LVDC-Redefining Electricity

First International Conference on Low Voltage Direct Current

New Delhi, India,
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International Electrotechnical Commission

Bureau of Indian Standards

Application of LVDC networks in rural distribution in Finland

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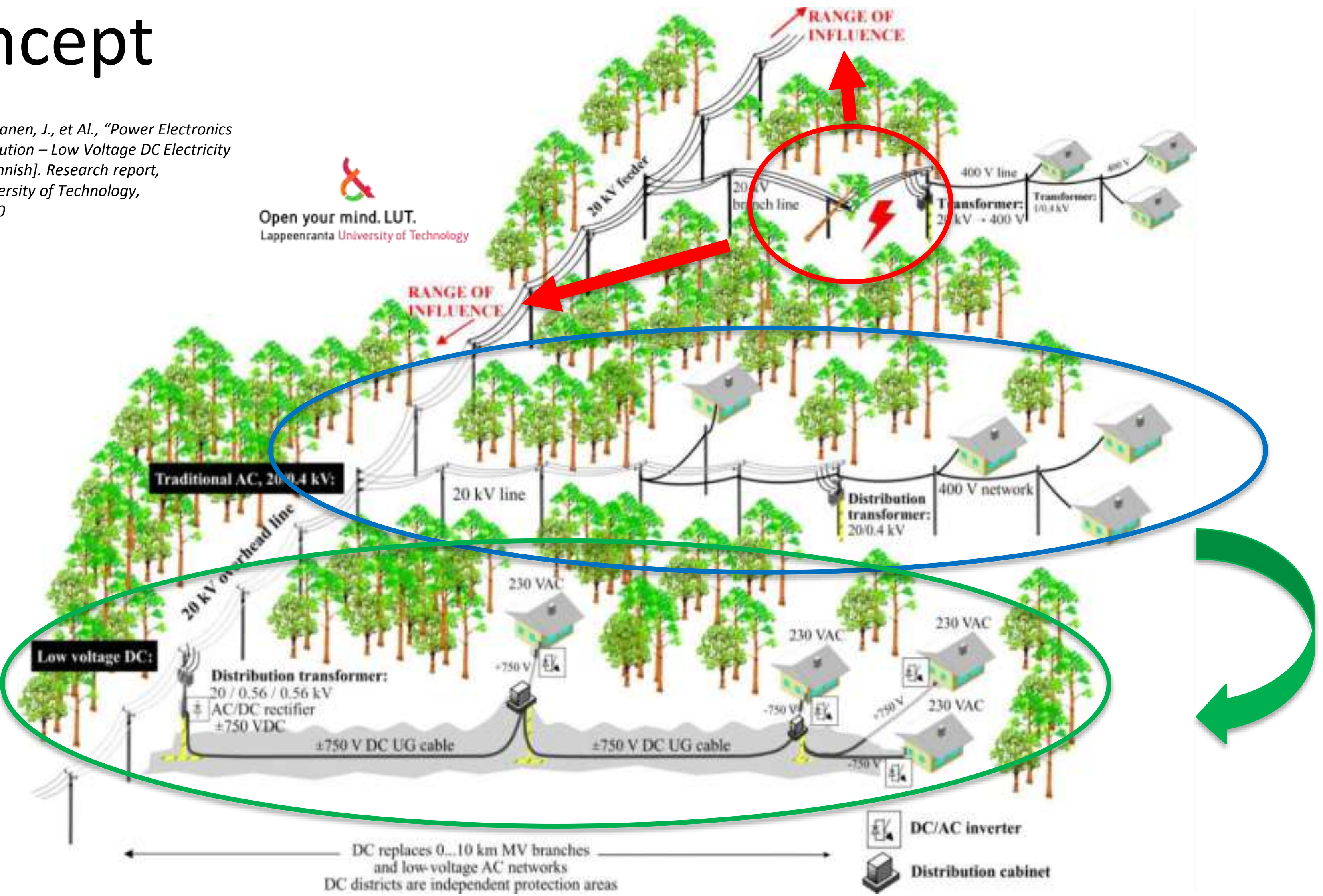
Rural-Area LVDC Distribution System Concept

