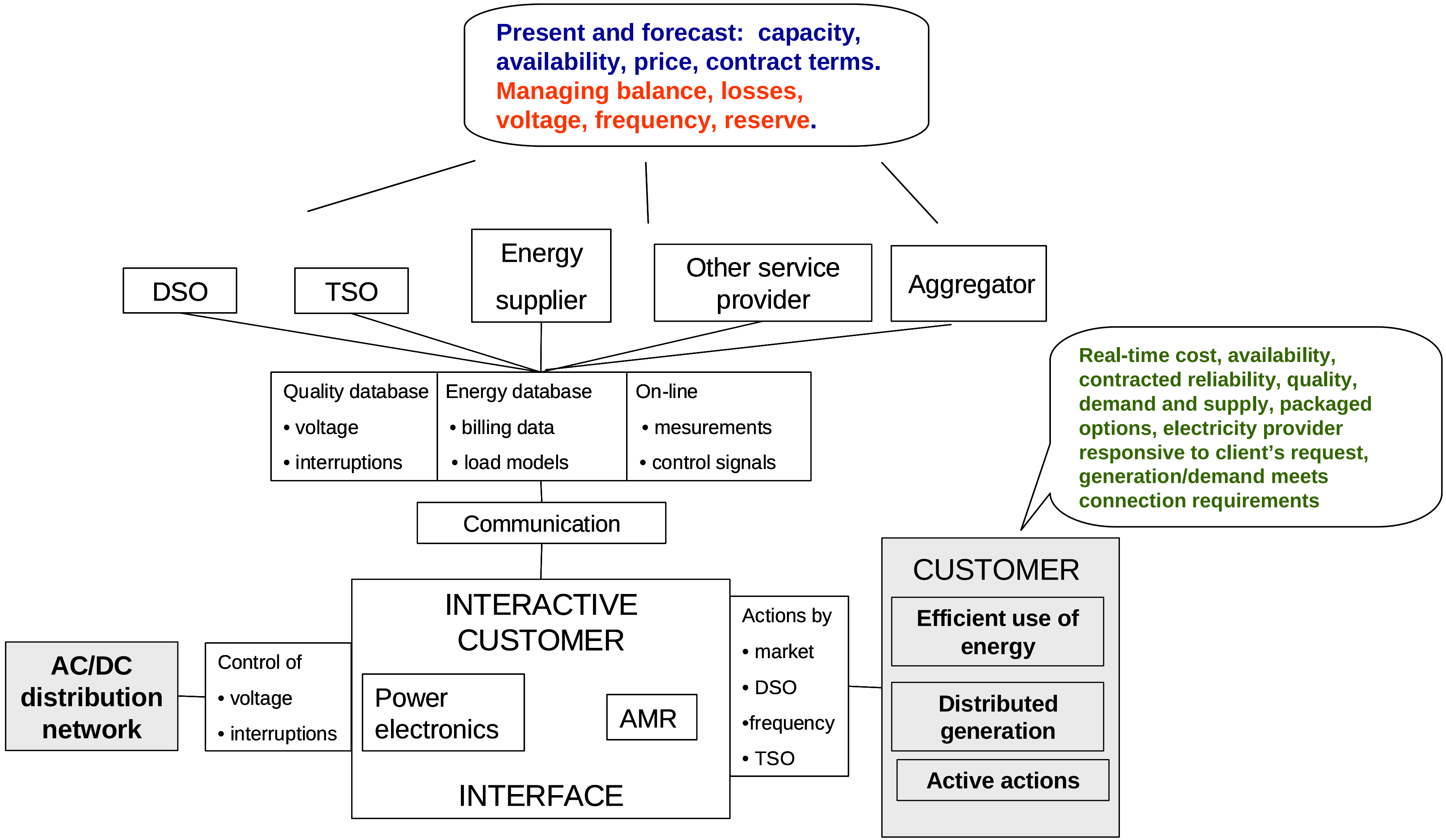
Interactive Customer Gateway



Intelligent Interface is the gateway

Interactive Customer Gateway Concept

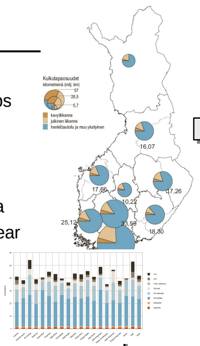
- Interactive customer interface concept:



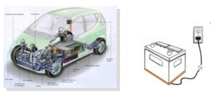
Intelligent EV Charging

Load effect evaluation methodology

National passenger transport survey
- Spatial and temporal variations in passenger trips
- Length of daily trips
- Annual length of driving (region dependent)
- Length of daily trips according to housing type
- Length of daily trips according to residential area
- Length of daily trips according to the month of year
- Length of trips according to the time of day
- Number of cars in households



Properties of electric cars
- Energy consumption, kWh/km
- Capacity of the batteries, kWh
- Charging power, kW
- Required charging time, h/day (battery properties)

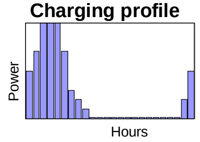


Town planning statistics
- Workplaces according to the area and time of day
- Residential areas (detached houses, terraced houses, apartment houses)

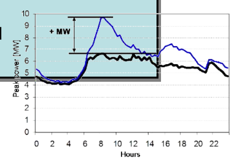
Penetration of electric cars
- Development of electric car markets

Tariffs and supplier
- Distribution fee

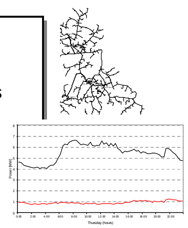
Area-specific additional energy
__ **kWh/day**
(working hours/ leisure time)



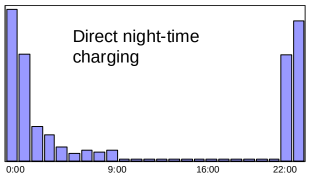
Network simulations and analysis results
- Load flow and loss calculations
- Estimation of reinforcements required

