LVDC and Power Electronics – Enabling Technologies

Roadmap 2025

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Tero Kaipia, Teuvo Suntio, Tuomas Rauhala
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Introduction

Power Electronics in Grids

SVC

110/20 kV

AC/AC

20 kV

DC

B

HVDC

110 kV, 50 Hz

20 kV, MF

Renner & al.

Wrede & al.

HVDC

AC/DC

110/20 kV

20/0,4 kV

G

G

20 kV

AC

DC

DC

AC

AC/AC

AC/AC

B

DC B

110 kV, 50 Hz

20 kV, MF

VSC / CSC

Wrede & al.

DSSC / D-FACTS

Renner & al.
Introduction
Why Power electronics and LVDC Distribution?

- **Motivation**
  - Even though the Smart Grids is a lot about new services, automation and adding new ICT and IEDs to make the power system more flexible, large investments will anyway be needed to renovate or build primary electrical infrastructure during the next few decades. New power electronics based technologies, such as the LVDC, enable killing two birds with the same stone by offering a mean to build infrastructure with inherent intelligence.

- **LVDC solution**
  - Renaissance of “Edison's” direct current electric system upgraded with modern power electronics and ICT. Offers a low-cost solution for distribution system development and renovation on supply areas with power demand up to 500 kW and area below 30 km², roughly saying.

- **Basic property**
  - Improved technical performance compared to existing low voltage grid solutions – more power transfer capacity with higher controllability by using the same low-voltage cables and line structures. Equal and constant locally controlled high quality power delivery for all end-user on an LVDC supply area. Natural platform for connecting small-scale renewable generation and batteries, and for realising local renewables based microgrids

- **Special feature**
  - Inherently increases the penetration rate of intelligent hardware (Intelligent Electrical Devices, IEDs) in grids, thanks to the converter technology. Provides an open hardware platform for implementing smart applications and services, eg. demand response, congestion management, etc.

- **Implementation philosophy**
  - Replacing existing AC low voltage networks and parts of medium voltage grid with LVDC reduces the total life-cycle costs of electricity distribution while enabling smart services for all the electricity market actors

*Adapted from: Kaipia, T., et Al., “A System Engineering Approach to Low Voltage DC Distribution”, CIRED 2013*
Tehoelekroniikka siirtoverkkotasolla: mahdollisuudet

- HVDC ja FACTS-järjestelmät ovat jo kymmenien vuosien ajan auttaneet ratkomaan yksittäisiä haasteita siirtoverkkotasolla
  - tehonsiirto pitkällä yksittäisillä siirtoyhteyksillä tai reiteillä
    - ilmajohdot >500-1000+ km
    - kaapelit >50-100+ km
  - tehonjaon mukauttaminen
  - jännitestabiilisuus
  - sähkömekaanisten heilahtelujen vaimennus

© Alstom Grid
© Hannu Heikkinen
Tehoelektroniikka siirtoverkkotasolla: haasteet

Luotettavuus

• HVDC ja FACTS laitteet koostuvat lähtökohtaisesti useammista komponenteista (säätö- ja automaatio, puolijohteet, jäähdys)
• laitteiden toimitusmäärät edelleen suhteellisen pieniä, kehitys kiivasta ja standardien kehitys alkuvaiheissa

Perinteisten lainalaisuuksien väistyminen

• inertian vähenneminen → voimakkaammat taajuusvaihtelut (vaihteluväli, muutosnopeudet)
• oikosulkutehon pienentyminen → jännitevaihtelut sekä säättöjärjestelmien keskinäisvaikutukset voimistuvat
• HV AC-järjestelmän tehonjako säätyy automaattisesti → HVDC ja FACTS-järjestelmien säätojen toiminta on koordinoitava
• harmonisen särön taajuusalueen muuttuminen → mallinnus-, mittaus- ja analyysimenetelmät päivitettyä

Korkean käyttövarmuustason saavuttaminen HV AC-teknologiaan perustuvalla voimajärjestelmällä kesti näkökulmasta riippuen 40-80 vuotta.

Kuinka uuden teknologian laajamittaisen hyödyntämisen vaikutus voimajärjestelmän toiminnan käyttövarmuuteen ja luotettavuuteen saadaan mahdollisimman lyhyeksi?
Renewable Energy Systems

DER (Distributed Energy Resources) composes of renewable energy sources such as solar and wind energy, fuel cells as well as energy storage units. DERs can be used as constant-power sources (Fig. 1a,b), which is known as grid-parallel operation, and as constant-voltage sources (Fig. 2a,b), which is known as grid-forming operation.

Fig. 1a Single-stage grid-parallel-connected PV system

Fig. 1b Double-stage grid-parallel-connected renewable-energy system

Fig. 2a Single-stage grid-forming-connected PV system

Fig. 2b Double-stage grid-forming-connected renewable-energy system
State of the Art - PV

TUT Experimental PV Power Plant
In operation since 2010, 69 PV panels organized in three strings with 17-23 modules in series, total peak power about 13 kW, comprehensive data acquisition system including irradiation and temperature sensors as well as weather station. The data sampling rate is 10 Hz. Accessible via internet: www.tut.fi/solar

- PV represents 3.5% of the electricity demand in Europe and 7% of the peak electricity demand.
- PV represents at least 1% of the global electricity demand.