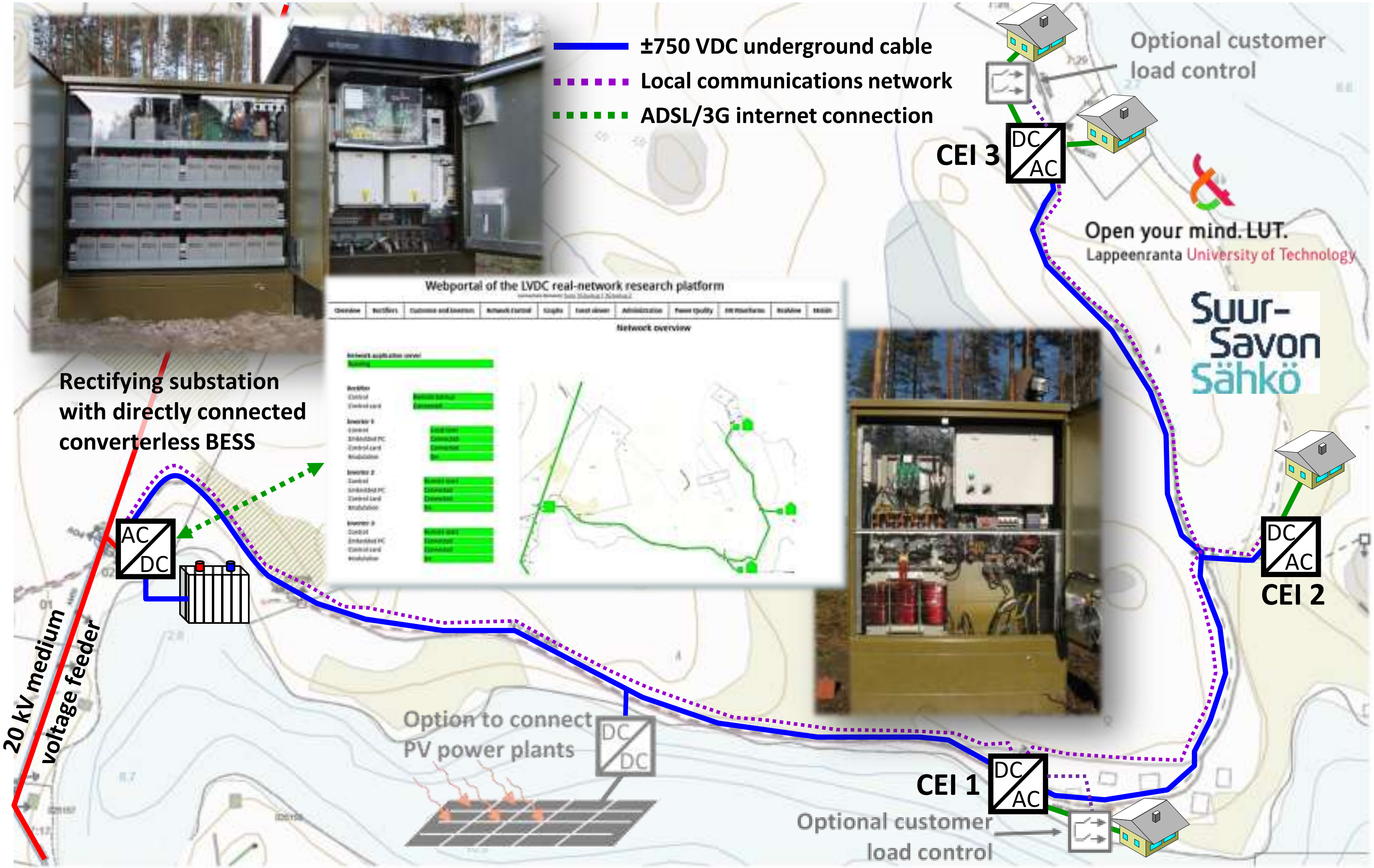
Adapted from: Partanen, J., et Al., "Power Electronics in Electricity Distribution – Low Voltage DC Electricity Distribution", [in Finnish]. Research report, Lappeenranta University of Technology, Lappeenranta, 2010

Open your mind. LUT.
Lappeenranta University of Technology



IEC

LVDC Research Site (LUT/SSS)



LVDC Research Site – General

- Commissioned in Jun. 2012 → 1200+ days of operation
- Co-operation of LUT and Finnish power company Suur-Savon Sähkö Oy (SSS)
- The objective was to implement a combination of a **fully functional LVDC system** and a **flexible research platform** to a **public distribution network**
- Basic features
  - 1.7 km long terrain-isolated bipolar ±750 V DC network
  - Three three-phase customer-end inverters (CEIs) with galvanic isolation, 16 kVA
  - Four actual electricity end-users
  - Local communications system with doubled connection to backhaul ICT
  - Web-based control and monitoring

Nuutinen, P., et. al. “Research site for low-voltage direct current distribution in an utility network - structure, functions, and operation”. *IEEE Trans. Smart Grid*, vol. 5, no. 5, pp. 2574–2583, 2014.

Phase 1: (Jun. 2012 - Oct. 2013)
- Initial start-up, unidirectional powerflow
- 12-pulse half-controlled thyristor bridge rectifier

Phase 2 (Nov. 2013 - Oct. 2014)
- Bidirectional powerflow
- Two grid-tie rectifying converters, 35+35 kVA

Phase 3 (Oct. 2014 onwards)
- Energy storage integration
- Converterless directly connected BESS, 60 kWh