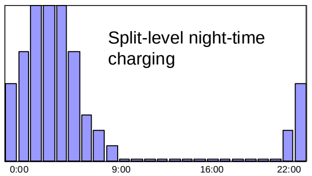


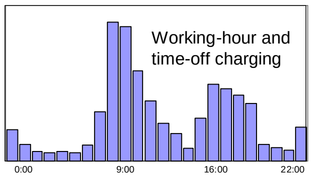
Electricity distribution network
- Network topology and customer information
- Feeder and hourly-specific actual load curves
- Network volume
- Replacement value
- Parameters: loss costs, load growth, lifetime, unit price of network components

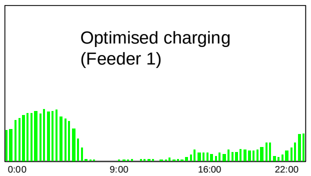


Considered charging alternatives

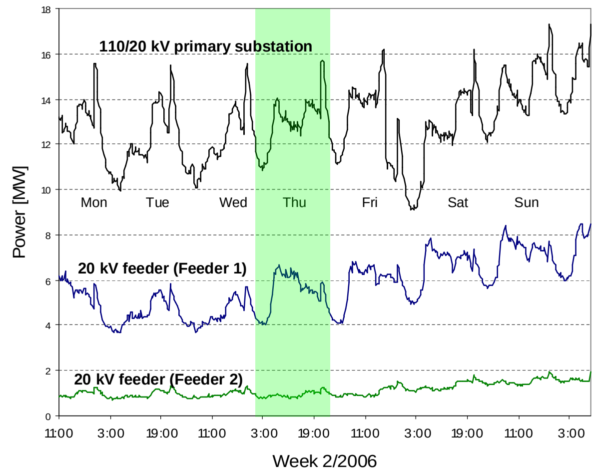


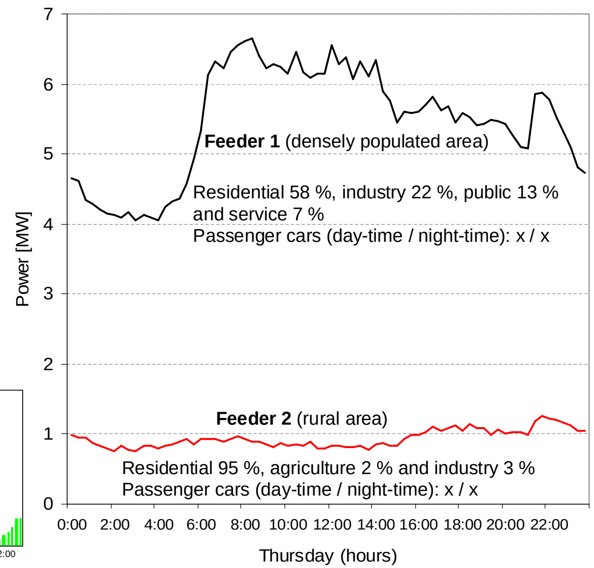




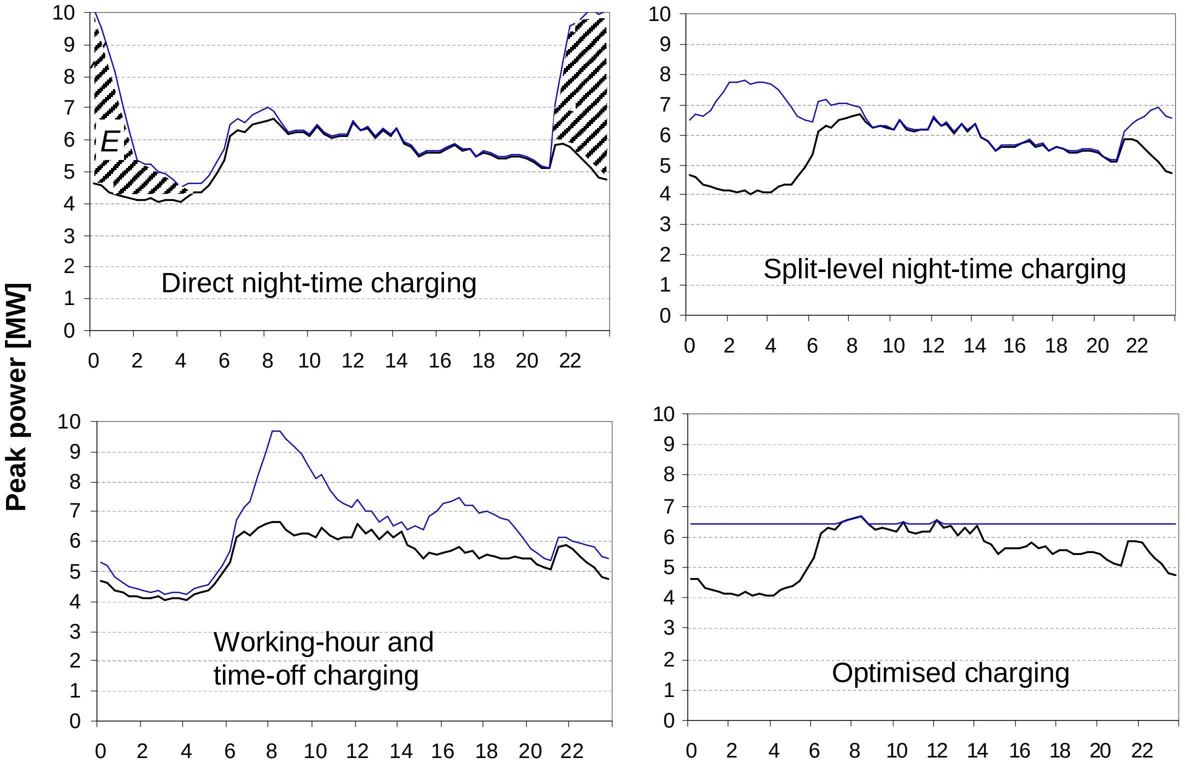


Present state load curves for example area





Intelligent EV Charging



20 kV feeder 1.
(densely populated area)

- Peak load of the day: 6.6 MW
- Minimum load of the day: 4.0 MW

- Number of electric cars: 2000
- Driving distance: 57 km/car,day
- Energy consumption: 0.2 kWh/km
- Charging energy: 11.5 kWh/car,day
  → 22.9 MWh/day for all cars on the feeder

- Charging power: 3.6 kW/car
- Additional power on the feeder: 0 – 3.5 MW (depending on charging method)

Charging energy (*E*) is equal in each charging alternative.