*Source: IEA PVPS report T1-26:2015*

Different grid-connected converters for PV power plants

**FIGURE 1: EVOLUTION OF PV INSTALLATIONS (GWp*)**

Installed capacity (IEA)
State of the Art – PV and IoT
Problems in Renewable Energy Systems

The grid integration of photovoltaic and wind-energy systems by using power electronics is noticed to induce following problems:

- Increase in harmonic currents (i.e., continuous and transients)
- Sub and super harmonic instabilities due to the behavior of output impedance of the grid-connected inverters
- Other stability problems due to improper sizing of DC link capacitors
- Limited short-circuit-current capacity
- Lack of inertia

Characteristics of PV and wind energy sources
- Fluctuations of power during a day especially in PV systems

Fig. a) above shows an electrical resonance problem in a PV Park 2012 in USA. The grid was stabilized by adding a good amount of capacitors in the grid (Fig. b)
Vision and roadmap

✓ In 2035, over 10% of electricity consumption in Finland will be produced with PV connected to weak grids and consumed locally

✓ More automation required on lower levels of the grid

✓ Different parts of the system need to communicate with each other

✓ Battery energy storages operating parallel to PV power plants will be in pivotal role

✓ Operating interconnected to home and grid automation

✓ Increasing amount of DG may lead to oversizing of the grids

✓ Can be avoided by developing the control and automation systems and electricity market models

✓ In the countries, where massive conventional power production based on hydro or nuclear energy still exists, etc., the problems are usually only local.

✓ If the entire electricity production is based on renewables, the grid would not really work in a stable manner.

✓ The stability problem means that there exists a maximum power, which can be produced by means of renewables at every point of connection.

✓ The power fluctuations can be at least in theory smoothed by using energy storages, but the dynamics of PV systems is very fast, which may pose problems in tackling the phenomenon with system topologies favored today.
LVDC

State of the Art

The research sites

Rectifying substation with directly connected converterless BESS

2750 VDC underground cable
Local communications network
ADSL/3G internet connection

Rectifier, DC cable, energy storage, island converter and transformer maintaining island grid – in operation since March 2014

400 VAC
Inverter

750 VDC
Rectifier

20/0.4 kV substation

Open your mind. LUT.
Lappeenranta University of Technology

Tero Kaipia
Technology hype cycle

- TRL of different LVDC applications vary largely
  - TRL of utility grid LVDC distribution is 4-6, depending on use case
- General hype of LVDC is rising sharply and concepts for novel applications are launched constantly
  - The fall of certain specific applications and use cases is inevitable
Part of IoT

Webportal of the LVDC real network research platform
Lappeenranta University of Technology

Tero Kaipia

Lappeenranta University of Technology
4.6.2015
Challenges

- Converters specially developed for LVDC distribution are not commercially available.
- Energy and cost efficiency with existing technology is not yet high enough for wide scale use – however, in some special cases they are on tolerable level.
- Basic components for grids and protection exist but the supply is inadequate, furthermore, the manufacturers often have not certified their products for DC use due to lack of standard test requirements.
- Standardisation development is suffering from the chicken-or-the-egg problem – standardisation would require hard evidence from practical installations, that do not exist partly due to lack of standard components and other rules.
- Other key standardisation gaps are found in EMC requirements and related test requirements, design and installation rules, and in component standards.
- There is not enough knowledge about the reliability, maintenance needs and lifespan of LVDC installations and their components.

- Energy efficiency of converters need to be improved.
  - Converter losses lead to losing efficiency benefits gained in LV network.
  - Especially energy efficiency of customer-end inverters (CEI) in critical role.
  - High number of inverters operating with low peak operating time.

New converter solutions!

LVDC

Vision

community microgrid
Modern LVDC = Smart Infrastructure

”Forget the limitations of the original Edison’s system, but keep its benefits”

- Modern LVDC systems combines the power of the three $Ds$:
  1. Direct Current
  2. Data communication and management
  3. Direct controllability

and the force of the three $Es$
  1. Electrical safety
  2. Efficient use of materials
  3. Economics

- LVDC technology promotes system and service integration
  - Facilitates implementation and exploitation of renewables, energy storages and demand response
  - Enabler of versatile ancillary services for the needs of all electricity market players

Vision and Opportunities

LVDC networks
- Are used to replace the low-voltage AC networks and when applicable also lateral parts of medium-voltage AC networks
- Provide superior level of electrical safety and a ready-to-use platform for smart monitoring, demand management and automated network control than an AC system with respective properties
- Can remarkably decrease the costs of the supply security investments required by the electricity market act and in any case will provide lower life-cycle costs
- Can form local microgrids, that depending on available resources, can operate in island mode and provide very high supply security
- Increases controllability of distribution systems by providing ready-to-use hardware for realising local reactive power/voltage control in MV networks without additional investments
- Increase controllability of the power system by providing ready-to-use hardware for frequency based controls can be easily taken into use, if suitable controllable resources (e.g. flexible loads or energy storages) are available
  → Virtual inertia can be introduced to stabilise the power system
- Ensure controlled high-quality supply voltage for customers’ appliances and an easy-to-control connection point for small-scale generation units and storages