LVDC Research Site – Functionalities

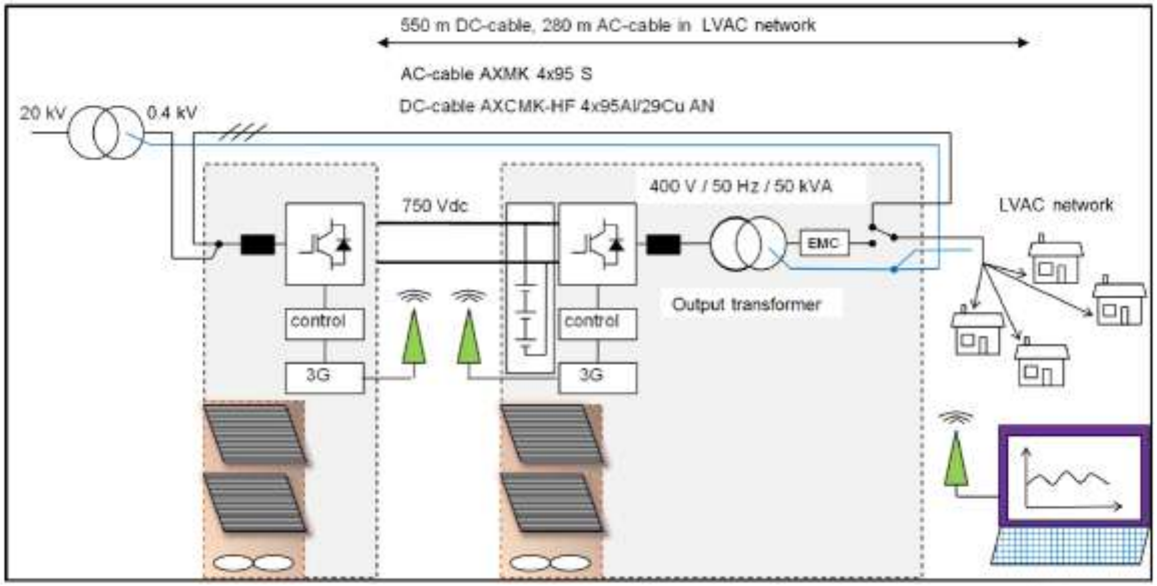
- BESS current/power control
  - Constant current (CC) stage during charging and discharging
- DC network voltage control
  - Constant voltage (CV) stage during charging and discharging
- Rectifier current/power control
  - MV grid supply power control → load leveling
- Island mode
  - Rectifier zero-current mode
  - Disconnection from the MV network
- Ancillary services for grid operators
  - MV grid voltage and reactive power control
  - Contribution to power system frequency control
- Customer-end load control / demand response (2016)

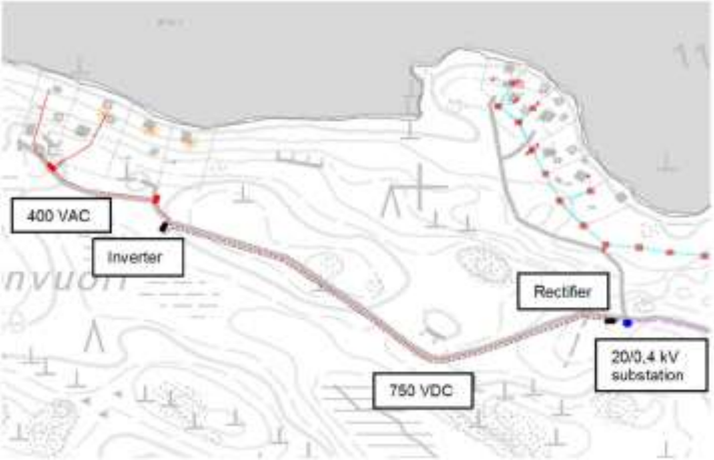
Rectifying Substation

Grid-Tie Rectifying Converter and BESS

Customer-End Inverters

Point-to-Point LVDC Network (Elenia/ABB)

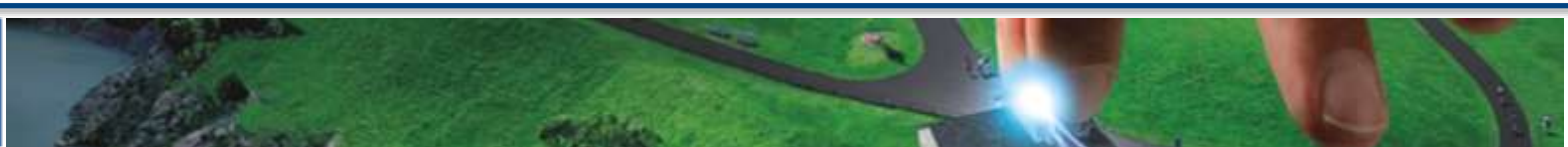




Point-to-Point LVDC Network – General

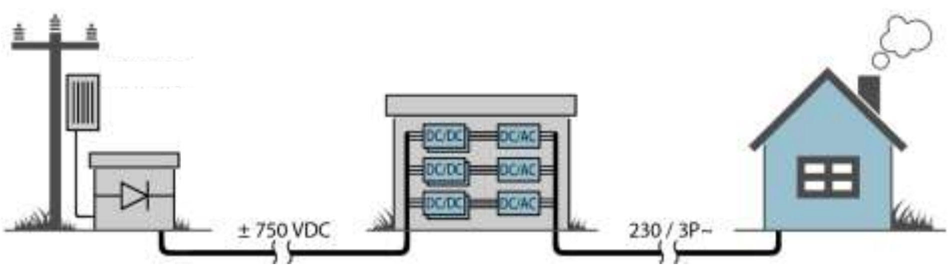
- Commissioned in Mar. 2014
- Co-operation of Finnish DSO Elenia Oy and ABB Oy Drives
- The purpose of the LVDC pilot is to gather long-term experiences of operation and maintenance and also specify life cycle costs of the system.