- In optimal charging method
  - Customer interfaces discuss with each other and modern DMS system
  - Interfaces time the charging on the basis of existing network capacity
  - Full exploitation of the network's transmission capacity, and thus, minimisation of the reinforcement needs due to EV load
  - Network losses per transmitted kWh are minimised

Interactive Customer Gateway Concept

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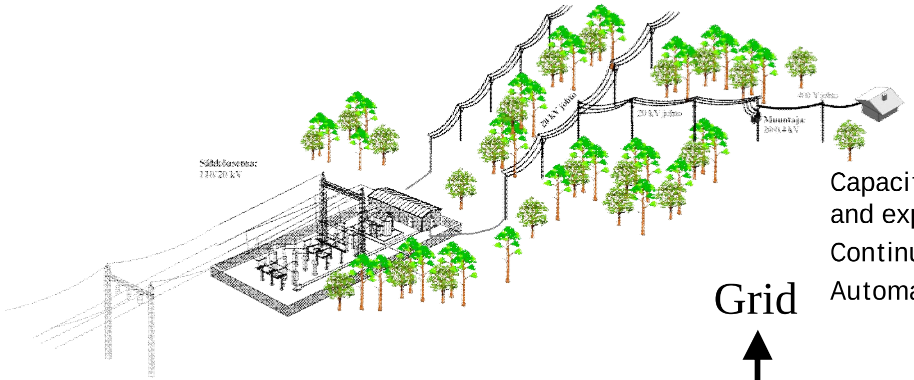


- Single logical interface, four-way connections and control

Grid

Capacity maximisation and exploitation
Continuous measuring
Automated local control

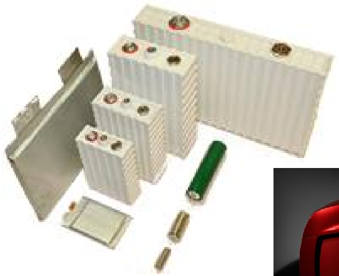
Generation

Photovoltaic
Wind
Fuel cells
Stirling engines
Diesel generators
Etc.

INCA
AC/AC, DC/AC, DC/DC

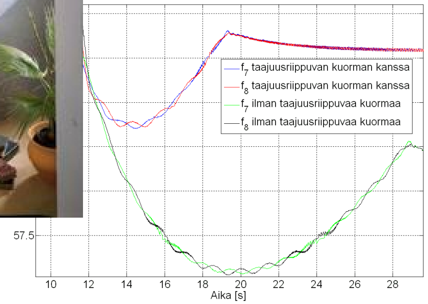
Storages

Batteries
Super capacitors
Superconductive coils
Flywheels
Mobile batteries (EVs)