Internationally emerging use cases

May have crucial impact on power systems internationally

LVDC in homes

LVDC in public networks

LVDC in ships

Fig. 1 Elements in a DC distribution power system

Source: Chi Zhang, Aalborg University, Denmark

Fig. 1. Single-line diagram of the KEPCO’s traditional MVAC distribution network at Boeun

Fig. 2 Basic architecture for a DC distribution power system

Source: Chi Zhang, Aalborg University, Denmark

Fig. 2. Configuration of the proposed LVDC distribution system to replace the traditional MVAC at Boeun

Source: David Afamefuna, Kookmin University, Korea

Sources: Wärtsilä / ABB Marine
Application history and prospects for future

**Roadmap**

LVDC

Source: Jeff Casady, John Palmour, Cree Power – Sept 2014 HMW Direct-Drive Motor Workshop
Example Scenarios for Commercialisation

Some international activities

New Low Voltage Direct Current Power Distribution
Code of Practice
14 May 2014
IET Communications team

Low Voltage Direct Current
Powering energy demands in our digital world
18 June 2015 | Broadway House Conference Centre, London, UK

DC in the Greenhouse
The greenhouse market is widely using LED lighting fixtures to illuminate the crops. When using supplemental lighting based on AC, a conversion of AC to DC is needed to convert it into DC in each lighting fixture. By centralizing conversion of AC to DC, instead of local conversion in each of the lighting fixtures, a lot of energy would be saved.

The “Stroomversnelling”
In a project renovation of 130,000 homes with a new concept of Zero-energy meter homes, with their own energy generation and energy storage, the building system is a DCM2 system. Direct Current Ltd implements a centralized DC system in three phases, with the aim to make it possible to have a home working completely on DC.

Public Lighting on DC Smart Grid
Direct Current Ltd has developed DC-sources for LED-lighting and a system for public lightings, as well as an intelligent DC system for a DC smart grid for public lighting. In co-operation with Cong tec, this is being implemented in several pilot projects.

MVDC/LVDC Converter
Within the EU project DC-M2DC, a part of this project involves the research and development at medium voltage to low voltage DC/DC converter.

DC=DeCent
In the project DC=DeCent generated power of local OPHs is being linked to a management system for regulating demand and supply of electric energy. The linking is realized by means of a small scale network on the back of direct current (DC), wherein the real limit is exceeded.

Drive Train Electric Mobility
Direct Current Ltd, already Daimler and currently TO Drift, invest, on their own lines in developing a new integrated drive system (drive train), sponsored by the Ministry of USA as a part of the HTUS Program by the Government. This development should lead to a greatly improved drive-train in which all parts are aligned.
R&D needs and next steps forward

- Converter technology
  - Solutions to improve energy efficiency
  - Life-cycle costs optimisation of converter design
  - Converter control systems and interfaces with the system level control
- Use of power electronics based solutions in protection
  - Solid-state breakers
  - use of converters as relay units
  - new fault identification methods
- Market models and respective control algorithms for microgrids and included DER
  - Implementation of market oriented services
  - ICT solutions and interfaces (M2M and H2M)
  - Automation systems and related systems oriented control algorithms
- Processes and tools for planning, construction and operating
  - Software solutions for network planning and calculations
  - Maintenance processes and condition monitoring solutions
- Regulations and legislation
  - Rules concerning ownership and utilisation of energy storages
  - Influencing to the development of standardisation for LVDC and other power electronics applications
- Large-scale piloting to support R&D, commercialisation and standardisation
- Education of DC grid specialists from fitters to designers
**Conclusions**

**Opportunities**

- Improving technical performance and decreasing of costs
  - Life cycle-economics
- Increased controllability
  - Can improve system dynamics and serve as an interface to provide inertial response to the system
  - Can be used to improve voltage quality and reliability
  - Source and drain impedances can be controlled → fault management
- Improved safety and management
  - More measured information
  - Redundancy to grid management
- Flexible platform for implementing versatile market-based services

**Challenges**

- Reliability and energy efficiency of converters
- Lifespan and maintenance needs
  - Life-cycle economics
- Change of system behaviour
  - Reduction of inertia and related dynamic stability issues
  - Behaviour of system impedance and short-circuit currents
- Increasing need for active control
- Standardisation and other requirements for instance for test procedures are immature
  - Standardisation is crucial to prevent problems due to poor design!

**Power electronics**

✓ applications will continue to increase along with increase of DG and implementation of other DER
✓ can be used to solve the technical problems that it may itself cause
✓ gives an opportunity to realise functionalities that are impossible with conventional grid technologies
✓ is central part of IoT for energy systems and markets