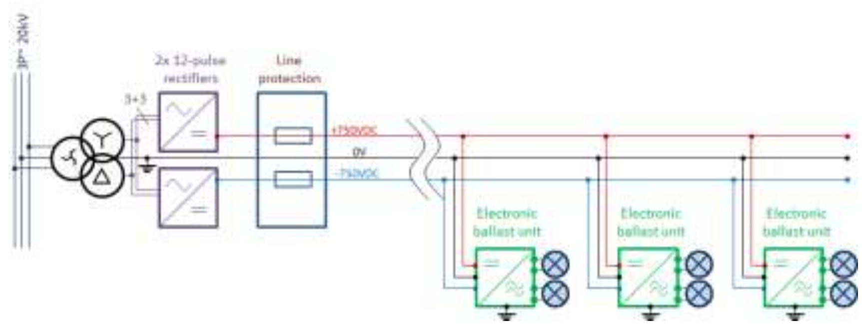
- The system features
  - ABB ACS800-11 active rectifier, 60 kVA
  - Underground unipolar DC cable, length 550 m, +750 VDC
  - ABB ACS800 converter, 150 kVA
  - Additional energy storage, DC-capacitors 187 mF



LVDC Test Network (Ensto Finland Oy)

- Commissioned in 2008, operational 2008-2009
- Co-operation of Finnish DSO and Ensto Finland Oy
- The purpose of the test network was to test DC and power electronics in LV electricity distribution
- Results revealed that the LVDC distribution is possible, but it requires intense research and converter development
- Since then, Ensto has been working with the LVDC distribution and has also developed street lighting solutions based on LVDC

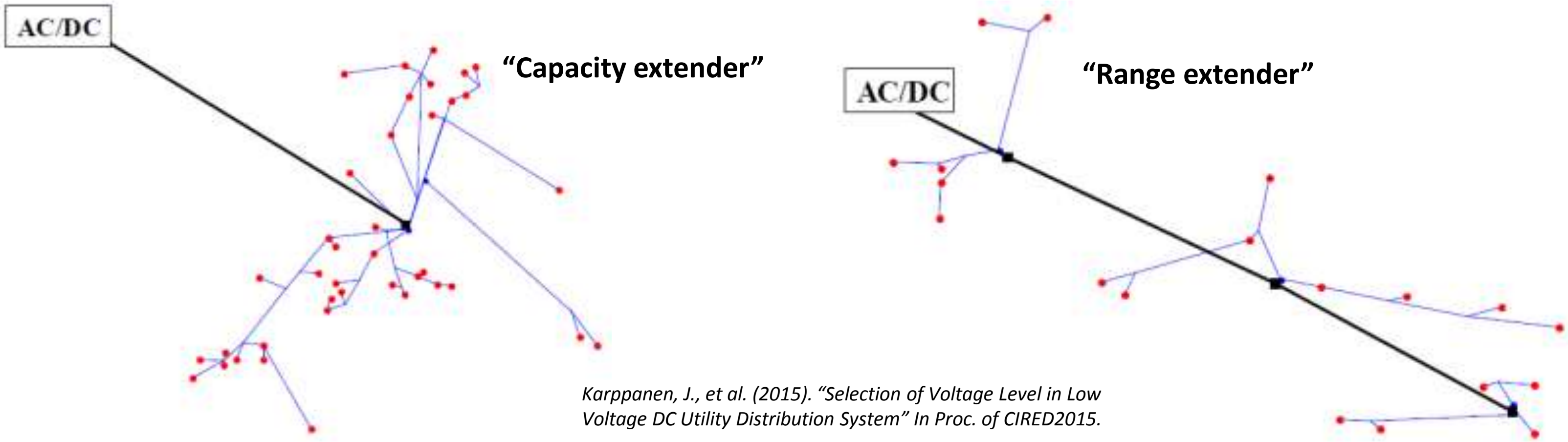




DC Voltage Level Selection

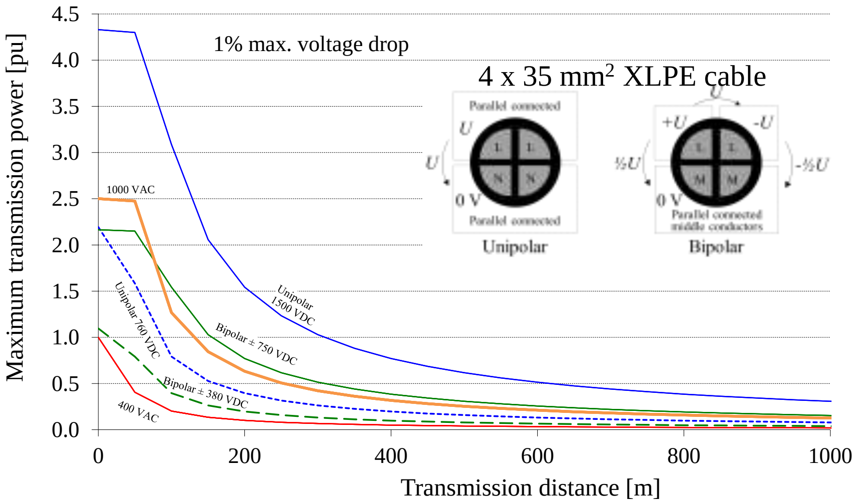
- Availability of the maximum allowed 1500 VDC (European Commission Low Voltage Directive (LVD/2006/95/EC)) is crucial for the feasibility of the rural-area LVDC
  - LVDC can be used to replace low-power 20 kV medium-voltage branch lines
  - long transmission distance (possibly over 10 km), less customers (“range extender”)
  - short transmission distance (from hundreds of meters to kilometers), more customers (“capacity extender”)