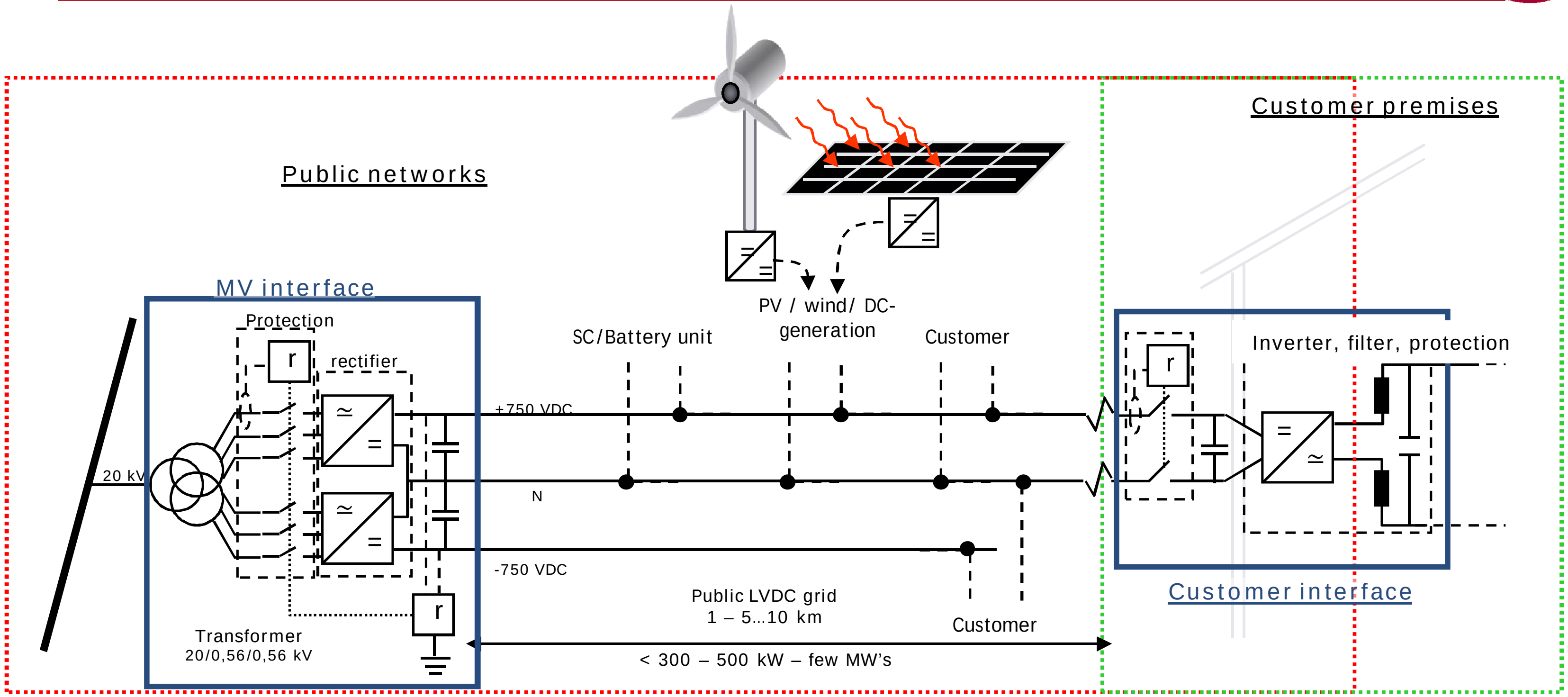


Loads

Frequency and voltage controlled heating
Electronic appliances
Load priorisation



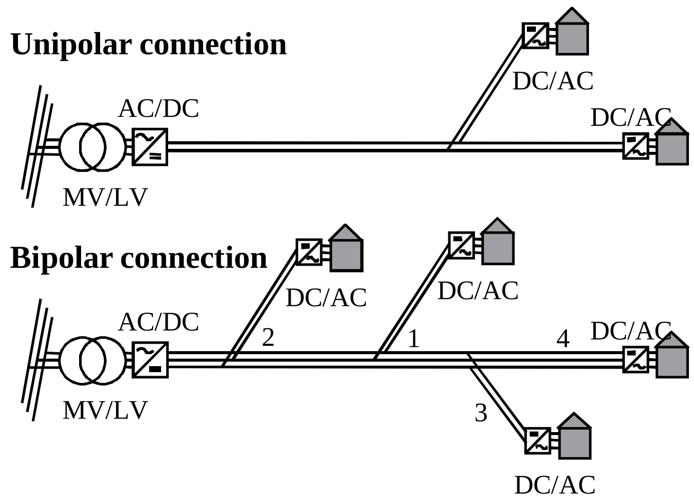
Development of Network Infrastructure
Concept of Low Voltage DC Distribution - LVDC

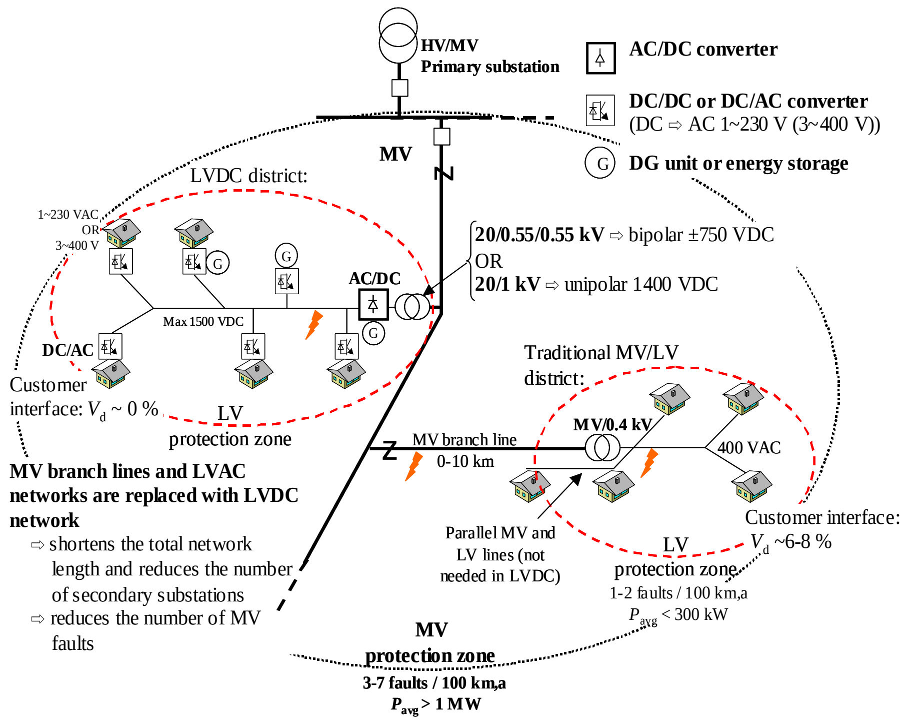


- According to the EU low voltage directive LVD 2006/95/EC rated voltage of a low voltage DC system is between 75 and 1500 VDC
- Technical functionalities set for the development of LVDC system
  - Rated DC voltage: 1500 VDC or ±750 VDC (bipolar), pulsation: max 10 %
  - DC voltage fluctuation in normal operation -25 % - +10 %
  - Customer AC voltage in normal operation 230 VAC ±0% 50 Hz ±0.1 Hz
  - THD U_{cust} and THD I_{cust}: 5 %
  - Converter energy efficiency 98 % (95 % achieved)

LVDC Distribution System Concept

- **An LVDC distribution system comprises power electronic converters and DC connection between the converters**
  - ✓ The entire low-voltage network is converted to DC
  - ✓ Each customer is connected through a DC/AC inverter
  - ✓ Lateral medium-voltage AC lines are replaced with an LVDC grid
- **LVDC system provides**
  - ✓ Safe and reliable electric energy transmission from the MV network to the LV customers
  - ✓ Constantly good-quality voltage supply for customers
  - ✓ An easy-to-control connection point for small-scale generation units and storages
  - ✓ A ready-to-use platform for smart metering, demand management and network control
  - ✓ Low costs of constructing and operating the distribution network