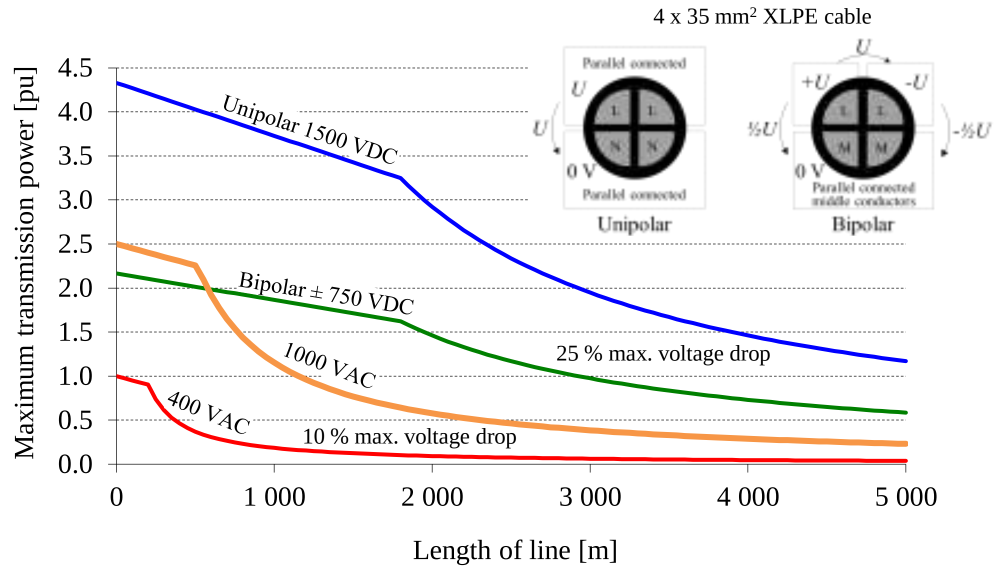
- Voltage selection is a techno-economic trade off
  - lower voltage – less transmission capacity, higher line costs, lower converter costs
  - higher voltage – more transmission capacity, lower line costs, higher converter costs
  - technical and economic benefits compared to AC technology are prerequisites → application potential
    - less transmission capacity, less use cases, less economic benefits



Karppanen, J., et al. (2015). “Selection of Voltage Level in Low Voltage DC Utility Distribution System” In Proc. of CIRED2015.

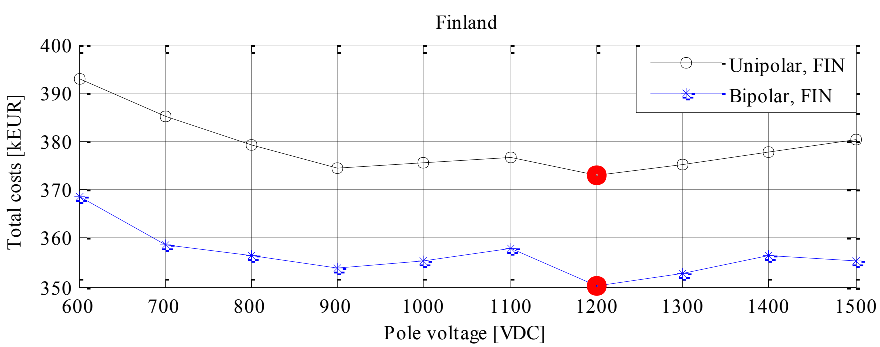
DC Voltage Level – Transmission capacity and economics

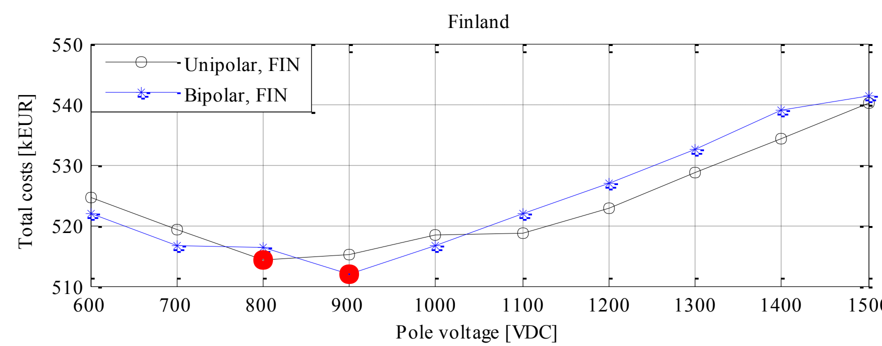




Kaipia, T., Stokman, H., "LVDC in marine vessels and in utility networks - Outcomes of research projects 2009-2014", presentation, IEC SMB SG4 meeting 27th Oct. 2014, Paris, France.

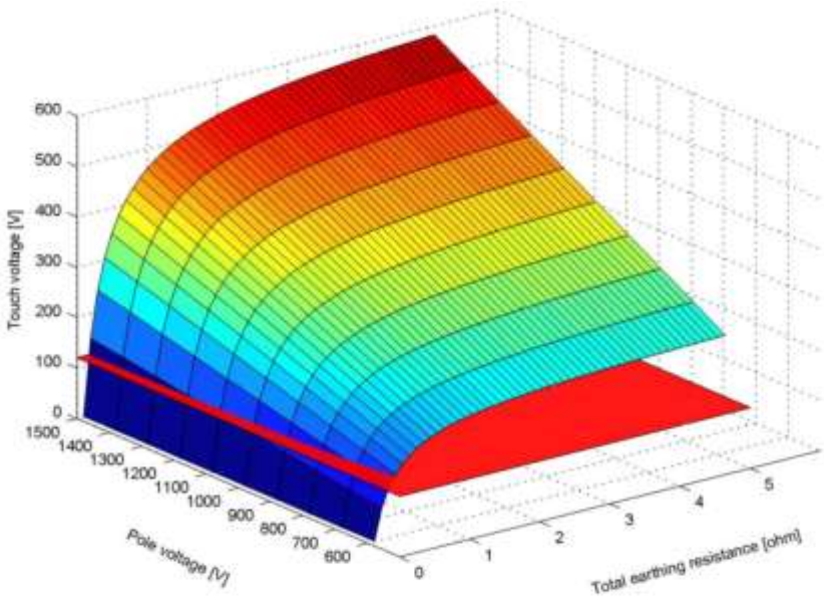
Kaipia, T., et Al., "Low-Voltage Direct Current (LVDC) Power Distribution for Public Utility Networks", EPE 2014, tutorial

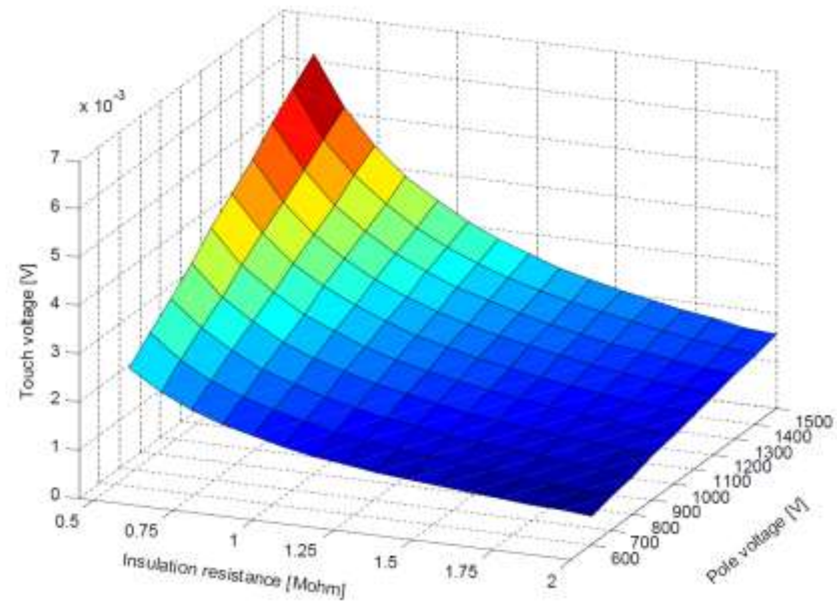




Karppanen, J., et al. (2015). "Effect of Voltage Level Selection on Earthing and Protection of LVDC Distribution Systems". In Proc. of ACDC2015.

Electrical Safety and EMI – Earthing





Earth potential rise in case of earth fault in earthed system with different voltage levels and earthing resistances. Red layer illustrates the limit of earth potential rise of 120 VDC.

Earth potential rise in case of fault between pole and earth in earth isolated system with different voltage andisolation levels. The used earth resistance value was 5 Ω.

Karppanen, J., et al. (2015). "Effect of Voltage Level Selection on Earthing and Protection of LVDC Distribution Systems". In Proc. of ACDC2015.

Electrical Safety and EMI – Short-Circuit Protection

- Causes challenges especially in a CEI that has a ***low nominal current*** and a ***high short-circuit current***
- In the Finnish national standard SFS 6000 series (based on HD 60364, IEC 60364, and IEC 60664)
  - SFS 6000-8-801: the ***recommendation*** for the minimum single-phase short-circuit current is 250 A_{rms}
  - SFS 6000-4-41: the required protection trip time is less than 0.4 s in the protection of customer-end branch circuits
- Typical end-user in Finland has a three-phase AC supply with 3x25 A fuses or circuit breakers

  → with 250 A_{rms}, the ***short-circuit current to nominal current ratio*** **(i_{sc}/i_n)** becomes 10

  → the short-circuit current has to be taken into account when selecting the CEI components
- In load group protection, typical C16A circuit breaker is considered to have the highest trip current
  - → 160 Arms is the current that guarantees the trip
  - → still, (i_{sc}/i_n) becomes 6.4

Electrical Safety and EMI – Short-Circuit Protection

- **Overcurrent supply is the 'Achilles heel' of power electronics that have adverse effect also to LVDC distribution**

- **Why to protect the beyond the state-of-the-art system with ancient methods?**

- **New unconventional protection methods have to be standardized**
  - Fault detection and identification methods not based purely on current magnitude, but on transients and rates of changes, etc.
  - Fault current limitation and interruption with converters and solid-state circuit breakers
  - Fault separation with converter controlled circuit breakers or switches

- **Despite the new protection methods, the CEI has to supply inrush and start-up currents**

Electrical Safety and EMI – Common-mode and radio frequency EMI

- Many electronic devices include an EMI filter, which attenuates frequencies notably higher than the line frequency
- When the customer-end network is supplied with a CEI, there are frequencies higher than 50 Hz, which can lead to three situations
  1. the current through the EMI filter to the earth can be higher than the filter rating, which can result in filter overheating, equipment failure, and a risk of fire
  2. a residual current device (RCD) may trip in normal operation especially if there are several devices with EMI filtering
  3. if a device with an internal EMI filter is connected to an unearthed socket, the potential of the device may rise → risk of an electric shock
- Common-mode current in the DC network has an impact on the feasibility of the power line communication (PLC) in the DC cable and it produces RF disturbances
- There is a need for standardization that covers disturbances from 2 kHz to 150 kHz
  - conducted and radiated – definition of compatibility levels in utility grids and emission/tolerance limits for grid equipment as well as test procedures
  - IEC TC 77A/WG 8 (Description of the electromagnetic environment associated with the disturbances present on electricity supply networks) is already working on part of the topic, but not necessarily considering LVDC in its work!