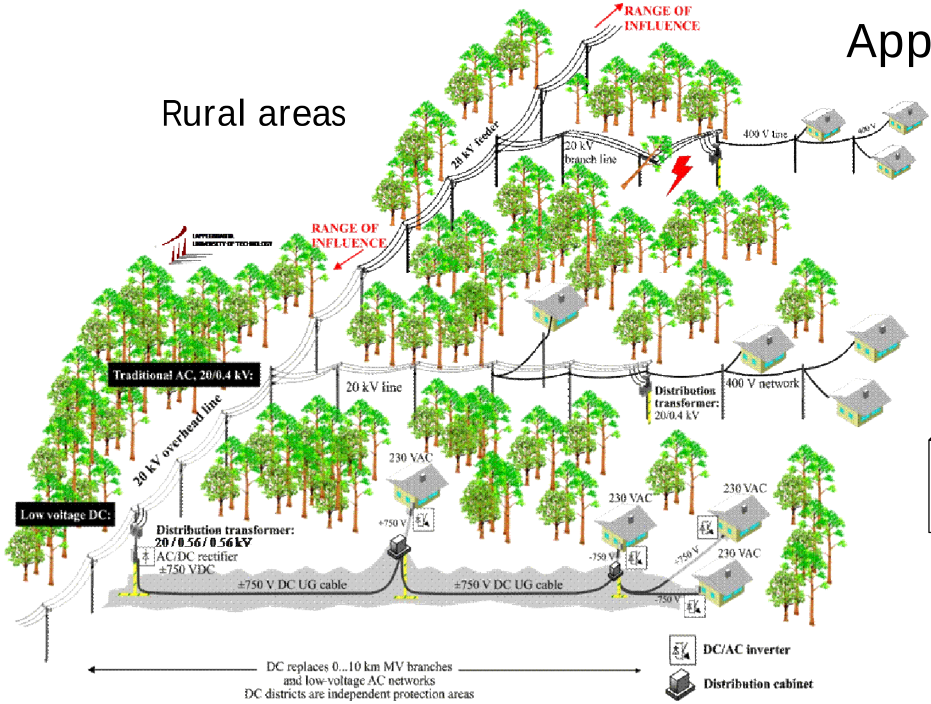




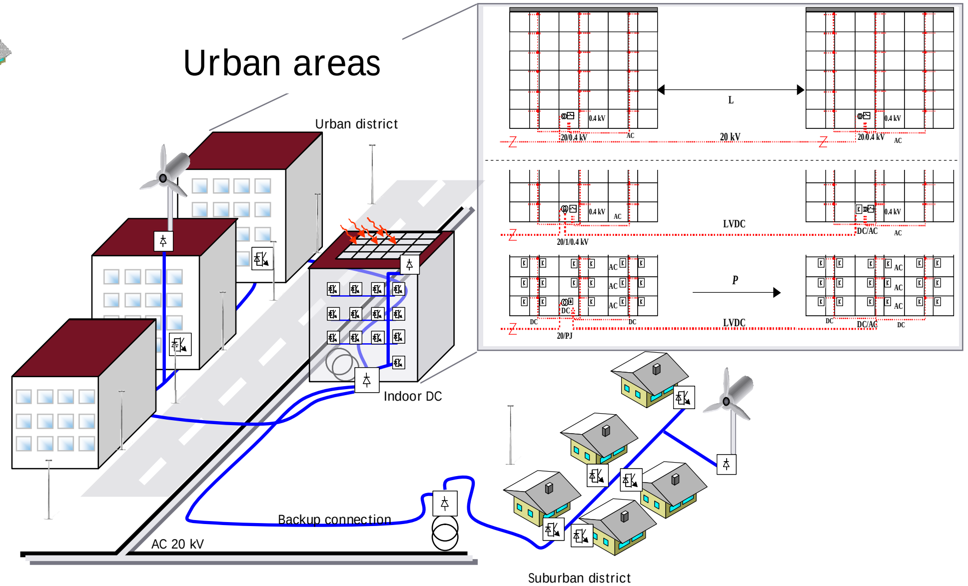
LVDC Distribution System Concept

Applications

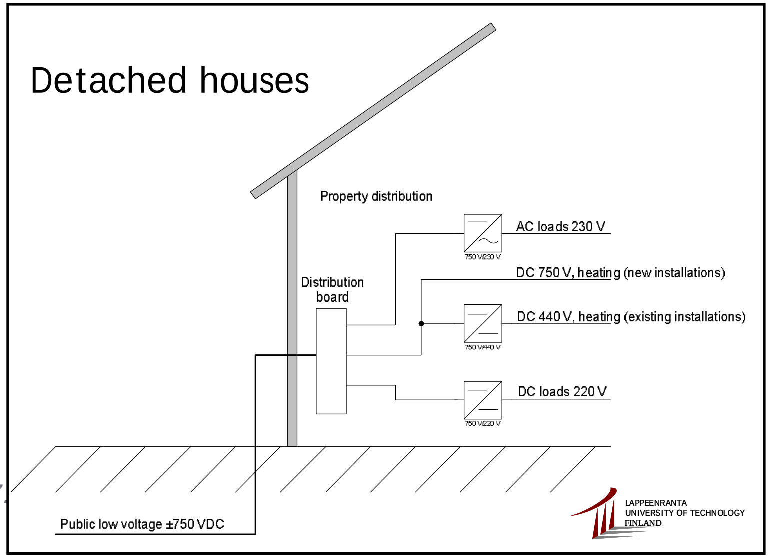
Rural areas



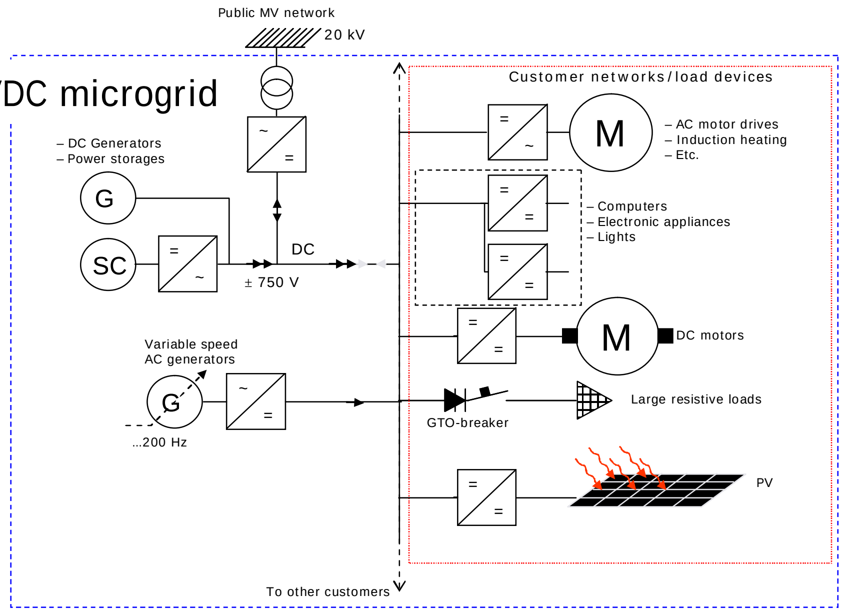
Urban areas



Detached houses



LVDC microgrid

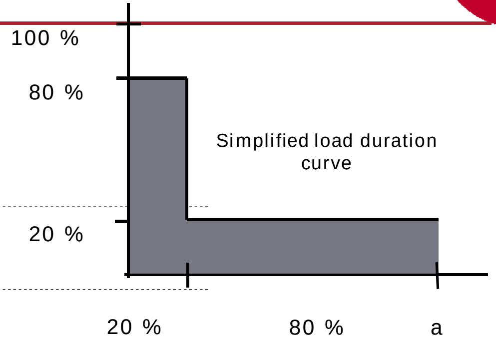


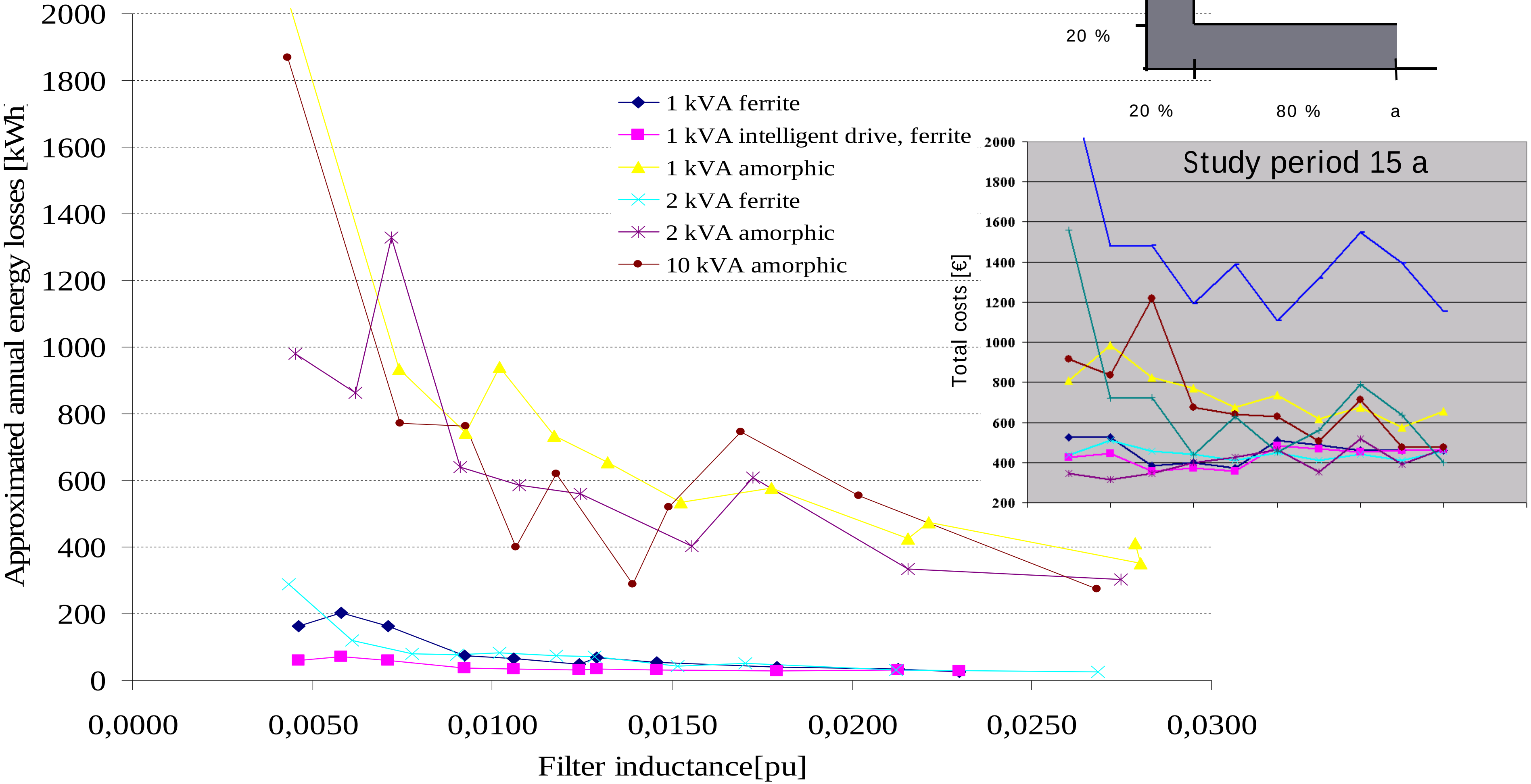
Converter efficiency and filtering

- Converter structures have high impact on
  - Energy efficiency of DC/AC and AC/DC conversions
  - reliability and maintainability of the system
  - Safety and protection system
  - Price of converters
- Main source of losses in converters are the filters and power switches
  - Filter structures and switching control need to be optimised with respect to the life cycle total costs of a converter
  - Main boundary condition is the customer voltage quality
  - Highly variable loading need to be considered through annual loading models especially when the converter is located at customer's connection point
- Also other selections, like the use of parallel converter structures, have impact on energy efficiency and costs but also to reliability and total costs

Converter efficiency and filtering

- Selecting optimal filter structures





Results for different sized inductors are proportioned to 10 kVA output power

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Planning and Calculation Methodologies

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- Considering growing application of power electronic converters poses new challenges for network planning and used calculation methods
  - Characteristics of power electronic converters need to be accommodated
    - Losses of power electronic converters do not follow pure i^2r-dependence
    - Rectifiers cause harmonic distortion
    - Active converters change all consumption to constant power loads that has no voltage dependence
  - Distortion and changes in current and voltage waveforms can not be neglected anymore
    - Extra losses due to distortion
    - Increase of operation temperatures
  - Distribution system stability has to be considered in planning as boundary condition
- In addition the LVDC system add its own special features, like
  - Techno-economically feasible LVDC application targets have to be recognised with respect to MV networks capability to accommodate power electronic loads
  - Selection has to be made between unipolar and bipolar DC system
  - Asymmetric loading of the bipolar DC network has significant impact on system losses and thus can not be neglected
  - Customer connection alternatives in the bipolar system have to be weighted
    - Cost optimum balancing of loads between DC poles
    - number of successive loads connected on a single pole unipolar branch