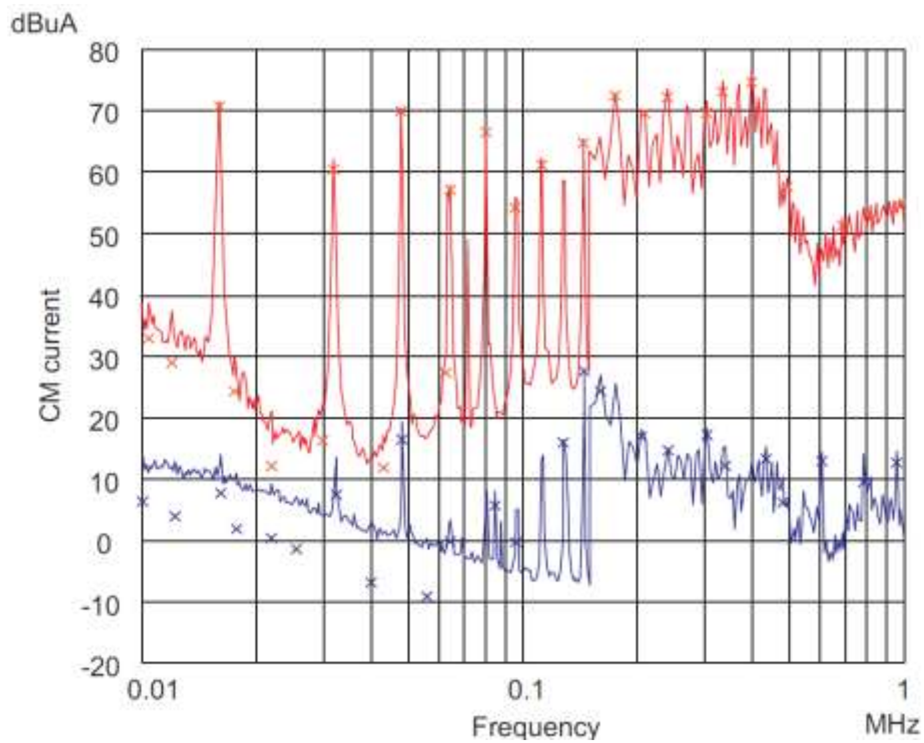
Electrical Safety and EMI – Customer-End

Common-mode EMI

Measured customer-end CM current at the LUT/SSS LVDC research site

Rectifier ON, CEI OFF (only DC network energized)

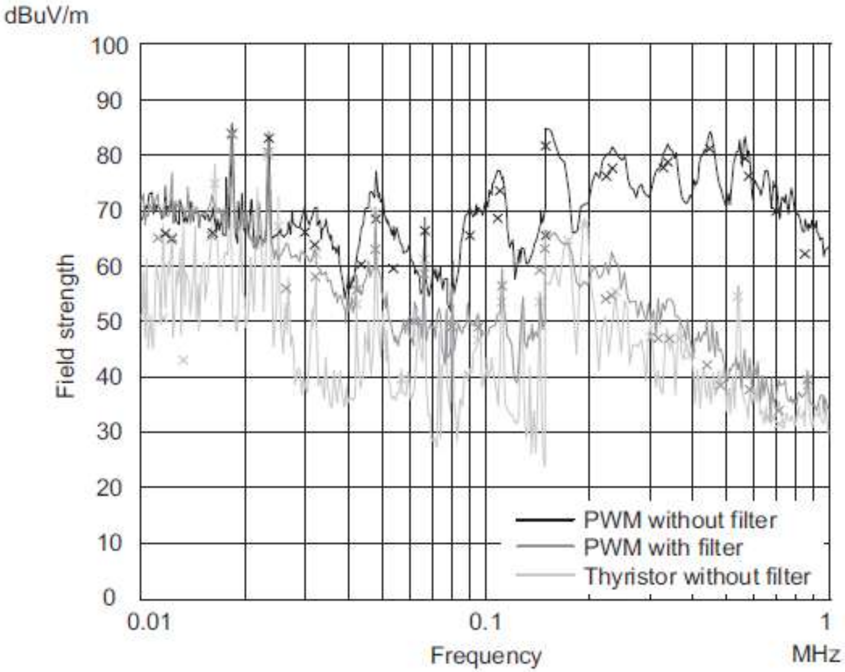
Rectifier ON, CEI ON (normal operation)



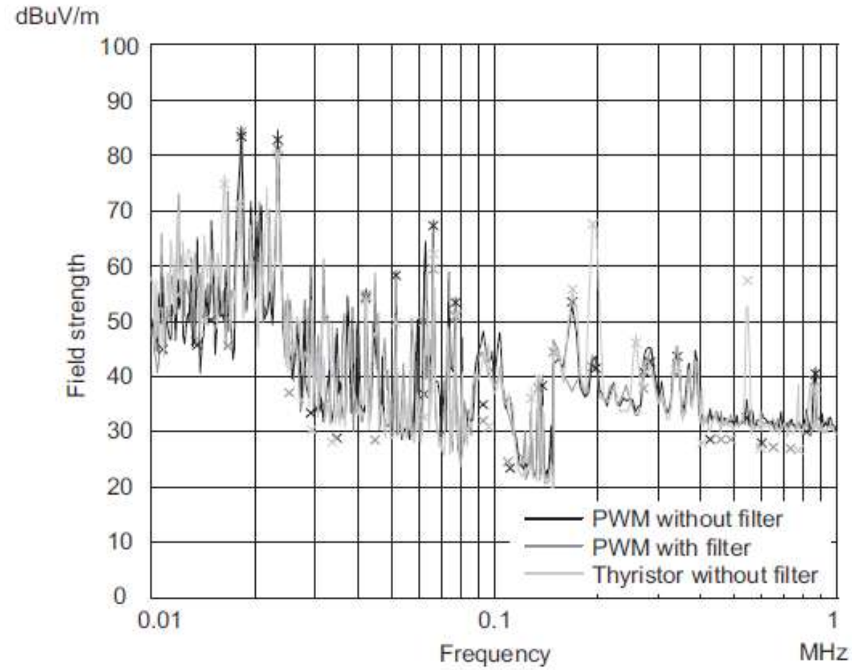
Adapted from Nuutinen, P., et. al. (2014). “On Common-Mode and RF EMI in a Low-Voltage DC Distribution Network.” *IEEE Trans. Smart Grid*, 5(5), pp. 2583–2593.

Electrical Safety and EMI – RF EMI

Measured RF EMI at the LUT/SSS LVDC research site with thyristor bridge rectifier and PWM grid-tie rectifying converter (with and without a common-mode filter)



Energized LVDC network



De-energized LVDC network

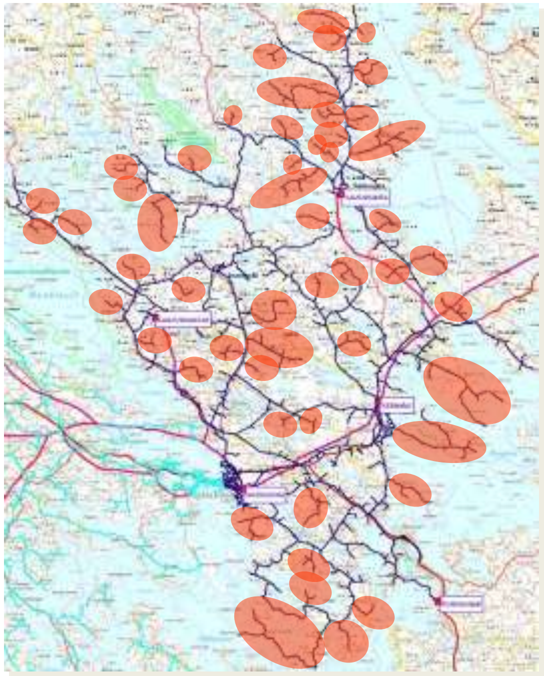
Nuutinen, P. et. al. "Grid-Tie Rectifying Converter Impact on Common-Mode and RF EMI in a Low-Voltage DC Distribution Network.", *in review*

Market Potential and Prospects

- Rural area example (Brenna et. al. and Kaipia et. al.):
  - 5 x 110/20 kV primary substations
  - 14 000 customers (165 GWh)
  - 1 054 km 20 kV medium voltage lines
  - → **approx. 40% of LVAC grids could be replaced with LVDC**
  - → **roughly 30% of end-users connected to markets via LVDC network**
  - → **25-35% life-cycle cost savings for the DSO**

- Elenia Oy (with market share of 12%) has decided to raise its cabling rate to 70% during the next 15 years → about 7,000 km of rural MV branch lines waiting for cost-efficient renovation
  - The utilization potential analysis (*Hakala, T., et. al. Low-Voltage DC Distribution - Utilization Potential in a Large Distribution Network Company. In IEEE Trans. Power. Del.*) shows **that almost all MV branches with a single transformer can be technically replaced by LVDC distribution (about 20% of the total MV network length)**

→ **LVDC distribution is not just a solution for special cases**



Brenna, M., et Al. and Kaipia, T., et Al. "Distributed Generation in DC Distribution System". In *Proc. of CIRED 2007.* Pictures only in conference presentation.

LVDC Stakeholders

- Distribution network/system operators (DSO's)
- Power electronics designers and manufacturers
- Electrical contractors and builders
- ICT solutions providers and network operators
- System installations and maintenance companies
- Software engineering companies (firmware, system control, design and planning, network management)
- Inspection services providers and classification societies
- Energy services providers and electricity traders (suppliers, aggregators, resource managers)
- Distributed generation and energy storage solutions providers
- Versatile consulting companies from technology and design to architecture and business
- Educational institutions (training of planning, design, installation, etc. personnel)
- International, regional and national standardization organizations
- International, regional and national energy associations and agencies
- Governmental energy agencies and authorities (Electricity markets, electrical safety)

Thank you!