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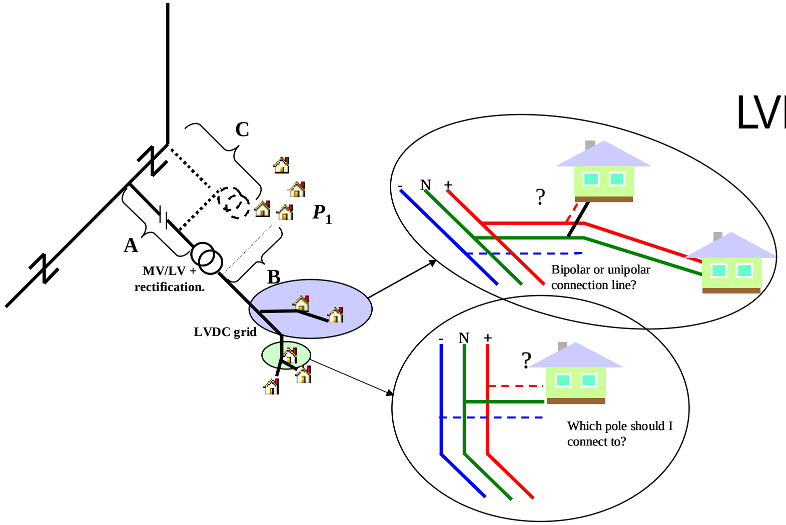
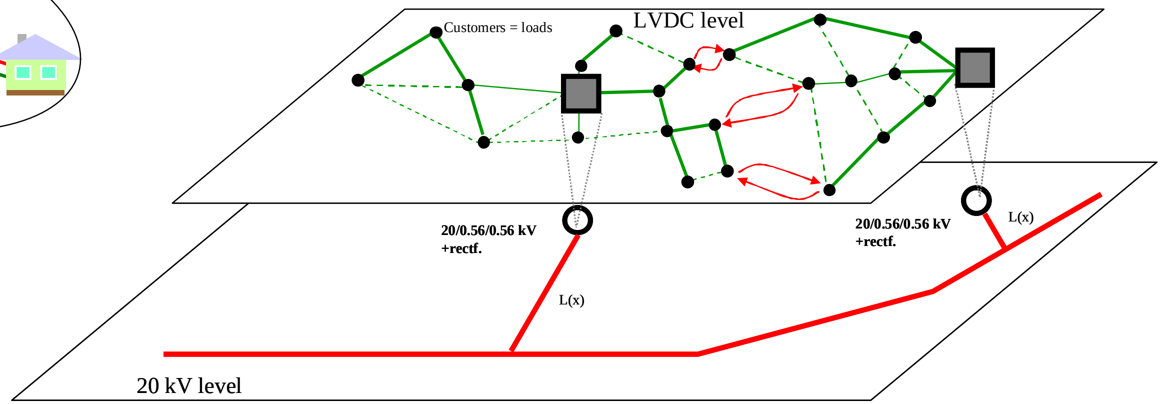


LVDC planning assignment



Load flow calculations

Bipolar DC

Unipolar DC

AC

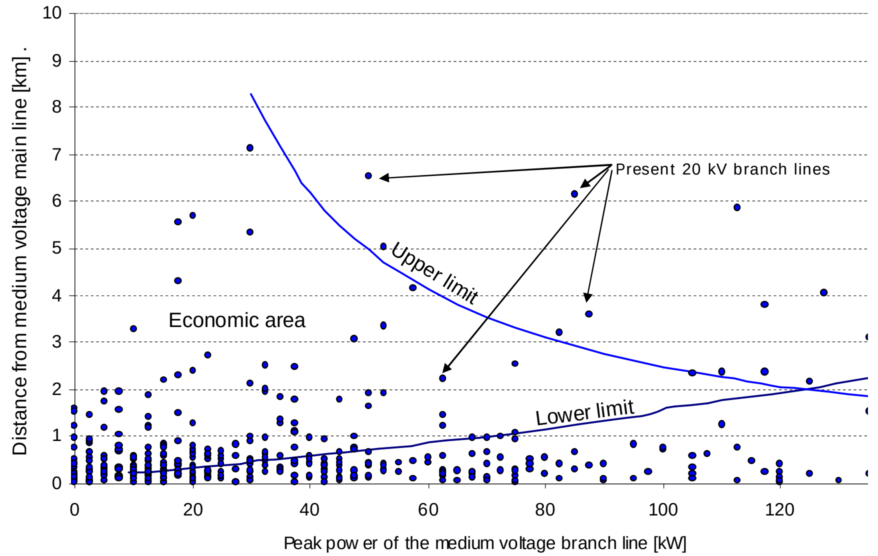
$$\boxed{V_d = V_i - V_{i+1} = \frac{P_{i+1}(t)\cdot R_i + Q_{i+1}(t)\cdot X_i}{V_{i+1}}}$$

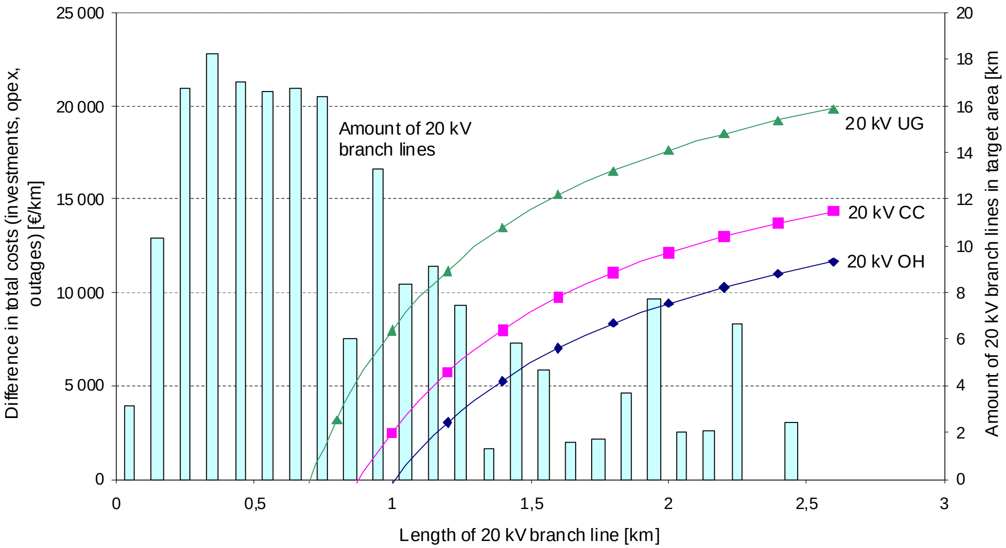
$$V_d = V_i - V_{i+1} = \frac{P_{i+1}(t)\cdot R_{UP,i}}{V_{i+1}}$$

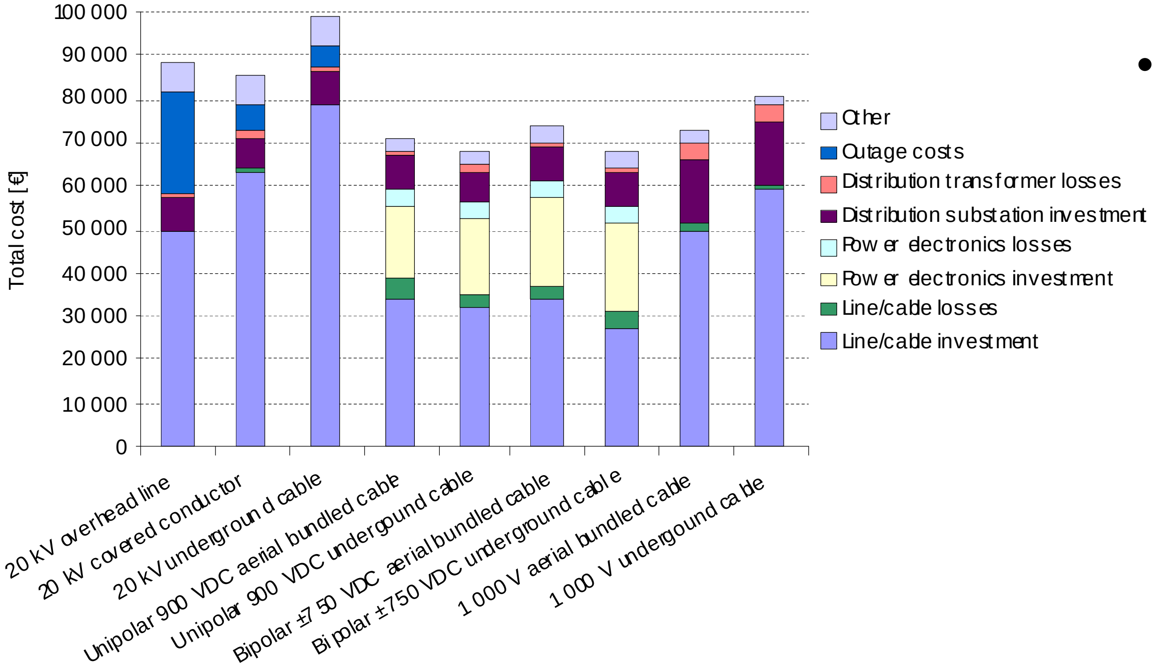
$$V_{1,i} - V_{1,i+1} = \frac{P_{1,i+1}(t)\cdot\left(R_{1,i} + R_{N,i}\right)}{V_{1,i+1}} - \frac{P_{2,i+1}(t)\cdot R_{N,i}}{V_{1,i+1}}$$

$$V_{2,i} - V_{2,i+1} = \frac{P_{2,i+1}(t)\cdot\left(R_{2,i} + R_{N,i}\right)}{V_{2,i+1}} - \frac{P_{1,i+1}(t)\cdot R_{N,i}}{V_{2,i+1}}$$

Planning and Calculation Methodologies
Economical application potential

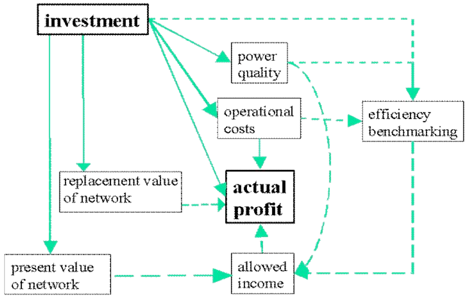






- On the case area, from all MV-branch lines (447 km)
  - ✓ 16-30 % can be economically replaced with LVDC (vs. MV-OH)
  - ✓ 19-31 % can be economically replaced with LVDC (vs. MV-CC)
  - ✓ 24-34 % can be economically replaced with LVDC (vs. MV-UG)

LVDC and operational environment



Regulation

- Total cost efficiency requirement
- Power quality requirements
- Revenue of investments

Reliability

- Network reliability
- Climate change – more major events
- Customer expectations for security of power delivery

Climate change

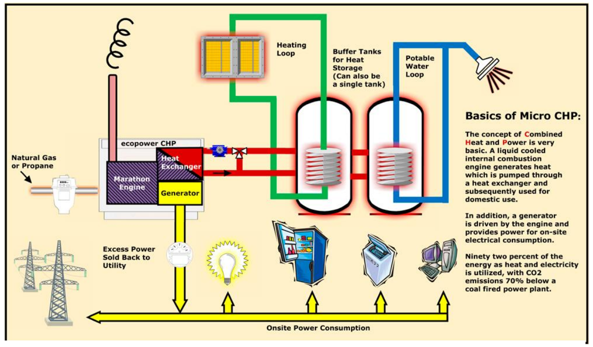
- Changes in energy usage patterns
- Emission cut down requirements
- Improving energy efficiency of energy chain

Increase of extreme climate conditions

Power electronics in electricity distribution

Aging infrastructure and developing installation techniques

- Growing amount of network renovation
- Cost efficiency of traditional network structures
- Change in society – concentration in large communities
- Decreasing prices of underground cables and improving installation techniques



DG and energy storages

- Network connection of storage systems: super caps, superconductive coils, fly wheels, electric vehicles
- DC generation systems: PV, fuel cells, hybrid cars, small turbine units
- Change in the role of customers towards more interactivity with the power system

Power electronics

- Positive price development
- Improving reliability
- Increasing life times
- Constantly developing technical properties
- Intelligent system management (AMR functions, load shedding, etc.)

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